Contributions to Economics

Anvita Arora
Fateh Belaïd
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Climate-Resilient Cities

Priorities for the Gulf Cooperation Council Countries

KAPSARC
مركز الملك عبدالله للدراسات والبحوث البترولية
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Foreword

The GCC Imperative: Building Climate Resilience in a Dynamic Region

The Gulf Cooperation Council (GCC) faces a complex opportunity: rapid urbanization. While the demographic shift necessitates innovative solutions to ensure sustainable energy security and social equity in its growing cities, it also presents a chance to boost economic growth and unlock the potential productivity of new urban residents. As these cities expand, the need for reliable and sustainable energy sources becomes crucial, as does equitable access for all residents. *Climate-Resilient Cities: Priorities for the Gulf Cooperation Council Countries* is a timely volume that addresses this critical issue head-on.

The aim of this volume is twofold. First, it provides an overview of key trends in city resilience development, covering approaches to enhancing essential systems such as energy, water, and transportation. Second, it examines how these trends intersect with the specific context of GCC cities and the broader region.

While projections indicate that two-thirds of the world's population will inhabit urban areas by 2050, the GCC cities have already exceeded this mark. As of 2023, the urbanization rates in GCC states surpass 80%, with some reaching over 90%. These cities face multifaceted challenges, ranging from environmental degradation and unsustainable energy use to social inequalities and natural disasters. Traditional urban planning approaches are no longer sufficient to address these interconnected challenges, which require innovative, holistic, and adaptive planning strategies. Resilient cities have the potential to create sustainable, prosperous, and livable urban spaces that can withstand various shocks and stresses. Implementing resilient city principles demands a paradigm shift in urban planning and governance, emphasizing interdependencies between urban systems and robust stakeholder engagement.

In recent years, the concept of resilient cities has generated notable interest from academia, industry, and policymakers within and beyond the GCC region. However, research into resilient cities remains nascent, and the concept, while gaining momentum, still lacks comprehensive practical frameworks. This book aims

to bridge this gap by aggregating various high-quality theoretical and empirical studies, focusing on the interaction of social, entrepreneurial, governmental, and ecological transformations in the GCC region.

Climate-Resilient Cities: Priorities for the Gulf Cooperation Council Countries explores urban resilience strategies tailored to the GCC region's unique challenges. The book examines how advanced technologies like the Internet of Things, artificial intelligence, and big data can integrate with community initiatives and strong policies to create thriving urban environments that prioritize well-being, transparency, economic competitiveness, and sustainability.

The book delves into a diverse range of topics, including innovative concepts and studies in the design, planning, implementation, and evaluation of resilient cities. Focusing on the GCC region is crucial because its cities face a unique confluence of challenges that necessitate tailored solutions.

Building resilient cities goes beyond addressing immediate needs, and this book explores the evolution of research in this critical field, asking pivotal questions such as: How has the concept of urban resilience been defined and refined over time? What are the key challenges and gaps identified by past research on resilient cities, particularly within the GCC context? The book does not stop here, either, as it delves into the crucial issue of determining the best policy mixes for fostering resilient cities: Which combinations of economic, social, and environmental policies have proven most effective in building resilience, specifically in the GCC region? How can policymakers leverage these findings to create a tailored policy mix that addresses the unique challenges of GCC cities? Recognizing the critical role of resilient energy systems, the volume also examines questions such as: Which energy technologies and infrastructures most effectively promote urban resilience in the GCC context? How can we ensure equitable access to clean and reliable energy in rapidly urbanizing GCC cities?

By addressing these critical questions alongside its focus on practical solutions, *Climate-Resilient Cities* offers a comprehensive roadmap for policymakers, planners, and citizens. It will help them to build strong and adaptable cities that can withstand climate change and other pressing challenges. The book goes beyond immediate solutions by laying the foundation for future advancements in building resilient cities throughout the GCC region.

This book is organized into three sections. The first section frames the issue by exploring city resilience concepts and mapping the research landscape on resilient cities. The second section delves into city systems' resilience, covering crucial elements such as buildings, water, transport, nature-based solutions, and social networks and communities. The final section addresses special zones and case studies, including the role of nature-based solutions in small island resilience, Riyadh's Urban Greenwave, and the resilience of GCC ports and airport infrastructures.

I would like to thank the editors and everyone who contributed to this volume. Their contributions and insights are essential for improving our understanding of urban resilience in the GCC. *Climate-Resilient Cities: Priorities for the Gulf Cooperation Council Countries* will be a valuable resource for policymakers,

planners, and researchers, providing essential knowledge and tools for building resilient and sustainable cities.

President, KAPSARC Fahad Alajlan
Riyadh, Saudi Arabia

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Advancing Cities' Resilience: A Comprehensive Review and Mapping of Research

Fateh Belaïd, Raphael Apeaning, and Anvita Arora

Abstract The concept of resilient cities has emerged as a critical paradigm for addressing the complex challenges facing urban areas in the twenty-first century. We conducted a comprehensive analysis integrating bibliometric techniques and latent topic modeling to elucidate the evolving research landscape on resilient cities. We used a dataset comprising 532 research articles from the Web of Science database to identify key themes and trends shaping urban resilience and development discourse. Through multiple correspondence analysis and structural topic modeling, we extracted and analyzed the underlying conceptual structure of the literature, uncovering interconnected topics and prevalent themes. Our findings revealed eight primary topics: smart urban development, climate adaptation, climate risks, governance, risk management, community planning, green infrastructure, and energy management. By visualizing the intricate connections between these topics, we provide a nuanced understanding of the multifaceted nature of urban resilience. Our findings underscore the imperative of integrated urban planning and policy-making approaches that transcend disciplinary boundaries and embrace the complex dynamics shaping urban systems. The insights gleaned from this study not only enrich scholarly discourse but also offer actionable guidance for policymakers, urban practitioners, and researchers, facilitating the development of evidence-based strategies to foster resilient, sustainable, and equitable urban futures.

Keywords Urban resilience · Sustainable cities · Climate adaptation · Inclusive urban development · Topic modeling

1 Introduction

The built environment, encompassing real estate and infrastructure, wields significant influence over human existence, extending from residential and commercial

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spaces to industrial facilities and transportation networks. Currently, approximately 57% of the global population, equivalent to 4.4 billion people, resides in urban areas—a figure projected to escalate to 70% by 2050 (World Bank, 2024). Urbanization dynamics are predominantly driven by population growth and the corresponding expansion of infrastructure, a trend particularly pronounced in developing nations.

Globally, the urban population is escalating at a rate of 2% annually, with Sub-Saharan Africa experiencing an even swifter growth rate of 4% (World Bank, 2024). This trajectory is expected to double the number of regional urban residents within two decades.

Urban centers, projected to contribute over 60% of total gross domestic product (GDP) growth by 2060 and accommodate an additional 2.1 billion inhabitants by 2050 (Zhou et al., 2019), are pivotal drivers of global economic advancement. However, this economic prosperity comes with a significant environmental cost as urban areas are responsible for a staggering 70% of global anthropogenic CO_2 emissions, exacerbating climate change and intensifying the frequency and severity of extreme weather events (Perera et al., 2023), which escalates city mortality rates and hinders economic progress (Romanello et al., 2021).

Projections suggest that, by 2050, the cumulative economic toll of climate change could reach US$8 trillion, potentially stifling GDP growth by 6.6% by the end of the century (Takakura et al., 2019). Consequently, there is an urgent need to prioritize enhancing climate resilience and sustainability in urban environments while also promoting urban densification. This multifaceted challenge demands immediate attention and concerted action.

Despite serving as catalysts for economic growth and hubs for innovation and sustainable development, cities face numerous challenges threatening their sustainability and well-being. Urban areas grapple with an array of stressors, including the ramifications of climate change, natural disasters, socioeconomic disparities, and pandemics. Hence, urban resilience, defined as the capacity of cities to anticipate, withstand, adapt to, and recover from these challenges, has emerged as a critical concept in the realm of urban studies and planning (Folke et al., 2010; Belaïd 2024; Ramdani and Kawalek 2024).

The concept of urban resilience encompasses a holistic understanding of cities as dynamic systems shaped by interactions between social, economic, environmental, and institutional factors (Pickett et al., 2004; Meerow et al., 2016; Ribeiro & Gonçalves, 2019). It recognizes the interconnectedness of urban systems and the need for integrated approaches to enhance cities' ability to thrive in the face of uncertainty and disruption. As such, urban resilience goes beyond mere survival to encompass the ability to bounce back stronger, fostering sustainable development and inclusive growth (Collier et al., 2013; Arup, 2014).

This review article aims to map out existing research on urban resilience, providing an overview of the key dimensions, methodologies, and emerging trends in the field. By synthesizing and analyzing a diverse range of literature, this review seeks to contribute to a deeper understanding of urban resilience and inform future research, policy, and practice aimed at building more resilient cities (Meerow et al., 2016).

Despite the growing interest and recognition of urban resilience and its importance in climate change adaptation and mitigation efforts, there remains a notable gap in the literature regarding a comprehensive synthesis and mapping of existing research in this field. While numerous studies have examined various aspects of urban resilience (Meerow et al., 2016; Cariolet et al., 2019), the absence of a cohesive overview that brings together the diverse strands of literature to identify common themes, methodological approaches, and emerging trends is evident. This gap underscores the significance of this review article. This review aims to address this gap by providing a systematic mapping of research on urban resilience, thereby contributing to the growing body of knowledge on this topic and supporting efforts to build more resilient, sustainable, and inclusive cities in the face of an uncertain future.

This chapter makes several contributions to the existing literature. First, it synthesizes existing knowledge by comprehensively analyzing a wide range of literature. Through this synthesis, this chapter offers an in-depth overview of the key dimensions, prevalent topics, and emerging trends in urban resilience research.

Second, this chapter identifies research gaps by scrutinizing existing literature. Through this process, it pinpoints areas for further research within the field of urban resilience. These insights are crucial for informing future research agendas and guiding scholars and practitioners in addressing critical knowledge gaps.

Third, this chapter integrates diverse perspectives and the interconnection between topics to provide a holistic understanding of urban resilience. Recognizing that urban resilience is a multidisciplinary and interdisciplinary field, drawing insights from urban planning, environmental science, sociology, economics, and other disciplines, this integration of diverse perspectives enriches the understanding of urban resilience and its implications for policy and practice.

Finally, this chapter offers guidance for policy and practice by highlighting key findings and emerging trends. It provides valuable insights for policymakers, urban planners, and practitioners seeking to enhance the resilience of cities. Practical recommendations and strategies are proposed for building more resilient, sustainable, and inclusive urban communities.

The remainder of this chapter is structured as follows. Section 2 outlines the methodology employed for the literature review and selection of studies. Section 3 presents and discusses the results according to different dimensions of urban resilience methodological approaches, and emerging trends. Finally, Sect. 4 concludes the article by summarizing key findings and highlighting avenues for future research.

2 Methodology

This study employed a hybrid methodology combining bibliometric and textual analyses to investigate the dynamic trends in resilient city research.

Bibliometric analysis is a quantitative method used to analyze patterns and trends within scientific literature. It involves examining bibliographic data, such as publication counts, citation counts, and co-authorship networks, to gain insights into the structure and dynamics of a research field (Aria & Cuccurullo, 2017). In this study, bibliometric analysis was employed to identify and analyze relevant articles on resilient cities from the Web of Science database. By examining publication trends, authorship patterns, and keyword co-occurrences, bibliometric analysis provides a comprehensive overview of the research landscape, helping to identify key themes and areas of focus within the literature.

We conducted searches using the Web of Science database to ensure a comprehensive examination, employing specific search criteria within the topic field.

Specifically, we employed the following search criteria within the topic field: *("climate change" OR "climate adaptation" OR "climate mitigation" OR "low carbon" OR "circular economy" OR "infrastructure") AND ("resilient city" OR "urban resilience").*

Initially, our search yielded a sample of 578 articles, which underwent rigorous scrutiny to ensure relevance and suitability for analysis. After this process, a final sample of 532 articles was selected for in-depth examination. Utilizing the bibliometrix package in R software, we conducted a Multiple Correspondence Analysis of Author's Keywords, allowing us to extract and visualize the conceptual structure present within the sample of articles.

To complement our understanding of the conceptual landscape, we employed latent topic modeling techniques using the structural topic modeling package stm in R.

Latent topic modeling is a natural language processing technique used to uncover latent themes or topics within a collection of textual data, such as research articles, essays, or social media posts. It allows researchers to identify underlying patterns in the discourse and explore the semantic structure of the text (Blei et al., 2003). This study applied latent topic modeling to extract thematic patterns and discourse within the articles on resilient cities.

This approach enabled us to identify latent themes and their prevalence in the literature, providing further insight into the nuanced discourse surrounding resilient cities research.

In summary, bibliometric analysis provides a quantitative overview of the research landscape, while latent topic modeling offers a qualitative exploration of thematic patterns and discourse within the literature. Together, these approaches enable a comprehensive examination of the evolving trends and thematic structure of research on resilient cities.

3 Results and Discussion

3.1 Research Trend

Figure 1 illustrates the dynamic evolution of research on resilient cities over the past decade, revealing a significant growth trajectory. During this period, a total of 532 articles have been published, reflecting a burgeoning academic interest in the subject. Notably, the field has experienced a consistent annual percentage growth rate of approximately 29%, indicating a sustained momentum in scholarly exploration.

Since 2018, there has been a remarkable upsurge in the number of publications focusing on cities' resiliency, accounting for over 80% of the total publications in this area. This surge underscores a rapid acceleration of interest in resilient cities in recent years, underscoring this topic's increasing importance and relevance in academic discourse.

3.2 Resilient Cities Research Landscape and Key Dimensions

Figure 2 illustrates the conceptual structure map, providing insights into the diverse dimensions of research on resilient cities. The map identifies critical areas of focus

Fig. 1 Articles published by year over 2009–2023. (*Source*: Authors' design)

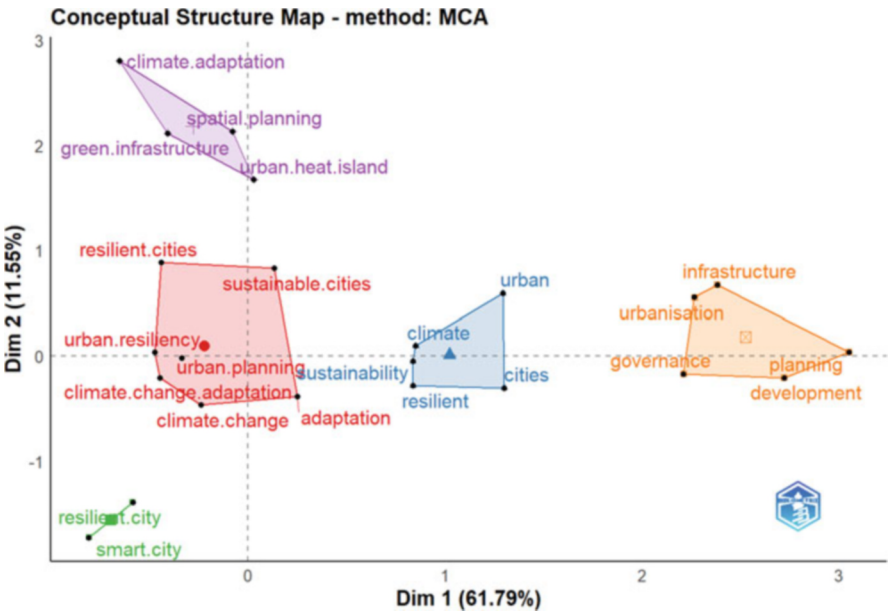

Fig. 2 Conceptual structure map. (*Source*: Authors' design)

and potential gaps in the literature, from environmental considerations to technological innovations and governance structures to urban development processes.

In the top-left quadrant, there is a pronounced emphasis on climate-related topics and green infrastructure, indicating a growing acknowledgment of the environmental aspects of urban resilience. This focus suggests an active pursuit of strategies to address climate change impacts and promote sustainable infrastructure development, aligning with global efforts to combat climate change and foster environmentally sustainable urban areas (Foster et al., 2011; Shade et al., 2020).

Conversely, the bottom-left quadrant underscores the increasing integration of technology and innovation in urban resilience strategies. Concepts such as smart city and resilience highlight a shift toward leveraging digital solutions and smart infrastructure to enhance cities' adaptive capacities (Belaïd & Anvita, 2024; Zerguini & Gaussier, 2024.; Belaïd et al., 2024a, b; Hachette & L'Hostis, 2024). This underscores the importance of integrating technological advancements into urban planning and management practices to build more resilient cities suited for the digital era (Williams & Charles, 2024; Gholami et al., 2024).

The absence of concepts in the top-right quadrant hints at potential research gaps or less-explored areas within the field of resilient cities. This quadrant presents an opportunity for further investigation into topics that may not have received as much attention or have not been extensively studied yet. Exploring this quadrant could uncover novel insights and perspectives, contributing to advancing the understanding of urban resilience.

In contrast, the bottom-right quadrant emphasizes urban management's structural and political dimensions in bolstering resilient cities (Vale, 2014). Concepts such as infrastructure, urbanization, governance, planning, and development underscore the significance of effective governance structures and urban planning processes in enhancing cities' resilience to various challenges. This quadrant underscores the interdisciplinary nature of resilient cities research, emphasizing the necessity for holistic approaches that encompass social, economic, political, and environmental factors.

Overall, the conceptual structure map provides valuable insights into the multi-faceted research landscape of resilient cities. While it illuminates key areas of focus, it also brings attention to potential research gaps, highlighting the need for further investigation into topics that have not received as much attention or have not been extensively studied yet. These gaps encompass various aspects, including the lack of studies addressing specific challenges such as social equity, cultural diversity, or community empowerment (Meerow et al., 2019; Fiack et al., 2021), as well as limited research on the effectiveness of resilience-building strategies across different urban contexts (Kapucu et al., 2021).

Moreover, there is a need for more interdisciplinary research that integrates insights from various fields, such as urban planning, environmental science, sociology, economics, and technology (Laskey et al., 2023). Additional gaps include the limited understanding of the long-term impacts of urbanization and climate change on resilience capacities (Leal Filho et al., 2019), the role of governance structures and policy frameworks in fostering resilience (Fastiggi et al., 2021), and the integration of traditional knowledge and indigenous perspectives into resilience strategies (Bohensky & Maru, 2011; Tsosie, 2019). Addressing these research gaps holds the potential to advance the field of resilient cities and inform the development of more effective policies, strategies, and interventions aimed at building resilient, sustainable, and inclusive urban communities.

The information gleaned from the map provides a comprehensive insight into the research landscape of resilient cities. These findings inform future research directions and guide urban planning practices aimed at constructing more resilient and sustainable cities.

3.3 Prevalent Topics and Their Ranking by Proportion

The analysis reveals eight main topics, offering a comprehensive view of the diverse research landscape on resilient cities. Each topic illuminates crucial aspects of urban resilience and provides insights into how cities can tackle various challenges, spanning from climate change and urban flooding to sustainable development and governance.

Figure 3 provides a visual representation of the highest word probabilities for each topic, revealing the most prevalent terms in discussions about resilient cities. Each topic is represented by a set of words with corresponding probabilities,

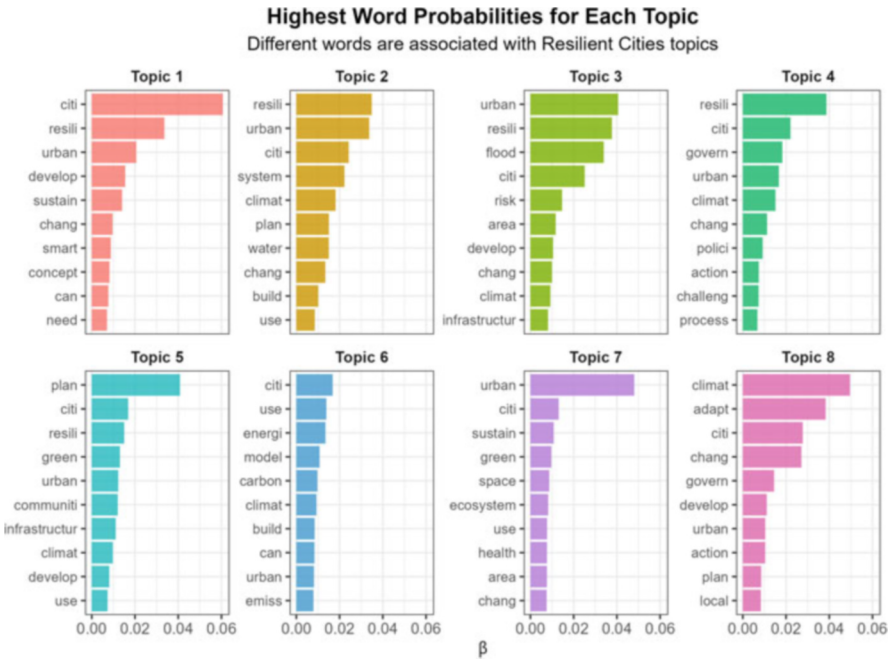

Fig. 3 The highest word probabilities for each topic. (*Source*: Authors' design)

indicating the likelihood of these terms being associated with that specific topic. Figure 4 displays a ranking of the identified topics according to their proportions, which denotes the percentage of total occurrences within the dataset. A number identifies each topic.

For instance, Topic 1, ranked the first, characterized by keywords such as "Cities," "Resilience," and "Urban," underscores the fundamental importance of resilience within urban contexts, highlighting the urgency of fortifying cities against various stressors and shocks (Chirisa et al., 2016). This topic underscores the integration of technology and innovation in urban planning to bolster cities' resilience against a myriad of challenges, including climate change, rapid urbanization, and socioeconomic fluctuations. It advocates for implementing smart infrastructure capable of adapting dynamically to changing conditions, thereby ensuring sustainable development and enhancing the quality of life for urban residents.

Meanwhile, Topic 2, ranked third, which includes terms such as "Resilience," "Urban," and "Cities," further emphasizes the centrality of resilience in urban planning and development strategies (Eraydin, 2012). Reflecting the imperative for cities to embed climate considerations across all facets of urban planning, this topic emphasizes the design of urban systems—such as transportation, energy, and water management—to curtail greenhouse gas emissions, bolster resource efficiency, and fortify cities against the impacts of climate change.

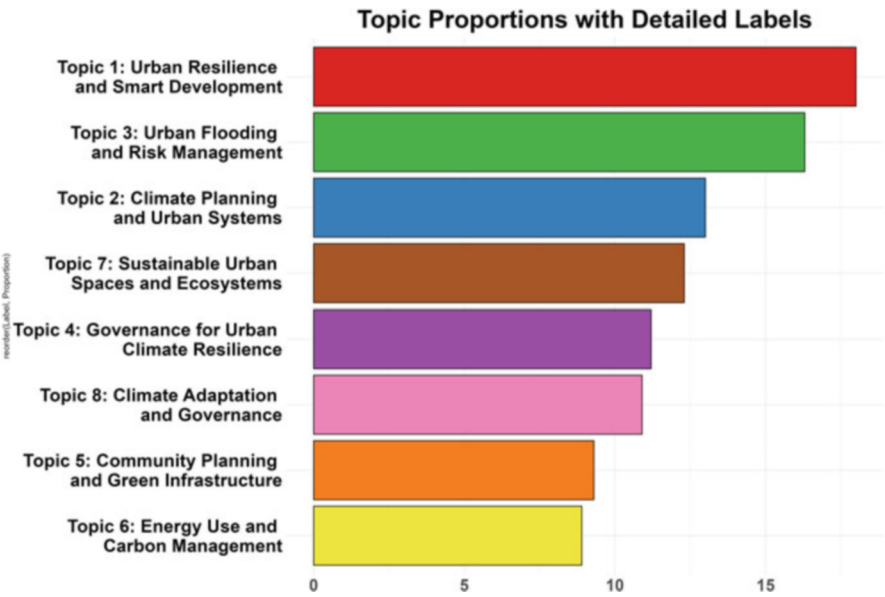

Fig. 4 Ranking of topics based on proportions. (*Note*: This ranking is determined by the expected proportions of the identified topics, highlighting their relative significance and prevalence within the analyzed dataset. *Source*: Authors' design)

Moving to Topic 3, ranked second, where terms such as "Urban," "Resilience," and "Flood" predominate, we observe a particular emphasis on addressing the growing threat of urban flooding and the imperative of implementing robust risk management measures to safeguard urban areas and their inhabitants (Jha et al., 2012). Addressing the escalating threat of flooding in urban areas, exacerbated by climate change and insufficient urban drainage systems, this topic highlights the importance of comprehensive risk management strategies. These strategies encompass flood prediction models, resilient infrastructure initiatives, and community preparedness programs aimed at mitigating the impacts of flooding on cities and their inhabitants.

Similarly, Topic 4, ranked fifth, featuring keywords such as "Resilience," "Cities," and "Governance," sheds light on the critical role of effective governance structures in bolstering urban resilience, emphasizing the need for cohesive policies and regulations to support sustainable development and climate adaptation initiatives (Tanner et al., 2009). Highlighting the indispensable role of effective governance in nurturing urban resilience in the face of climate change, this topic emphasizes the need for policies and regulations that endorse sustainable development, climate adaptation, and disaster risk reduction. Moreover, it underscores the significance of stakeholder engagement and cross-sector collaboration in attaining these objectives.

Transitioning to Topic 5, ranked seventh, which includes terms such as "Planning," "Cities," and "Resilience," we discern a strong emphasis on community-centered planning approaches and the integration of green infrastructure solutions to foster more resilient and livable urban environments (Desouza & Flanery, 2013). Emphasizing community involvement in urban planning processes and the deployment of green infrastructure solutions, this topic advocates for creating more resilient and livable cities. It promotes sustainable transportation, renewable energy adoption, efficient water management, and the development of green spaces—all rooted in active community participation and responsive to local needs.

Moreover, Topic 6, ranked eighth, comprising terms such as "Cities," "Use," and "Energy," draws attention to the significance of energy management and carbon reduction strategies in mitigating the environmental footprint of urban areas and advancing toward low-carbon urban development (Thellufsen et al., 2020). Focusing on strategies to diminish energy consumption and regulate carbon emissions in urban areas, this topic advocates for energy efficiency measures, the transition to renewable energy sources, and the implementation of carbon capture and storage technologies. The overarching aim is to steer urban development toward a low-carbon trajectory, thereby contributing to the global effort to mitigate climate change.

In Topic 7, ranked fourth, where terms such as "Urban," "Cities," and "Sustainability" prevail, we encounter a focus on promoting sustainable urban spaces and ecosystems, highlighting the crucial role of green infrastructure in enhancing the overall resilience and sustainability of cities (Childers et al., 2014). Focused on the establishment and upkeep of green spaces and ecosystems within urban environments, this topic underscores the value of parks, green roofs, urban forests, and water bodies. These elements play pivotal roles in enhancing air and water quality, providing recreational spaces, fostering biodiversity, and bolstering cities' overall resilience and sustainability.

Finally, in Topic 8, ranked sixth, which encompasses keywords such as "Climate," "Adaptation," and "Cities," we discern a specific emphasis on climate adaptation strategies tailored to urban contexts, underlining the urgency of proactive measures to address the impacts of climate change on cities (Geneletti & Zardo, 2016). This topic closely aligns with the preceding label but places particular emphasis on adaptation strategies tailored to combat the impacts of climate change. It stresses the indispensability of adaptive governance frameworks characterized by flexibility, inclusivity, and integrating scientific insights with local knowledge to craft effective climate adaptation measures.

In essence, Fig. 3 not only provides a snapshot of the predominant themes within resilient cities discourse but also offers valuable insights into the multifaceted strategies and approaches employed to build resilient, sustainable, and adaptive urban environments. The ranking illustrates the varying emphasis placed on urban resilience and sustainability aspects, each offering unique approaches to managing urban challenges.

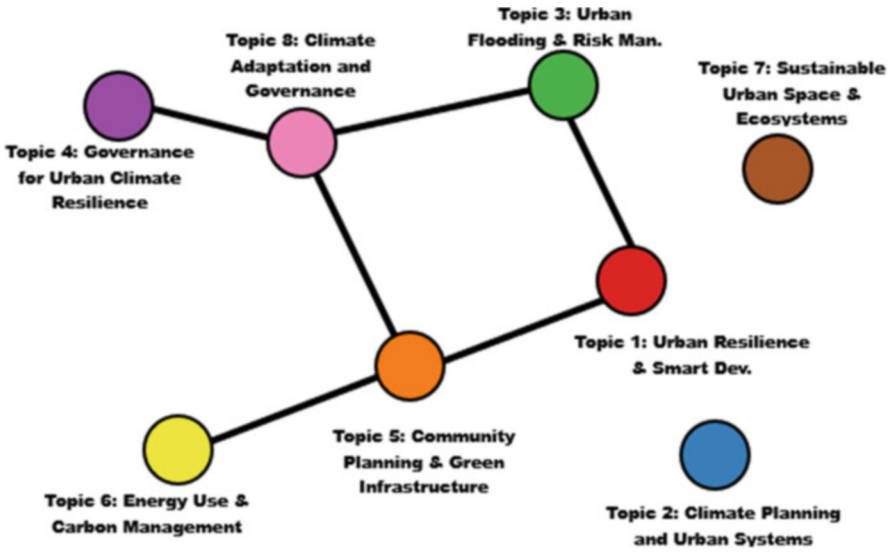

Fig. 5 Topic interconnections map. (*Source*: Authors' design)

3.4 Topics Interconnection

Figure 5 presents a network graph illustrating the interconnections among the extracted topics, providing insights into the complex landscape of urban resilience and development. Each topic plays a role in the multifaceted challenge of creating sustainable and resilient cities.

Urban Resilience and Smart Development (Topic 1) is linked to Urban Flooding and Risk Management (Topic 3), suggesting that smart urban development practices are foundational to addressing specific issues like urban flooding. This underscores the holistic approach needed to tackle urban challenges.

Urban Flooding and Risk Management (Topic 3) is further connected to Climate Planning and Urban Systems (Topic 2), indicating that managing urban flooding risks is integral to broader climate planning and the design of resilient urban systems. The progression from specific challenges to broader considerations reflects the scaling of focus needed in urban planning.

The connection between Governance for Urban Climate Resilience (Topic 4) and Climate Adaptation and Governance (Topic 8) highlights the close relationship between governance practices, urban climate resilience, and adaptation strategies. It underscores the pivotal role of governance structures and policies in facilitating adaptive measures to climate impacts in urban areas.

The graph structure, with Topics 1, 3, and 2 forming a connected component and Topics 4 and 8 forming another, indicates two clusters of closely related themes. The other topics—Topic 5: Community Planning and Green Infrastructure, Topic 6: Energy Use and Carbon Management, and Topic 7: Sustainable Urban Space

and Ecosystems—are not directly connected in the graph, suggesting that they may represent distinct but equally important areas within the broader theme of urban development and resilience.

4 Conclusions

In the face of rapid urbanization and increasing environmental challenges, the concept of resilient cities has garnered significant attention among scholars, policymakers, and urban planners. Resilient cities are those capable of effectively responding to and recovering from various shocks and stresses, including natural disasters, climate change impacts, and socioeconomic disruptions, while maintaining the well-being of their residents and ecosystems. Understanding the dynamics of resilient cities is crucial for devising strategies to build sustainable urban environments that can withstand and thrive in the face of adversity.

This study employed a novel hybrid approach to explore the evolving landscape of research on resilient cities, integrating bibliometric analysis and latent topic modeling. We identified key themes and trends shaping urban resilience and development discourse using a dataset of 532 comprising scholarly articles from the Web of Science database. Through multiple correspondence analysis and structural topic modeling, we extracted and analyzed the underlying conceptual structure of the literature, uncovering interconnected topics and prevalent themes.

Our analysis revealed eight primary topics, each offering insights into critical aspects of urban resilience and development. These topics encompassed a wide array of issues, including smart urban development, climate adaptation, governance, risk management, community planning, green infrastructure, and energy management. By examining the interconnections among these topics, we elucidated the complex web of factors influencing urban resilience and highlighted the need for integrated approaches to urban planning and policy-making.

The findings of this study have several key implications for research and policy. First, they provide a nuanced understanding of modern cities' multifaceted challenges and offer guidance for prioritizing research efforts and policy interventions. By identifying gaps in the literature and highlighting emerging topics, our analysis can inform future research agendas, facilitating interdisciplinary collaboration and knowledge exchange.

Moreover, the insights gleaned from this study can guide policymakers and urban planners in developing evidence-based strategies to enhance urban resilience and sustainability. By leveraging the identified themes and trends, stakeholders can design more effective policies and interventions to build resilient cities capable of adapting to changing environmental, social, and economic conditions. From integrating smart technologies and green infrastructure to fostering community engagement and adaptive governance, our findings underscore the importance of holistic approaches to urban development.

In conclusion, this study advances our understanding of resilient cities and provides valuable insights for research, policy, and practice. By bridging the gap between academic scholarship and real-world applications, we aim to support efforts to create more resilient, sustainable, and inclusive urban environments for the benefit of current and future generations.

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Building Resilient Cities with Integrated Resiliency Analyses

John R. Hummel, Jennifer L. Schneider, and L. Paul Lewis

Abstract From a regional development perspective, making our communities and regions more resilient to disruptions, whether from natural or human-induced events, is imperative, not only to preserve our way of life, and life itself, but also to limit our long-term global expenditures related to climate change–related disasters, both slow-moving and sudden. There is concern over the potential for more frequent and more intense weather-related disruptions; however, our ability to assess our current state and our potential to increase our long-term resilience capability is critical to attaining and maintaining community resilience.

In this chapter, we present a general discussion of the foundational characteristics of community resilience and why a systems-level view of resilience is required to study, model, and assess community resilience. We also explore interconnections and dependencies among community systems, how a change in one component can have cascading impacts, and the importance of including the populations who are ultimately impacted by these issues in the discussion. We discuss how resilience can be assessed and present case examples for emergency response systems assessment. Finally, we frame the Gulf Cooperation Council (GCC) regional pandemic experience and then pose specific COVID-19 local pandemic case studies focused on the United States and explore how similar methodologies may be applied to assess capacity of communities in the GCC.

1 Introduction

From a regional development perspective, making our communities and regions more resilient to disruptions, whether from natural or human-induced events,is

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imperative, not only to preserve our way of life, and life itself, but also to limit our long-term global expenditures related to climate change-related disasters, both slow-moving and sudden. There is concern over the potential for more frequent and more intense weather-related disruptions; however, our ability to assess our current state and our potential to increase our long-term resilience capability is critical to attaining and maintaining community resilience.

In our studies, we have been utilizing the following definition of resilience (Hummel, 2013):

> Resilience is the ability of an entity—e.g., asset, organization, community, region—to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance from either natural or man-made events.

This definition is similar to that adopted for this book but is based on one originally used to support analyses of vulnerabilities in physical infrastructure. The definition was expanded to reflect a system view of resiliency, including the capacities and capabilities that drive it. It is important to note that impacts from disruptions can potentially provide positive benefits across a community system. As an example, during the early lockdown period of the COVID-19 pandemic, carbon dioxide emissions were initially reduced as a result of decreased industrial and transportation activities. COVID-19 spurred remote work options that may push communities to consider urban design that prioritizes spaces for gathering, rather than commuter traffic, and support work–life balance and community engagement.

Becoming resilient is more than just achieving a static desired state; rather, it involves the execution of a series of strategic efforts to attain and maintain that resilience. Resilience is framed through actions that take place over time and place to reflect the evolving environment and challenges, both predicted and unforeseen, that arise.

In this chapter, we will present a general discussion of the foundational characteristics of community resilience and why a systems-level view of resilience is required to study, model, and assess community resilience. We will also explore interconnections and dependencies among community systems and how a change in one component can have cascading impacts. We will next discuss how resilience can be assessed and present case examples for emergency response systems assessment. Finally, we frame the Gulf Cooperation Council (GCC) regional pandemic experience and then pose specific COVID-19 local pandemic case studies focused on the United States and explore how similar methodologies may be applied to assess the capacity of communities in the GCC.

2 Background

2.1 Characteristics of Community Resilience

Resilient communities must first possess four basic characteristics/traits that are noted in Fig. 1. The literature (Schneider et al., 2015) identifies many formative

Fig. 1 The characteristics of resiliency that contribute to resilient communities

characteristics, but the features are quite similar: (1) *capacity* to meet the basic needs of the community and its people (defined here as sustainability); (2) *will* to improve the quality of life beyond the basic needs (social responsibility); (3) *services and functionality* (social opportunity) to improve the quality of life; and (4) *ability to provide security to protect* the citizens and resources of the community from internal and external threats thereby collectively creating the *capability* of the community. Capacity focuses on the functional resources to meet the needs of the community, while capability is a measure of that community's ability to appropriately apply those resources to maintain and grow beyond basic needs. Together, they represent the state of resilience for today and the potential of resilience for tomorrow.

These formative characteristics are critical to creating community resilience within the public and private enterprises that serve the community, but also across the community itself. Figure 2 (Schneider et al., 2018) illustrates how these capabilities build toward prosperity for organizations and their community. Sustainability is a reflection of a community's ability to meet individual and collective needs, manage immediate and long-term impacts, and contribute to creating value and prosperity. Resilience is the ability to manage disruptions of all sorts through planning, social capacity, and flexible, robust, and secure operations. The overall prosperity of the resulting state of the community is derived from the interrelationships between the contributing systems. The connections between these systems, and their capacity to create resilience and sustainability, also mean that we can *use* those relationships to either model operative needs or assess capability to attain our resilience goals.

2.2 System-Level View of Resilience

Resilient communities are integrated, system of systems, whether privately or publicly managed. Figure 3 gives a high-level view of the system components that contribute to a resilient community. Most of the components in Fig. 3 have obvious

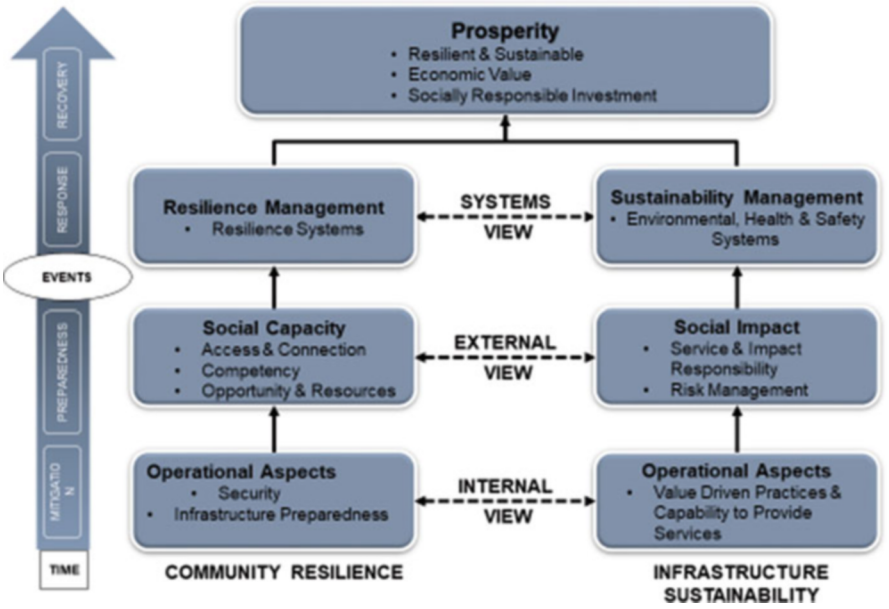

Fig. 2 The formative system of community resilience

Fig. 3 A system-level view of the components that contribute to resilient communities

roles, but we will discuss some unique aspects associated with the Governing System, the Natural Environment, and the Human Landscape system.

The Governing System is deliberately *not* called a Government System. The reason is that this system is intended to be used at multiple levels of population

granularity—groups, villages, tribes, communities, countries, and so on. They will have different ways in which they organize themselves, and the organizing details may or may not be formalized and may or may not be codified. Organized criminal networks, for example, have strong governing and enforcement mechanisms that are clearly understood by the members, but they are not codified in any written form. GCC countries have different governing systems—constitutional monarchies in Bahrain and Kuwait; absolute monarchies in Oman, Qatar, and Saudi Arabia; and a federation of monarchies in the United Arab Emirates. Each country has a supporting government in order to provide essential services and protections, but in the majority of cases, the ruling families are the dominant force leading the country.

The Natural Environment is the geo-located backdrop of the other systems and where natural forces (e.g., extreme weather events, climate change, and earthquakes) and most human-induced disruptions (e.g., terrorist attacks and conflicts) are felt. The Natural Environment is also where all of the human-built infrastructures are located and operate.

The Natural Environment of the countries that make up the GCC has climates that range from arid to desert with limited precipitation which offer unique challenges to the resilience of the countries. The GCC countries have limited arable land and few freshwater sources and depend upon groundwater and desalination. The lack of arable land makes the GCC countries dependent—and potentially vulnerable—to disruption in food supplies. GCC countries are able to import the required foods, but because those resources are ultimately finite and vulnerable to broader market forces, they cannot be considered a reliable contributor to community resilience. Table 1 gives a high-level overview of the Natural Environment for the Gulf Cooperation Council countries (CIA, 2020). The chapter by Dr. Jan Braun in this book provides greater detail on climate change issues, and the chapter by Dr. Maha Zubi provides insights into the Water-Food nexus facing the GCC countries.

Why is a *systems*-level perspective required? The connections, capability, and impacts of a given system extend beyond the scope of the system. A public health system, for example, is more than doctors, healthcare workers, and brick and mortar buildings and facilities. It depends on the foundational contributions from other community systems, as shown below in Fig. 4. It depends on an educational system that trains and prepares the staff required to operate and maintain the system; a governing system that provides regulatory and legislative guidance; a foreign labor control mechanism that recruits and manages expatriate medical staff; a financial system that provides operating and investment capital; and so on. Unfortunately, many reconstruction activities after natural disasters or conflicts have only focused on rebuilding the physically damaged systems (i.e., build back) and did not consider the need to address the interdependencies for other system components that cannot be seen or touched, and therefore, did not move toward robust capacity building increased resilience (i.e., build back better) (Parker, 2006).

The COVID-19 pandemic has forced a rethinking of how community resilience is modeled and assessed to include more social and operational components rather than just the triggering event and where it occurred. Resilience modeling of

Table 1 Summary of environmental aspects of the Gulf Cooperation Council countries

	Bahrain	Kuwait	Oman	Qatar	Saudi Arabia	United Arab Emirates
Annual precipitation (mm)[a]	70	140	103	75	111[b]	89
Total area (sq km)[c]	760	17,818	309,500	11,586	2,149,690	83,600
Land (sq km)[c]	760	17,818	309,500	11,586	2,149,690	83,600
Open water (sq km)[c]	0	0	0	0	0	0
Irrigated land (sq km)[c]	40	105	590	130	16,200	923
Agricultural land (%)[c]	11.3	8.5	4.7	5.6	80.7	4.6
Arable land (%)[c]	2.1	0.6	0.1	1.1	1.5	0.5
Permanent crops (%)[c]	3.9	0.3	0.1	0.2	0.1	0.5
Permanent pasture (%)[c]	5.3	7.6	4.5	4.3	79.1	3.6
Forests (%)[c]	0.7	0.4	0	0	0.5	3.8

[a]https://www.climatestotravel.com/climate. Accessed 22 June 2020
[b]Measured in Riyadh
[c]CIA World Factbook (2020)

disruptions to communities tended to be punctuated events at specific locations (e.g., earthquakes, floods, and hurricanes). After the virus first appeared in China in late 2019, it quickly spread through China and then across the globe, impacting every system in Fig. 4. While communities sustained no physical damage, there certainly was an impact on the operational capacities of many community systems, like public health.

2.3 Developing Models of Resilient Communities

Developing models of resilient communities can enable planners to test concepts and policies to see if they can achieve a set of desired goals. Because the models are computational representations of real-world processes, they should not be relied upon to give absolute answers. Instead, they should be used to provide *insights* and illustrate capacity trajectories for how resilient communities operate so leaders can make informed decisions.

The first step in developing a model of a resilient system involves identifying the critical systems and subsystems that are important to the analysis, and the level of detail required for the context of the study. The next step involves determining

Fig. 4 Interdependency of a public health care system on foundational community systems

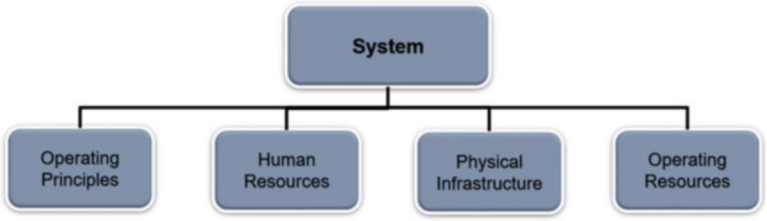

Fig. 5 The functional elements used to represent the actions taken by a system

the actions and outputs the systems must perform to simulate what the real-world systems accomplish.

In developing the computational representations of the system—how the actions will be performed, and the resources, including capacities required to perform the actions—a set of functional components summarized in Fig. 5 can capture the attributes and specific data required to model the systems. The Operating Principles are the processes that regulate how a system functions. The Human Resources are the people-driven capacities that operate and maintain the system. The Physical Infrastructure is the physical facilities and mechanisms that support the mission and its operation. Taken together, these represent the capability of a system to create output. Finally, the Operating Resources are the consumable and non-consumable

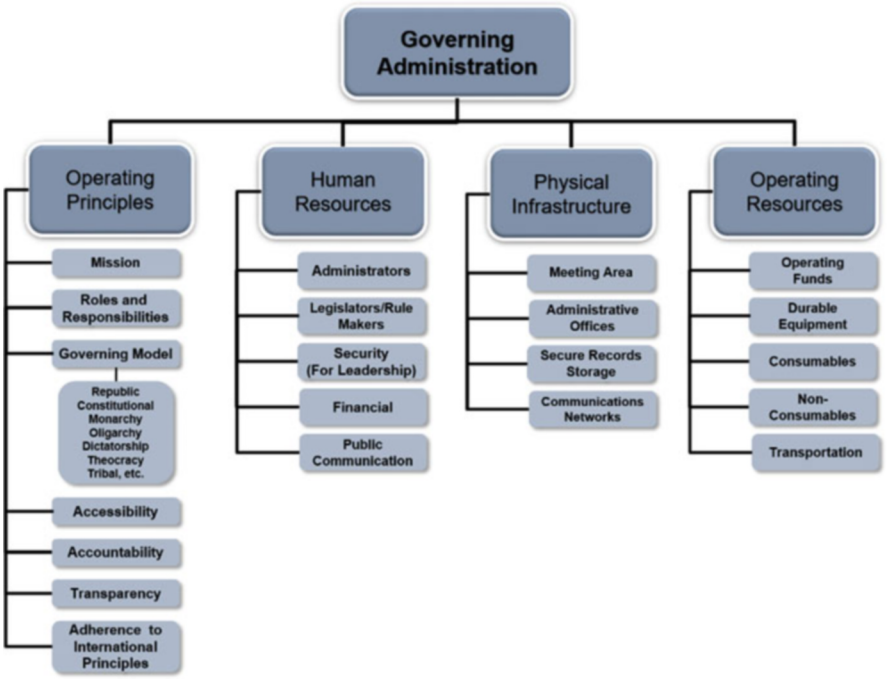

Fig. 6 A potential decomposition of a governing administrative system

items used in the day-to-day operation of a system (e.g., office supplies, money, and spare parts). These elements can be expanded as necessary to capture the real-world functionality of a system, responding to the increased need for capability.

The generalized system functional elements in Fig. 5 are slightly modified to accommodate the differences found in the Natural Environment. The Operating Principles for the Natural Environment are the physics principles that govern the atmospheric, oceanic, space, and terrain domains. The physical components of the atmosphere, ocean, space, and terrain domains are analogous to the physical infrastructures in a physical system.

Figure 6 is an example of how a Governing Administration may be developed. Each of the notional components listed represents an attribute of a governing administration, and the data associated with each attribute will be at the level of detail required for the context of the actions that the system performs.

The specific algorithmic representation of the dynamic processes that impact community resilience can be modeled with a variety of techniques. For example, the physical and engineering-level systems can be represented by first principles or numerical approximations of the physical and engineering processes, while the socioeconomic and social processes can be modeled using agent-based (e.g., North & Macal, 2007) or systems dynamics models (e.g., Sterman, 2000; Martinez-

Moyano & Richardson, 2013) that employ rules or empirical representations to describe how individuals react and interact under different conditions.

Finally, any study of community resilience will involve the intersection of physical, environmental, economic, social, and behavioral processes—which operate within different spatial and temporal domains. Physics processes can operate at both micro and macro spatial and temporal scales (weather and climate), while changes to social and cultural factors can take generations to evolve; the differences in these scales can lead to significant computational challenges to model integrated physical, environmental, economic, social, and behaviors. Studies that capitalized on this type of thinking include examinations of the early agrarian Mesopotamian civilization and environmental variations that contributed to the evolution of the civilization, including the development of trade between villages (Christiansen & Altaweel, 2006; Wilkinson et al., 2007). These methods have also been used to study the spread of infectious diseases, such as Ebola, MRSA, and COVID-19 (Macal et al., 2014). Current studies on the role of densely populated living quarters and the spread of the virus in GCC communities provide additional insights into the convergence of factors that converge to an increase in risk to the larger community.

2.4 Assessing Community Resilience

Measuring community resilience often involves determining the capacity of various community systems, such as the number of hospital beds or energy generation. Other measures of community resilience can involve the capability of systems, such as the number of physicians per 1000 people. These indicators can generate snapshots of the state of the community resilience at specific moments in time. Examples at the country level are available from the CIA World Factbook (US Central Intelligence Agency, 2020). While snapshots of the state of resilience are important when dealing with specific events, the rate of change (or trajectory) of community resilience is critical in determining how effective the community is in meeting its own needs on an ongoing basis. (i.e., are conditions improving?) These assessments not only provide a snapshot but also reflect the evolving conditions or environment that the community exists within and must react to, including dynamic risk.

Resilience can be assessed in two fashions: (1) the coordinating subsystems systems can be examined through dynamic means to provide an *operational* perspective within a community *OR* and (2) the assessment can measure the health of the system by gathering informational indicators related to those subsystems, and build an index that measures the relative resilience and robustness of a component system or of the overall community.

If the aim is to assess future capability rather than today's capacity, once the contributing systems are defined and discretely organized, both *metrics and indicators* can then be selected to represent the components as they are measured over time. Indicators are associated with the operating system and illustrate resulting

capacity, but they may not be a direct measure. Metrics are defined as indicators that can illustrate both capacity and an overall trajectory of the performance, such as a rate per unit of time. For that reason, metrics are typically preferred, but they might not be available in all cases. In our work across many communities, we have found that initial metric and indicator sets should be limited to approximately 30 values that focus on the operations of interest. Tracking more can bring a level of complexity that is not beneficial to the community planners. These metric/indicator sets can then drive community planning: as one set is achieved, the set can be diversified or broadened to include more critical capabilities and impacts. Some data are simple to obtain, such as power output versus degree days, while others are difficult such as those that speak to the human experience in the locality, such as how individuals or groups obtain resources or services to maintain a lifestyle during or after a crisis, and how a crisis disrupts normal channels of support.

The Human Landscape System is often the most overlooked system in resilience assessments, yet it is probably the most important. Chapter 10 on Social Infrastructure covers how this concept applies in communities in the GCC, but from an integrated modeling perspective, one must represent the actors who are the decision-makers, the implementers of plans and activities, and the elements of the general population that will be impacted by the plans and the forces that can disrupt the community. The Human Landscape is also often the system where the measures of effectiveness of resilience activities are assessed. For example, during the COVID-19 pandemic, the efforts to reduce the spread of the virus depended upon the collective behaviors of people to shelter in place, practice social distancing, and wear barrier masks in public. The fundamental measures of effectiveness to control the spread of the virus were the number of cases of infection hospital strain and lives lost.

Figure 7 illustrates a set of indicators and metrics that can be used to give a strategic-level assessment of the resilience of communities or regions. The parameters are from a variety of data sources of human and community development indicators and metrics (e.g., Chen et al., 2015; FAO, 2014; Florin & Linkov, 2016; Kaufmann et al., 2009; Schneider, et al., 2016a, b; UNDP, 2019).

Many of the data sources noted above present data at a country level. Obtaining more local assessments often requires considerable “boots on the ground” information and tailoring to the social and cultural dynamics at play in the GCC. Assessing community resilience follows a process of engagement and local understanding, beginning with obtaining feedback from internal and external stakeholders, and determining the overall stance of the community—for example, will the community aim to be the most resilient, or will it simply work to protect its systems? The next step involves assessing and leveraging local culture and environment. In many applications, this step is not given the attention it deserves. However, as no effort exists in a vacuum, system implementors need to consider organizational structure and systems of accountability, as well as the external context/environment occupied by the community. The implemented system, goals, and actions must also reflect the context in which the community finds itself, not the context it wishes to occupy. Over time, the system can be modified to reflect growth by exchanging out or

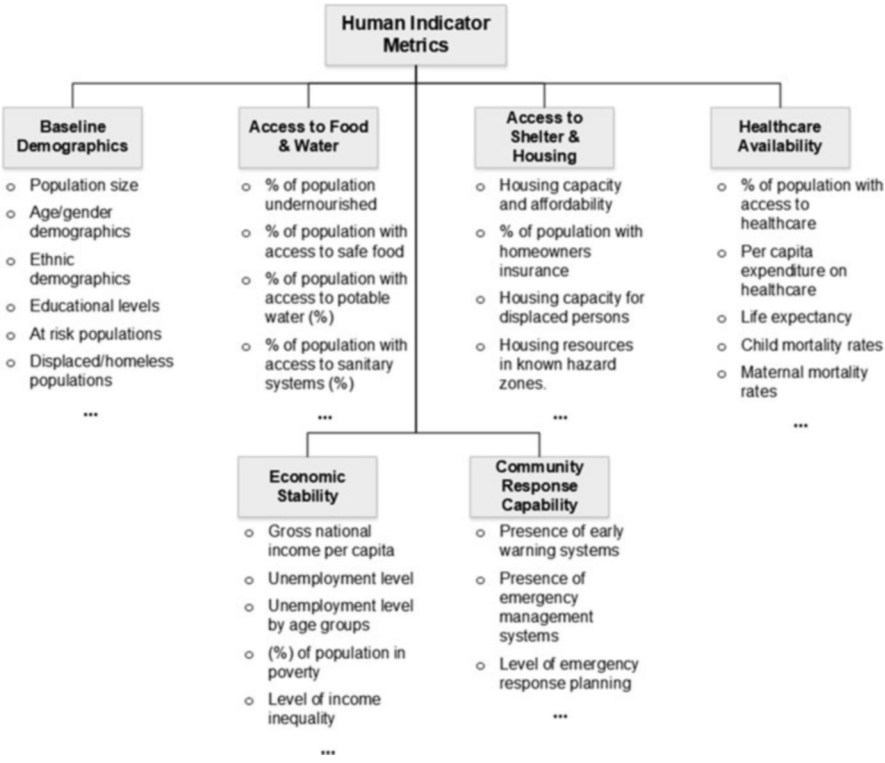

Fig. 7 Set of human landscape indicators and metrics

adding to the original list of metrics and indicators. Sometimes, simply obtaining the data in a systematic fashion is enough to spur continuous improvement, because actors know that they are accountable. Sharing assessment results with the relevant stakeholders, especially those stakeholders that are engaged in creating resilience, is critical to buy-in and the ultimate success of the system. Then, regular review is necessary to support further efforts. An example of a strategic city-level resilience assessment tool is the city Disaster Resilience Scorecard developed for the United Nations Office for Disaster Risk Reduction (DRR) (Williams & Sands, 2016). The scorecard focuses on the ten essentials of disaster risk reduction developed by the United Nations, which are listed in Table 2a. Those essential actions are then mapped to the systems that contribute to their attainment in Table 2b. It is important to note that the scorecard is focused on resilience to *natural disasters* and not the full array of threats.

Each of the ten essentials is broken down into a set of individual measurements and scored on a scale from 0 to 5 where 0 indicates no preparation and 5 means continuously improving processes to maintain resilience. A scorecard for a community or region is developed from a detailed study of a city's disaster-resilience posture, a process that could take weeks, or as a facilitated discussion

Table 2 (a) The UN's essentials for disaster risk reduction and their (b) mapping to the systems that contribute to community resilience

(a)
1. Organize for disaster resilience
2. Identify, understand, and use current and future risk scenarios
3. Strengthen financial capacity for resilience
4. Pursue resilient urban development and design
5. Safeguard natural buffers to enhance the protective functions offered by the natural ecosystems
6. Strengthen institutional capacity for resilience
7. Understand and strengthen societal capacity for resilience
8. Increase infrastructure resilience
9. Ensure effective disaster response
10. Expedite recovery and build back better

(b)

	UN essentials for disaster risk reduction									
Community system	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Education		X				X	X			
Financial	X		X			X	X		X	X
Natural environment		X			X			X		X
Industry/business	X	X				X		X	X	X
Human landscape	X	X				X	X			
Utilities/public infrastructure	X	X	X	X				X	X	X
Public health	X	X			X			X	X	X
Governing	X	X	X	X	X	X	X	X	X	X

in a workshop setting. The resulting scorecard is intended to be a framework for creating a living process where organizational capacity is assessed periodically to measure the achievement of desired goals. Inherent to this process is the evaluation of local risk-resilience posture, including an estimation of the relative risks, based on the scope of the hazard and the specific community's capacity to respond to that hazard.

Our GCC application here will be on aspects of the UN DDR essentials 5 and 6. Importantly, local action typically spans more than one essential. Essential 5 calls for "the identification, monitoring and protection of critical ecosystem services that confer a disaster resilience benefit." Specific ecosystem services may include but are not limited to water retention or water infiltration; afforestation; urban vegetation; floodplains; sand dunes; mangrove and other coastal vegetation; and pollination. Two key understandings here are climate trends and urban development and their relationship to each other. As most of the GCC landmass continues to be under significant water stress, we will focus on water retention and use. Since the 1970s, the GCC countries have undertaken wide-ranging efforts to preserve water sufficiency. This effort has not preserved the natural stores of water, and in fact, the situation has become ever more dire as the twin challenges of demographic shifts (younger and more mobile) and changing use patterns (modernization and

urbanization) have continued to drive the need for water. Furthermore, food sufficiency efforts have increased the requirements for irrigation, primarily through surface water and shallow aquifers. For this broad, critical challenge, we provide a brief index of indicators and metrics in Table 3 that can illustrate the "water resilience" index for a GCC locality, using a subset of the GCC Water parameters (Al-Zubari et al., 2017; Al-Saidi, 2021). This is only an example, and a specific index set should be customized to each city in question. Some parameters are best measured initially at the nation-state level, while others are best applied at the local level. Strategic accomplishments are often measured as a set of actions (i.e., plan adopted). Local parameters are often best reported as a rate, rather than a raw number, such as % capacity or incident rate over time, reporting local capability as shown below. Capacity levels are rated through the efforts of localities as noted in the top row, with specific notes on local capacity efforts for each parameter being assessed. Thus, the Water Services index reflects both nation-state goals and local attainment and describes the state of water resilience on a local scale. Local indexes can then be combined by weighing importance (i.e., population served, volume, or the impact of capacity on the whole) to reflect overall progress.

As both capability and then capacity expand, the number of parameters can evolve and expand to best reflect both the current state and provide a gap analysis to the goal. In addition, all parameters can be rolled up into an overall index that can be compared across localities. This type of assessment is particularly useful for evaluating the overall system capacity to guide strategic efforts.

UN DRR Essential 6 emphasizes that "capacity should be developed across the five key Disaster Risk Reduction areas of understanding, prevention, mitigation, response and recovery planning." Leaders should focus on "creating and implementing information and data frameworks for resilience and disaster risk reduction that build consistency in data capture and storage and enable data access, use and reuse by multiple stakeholder groups for regular development processes."

Alternatively, we present below another method to assess capacity during an unfolding event. This type of evaluation is effective for illustrating evolving operational capacity, particularly in the response phase where the system is forced to react to a disruption. In Table 4, we show a simple example of DRR resilience metrics for local access to emergency response based on a model of a small US locality of approximately 100,000 persons in the response phases of a natural emergency. In the example, the natural emergency blocked thoroughfares and resulted in a significant need for emergency management resources (Romanowski et al., 2016). The model includes functional unit availability (capacity) and access route accessibility (capability), which is then assessed over the course of an event, or even over a normally operating month or similar timeframe. This modeling can be replicated by using local event and response data, combined with local risk knowledge to further understand capacity and capability in times of crisis.

If we wish to get more sophisticated and go beyond assessing individual scores, we can then use those metrics as values in a Partial Resilience calculation, where partial indices will be weighted by subject matter experts/community members and summarized to obtain the final Resilience Score, especially post-disaster event.

Table 3 Potential water services indicators and metrics

Water service indicator	Capacity level					
	0	1	2	3	4	5
National capacity development						
Establish and monitor natural water services	Nonexistent or sporadic attention	Assess natural services state and project use	Some natural services omitted from assessment	Ad hoc monitoring	Strategic and regular monitoring	Regular integration of ecosystem health into adaptation planning
Localized capacity development						
Emergency preparedness plan	Non existent	Plan written	Plan adopted	Plan funded	Plan operational locally	Plan continuously improved via lessons learned and operational measures
Water governance	No governance	Water grid committee created	Unified framework and tariff guidelines developed	Unified framework and tariff guidelines implemented	Comprehensive bilateral gridding with local implementation (% complete)	Adjustable local water sourcing
Water desalination	None	Identify demonstration projects	Demonstration projects developed	Local level implementation	National level implementation	Coordinated with other water sources

Renewable energies in water sector	None	Projects selected	Demonstration renewable projects developed	Integrated renewable energy systems	% of capacity through renewable systems	Continuous adoption
Collected, reused, and treated wastewater	None	Pilot projects identified	Pilot projects developed	Operational projects implemented	Goal to collect, treat, and reuse 60% by 2030	Goal to collect, treat, and reuse 90% by 2035
Water system leakage	Unknown	Measured in situ	Remediation projects	Develop targeted water loss testing	Develop system-wide water loss testing	Goal to achieve an average of 10% leakage of all water utilities
Water consumption	No measurement	Ineffective measurement	Communication and measurement plan developed	Plan implemented	Coordinated supply	Goal achieve 250 L/capita/day by 2035

Table 4 Responder resiliency indicators and metrics

Transportation systems	Parameters	User input	Percent available
Critical personnel access routes	Total number of routes meeting accepted response time	144	23
	Total number of routes in community	627	
Fire asset response	Fire response units available	7	64
	Total number of units	11	
Police/safety asset response	Police units available	9	6
	Total number of units	15	
Emergency medical asset response	Units available	29	54
	Total number of units	54	

The equation for the Partial Resilience Index (PRI) in a given sector is

$$\text{PRI} = \sum w_i * m_i \tag{1}$$

where:

PRI = Partial Resilience Index.
w_i = Sector subcategory weight. Expected value from 0 to 1.
m_i = Value for sector subcategory metric calculation. Expected value from 0 to 1.

The equation for the Overall Resilience Index is

$$\text{ORI} = \sum W_i * \text{PRI}_i \tag{2}$$

where:

ORI = Overall Resilience Index.
W_i = Predefined sector weight. Expected value from 0 to 1.
PRI_i = Partial Resilience Index per sector. Expected value from 0 to 1.

Table 5 is an expansion of the example from Table 4 showing PRI results for the various elements that contributed to the overall emergency response efforts. The checkmarks indicate when the elements come into play during the emergency management and recovery phases.

In summary, measuring the resilience index can be accomplished on whatever scale is desired and across one system component or reflect several. It can also be targeted to assess against possible risks of interest and unfolding disruptions and

Table 5 Post-disaster Partial Resiliency Index assessment

	Emergency management and recovery phase					
	Short term	Intermediate	Long term	% Avail	Wt	PRI
Transportation systems						
Critical personnel access/routes	√	√	√	23	15	0.03
Fire response	√	√	√	64	5	0.03
Police/safety response	√	√	√	60	5	0.03
Emergency medical response	√	√	√	54	5	0.03
Health care and public health route availability						
Route A	√	√	√	0	10	0
Route B	√	√	√	100	5	0.05
Food access points route availability						
Route C	√	√	√	100	8	0.08
Route D	√	√	√	0	4	0
Functional roadways						
% Arterials	√	√	√	51	7	0.04
% Collectors	√	√	√	62	3	0.02
% Local roads	√	√	√	86	2	0.02
Functional bridges						
% Arterial bridges	√	√	√	28	6	0.02
% Collector bridges	√	√	√	45	3	0.01
% Local bridges	√	√	√	53	2	0.01
% Rail bridges	√	√	√	0	3	0
Functional railways						
% Commercial		√	√	0		
% Commuter	√	√	√	0	5	0
% Commodities		√	√	0		
Functional air and water transport systems						
Maritime ports		√	√	0		
Navigable waterways		√	√	0		
Airports—landing locations	√	√		0	3	0
Airstrip (non-commercial runways)	√	√		0	3	0

(continued)

Table 5 (continued)

	Emergency management and recovery phase					
	Short term	Intermediate	Long term	% Avail	Wt	PRI
% Functional primary/critical airports		√	√	0	4	0
% Functional secondary/non-critical airports		√	√	0		
Summary assessment of all critical infrastructures						
Efficiency score	√	√	√	80	5	0.04
			Overall Resilience Index			0.41

can be used to compare across case studies, which is a powerful tool for decision-makers, funders, and policy developers.

3 Resilience Issues from the COVID-19 Pandemic

In 2019, the Global Health Security Index (Johns Hopkins, 2019) assessed pandemic preparedness for the globe through measurement of 85 indicators. The evaluation showed that the United States had the highest score of 195 nations. However, as the COVID-19 pandemic has shown, nation-state indicators alone do not tell the entire story, and national capacities are not always reflected in the local experience. In an emergency, local preparedness and practice is what matters. The global COVID-19 pandemic has demonstrated the importance and limitations of public health systems around the world. Public health systems in major—and very affluent communities—have faced shortages of critical personal protective equipment and medical supplies. During peak periods, some public health systems have reached and exceeded capacity to treat patients and, in some cases, have had to turn patients with COVID and non-COVID conditions away. In many communities where public health facilities are more limited, patients have had to travel long distances to get access to tests and treatments.

3.1 Snapshot of GCC Pandemic Experience

The COVID-19 crisis presented a unique challenge to the countries within the GCC. The GCC countries had built out travel, hospitality, and logistics infrastructure in the last couple of decades as a key characteristic of opening up their economies. However, much of their emerging economy still relied on foreign workers who

Table 6 COVID-19 reported cases and mortality data for Gulf countries as of May 2021

Country	Infected cases	Deaths	COVID-19 deaths/100 k
Bahrain	226,416	882	52
Kuwait	303,039	1751	41
Oman	212,904	2293	45
Qatar	216,397	552	19
Saudi Arabia	444,780	7295	21
UAE	561,048	1611	16
Jordan	733,198	9407	92
Iran	2,865,864	79,219	94

lived in crowded conditions, which left them uniquely vulnerable to pandemic woes (Kempe et al., 2020; OECD, 2020). Furthermore, GCC countries were inordinately impacted by COVID-19, primarily due to the dual shocks of healthcare surge and oil price depression. As the crisis took hold across the globe, slowdown in energy demand, especially for oil, increasing supply and storage impacted key drivers of the GCC economies. By spring 2020, oil price per barrel dropped nearly 20% from all-time highs and then bottomed out at less than $20/barrel (Baghat, 2020; Kempe et al., 2020; OECD, 2020).

The resulting budgetary pressure occurred just as the GCC governments were forced to respond to the pandemic needs across their healthcare sector. Fortunately, the Middle East Respiratory Syndrome (or MERS) experience of 2012 had influenced actions and many GCC nations had invested in healthcare infrastructure, including trained personnel needed on the front lines and health surveillance systems and technologies, and had practiced managing tourists and pilgrims (Kempe et al., 2020; OECD, 2020). While the GCC region remains behind world averages in expenditure per capita, investment has made a difference. A World Health Organization (WHO) report of March 2020 (WHO, 2020b) found that all GCC countries except Qatar rated a 4 or better on a healthcare capacity scale where 1 was no capacity and 5 was sustainable capacity. This capacity, along with strict control policies like restricted movement and quarantine showed early promise for dampening the first surge of COVID-19. As restrictions were generally eased after the first months in later summer, cases rose, and healthcare systems were strained. As in most areas of the world, GCC medical professionals lacked a supply of many critical items needed for care, faced a ballooning process for what was available, and experienced skyrocketing need for service at the same time. Table 6 represents the reported death rate from COVID-19 for the region as of May 2021 (WHO, 2020a; Worldometer, 2021; Johns Hopkins, 2021) comparing the GCC experience with regional neighbors of Iran and Jordan. It is important to note that these data only reflect the *reported* cases and that there are many underlying factors, including healthcare accessibility and efficacy, which influence these outcomes. The impact of the pandemic may have been even greater without these preparatory measures.

The WHO State Party Self Reporting (SPAR) Tool data feed the International Health Regulations reporting. While these data are not verified, it does illustrate

Table 7 IHR indicator scores and pandemic mortality data for Gulf countries

Country	Reported overall IHR score	National Health Emergency Framework	Health service provisions	COVID-19 deaths/100 k population	Ratio of IHR score to deaths
Bahrain	NR[a]	NR	NR	52	NA[b]
Kuwait	84%	100%	67%	41	0.02
Oman	79%	93%	93%	45	0.02
Qatar	92%	80%	100%	19	0.05
Saudi Arabia	79%	87%	87%	21	0.04
UAE	96%	100%	100%	16	0.06
Jordan	43%	40%	67%	92	0.005
Iran	88%	100%	100%	94	0.009

[a]Not reported
[b]Not available

nation-state capacity across 24 indicators for 13 capacities related to detect assess, notify, report, and respond to public health and emergency public health events. The 2020 data below largely reflect capacity before and at the initial stages of the COVID-19 pandemic, showing how prepared each nation considered itself to be for a public health emergency (WHO, 2020a). A simple ratio of overall IHR score to reported pandemic deaths roughly indicates how well that capacity actually fared during the pandemic: the higher the ratio, the better (Table 7).

Despite early interventions by many GCC governments to shore up localized economies through stimulus investment, there will be significant gross domestic product and social impact, particularly as the world itself recalibrates from COVID-19 (OECD, 2020). The pandemic has illuminated regional and national social and healthcare disparities, and it provided both an opportunity to advance social change and capacity or retreat from it at a nation-state, regional, and even local-level implementation of policy changes. This measure of social capacity and healthcare access is often felt first on a local scale, as patients and communities seek support and assistance as shown in the next section.

3.2 Localized Health Access in Chicago, IL, United States

Community health outcomes will be influenced by localized accessibility to healthcare, drugs, and food. Here we present an example using an analysis of the greater Chicago area healthcare and food infrastructure accessibility and choice during the pandemic. The methodologies employed used techniques developed to support recovery operations in Puerto Rico following the 2018 hurricanes and are easily extensible to locations around the world.

For these studies, the geo-locations of hospitals, pharmacies, and grocery stores were identified, and the travel times to them were calculated. The travel times assumed people had access to personal vehicles and considered the volume levels and regulated speed limits of the transportation network. The travel times calculated can be assumed to be "best case" assessments seeing that not all residents have access to personal vehicles, either by choice or economic issues. The locations of the hospitals, pharmacies, and grocery stores were then mapped to US census tract data which enabled us to assess the number of choices residents could select to visit. Finally, the travel time and census tract analyses of access to facilities were combined to generate an accessibility assessment in the form of a "heat" map.

Figure 8 shows the results of the accessibility analyses for hospitals. In each figure, the image in the upper left shows the locations of each infrastructure type. The upper-right image shows the drive time limits to the locations, binned by different time ranges. The lower-left image shows the number of choices people in the different census tracts have and the lower-right image shows the final accessibility assessment, in which red denotes areas with greater accessibility to hospitals and blue areas represent limited accessibility. Although not shown here, the results were similar for the analyses involving pharmacies and grocery stores. Each analysis noted that for some areas of the city, only one facility may be available at significant trip time, even if personal vehicles or public transportation options are available to lower-income residents.

The example analysis shows that some commonalities exist in the infrastructure accessibility results. The core area of Chicago offers residents the greatest access to hospitals, pharmacies, and grocery stores. The density of pharmacies and grocery stores is more evenly distributed in Chicago, while the highest density of hospitals is found in the city's core. The areas with reduced access to these critical infrastructures also correspond to some of the generally disadvantaged areas of the city with residents with lower incomes, limited access to personal transportation, and greater reliance on public transportation. These areas can be interpreted as potential "desert" areas from an infrastructure access perspective, thereby providing guidance to decision-makers on where to make potential investments.

3.3 Risks to Essential Workers

The COVID-19 pandemic introduced another significant resilience challenge for communities and regions. Typically following natural disasters, businesses, schools, and infrastructure experience significant damage that makes it difficult for people to access these community resources. In the case of the COVID-19 pandemic, there has been no physical damage to these resources, and the concept of essential workers was created that *mandated* that the workers continue to provide the necessary community and commercial services, often in frontline capacities that increased their risk of exposure to infection by the virus and spreading it to families and co-workers. In the United States, the U.S. Department of Homeland Security (DHS)

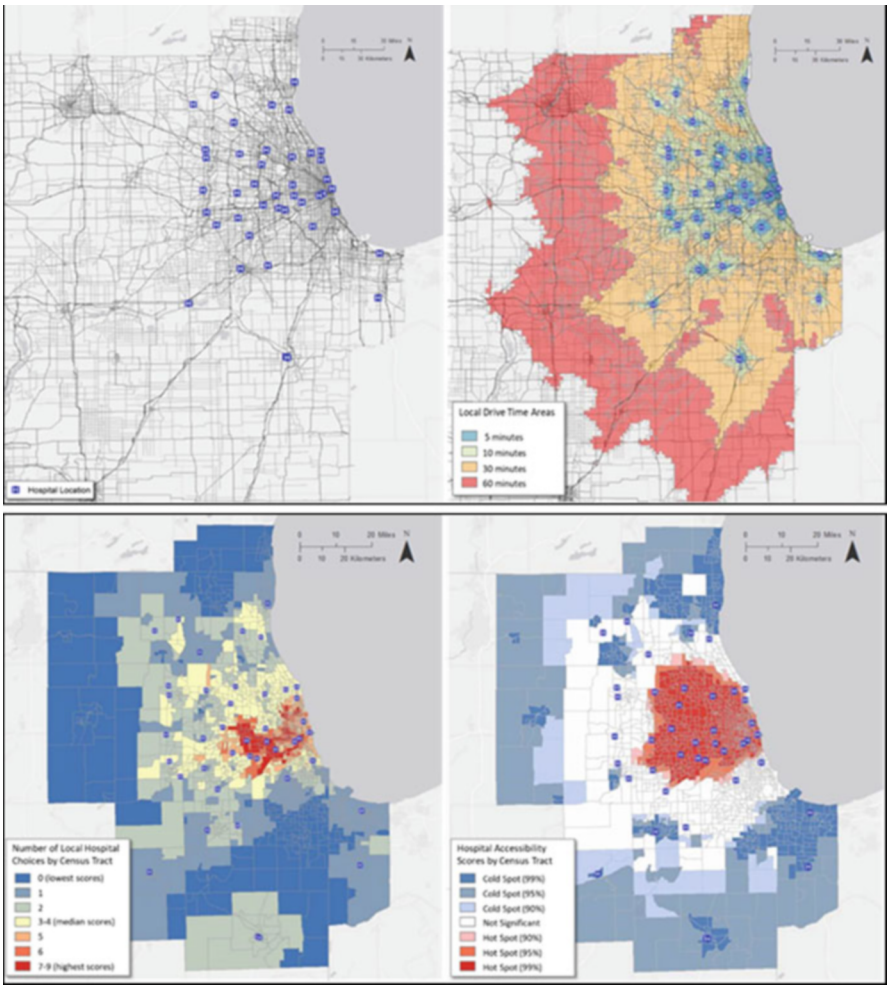

Fig. 8 Analysis of accessibility to hospitals in Chicago. (Source: Argonne National Laboratory)

provided recommendations for lifeline industries, businesses, infrastructures, and governmental functions that could be considered to be essential, but the final decisions were left to the individual governors of the states. In some states, individual mayors created essential industry lists that differed from those of their state. In addition, localities and businesses lacked uniform procedures to safely provide the needed services to protect both the workers and those being served.

In this example, workforce data were collected from the U.S. Bureau of Labor Statistics for each county in the United States, the U.S. Virgin Islands, and Puerto Rico. The data included the number of industries in each county and the number of employees in each of the industries for each month of 2019. Using

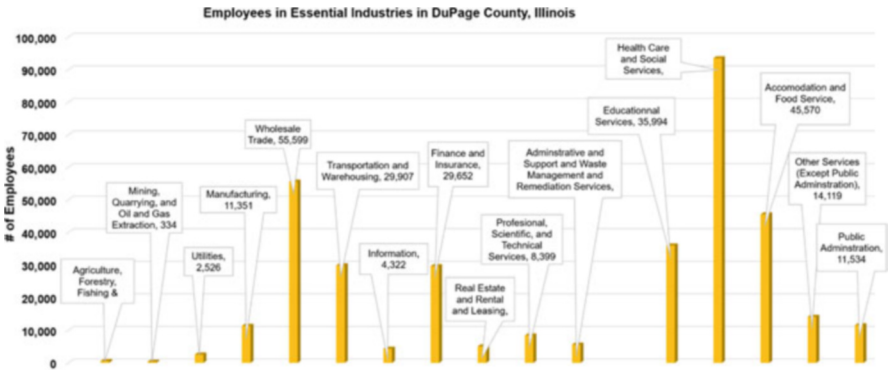

Fig. 9 Employees in essential industries in DuPage County, Illinois. (Source: Argonne National Laboratory)

the DHS guidance on what are essential industries, combined with information on how specific states defined their essential industries, we developed a default representation of what constitutes an essential workforce in a region (county). We further subdivided the essential workforce into the frontline elements that are potentially at the highest risk because they must interact with the general public and are largely unable to engage in social distancing. An example of such an analysis is presented in Fig. 9 for DuPage County, Illinois. In the county, 59% of the workforce is in an essential workforce, and of those employees, 15% are in frontline industries.

4 Discussion and Future Efforts

Manifesting community resilience depends upon knowledge of the processes, systems, people, and social and cultural foundations that make up the community. In addition, none of the individual data points can be considered singularly, but only in concert with others. Dynamic subsystem modeling is especially useful when seeking to illustrate the capacity of a particular critical system or its vulnerabilities. Measurement of system capacities and metrics allows decision-makers to determine where resources may need to be deployed. Both modeling and measures illuminate the options, needs, and choices available to build resilience, and they serve stakeholders at all levels. The COVID-19 pandemic is a truly historic disruption that impacts communities on all scales and all scales of communities. Creating resilience to such disruption requires a detailed understanding of the systemic processes and social ties and supports that allow a community to serve and preserve itself, as the pandemic has also created competition for resources and stretched capability like no other.

Since resilience is ultimately driven by a system-of-systems approach, this affords us multiple ways to parse our solutions. We can investigate simplistic

models that probe simple causal relationships, and answer a single question, or we can incorporate various levels of complexity to more effectively reflect real-world processes, such as dynamic or stochastic systems. Such sophistication gives decision-makers a more complete understanding but is impacted by data availability and precision. Sometimes less is more, particularly if a locality is just beginning to use data to support policy. In addition, integrating social systems with physical and operational components can be fraught with even more complexity as we attempt to simulate human nature. The attributes of the COVID-19 pandemic actually afford us a unique opportunity to refine our processes, as resilience is driven ever more locally, as experience is both individual and society driven, especially, as most communities share the experience. The pandemic event has taught us how tightly coupled our critical infrastructures are, and similarly, in many places, how brittle.

Measurement of resilience capability and building of a physical, operational, and social index is not a minor effort; long periods of time may be required to show significant changes. A challenge in relatively normal times is that the broadly impactful nature of the pandemic makes assessing resilience even more difficult and even more necessary for leaders. As COVID-19 has aptly shown, no locality wants to learn about its lack of capability in a time of crisis, when it needs all it can muster.

The examples presented from the US COVID-19 response efforts are extensible to any country or region. The analysis methodologies are applicable anywhere, once appropriate local data sources are identified in the GCC countries. The US workforce data are based on an industrial classification system used by Canada, the United States, and Mexico, the North American Industry Classification System. The United Nations has developed a similar standard, the International Standard Industrial Classification of All Economic Activities (UN, 2008), that a majority of countries around the world use or is the basis for specific country classification schemes. The structure of the classification systems is similar at the high-level sector level, but differences are likely in some of the finer-level industrial definitions.

Communities can be impacted by disruptions from natural and human events, and the disruptions can be punctuated by a natural disaster like an earthquake or hurricane or be the result of a sustained event such as climate change or a global pandemic. Responding to these events requires a system-level analysis because the impacts can cascade through the infrastructures in a community, region, or country and be felt far from the location where the disruptive event may have occurred. The success of any response or mitigation efforts will also be highly dependent upon the level of social cohesion in the community. As has been dramatically demonstrated during the COVID-19 pandemic, the needs of the larger community (i.e., the “we”) must be put ahead of the needs of the individual (i.e., the “me”).

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Part I
Resilient Systems

Heat Resilience: A Matter of Both Adaptation and Mitigation for the GCC

Jamila El Mir

Abstract The Gulf Cooperation Council (GCC) and the wider Middle East and North Africa (MENA) region are also warming twice as fast as the global average, with temperatures already reaching a 2 °C scenario compared to preindustrial temperatures. According to the United Nations Environment Program, cooling generates around 7% of the global greenhouse gas emissions, while it is responsible for 70% of the peak electricity demand in the GCC. This highlights the prominence of heat as a key climate impact for the GCC region and it really is a matter of both climate mitigation as well as adaptation. Heat resilience and cooling therefore become priority action areas for the governments of the region to deliver on the Paris Goals in a locally responsive manner. This article aims to provide an overview of the impacts of increasing heat on the GCC region, current efforts to address them, and opportunities for enhanced climate action for a heat-resilient future. It highlights existing practices in mitigating the impacts of increased heat through urban planning, public realm design, and building design as well as workforce guidelines for outdoor jobs. It also identifies key areas requiring additional research within the region and key policy recommendations for countries in the GCC to better address the various impacts of increasing temperatures.

Keywords Heat resilience · Cooling demand · Energy demand · Water demand · Building · Health impacts · Urban planning

1 Introduction: Increasing Heat: What It Means for the GCC

The Gulf Cooperation Council (GCC) is warming at twice as fast as the global average with some of the region's capitals already experiencing temperatures 1–2.4 °C higher than preindustrial levels (Aeon Collective and Community Jameel,

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2022)—and could reach up to 4 °C warmer than preindustrial levels by 2050 if it continues on the same trajectory (Hergersberg, 2016).

The three main climate impacts of concern for the Middle East and North Africa (MENA) region as identified by the United Nations Environment Program (UNEP) FI based on the Intergovernmental Panel on Climate Change (IPCC) are increased temperatures, reduced precipitation, and sea level rise, with some of the Gulf countries witnessing the greatest increase in temperature by the end of the century among the countries of the region (Al-Delaimy, 2020).

These in turn pose considerable risks on health, infrastructure, and economic activities while also increasing the need for both mitigation and adaptation measures.

The IPCC's sixth assessment report AR6 highlights that the Middle East region showed the highest shortage in terms of investment in mitigation compared with what was needed among all regions, receiving 14–28 times less finance than required (IPCC, 2023).

Furthermore, a study performed by Giovanis and Ozdamar identified that heat will have highly probable impacts on the gross domestic product (GDP) and fiscal balance of the MENA region, while rainfall does not seem to have as certain an impact on the regional economy as heat. This will impact the productivity of the workforce. It will also lead to higher government expenditures for relief payments as a result of reduced economic output (Giovanis & Ozdamar, 2022). Indeed, the UNEP FI estimates that the MENA region could lose between 0.4% and 1.3% of its GDP due to climate change, and this could reach 14% of total GDP without appropriate climate action (UNEP FI, 2023).

This chapter focuses on the impacts of increasing heat in the region of the Gulf Cooperation Council (GCC) which includes six countries: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. It provides an overview of the key measures currently in place to enhance resilience to heat, looking at four key dimensions: indoor built environment, outdoor built environment, economic and health impacts, and water resources.

This chapter highlights existing practices in adapting to and mitigating the impacts of increased heat through urban planning, public realm design, and building design as well as workforce guidelines for outdoor jobs. It also identifies key areas requiring additional research within the region and key policy recommendations for countries in the GCC to better address the various impacts of increasing temperatures.

2 Zoom In: Indoor Built Environment

To escape the heat, people in the GCC spend most of their time indoors, and all buildings are equipped with cooling equipment. This points to the importance of the indoor built environment in addressing increasing temperatures, from both an indoor environmental quality and the resulting impact on cooling demand.

2.1 Indoor Environmental Quality

Increasing heat will result in two main impacts on indoor infrastructure. First, it will result in increased time spent indoors. People already spend around 90% (Amoatey et al., 2018) of their time indoors in the GCC, and hence it is not expected that a major shift is required to the current approach to the provision of indoor facilities and venues provided by local and national authorities. This does, however, re-emphasize the importance of indoor environmental quality. Several studies looking at indoor air quality in the region have highlighted the poor air quality found in indoor spaces (Amoatey et al., 2018). This is all the more important given that studies have shown a direct relationship between outdoor and indoor air quality, and that another likely climate change impact to occur in the GCC is increased airborne dust and dust storms (UNEP FI, 2023). Studies have shown a possible link between increasing temperatures and increasing concentrations of airborne particulate matter and poorer outdoor air quality (Neira et al., 2023; Hergersberg, 2016), which in turn can lead to increased indoor air pollution (Amoatey et al., 2018; Akasha et al., 2023). There is, however, an opportunity to conduct further assessments to determine the impacts of climate change on the region's air quality.

Building codes in the GCC countries address indoor air quality to varying degrees. While all countries have environmental standards adopted for industrial practices, only a select number of countries address indoor environmental quality through the building permitting requirements and these include Estidama and Al Safat regulations in Abu Dhabi and Dubai, respectively, and Qatar's Global Sustainability Assessment Standards. It is worth noting, however, that in all three standards, specific criteria for indoor furnishings and enhanced performance of heating, ventilation, and air conditioning (HVAC) systems leading to improved air filtration are optional. For example, the minimum requirements in GSAS and Estidama refer to the minimum requirements of ASHRAE 62.1 2007 for ventilation (reference Estidama and GSAS). This highlights the opportunity to update building codes accordingly to enhance indoor air quality while also adapting to greater concentrations of particulate matter expected due to increasing temperatures and a drier climate. Design guidelines would need to take into consideration the local climatic conditions, as highlighted in Amoatey et al.'s (2018) study.

2.2 Increased Cooling

The second impact will consist of the need for increased cooling demand, where the direct trade-off between adapting to climate change and mitigating it becomes most salient in the region. Today, cooling accounts for around 7% of global emissions and 70% of the peak annual electricity consumption in the GCC (Al-Badi & AlMubarak, 2019; KAPSARC, 2021). Studies modeling the impact of climate change in the region, and specifically increased temperatures, highlight a likely increase in cooling

demand by 22% by 2050 and 40% by 2080 in the UAE (Shanks & Nezamifar, 2013) and an increase in cooling demand by 84% by 2100 globally (Mohammed et al., 2024).

Reducing energy demand for cooling poses, therefore, a key area of intervention for countries of the Gulf to reduce their overall carbon footprint. Several countries, including Bahrain, Kuwait, Oman, Qatar, and the United Arab Emirates, have set efficiency targets for air cooling systems. Bahrain has also set thermal insulation and building envelope criteria, including air tightness and material reflectivity, aimed at limiting the heat gain of buildings and consequently, the cooling demand as part of its National Energy Efficiency Action Plan[1] (Pohl et al., 2022) as well as the UAE in its National Green Building Regulations launched in 2021.

There remains, however, ample opportunity to limit the cooling demand. Estimates of savings to be potentially made from adopting more stringent envelope performance, and thermal insulation requirements range between 15% and 40% of total building cooling demand (Al-Tamimi, 2021) and potentially up to 50% (Alaboud & Gadi, 2020). Improving overall HVAC equipment efficiency is also a necessary area of intervention to decouple the need for increased cooling from increased greenhouse gas emissions. It is estimated that improving specifications for the air conditioning units in the Kingdom of Saudi Arabia can help reduce 33 TWh/year in electricity consumption and 24 million tons of CO_2 in annual greenhouse gas emissions (Krarti & Howarth, 2020). Researchers in KAUST have also tested more environmentally friendly refrigerants and have been able to achieve higher efficiency cooling, which points to an opportunity for further consideration within the standards for refrigerants in the region (Pohl et al., 2022). Countries in the region have also been looking at district cooling as an opportunity to increase cooling efficiency at scale in high-density neighborhoods. The UAE has also ventured into a partnership with India to provide cooling as a service, which could provide new contractual and financing models for cooling for the region (UNEP, 2023).

Finally, there is a link between the outdoor environment and the urban heat island (UHI) effect and indoor thermal conditions (Radhi et al., 2013; Bande et al., 2022; Romano et al., 2021) which is covered in Sect. 3. Studies have shown that building cooling demand can increase between 3% and 7% in the case of Italy (Romano et al., 2021) and up to 19% in the case of China (Li et al., 2019) as a result of UHI. There are no studies assessing the quantitative impact of UHI on the cooling energy demand in buildings for the GCC which highlights the need for additional studies to better understand the correlation between these two parameters on a local level in the GCC.

[1] Several countries couple their national energy efficiency with nation-wide, or city-wide demand side management strategies such as in the case of the emirates of Abu Dhabi, Dubai, and Ras Al Khaimah in the UAE which also has a federal demand side management strategy, the city of Riyadh in the Kingdom of Saudi Arabia, Qatar, and Bahrain at a national level.

3 Zoom Out: Outdoor Built Environment

With increased heat, one of the main impacts will consist of the ability to use the outdoor spaces, for work, recreation, and movement. This highlights the urgent need for adapting the public realm and outdoor spaces to the increasing temperatures to ensure the safety and continuity of their usability for these same activities. This section looks at two key areas of intervention: urban planning and planning for outdoor thermal comfort.

3.1 Urban Planning: Forgotten Area of Intervention

While urban planning sets the foundation for developing the urban fabric, it has not been sufficiently leveraged as an area of intervention for climate transition plans and climate resilience for the region, and globally (Home, 2022). In fact, the IPCC report only explicitly acknowledged the role of urban planning in its fifth assessment report and has since been broadening the recommendations falling under the realm of urban planning. The World Bank's Roadmap for Climate Action in the Middle East and North Africa (MENA) has also recognized "climate-informed urban planning" as one of its key areas of climate action in the region (UNEP FI, 2023).

We note that several of the recent urban plans of the major cities in the GCC have integrated climate change as a key consideration, including Sharjah 2040, Dubai Plan 2040, and Oman Urban Plan 2040.

Under urban planning, there are several measures that need to be taken into consideration to enhance heat resilience in the face of increasing temperatures. Figure 1 illustrates the different elements constituting the urban space. Section 2 covers the façade (envelope) and materials aspect, while urban planning traditionally covers the remaining elements from urban fabric and structure to streetscape and landscape.

While this chapter does not aim to provide a holistic list of the urban planning interventions needed to address increasing heat, it does aim to provide a high-level overview of the possible measures that can be taken. This will help reflect on what a comprehensive approach to heat resilience looks like at a city scale in the GCC and which stakeholders are needed to ensure the appropriate measures are taken.

These measures include connectivity, human-scale development, passive and active cooling measures such as shading structures (Bande et al., 2022) or urban design and street geometry practices previously applied in traditional neighborhoods which optimize permanent shadows (Sharifi & Lehmann, 2012; Elkhazindar et al., 2022) and wind flows (Sharifi & Lehmann, 2012; Elkhazindar et al., 2022; Radhi et al., 2013) as well as vegetation (Sharifi & Lehmann, 2012; Radhi et al., 2013; Romano et al., 2021).

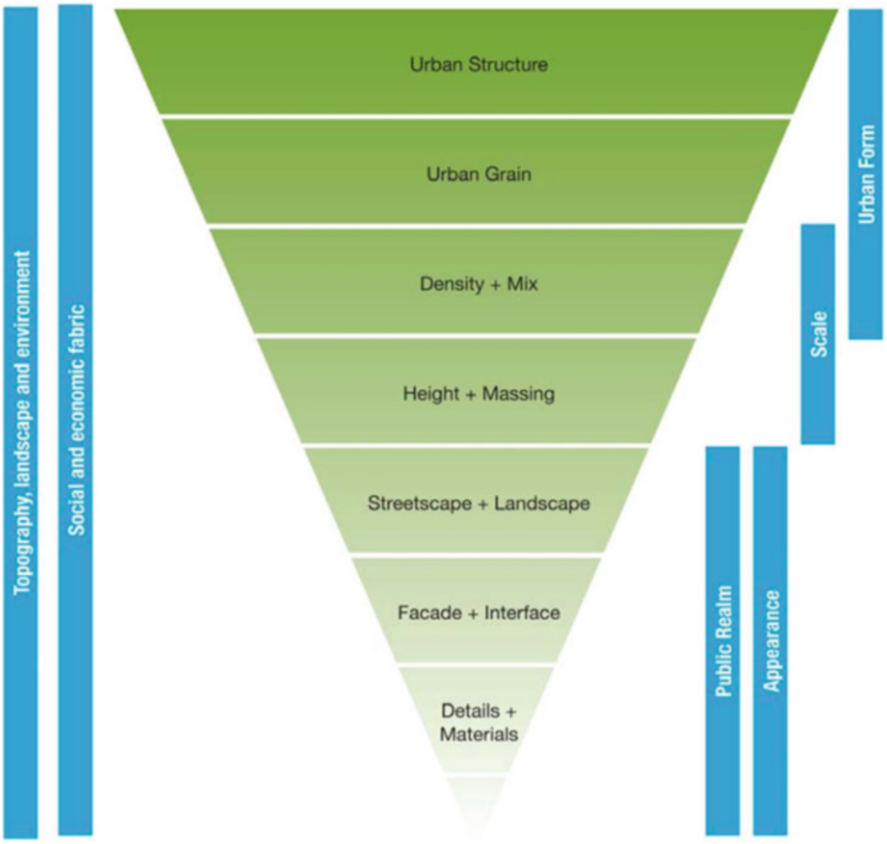

Fig. 1 Elements of urban form. (Source: Creating Places for People: An Urban Design Protocol for Australian Cities, 2015, p. 15)

On the connectivity front, there has been increased attention to mode share shifts, especially with the planning and development of metro lines in Doha, Riyadh, and Dubai. This has led to a greater focus on the connectivity of modes of transport and a shift away from single-ridership vehicles. Abu Dhabi, Dubai, Doha, and Riyadh have all developed integrated transport plans which include private cars, public road transport, metro, as well as non-motorized transport modes. However, as several studies looking at the city of Doha highlight, it is important to ensure that the urban fabric connecting the different transit nodes is conducive to alternative modes of transport to bear the full fruits of transit-oriented developments, including walkability, enhanced liveability, and improved resilience to increasing temperatures (Furlan et al., 2019; Al-Thani et al., 2019) as well as accessibility.

3.2 Considerations for Outdoor Thermal Comfort

The study of urban heat island effect in the cities of the GCC has increasingly become common, especially for masterplan scale projects where a single developer is looking to optimize the experience of walking and spending time outdoors for users of its development. Examples include Msheireb Downtown and Katara in Doha, Masdar City, and Dubai International Financial Centre in the United Arab Emirates. Acknowledging the importance of this topic, Ras Al Khaimah's American University established a research center for outdoor thermal comfort in 2023.

However, there are fewer examples of urban design guidelines being adopted at a city or local scale to ensure outdoor thermal comfort and walkability holistically, with only a few exceptions, such as the Abu Dhabi Urban Planning Council's Urban Design Street Manual published in 2008, Qatar's Urban Design Compendium published in 2019, and Duqm's urban design guidelines in Oman. What is more common is to see components of city-wide interventions such as city-wide landscaping and greening strategies aiming to reduce UHI and enhance the liveability of the city, such as in the case of Riyadh and Manama (Arab Urban Development Institute, 2024) as well as Dubai through its 2040 plan. On the counterpart, water demand is not an aspect taken into consideration by default within city landscaping plans and strategies (El-Keblawy, 2018), therefore leading to a negative cycle where one adaptive measure to heat—greening—aggravates the impact of another impact: water demand. Certain cities in the region have begun looking at it, one of the first being the city of Abu Dhabi through its Public Realm Design Manual which listed a detailed appendix of plant species native and locally adaptive species and the water demand of each species.

Water features are also considered a possible intervention to enhance outdoor thermal comfort. However, studies show that they yield a different impact on UHI depending on their design: while Radhi et al.'s study highlights a positive and cooling effect of water on UHI, Sharifi and Lehmann's study highlights a negative impact and increased heating effect from large water bodies in densely built areas. This puts forward the need for additional studies on the impact of water features and bodies in the cities of the GCC. These would have a more direct effect on the use of outdoor space for leisure and mobility but will most likely not have an effect on jobs undertaken outdoors.

The two sections above highlight the importance of developing guidance on locally responsive urban design and landscaping practices as necessary tools to mitigate the impacts of increased heat for the cities in the region.

4 Rising Temperatures: Economic and Health Impacts

Beyond the physical dimensions of the impact of heat on the indoor and outdoor environment, there are direct impacts on certain economic sectors and those who are

employed in these sectors. Increasing temperatures also affect the health of the wider community as well. The section below covers the impacts of increasing temperatures in the GCC on these two areas: economy and health.

4.1 Economic Impacts: GDP and Jobs

Jobs most impacted by increasing heat include: agriculture, environmental goods and services (natural resource management), construction, refuse collection, emergency repair work, transport, tourism, and sports (ILO, 2019). As mentioned above, the UNEP FI estimates that the MENA region could lose between 0.4% and 1.3% of its GDP due to climate change, and this could reach 14% of total GDP without appropriate climate action. The World Bank Group, on the contrary, estimates that water scarcity—exacerbated by increasing temperatures—would lead to a reduction in annual GDP ranging between 6% and 14% in the GCC region (World Bank Group, 2017).

The study performed by the International Labor Organization highlights that the UAE will witness the greatest loss in terms of jobs as a result of heat stress by 2030, standing at 164,100 full-time equivalent lost jobs and 2.6% of total working hours, while Qatar will experience the highest percentage impact on its economy with a loss of 5.3% of total hours lost to heat stress followed by Bahrain which is projected to lose 4.1% of its working hours. Overall, the GCC is expected to lose a total of 369,200 full-time jobs by 2030 due to heat stress (ILO, 2019). In all countries, the highest impacts are seen in the agriculture and construction sectors, highlighting the specific vulnerability of these two activities to increasing heat temperatures. Oman and Saudi Arabia's economies appear to have lower vulnerability, with hours lost constituting 0.5% of overall working hours.

This highlights specific considerations to consider in the economic planning targeted by the region's countries. For example, most countries in the GCC have set tourism as a key sector to diversify away from fossil fuel revenues. With increasing temperatures, it will become more difficult to attract tourists. Increasing temperatures will also pose problems for the job security of people working in the tourism and services industry and the gig economy, increasing the burden of governments to relocate employees affected by the loss of jobs (Giovanis & Ozdamar, 2022; Nandi, 2019). This might compromise the economic objectives of the GCC countries with regard to the role this sector can play in their economic diversification.

More detailed studies looking at the detailed impacts of increasing heat, and the broader cumulative impacts of climate change on jobs—including the construction sector, refuse collection, transport, and the gig economy—in the GCC region are lacking. Therefore, this area requires additional research to support countries in their economic planning leading up to 2050.

4.2 Health Impacts

Increasing evidence shows that increased heat temperatures result in increased health-related incidences (Aeon Collective and Community Jameel, 2022; Dasari et al., 2021) and this will only increase with climate change (Al-Bouwarthan et al., 2019). Studies project a potential increase in heat-related deaths from 2.1 per 100,000 to 20.3 deaths per 100,000 by the 2060s in a 2 °C scenario, under the SSP1-2·6 scenario (Hajat et al., 2023).

Finally, there is varying adoption of early warning systems for heat waves within the GCC member countries, mostly residing within the national meteorology authority. The relevant authority monitors the occurrence of heat waves and typically uses formal communication channels including mobile networks and social media to provide guidance to the public about the need to remain hydrated and avoid staying outdoors in the heat.

Regarding the monitoring of heat-related health incidents, all countries have a system for recording and reporting them. The reporting is, however, not consistent among cities within the healthcare facilities. As a precautionary measure, all the GCC countries have a mandated midday break during the summer months (ILO, 2019). There are, however, exceptions to who these rules apply to, such as delivery drivers on motorcycles. Dubai's Road and Transport Authority has been working on an integrated plan to provide air-conditioned rest areas for delivery drivers as an adaptation measure to increasing heat.

With increasing heat, such initiatives will need to be further reinforced as current studies highlight key areas for improvement. Such improvements will, for example, require amendments to the mandatory midday break being adjusted to respond to actual temperatures (Al-Bouwarthan et al., 2019) rather than be based on fixed hours and a set period as was the case by Qatar's Supreme Committee for Delivery and Legacy (ILO, 2019) in addition to applying to all outdoor workers without exceptions. Additional mitigation measures include increased awareness among workers about the health risks of heat as well as enhanced inspection mechanisms to monitor compliance with existing heat-related health and safety regulations put in place (ILO, 2019).

5 Water: A Critical Resource on the Frontline of Heat Impacts

Finally, with the region being endowed with very limited water resources, it is critical to assess the impacts of increasing heat on the water supply and demand in the GCC. This section looks at two key aspects of water supply: desalinated water and groundwater and how they will be impacted by increasing heat.

5.1 Managing Water in the Face of the Energy and Water Nexus

The region is already marked as the most water-scarce region in the world. Today, GCC countries rely on desalinated water to varying degrees, ranging from 87% in Qatar, 50% in Saudi Arabia, 42% in the UAE, 36% in Bahrain, and 27% in Oman (Sherif et al., 2023). The remaining water source is predominantly groundwater, highlighting the high risk of depletion of a limited resource in a highly arid region.

Separately, over 80% of the water used goes to agriculture in Saudi Arabia, the UAE, and Oman, while between 45% and 59% of total water consumption in Bahrain, Kuwait, and Qatar is used for agriculture (Sherif et al., 2023). On the contrary, 73% of total wastewater is treated and around 39% is reused, with Oman and Qatar reusing 100% of their treated wastewater, closely followed by Bahrain, which reuses 90% of it, Kuwait ruses 61%, and UAE reuses 55%, and Saudi Arabia only reusing 16% of total treated wastewater (Qureshi, 2020).

There is a vicious cycle linking increasing heat, increased energy, and water demand: increased heat will increase the water demand, which then will add pressure to produce more desalinated water which in turn will increase energy demand (Jägerskog & Barghouti, 2022). Indeed, studies performed in Egypt highlight an increase in water demand for agriculture between 11% and 13% for winter crops and between 9% and 10% for summer crops by 2100 (Mostafa et al., 2021). It can be anticipated, therefore, that the GCC will also experience an increase in water demand for agriculture and irrigation, while further studies would be required to determine the quantitative impact.

This will increase the need for both mitigation and adaptation actions to address the impacts of increasing temperatures in the region:

- On one hand, increased temperatures will result in inefficiency in power generation, which will be impacted by the increased demand for cooling (EWS-WWF & Acclimatise, 2017).
- On the other, increasing temperatures and evaporation rates, as well as increased salinity of the Gulf, will increase the energy demand for water desalination (Jägerskog & Barghouti, 2022).

This calls for significant efforts to manage water resources in the GCC, which is already a high priority for the countries in the region.

Decoupling water production from electricity generation and fossil fuel consumption is necessary. Saudi Arabia has been particularly active in trialing desalination using renewable energy and has been making considerable progress in lowering the carbon footprint of desalination. This, however, does not mitigate the impacts on the marine ecosystem and therefore needs to be coupled with water demand reduction measures to minimize the impacts of climate change. Indeed, all countries are adopting demand-side management strategies for water both indoors and for outdoor city-scaping purposes.

Additionally, Saudi Arabia, the UAE, and Oman have built dams to collect surface runoff water (Chowdhury & Al-Zahrani, 2015; Sherif et al., 2023; Parimalarenganayaki, 2020). Countries in the GCC are also developing aquifer storage and recovery reserves, mostly trialed in Saudi Arabia and the UAE using desalinated water and treated wastewater (Parimalarenganayaki, 2020).

5.2 Managing the Hidden Reserves: Groundwater

Over-extraction of groundwater has led to the depletion of the non-renewable water reserves of the GCC countries, resulting in the drying of wells, and seawater intrusion in coastal areas (Sherif et al., 2023; Parimalarenganayaki, 2020; Baig et al., 2023). It is estimated that the average rate of extraction of groundwater resources in the GCC countries is five times the rate of recharge (Qureshi, 2020).

Several countries are adopting groundwater conservation policies, including Saudi Arabia, which has revisited its national food security objectives to reduce the pressure on local production targets (Sherif et al., 2023), and the UAE, which has enacted policies to regulate the use of groundwater resources in addition to local policies in the emirates of Abu Dhabi and Dubai.

There is, however, a strong cultural aspect to having access to groundwater for use in the home of the nationals and their farms within the GCC. This requires strong stakeholder engagement and a gradual introduction of management measures and regulations to allow a smooth transition to a new way of using what has historically been a natural right: the resources on privately owned land. Such measures include stricter permitting and monitoring of wells, tariffs, and subsidy reforms as well as enhanced awareness of water scarcity and management to the wider public and stakeholder groups most impacted such as farm and land owners (Parimalarenganayaki, 2020). There is, however, a need to cater to social specificities in terms of affordability such as the case of Oman's tiered water tariffs (Jägerskog & Barghouti, 2022).

Looking more broadly at water, several opportunities exist to further enhance water conservation and mitigate increasing water demand in the region. It is estimated, for example, that if the GCC countries were to fully utilize their wastewater, treated wastewater would help meet 11% of the total water demand and reduce groundwater use by up to 15% (Qureshi, 2020). Another key challenge in the region consists of the high subsidies for both fossil fuels (Al-Badi & AlMubarak, 2019; Jägerskog & Barghouti, 2022) and water (Jägerskog & Barghouti, 2022), which hinder the business case for reducing demand. Effectively reducing the demand for water and decoupling water production from increased energy consumption would require subsidy reforms that would encourage the needed economic incentive to change behavior and practices by corporates toward enhanced water stewardship.

6 Conclusion

The aforementioned discussion highlights the various impacts resulting from increasing temperatures in the region of the GCC. These include greater heat-related health incidents, degradation of outdoor and indoor air quality, increased cooling demand, greater water stress, as well as impacts on core economic sectors, especially tourism, construction, and agriculture.

This confirms that heat is both a matter of climate mitigation and adaptation for the region.

This chapter covered the various existing efforts to mitigate each of the impacts listed, and it also highlighted the opportunities for enhanced heat resilience and mitigation.

The GCC has various key opportunities to create a significant improvement in its preparedness for increasing temperatures and to leverage its historical knowledge and experience in dealing with heat. At a building level, key areas of improvement consist of enhancing envelope performance and specifications for HVAC equipment. On an urban scale, this includes reviving traditional approaches to urban planning that optimize shading and walkability while also minimizing urban heat island effects. Locally responsive urban design guidelines and public realm design guidelines provide powerful tools for city planners and developers to consistently deliver against these objectives. With regard to mitigating the impacts of increased temperatures on jobs in the region, this chapter highlighted an urgent need to revisit the current preparedness of the health services, including policies for working during the summer months as well as the use of early warning systems and the improved monitoring and reporting of heat-related health incidents.

This chapter also covered some of the best practices taking place in the region, including research on environmentally friendly refrigerants in Saudi Arabia, innovation in contracting district cooling services in the UAE, considering connectivity and outdoor thermal comfort through urban design guidelines, advanced health and safety measures adopted in Qatar to protect outdoor workers from heat and finally efforts to decouple desalination from increased demand on fossil fuels for energy in Saudi Arabia and aquifer storage reserves developed to increase water safety in Saudi Arabia and the UAE.

This chapter identified several areas that would benefit from more detailed research focused on the GCC, including the cooling effect of water bodies and water features in the GCC, the impacts of climate change and increasing temperatures on jobs in the region, and the impact of increasing temperatures on indoor cooling demand as well as water demand for irrigation.

The GCC also has an opportunity to harmonize standards for cooling equipment, which would help improve the region's market maturity in the provision of high-performing HVAC systems. Finally, establishing a regional dialogue on lessons learned to address the different impacts would expedite capacity building and the adoption of national and regional policies that would help enhance the GCC's resilience to the projected increase in heat.

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Resilient Urban Transport Systems: The Role of Transit-Oriented Development in the GCC Cities

Anvita Arora, Toasin Oakil, and Nourah Alhosain

Abstract An effective and resilient transport system is a crucial component of urban infrastructure. Its resilience has far-reaching implications, including facilitating economic growth, encouraging equity, ensuring sustainability, and mitigating the adverse impacts of climate change. Resilient transport systems can endure and recover from various sources of disruption, whether anticipated, such as natural disasters and extreme weather events, or unexpected incidents like accidents and other factors. However, the discussion on resilience in transportation systems is often limited to their ability to enable evacuation in extreme weather events overlooking the potential of transition toward more energy-efficient cities as a tool to create resilience. This chapter focuses on embedding resilience in the design of city systems using transit-oriented development (TOD) a concept that supports dense, mixed-use development around public transit stations. From a transport climate resilience perspective, TOD helps mitigate adverse environmental consequences as it increases energy efficiency and reduces greenhouse gas emissions in the city by reducing car use and increasing the use of energy-efficient transit ridership combined with walking and cycling. With increasing investment in Public Transit, the fast-urbanizing cities in the Gulf Cooperation Council (GCC) region can embed resilience by design in the city infrastructure. Saudi Arabia, UAE, and Qatar have initiated national TOD strategies that Synergize with the operational mass transport systems in Dubai and Doha, and close to completion in Riyadh. Furthermore, other major cities in the GCC have similar large-scale initiatives in various stages of planning and implementation.

Keywords Transit-oriented development · Energy efficiency · Resilience · Mixed land use · Density

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1 Introduction

Gulf Cooperation Council (GCC) countries are characterized by dry and hot weather and experience excessive rates of desertification, droughts, sand and dust storms, heat waves, and flash floods (El Raey, 2010). All members of GCC have extreme water stress, which is likely to be aggravated by the increasing temperature. Furthermore, rising temperatures cause other natural incidents around the globe, such as rising sea levels, melting ice caps, and an increase in the number of extreme weather events (Raouf, 2008). A major share of the GCC countries' population and activities are near coastal areas, making these countries vulnerable to sea level rise due to global warming. Coastal areas as well as natural and man-made islands in the GCC region will be inundated. For example, Bahrain may lose up to 15 km of its coastline (Raouf, 2008). According to Bahrain's Supreme Council for Environment, approximately 27 km^2 or nearly half of all wetlands in Bahrain would be inundated if sea levels rise by up to 0.5 m, with nearly three-quarters lost if sea levels rise by up to 1.5 m (SCE, 2020). Based on the Intergovernmental Panel on Climate Change (IPCC) projection scenarios, Saudi Arabia will lose about 401 hectares of sandy beaches for the low-rise scenario (0.2 m) and it will almost double at the high-rise scenario (0.86 m) (El Raey, 2010).

According to Williams (2013), the increase in carbon emissions since the Industrial Revolution is responsible for the increase in the global mean temperature of the air and ocean. This is causing ice sheet melting and steric expansion leading to global sea-level rise. European Union (EU) Emissions Database for Global Atmospheric Research (EDGAR) reported that carbon emissions from GCC countries are significantly high (EDGAR, 2023). The magnitude of damage caused by carbon emission has the potential for irreversibility (Solomon et al., 2009). According to Hansen et al. (2013), cumulative emissions of ~1000 GtC, which is associated with 2 °C global warming, could eventually lead to warming of 3–4 °C. Rapid reduction in carbon emissions is necessary to avoid sea-level rise and to restore the ecological balance before it is too late. Carbon emission comes from different sectors, especially from the industrial, transport, and building sectors. We need to be climate resilient in every sector to achieve the desired climate goal. In recent years, GCC countries have taken many initiatives to reduce carbon emissions, among which several initiatives have focused on the transport sector. In this chapter, we reflect on transport resilience, specifically examining transit-oriented development (TOD) as an initiative aimed at enhancing transport resilience in GCC countries.

2 Transport Resilience and GCC Countries

An effective and resilient transport system is a crucial component of urban infrastructure. Its resilience has far-reaching implications, including facilitating

economic growth, encouraging equity, ensuring sustainability, and mitigating the adverse impacts of climate change. Resilient transport systems have the capacity to endure and recover from various sources of disruption, whether they are anticipated, such as natural disasters and extreme weather events, or unexpected incidents like accidents and other factors. For the purposes of this chapter, we look to Hughes and Healy (2014) for a resilience definition:

> The concept of resilience is wider than natural disasters and covers the capacity of public, private and civic sectors to withstand disruption, absorb disturbance, act effectively in a crisis, adapt to changing conditions, including climate change, and grow over time.

This is the preferred definition because it acknowledges that the system is vulnerable to a wide variety of threats, ranging from "normal" weather to growing concerns with climate change and pandemic risks. The core aspect of building resilience lies in ensuring the transport system's ability to withstand stress, prevent failure, adapt to disruptive circumstances, and involve both governmental and private sector entities.

Academic literature helps draw the connection between a resilient transport system and economic development (Banister & Berechman, 2001) with nuanced perspectives on Asia (Pradhan & Bagchi, 2013; Hong et al., 2011), Africa (Boopen, 2006), and OECD countries (Farhadi, 2015). According to Nidziy (2017), transport infrastructure stimulates investments, decreases production costs, saves time, brings equity through accessibility, and decreases negative externalities. From a social perspective, transport infrastructure contributes to well-being and is a critical enabler of employment, education, and development of social networks (Popova, 2017; Roelich, 2020).

In contrast, an inefficient and unsustainable transport system can be a bottleneck for domestic economic growth and pose risks to global economies during disruption. The economic costs of transport interruptions are significant, and these interruptions can reverberate into the global economy in the event of a longer-term disruption. Therefore, the importance of establishing an efficient and sustainable transport system becomes evident, as it not only supports local economic development but also contributes to the stability and resilience of the global economy. For example, revenue loss in the aviation sector due to COVID-19 travel restrictions is USD 22 billion in the Middle East, and globally, this disruption led to a contraction of world GDP between 3.3% and 4.3% (ICAO, 2021). Like other systems of a city, transport is something that many citizens take for granted and do not value until there is a severe disruption and citizens are unable to go to work, school, or meet up with family and friends (Banister, 2005).

Today's transport system faces many challenges and threats, many of which are connected to global warming. Extreme weather events can affect a transport system from a safety and efficiency perspective, causing congestion on the roads, cancellation of flights, and longer travel times (Bloetscher et al., 2012; Koetse & Rietveld, 2009). Koetse and Rietveld (2009) pointed out the leading causes of transport disruption attributed to climate change, including sea-level rise, storm surges, flooding, and weather pattern shifts. Most notably, a rise in sea level means

Fig. 1 Flooded street in Dubai on April 16, 2024. (Source: CBS News, 2024)

that substantial areas are at risk of flooding, and transport infrastructure in coastal and low-lying areas will be underwater, damaged, or unsafe to use. Moreover, Inadequate planning and implementation of flood mitigation measures can have significant consequences as seen by the flash flood incident in Jeddah (Fig. 1) where several factors played a major role in the worsening of the flood disaster, among which was climatic change and the lack of an efficient drainage system (AlSaud, 2010; Youssef et al., 2015). Similar outcomes are also seen in the UAE (Fig. 2) where the government is concerned about the imbalance of water demand and supply due to global warming. While water shortage is aggravating in the country, some places are getting flooded frequently (UAE Gov, 2020), leading to severe disruptions such as airport delays or school closures.

Studying 84 countries, Dasgupta et al. (2009) highlighted the potential consequences of a 1-m rise in sea level in urban areas. According to their findings, such a rise could affect an average of 1.02% of urban areas. Given that cities often host a significant portion of transport infrastructure, the impact of a 1-m sea level rise could be catastrophic. Among these 84 countries, the Middle East and North Africa emerged as high-risk areas with a chance of 1.94% of urban areas being affected. Furthermore, the effect might get as high as 4–6% for the UAE. According to the Environmental Agency—Abu Dhabi, over 90% of the UAE's infrastructure is situated within a few meters of sea level in low-lying coastal areas (UAE Gov, 2020). According to the estimates of Hassan and Hassaan (2020), about 540.79 km^2 of Kuwaiti coastal areas have high vulnerability to sea-level rise, affecting severely

Fig. 2 Flooded street following heavy rain in the city of Jeddah on December 30, 2010. (Source: Arab News, 2019)

human activities and infrastructure located at Boubyan Island, Failaka Island, the northern coast of Kuwait Bay, and the Al-Khiran area.

In addition, it is important to consider the relationship between transportation choices and climate change. The transportation sector is not only affected by climate change but also contributes to its acceleration. Due to its high energy demand, the transport sector significantly contributes to greenhouse gas (GHG) emissions. According to EDGAR (2023), the transport sector in GCC emitted around 224 Mt CO_2 in 2022, which is about 3% of the global total carbon emission. The transport sector's contribution from the overall CO_2 emissions within each country is 23% in KSA followed by 18% in the UAE, 15% in Qatar, 14% in Oman, 12% in Kuwait, and 10% in Bahrain. EDGAR report also highlighted that the transport sector's emissions have remarkably increased between 2005 and 2022 in some GCC countries, for example, Oman (+251%) and Qatar (+218%). While a decrease in overall carbon emissions is expected, carbon emissions from the transport sector in various GCC countries have also continued to increase significantly. For instance, Bahrain has witnessed a 45% increase, Kuwait a 65% increase, the UAE a 73% increase, and Saudi Arabia an 84% increase. While the overall trend of carbon emissions in the transport sector of GCC countries has been increasing, there are positive signs of a slowdown in Kuwait, Bahrain, and Saudi Arabia in recent years. From 2017 to 2022, Kuwait witnessed a decline by 10%, Bahrain by 2.5%, and KSA by 2%. These changes may be attributed to notable efforts aimed at creating more energy-efficient transport systems, including investments in public transportation

and initiatives to manage oil demand, particularly following the Paris Agreement in 2015.

As cities were striving to develop sustainable transportation systems, the COVID-19 pandemic presented new challenges. The pandemic impacted people's lives in various ways, and although it did not physically damage infrastructure, it severely disrupted mobility. Cities have been actively promoting mass transit systems to reduce per capita energy consumption and GHG emissions. However, the pandemic posed a significant threat to the mass movement of people, impeding progress toward sustainable transportation goals. To quote Hughes and Healy (2014)

> the services we take for granted may be robust in the face of predictable hazards/failures, but are in fact extremely fragile in the face of unanticipated shocks.

Therefore, a resilient transport system should be adaptive to the current crisis and future threats. A resilient transport system should be capable of withstanding and recovering from frequent storms, sea-level rise, and extreme weather events that could potentially damage transport infrastructure. Additionally, it should actively contribute to mitigating climate change impacts by reducing energy consumption and carbon emissions.

In transport, resilience is often seen from a physical infrastructure perspective, focusing on road networks, public transportation systems, and air and water transport networks (Mattsson & Jenelius, 2015). Network analysis helps identify the critical nodes in the network and assess the impact of capacity constraints and network failures, enabling planners to design redundant options for accessing these crucial nodes. However, resilience in the transport system cannot be fully explained by a topological perspective alone. To fully grasp the concept of resilience in the transport system, it is necessary to adopt an integrated perspective. Even if the physical network remains unaffected, the system can still collapse due to significant shocks that disrupt people's mobility. The COVID-19 pandemic, for example, has severely impacted mobility and activity participation, leading to a decline in quality of life and overall well-being. Therefore, a resilient transport system should not only be physically robust but also adaptive to climate threats, sustainable, capable of mitigating climate risks, and prioritize the well-being of individuals through enabling activity participation.

Furthermore, energy transition in the transport sector should not be approached as an isolated endeavor. Instead, it should be seen as an integrated process that encompasses land use, community, and transport. TOD is an urban development principle that can promote resilience by integrating community development with sustainable transportation initiatives.

3 Transit-Oriented Development and Transport Resilience

With ever-increasing urban sprawl, suburban commutes have become frustrating with congestion and arduous commutes (Belzer & Autler, 2002a). To address this

issue of urban sprawl, it is important to focus on densifying existing neighborhoods to accommodate the growing population, economy, and demand for land. TOD can effectively counter urban sprawl through efficient land-use planning at a regional scale as well as neighborhood scale along with the expansion of transport choices (Belzer & Autler, 2002b).

TOD involves the integration of transportation and the built environment. In broad terms, it refers to the development of high-density communities centered around rapid transit stations. Calthorpe (1993) defined transit-oriented development as a mixed-use community that encourages people to live near transit services and decreases their driving dependence. Other perspectives on TOD come from the California Department of Transportation (2002) with the following terms for TOD: "Transit oriented Development (TOD) is moderate to higher-density development, located within an easy walk of a major transit stop, generally with a mix of residential, employment, and shopping opportunities designed for pedestrians without excluding the auto. TOD can be new construction or redevelopment of one or more buildings whose design and orientation facilitate transit use."

Bernick and Cervero (1997) defined TOD in the name of Transit Village as "A compact, mixed-use community, centered around a transit station that, by design, invites residents, workers, and shoppers to drive their cars less and ride mass transit more."

TOD is a smart city development principle that revitalizes declining inner-city communities and expands lifestyle choices within the community (Cervero, 2004). It maximizes access to mass transit and nonmotorized transport by ensuring high-density commercial and residential development surrounding centrally located rail or bus stations (Dittmar & Ohland, 2012).

A successful implementation of TOD requires the efficient integration of transport and built environment characteristics. The built environment characteristics commonly used in TOD are based on the work of Cervero and Kockelman (1997) and are known as the "3Ds"—density, diversity, and design. Density refers to the concentration of people living within the catchment of transit stations, diversity pertains to the mix of different activities within those areas, and design focuses on the ease of accessibility to various activities for residents. The guiding principles of TOD are based on the ideas of designing an urban form with relatively high density, compact and mixed form, and providing high quality, efficient mass transport services, together with a pedestrian-friendly environment (Loo et al., 2010).

In a state-wide transit-oriented development study, the California Department of Transportation (2002) named several benefits relating to social and economic aspects as well as environmental and ecological benefits. The study listed the benefits to include improved quality of life, enhanced mobility, health benefits, freedom of choice, enhanced sense of community, reduced infrastructure costs, affordable housing, jobs/housing balance, revitalization of declining urban centers, economic prosperity, enhanced public safety, safer pedestrian and bicycle movement, reduced driving and thus accidents, improved air quality, reduced energy consumption, and reduced greenhouse gas emission and conservation of resource lands. Among these benefits relevant to mobility, resilience comes from enhanced mobility options, safer

pedestrian and bicycle mobility, improved air quality, reduced energy consumption, reduced GHG emission, and conservation of resource lands.

TOD enhances mobility by adding transit options to auto-dependent neighborhoods. Furthermore, it creates a safer environment for walking and cycling. Multiple studies have indicated that transit ridership, as well as the number of walking and cycling trips, is greater in TODs compared with conventional neighborhoods that heavily rely on automobiles. Sung and Oh (2011) showed that the mixed land-use strategy of TOD is one of the important requirements for higher transit use. Zamir et al. (2014) showed that people living in TODs make more trips by all modes, including walking and cycling but make fewer trips by auto. Residents of TODs enjoy more flexibility in terms of mobility options as well as activity choices. The ability to choose from various mobility options is a significant factor in determining resilience. This criterion provides individuals with a wide array of choices to reach their destinations. Even in situations where the transit system or road network is disrupted due to extreme weather or accidents, people can still make their trips by utilizing alternative modes of transportation, such as walking or cycling. The feasibility of making a trip by walking or cycling comes from mixed land use and density, which creates opportunities to reduce travel distances.

From a transport climate resilience perspective, TOD helps mitigate adverse environmental consequences by increasing energy efficiency and reducing greenhouse gas emissions. TOD does that by reducing car use and increasing transit ridership (Cervero, 1994). Chen et al. (2017) found that person vehicle kilometers traveled are lower in TODs because of better connectivity and mixed land-use concentration. Zamir et al. (2014) found that people living in TODs generally make shorter trips. This can be associated with well connectivity and high-density mixed land-use patterns of TODs. In addition, public transport is much more energy-efficient than automobiles. For instance, Kenworthy (2018) found that per capita energy consumption is significantly less in public transport compared with car driving.

4 Transit-Oriented Development in GCC Cities

Currently, privately owned cars are the prevalent mode of transport, especially in urban environments, in the region as shown for some GCC cities in Fig. 3. This heavy dependence on cars has led to significant problems such as excessive pollution, traffic congestion, and urban sprawl. Moreover, a TOD approach is increasingly recognized as a sustainable solution to increase access to transit and reduce dependency on cars. Several GCC cities are making substantial investments in building new or enhancing existing public transport systems. Additionally, many cities have set ambitious initiatives to embrace advanced smart mobility technologies. These initiatives aim to reduce reliance on private vehicles and promote efficient and sustainable public transportation modes. Such transformations not only enhance transport systems but also reshape urban structures, fostering more resilient cities.

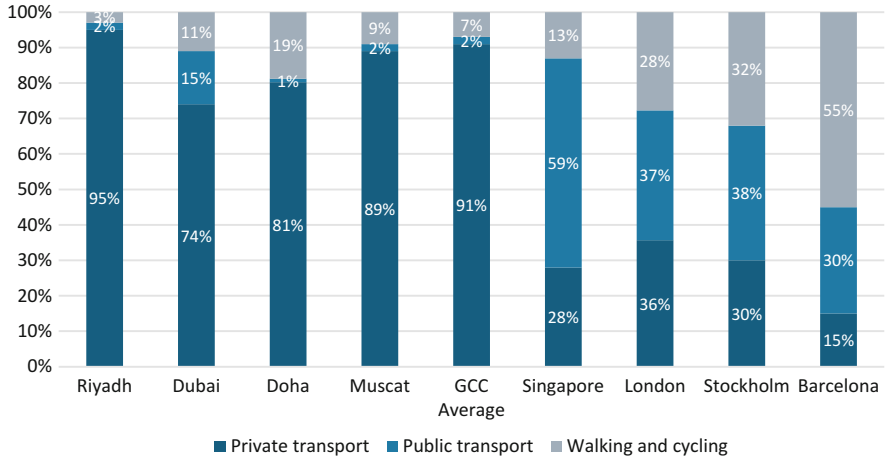

Fig. 3 Share of transport modes in some GCC cities compared with cities around the world. (Source: Strategy&, 2021)

The planning of GCC cities was shaped by car-centric practices, which resulted in a postponement of the integration of public transit in Gulf cities. In recent years, there has been a growing recognition of the need to shift away from car-centric planning and promote sustainable and alternative modes of transportation. Currently, the GCC members are working to increase connectivity among member states through regional railways (MEED, 2023). Moreover, cities within the GCC have put forth plans for rapid transit systems to connect city centers with residential communities (Almardood & Maghelal, 2020). Rapid transit systems enhance the ability of cities to respond to transportation disruptions by improving mobility and accessibility, thus increasing transportation resilience. These systems play a crucial role in tackling urban sprawl, a significant challenge faced by GCC cities, and TOD practices further reinforce this effort. Through the integration of transportation and land-use planning, complemented by TOD practices, these systems promote higher population densities and mitigate car dependency, which is crucial for GCC cities, given their heavy reliance on private automobiles. This section illustrates the current state of TOD in different GCC cities.

4.1 Riyadh's Transit-Oriented Development

Saudi Arabia is currently experiencing a rapid transformation to realize the ambitious targets outlined in Saudi Vision 2030. One of the primary objectives of this vision is to reduce energy consumption and enhance overall quality of life (Vision 2030, 2016). This transformation is manifested, in part, by the implementation of a sustainable public transportation system that can contribute to enhancing mobility

and reducing traffic congestion and energy consumption. Moreover, the Saudi National Transport and Logistics Strategy plays a vital part in the Kingdom's plans given that the transport sector is a high-energy demanding sector and one of the large contributors to emissions in the Kingdom.

The rapid expansion of economic activities, population growth, and infrastructure development Saudi cities are undergoing have led to the outward expansion of urban areas, resulting in the phenomenon of urban sprawl. While urban sprawl has provided opportunities for development and economic growth, it also brings major challenges as Mubarak (2004) termed it as dysfunctional sprawl. Thus, balancing the need for growth with sustainable urban planning and smart development strategies is crucial to mitigate the negative consequences of urban sprawl and ensure the long-term livability and resilience of Saudi cities.

Riyadh, the capital city, is undergoing a significant urban development transformation through several significant projects including Riyadh Metro, Sports Boulevard, New Murabba, King Salman Park, and King Abdullah Financial District. These projects and other initiatives drive the city toward increased resilience by enhancing connectivity and environmental sustainability and promoting urban regeneration and economic diversification.

The Riyadh Metro project is Saudi Arabia's first urban metro network and part of the largest public transport system in the region. The metro is integrated with a bus network that was launched in December 2023 covering more than 1900 km with around 2000 bus stations served through more than 800 buses as shown in Fig. 4 (Riyadh Bus, 2024). On the contrary, the metro consists of two phases; the first already constructed with 6 main lines and 85 stations covering a total length of 176 km (Fig. 5). Moreover, the second phase includes the addition of a more than 65 km long line connecting Riyadh's main landmarks with Qiddiya Entertainment City that is located southwest of Riyadh (MEED, 2024). Riyadh public transport stations cover most of the highly populated districts, government facilities, and educational and commercial outlets.

It is realized that the success of a transit system depends on the well integration of land-use development and urban forms. Therefore, the Royal Commission for Riyadh City (RCRC) is taking the opportunity to transform Riyadh City into an efficient transit-oriented city. The aspiration is to bring resilience and economic, social, and environmental sustainability. In line with these aspirations, RCRC created a detailed guideline to design and implement TODs across the city of Riyadh (RCRC, 2013). The TOD Urban Design Guidelines for Riyadh set out the principles for development around transit stations and integration between transit and land use. These guidelines will serve as coordination principles for RCRC, government departments, landowners, and developers, facilitating collaboration to identify and evaluate TOD opportunities and potential for rezoning and reviewing planning proposals.

The guidelines represent a detailed design outlook for TODs, which follow the basic principles as shown in Fig. 6. A high-density mixed land use will be developed around metro stations. The guideline defined the potential TOD zone as within 800 m from the station. The potential TOD zones are then further divided into three

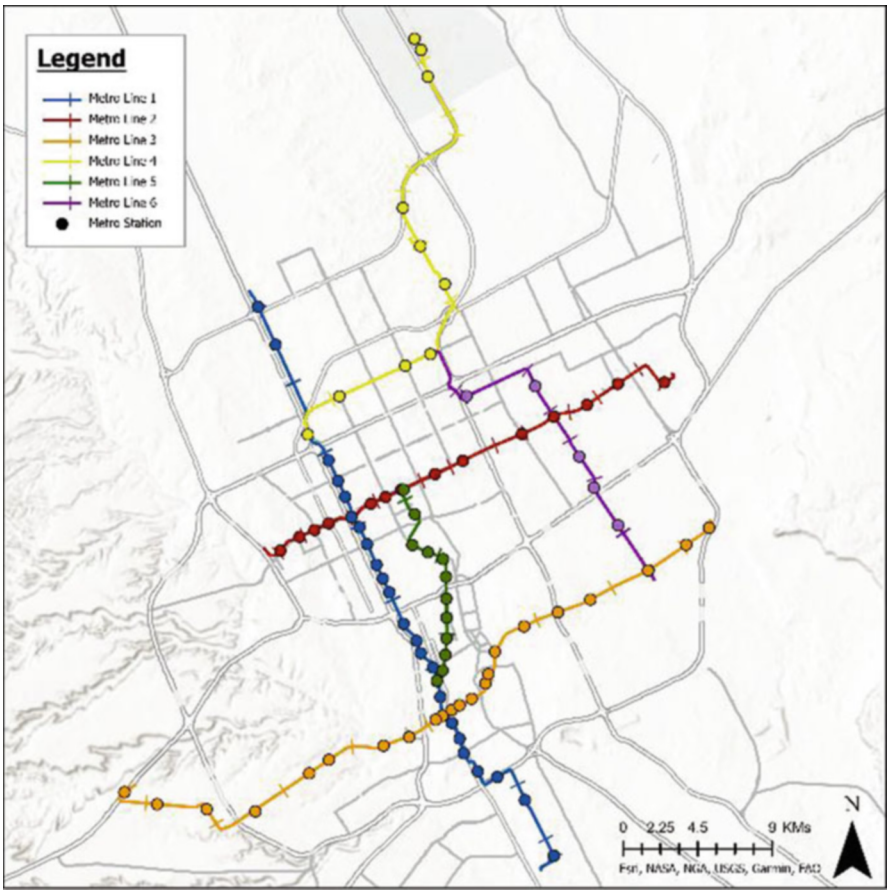

Fig. 4 Riyadh constructed metro lines. (Source: RCRC, 2023)

zones with a core zone within 200 m, a primary zone between 200 and 400 m, and a secondary zone between 400 and 800 m. Each zone has a unique purpose with differing characteristics of urban form and strategies.

The guidelines for each zone were based on five criteria—(i) connectivity, (ii) public realm and open space, (iii) density and built form, (iv) land-use mix, and (v) car parking management. Here, density is defined by floor-area ratio (FAR), which can go as high as FAR = 10 with permission to construct 20-story-high buildings. Land-use mix has been proposed as a mixture of residential and non-residential land use, where non-residential land use includes commercial uses such as retail, offices, hotels, medical, institutions, government and university use, and community uses such as schools, mosques, and cultural and community center uses.

Although the criteria for zoning within TODs remain the same, the guidelines vary based on TOD categories. In Riyadh, TOD guidelines classify areas into six

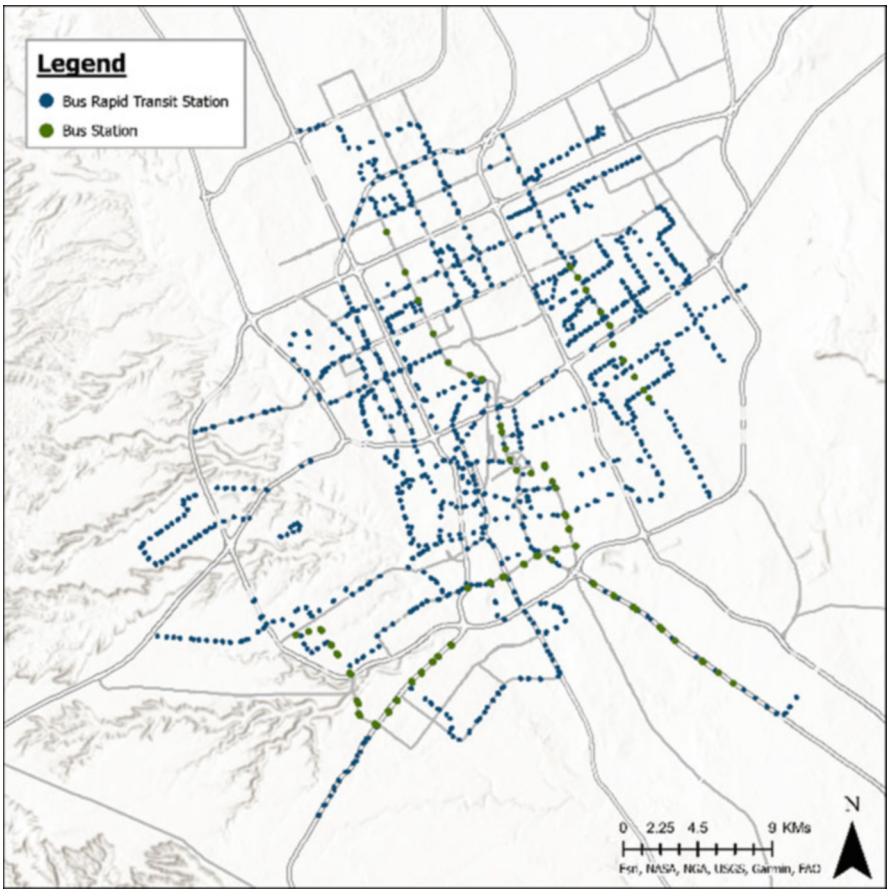

Fig. 5 Riyadh bus network. (Source: Riyadh Bus, 2024)

categories—(a) city center and central business district (CBD), (b) activity center, (c) district center, (d) destination center and (e) neighborhood center, and (f) area for urban revitalization. In addition, there is a corridor development plan for bus-rapid-transit (BRT), namely, BRT corridors. The city center and CBD are classified to serve commercial purposes that include 20% of residential uses at the core zone to 40% of residential uses at the secondary zone and suspend on-street car parking. In contrast, the neighborhood center is classified as a residential center and includes 60% of non-residential uses at the core zone and excludes on-street car parking in the core and primary zones.

Riyadh TOD is designed based on the basic principles to create high-density development, where commercial centers include residential uses and residential centers include non-residential uses. TODs are proposed to be built within 800 m

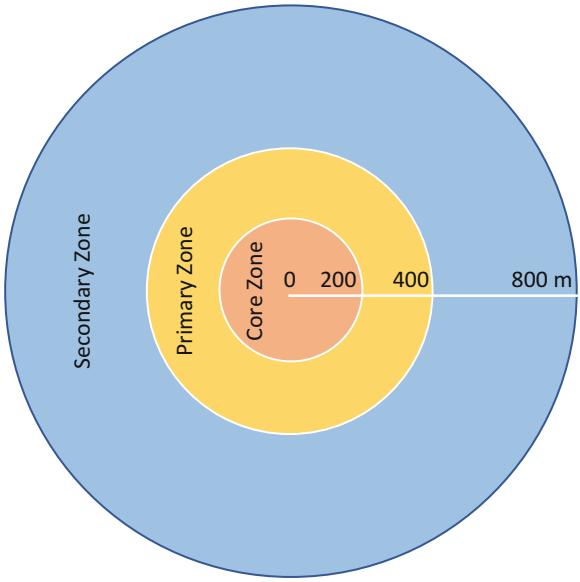

Fig. 6 TOD zoning guidelines. (Source: RCRC, 2013)

from the transit stations to allow pedestrian or cycling accessibility. Moreover, density, diversity, and design—all 3Ds of the built environment—are considered.

Riyadh's public transit system is considered a big enabling solution to reduce the dependence on private cars, encourage walking, and improve the quality of Riyadh's citizens. Many of the other transformational projects in Riyadh (i.e., Sports Boulevard and King Salman Park) are contributing to providing open spaces for the communities and adopting mixed land-use developments that are in line with TOD's main principles. With the introduction of the buses and nearing completion of the metro, the effectiveness and value of TOD plans will be assessed, particularly considering the behavioral shift from traditional auto-dependent practices in cities like Riyadh.

4.2 Dubai's Transit-Oriented Development

With different initiatives focusing on sustainable transport and mobility, the UAE ranked sixth globally in terms of satisfaction with public transportation as per the 2023 Legatum Institute's Prosperity Index (Legatum Prosperity Index, 2023). The public transport network that includes buses, metro, and trams is operational through different emirates. The Emirate of Dubai is considered the pioneer in transit system development among GCC cities by promoting a fundamental change in reliance on cars to embracing a comprehensive public transportation system, reinforced by the launch of a metro network back in 2009. According to Hannawi et al. (2019), Dubai

is the first city in the GCC to move from traditional "problem oriented" or reactive urban and transport planning, to an "objectives-led" or pro-active approach.

To accommodate rapid growth and continued economic diversification, Dubai has spread significantly causing around a 60% increase in the number of urban housing units between 2015 and 2022 (Dubai Statistics Center, 2022). According to Chaudhry (2012), key transport challenges for Dubai were traffic congestion, heavy dependence on private cars, high road accident fatality rate, low public transport ridership, and transport pollution. Recent statistics by Dubai's Road and Transport Authority (RTA) highlight the effectiveness and impact of Dubai's public transport system in addressing the various transport challenges mentioned. In 2023, ridership for public transport and shared mobility reached 702 million, which grew from 6% in 2006 to 18.49% in 2021 and further to 34% in 2023 (Government of Dubai media office, 2024). In addition, 3.3 million tons of Carbon emissions were avoided in the last 5 years (RTA, 2022).

Dubai metro is considered the world's longest driverless metro network covering around 90 km with more than 50 stations across the city in 2022 as shown in Fig. 7 (Guinness World Records, 2016; RTA, 2022). The current metro network was extended in 2020 as part of the city's preparation for hosting Expo 2020. In addition, Dubai's bus network consists of 178 routes with around 1400 buses covering a network length of more than 4000 km (Fig. 8). In line with Dubai, 2040 Urban Master Plan, RTA is expanding the metro network by 30 km that encompasses 14 new stations that are planned to be launched in 2024 (Government of Dubai Media Office, 2024) with the aim to link significant areas in Dubai and accommodate the anticipated population increase of around one million residents outlined in the Dubai, 2040 Urban Master Plan (Government of Dubai, 2023).

Besides, the Dubai, 2040 Urban Master Plan includes the active promotion of TOD, which recognizes the importance of integrating land use and transportation planning to enhance mobility, improve connectivity, and optimize the use of public transportation. According to Hannawi et al. (2019), the RTA developed the Dubai Transport Integration Manual in 2016 to encourage developers to integrate their developments with public transport networks, supported by an integrated multimodal transport system. They pointed out that there are no regulations or guidelines for the integration between development and public transport. RTA took an approach to call for tender from private developers for the development of TOD around selected metro stations. The idea is to create a public–private partnership (PPP) and bring the best proposal of TOD into practice around the stations.

Union 71 (formerly known as Union Oasis) TOD Project in the Deira area is expected to be a landmark destination with shops, restaurants, offices, and residential areas. This development is a part of Dubai's sustainable urban development initiatives which intends to increase metro ridership through high-density and diverse development near the Union 71 metro station, which is one of the busiest interchange stations in the Deira area connecting the red and green lines, that is expected to be completed by 2026 according to RTA (Government of Dubai, 2024).

The key target of Dubai's, 2040 Urban Master Plan is to have 55% of the population living within a maximum of 800 m from a main public transport

Fig. 7 Dubai metro map. (Source: UAE Union Atlas, 2024)

station (Government of Dubai, 2023). To achieve that, the plan encourages the development of mixed-use centers that play a pivotal role in the plan's transit-oriented development approach and also align with the aspirations to create a "20-minute city" that ensures accessibility to essential services within a 20-min travel time.

4.3 Doha's Transit-Oriented Development

Like other GCC countries, Qatar has witnessed a substantial economic growth as well as a notable increase in its population. Consequently, the need to enhance the land transport infrastructure has become increasingly vital to support and

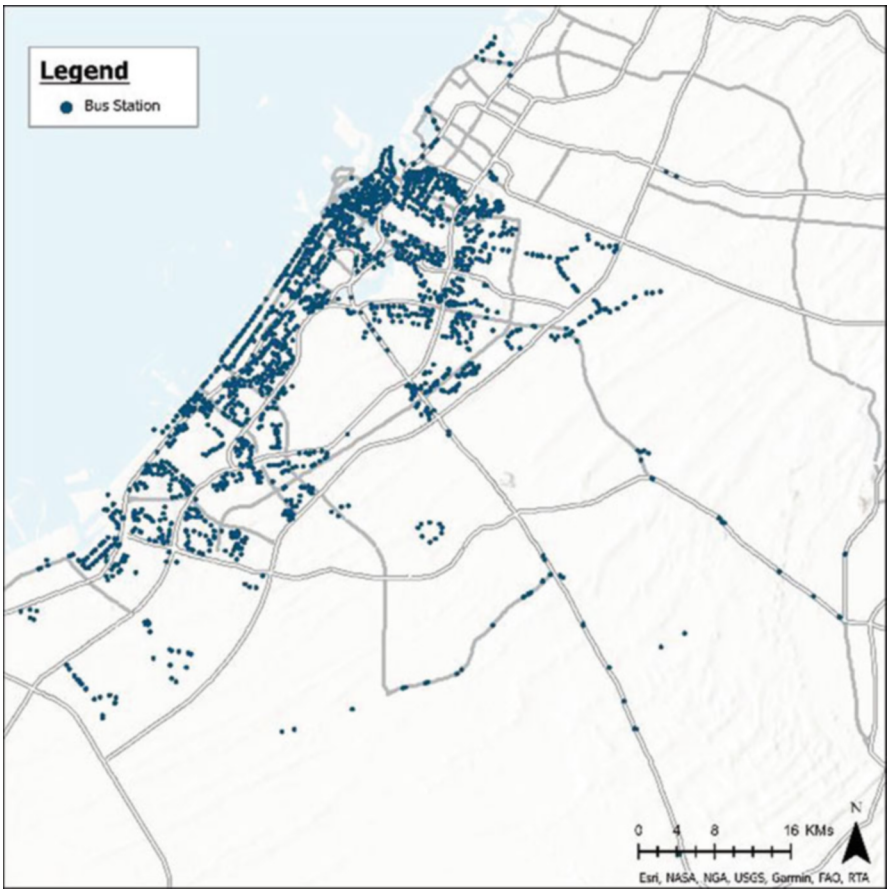

Fig. 8 Dubai bus stations (Source: Dubai Pulse, 2024)

align with the ongoing expansion and development plans. In line with that, the Qatar government established the Qatar National Development Framework (QNDF) which acts as a long-term roadmap that sets the direction for future growth and development while considering social, economic, and environmental factors. One of the key objectives of the QNDF focuses on ensuring that urban expansion adheres to the principles of transit-oriented development exemplified by integrating the metro into the urban landscape and supporting mixed-land-use development patterns (Rizzo, 2014; MME, 2016).

Doha, the capital city of Qatar, has undergone a rapid urban transformation including the initiation of Doha metro construction back in 2013 (Furlan et al., 2021). According to Furlan and Faggion (2015), a large investment has been made to develop new urban public transit networks including the Doha Metro, the Lusail light rail transit (LRT), and a bus rapid transit (BRT) (Fig. 9). Moreover,

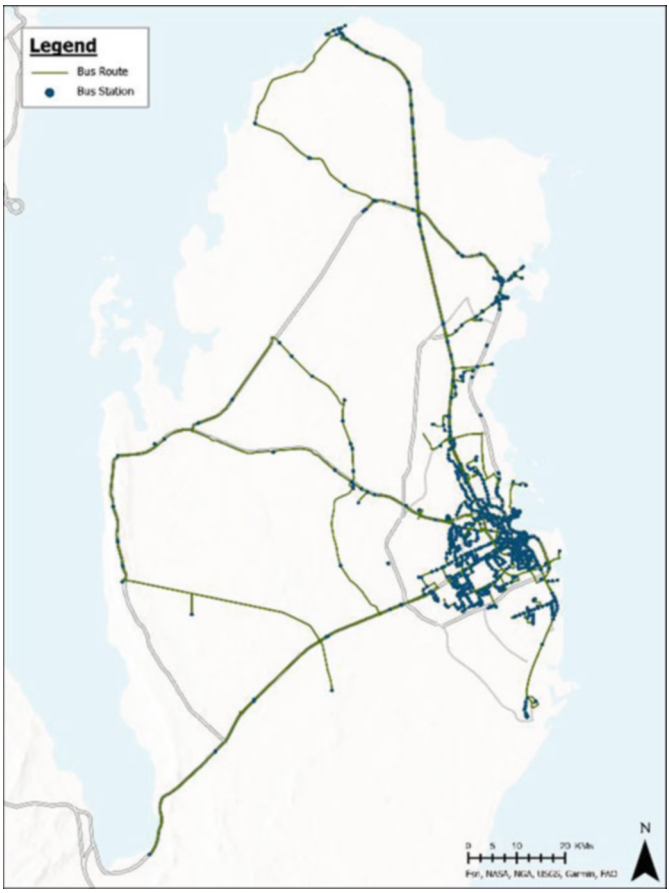

Fig. 9 Doha bus network. (Source: Qatar Atlas, 2024)

a strong emphasis was placed on the development of an efficient and sustainable transportation system to ensure that necessary infrastructure, services, and facilities are in place before the FIFA World Cup, which Qatar hosted back in 2022. Doha's metro phase 1 consists of three lines stretching over 75 km network serviced through 37 stations that were launched in phases since 2019 as shown in Fig. 10 (Qatar rail, n.d.). Phase 2, which is expected to be completed by 2026, includes expansion plans for existing lines in addition to constructing a new line with 60 stations that will expand the coverage and enhance the connection with suburban areas (AlKhereibi et al., 2022).

The spatial strategy for Metropolitan Doha (2030) supports a hierarchy of mixed-use centers that cluster residential, office, retail, leisure, government community, and cultural activities. The strategy identifies a four-level hierarchical center: capital city center, metropolitan center, town, and district centers (QNMP, 2030). TOD

Fig. 10 Doha metro network. (Source: Qatar Atlas, 2024)

underpins the centers by focusing on medium- and higher-density development activities with high capacity, high-frequency public transport facilities and services, optimizing accessibility and economies of scale, and reducing the need to travel by private car. A conceptual understanding of how different centers will work is shown in Fig. 11.

Each center is defined by layers of density and land-use activity radiating outward from the public transport node (as shown in Fig. 12). High levels of ridership and a critical mass of pedestrians flowing between transit hubs and places of work, recreation, and home are achieved through a balance of interconnected land-use activities.

The guidelines for different centers according to QNDF are as follows:

"Capital, Metropolitan and Town Centers in Metropolitan Doha are characterized by a core of high density 200–300 pph (approximately 50–75 dwellings per

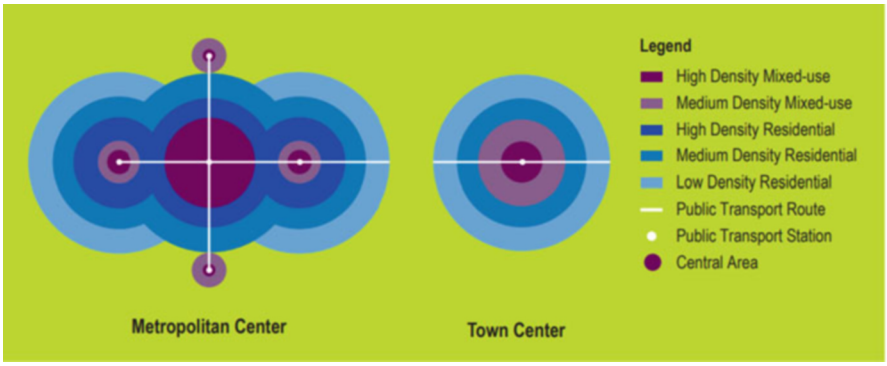

Fig. 11 TOD centers. (Source: MME, 2016)

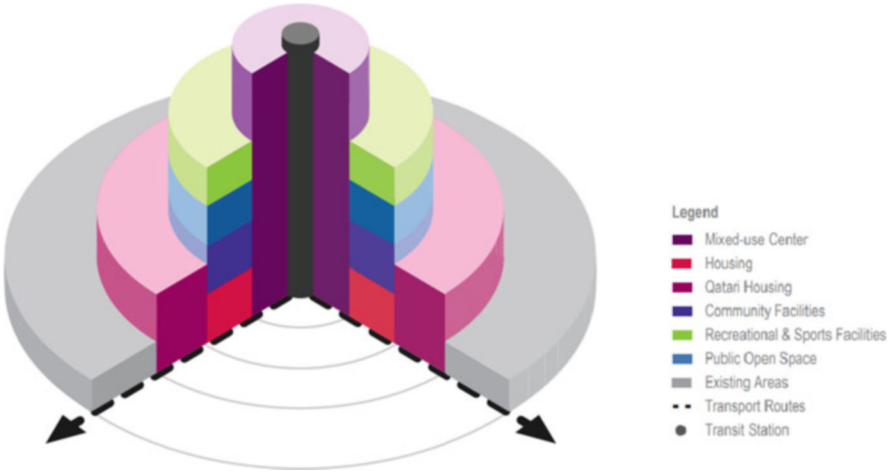

Fig. 12 Concept for mixed-use, mixed-density centers. (Source: MME, 2016)

hectare) and concentrated employment activities (e.g. retail and office), gradually merging with a medium-density periphery 60–200 pph (approximately 15–50 dwellings per hectare) and increased proportions of housing and community uses. The optimal range for Capital, Metropolitan and Town Centers is 30–70% commercial, 40–60% residential and 5–15% community facilities. Elsewhere town centers will have densities and a pattern of use in keeping with the community that they support.

District and Local Centers serve the communities daily and weekly needs and are within walkable distance of the catchment population, these centers are defined by medium density and support an optimal range of 10–40% commercial, 50–80% residential and 10–15% public facilities, with a lower density residential periphery. The land size of the center will be dictated by a reasonable walking distance from its central core, normally a public transit station and public space.

The concentration of density and mixed land uses around this core will ensure that the majority of people are within an easy walking distance of 250 m from public transit, defined as 10–15 minutes in the Qatari climatic context, and their daily and weekly needs" (MME, 2016, p. 45).

4.4 Prospective Transit-Oriented Development in GCC

Dubai, Doha, and Riyadh are the three major cities with TOD plans under implementation as part of dedicated national initiatives. Other GCC countries have the prospect of incorporating the TOD concept into their planned systems. In Bahrain, the economic vision 2030 is built upon three fundamental principles, sustainability stands as a significant focus with emphasis on the importance of robust and resilient infrastructure (Bahrain's National portal, 2008). A key area of focus within this plan is the development of an efficient and effective transportation system. In 2021, the government of Bahrain approved the construction of the first phase of Bahrain's metro project which includes a total of four lines covering around 109 km network (Railway Technology, 2021).

As for Oman, the National Spatial Strategy (ONSS) was approved in 2021 as an enabler to achieve Oman's 2040 vision. One of the main objectives of the strategy is to develop an integrated, sustainable, and efficient transport system. Moreover, a transit-led approach is encouraged for urban expansions which will play a pivotal role in reducing traffic, creating infrastructure-efficient urban areas, and defining active multimodal urban centers. The ONSS also identifies potential TOD sites with defined selection criteria (MoHUP, 2021).

On the other hand, Kuwait announced the Fourth Kuwait Master Plan (4KMP) in 2023 which is in alignment with New Kuwait Vision 2035 (MoFA, 2017; KUNA, 2023). One of the key objectives of Kuwait's national plan is to maintain a continuous investment in infrastructure, with a particular focus on further developing the transportation system (KPPC, n.d.). The Ministry of Communications finalized the network plan for a 160 km metro network in 2014 (IRJ, 2020). Unfortunately, despite the initial intention to begin construction in 2017, the planned project was officially canceled in 2023 due to the significant financial burdens associated with its implementation.

5 Emerging Challenges and Policy Consideration

The COVID-19 pandemic highlighted the importance of transportation resilience in maintaining essential services, supporting economic activities, and facilitating the movement of goods and people. Moreover, the traditional approaches of improving the transport network to address extreme weather situations or developing mass transit systems to mitigate climate threats proved inadequate in handling the

challenges posed by COVID-19. The limitations on activities such as commuting to work, taking children to school, and shopping resulted in reduced car usage which consequently led to a decrease in carbon emissions and a notable improvement in air quality (Sokhi et al., 2021; Liu et al., 2020). While this outcome is positive from an environmental and climate perspective, it adversely affected the overall quality of life.

Transportation plays a vital role in the pursuit of enhancing the quality of life, a key objective for the national development plans of most GCC countries. In this regard, TOD emerges as a pivotal strategy that can substantially contribute to achieving this objective. TOD emphasizes integrating land use and transportation planning to foster self-sustaining communities. These communities are designed so that daily needs are conveniently accessible by walking or cycling, while also providing efficient transit connections to the broader city. By promoting compact development and minimizing the need for long-distance travel, TOD contributes to a more robust and resilient transportation system.

Furthermore, multimodality, the integration of different modes of transportation, is crucial for creating a sustainable, efficient, and accessible transportation system. This was specifically evident during the pandemic when countries with an established bicycle infrastructure benefited from it as a reliable alternative for commuting and essential travel (Dunning & Nurse, 2020). Additionally, the integration of different modes of transportation improved last-mile connectivity, ensuring that people had access to essential services and supplies.

Indeed, extreme weather conditions in GCC states can pose challenges to walking and cycling as modes of transportation. However, the success of TOD in the region relies on ensuring convenient access to transit stations and the immediate surroundings (Ewing & Cervero, 2010). The principles of density, diversity, and design are crucial in achieving this goal. Providing adequate shade, green spaces, and rest areas along walking and cycling routes can enhance the overall experience and mitigate the impact of extreme temperatures. The integration of different elements, such as a bus station with a garden path, exemplifies the balance required for a resilient environment. The garden acts as the community's central spine connecting different aspects of the TOD, while enhancing the overall aesthetic appeal of the space, contributing to its desirability and livability. Pimenta et al. (2021) found that residents of transit-adjacent neighborhoods in Abu Dhabi were more likely to do physical activity than the average of all residents in Abu Dhabi.

TOD projects require a comprehensive understanding of the connectivity of the pedestrian environment around transit stations. Alawadi et al. (2020, 2021) have highlighted the potential of utilizing alleyways in GCC cities, including Dubai, which have traditionally incorporated alleyways into their urban fabric. The authors emphasized how leveraging the potential of alleyways in Dubai can enhance the efficiency and effectiveness of TOD projects in the city. This perspective extends beyond Dubai, as other GCC cities such as Riyadh and Doha also have characteristics similar to those of their alleyway-filled traditional settlements. Furlan (2016) also highlights the pedestrian-friendly nature and community-oriented atmosphere of traditional areas like Doha's "Souq Waqif." Moreover, given their narrow

structure and ability to provide shade from extreme heat, these alleyways can be transformed into valuable assets for creating more pedestrian-friendly cities.

In addition, a resilient transport system should offer alternatives for long-distance travel. Mobility-as-a-Service (MaaS) has been developed from a mobility perspective to provide users with access to various modes of transportation. It recognizes that journeys may require multiple modes of transport, such as walking to a station, taking a bus/tram/metro, and potentially using a bike or car to reach the destination. Furthermore, MaaS promotes multimodal travel and aims to discourage car usage, thereby increasing cycling, walking, and transit ridership while reducing car ownership and travel. This can ultimately lead to a reduction in energy consumption and carbon emissions. Integrating MaaS with TOD is crucial, not only to boost transit ridership but also to enhance resilience during disruptions.

Integrating efficient transportation systems with mixed-use development, TOD can contribute to climate change mitigation and adaptation. In addition, TOD's compact and interconnected urban design can also mitigate the impact of natural disasters. Moreover, TOD's mixed-use nature promotes economic diversification and reduces vulnerability to socioeconomic shifts by creating vibrant, self-sustaining communities. By adopting TOD principles and implementing resilient infrastructure, GCC cities can enhance their preparedness and capacity to withstand and recover from climate-related events, natural disasters, and socioeconomic changes, ultimately ensuring a more sustainable and resilient future.

In conclusion, by adopting TOD principles and deploying resilient infrastructure, GCC cities can enhance their readiness and ability to endure and recover from climate-related events, natural disasters, and socioeconomic changes. This approach paves the way for a more sustainable and resilient future.

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Water-Resilient Cities: GCC Strategies and Policy Recommendations

Amr Al-Zu'bi, Yara Elborolosy, Mohamad Hejazi, and Yoshihide Wada

Abstract This chapter addresses the critical issue of water scarcity in Gulf Cooperation Council (GCC) cities, focusing on the diverse strategies and challenges encountered by Riyadh, Dubai, Doha, Muscat, and Kuwait. It examines advancements in various sectors, including technological innovations in desalination and irrigation, and initiatives aimed at reducing water consumption within the water cycle to mitigate the impacts of arid climates and rapid urban growth. This chapter also highlights efforts toward sustainability through the reuse of treated wastewater. Emphasizing the necessity of an integrated approach, it advocates for combining policy interventions, technological advancements, and community engagement. Concluding with strategic policy recommendations, this chapter aims to enhance water security, foster sustainable development, and strengthen the long-term resiliency of the GCC cities.

Keywords Water stress · Sustainable water management · Arid cities · Urban water challenges

1 Introduction

Water stress, a pressing and escalating global crisis in many regions and cities around the globe (Chellaney, 2013; He et al., 2021), exists in two distinct yet interrelated forms: economic and physical water scarcity (He et al., 2021; Liu et

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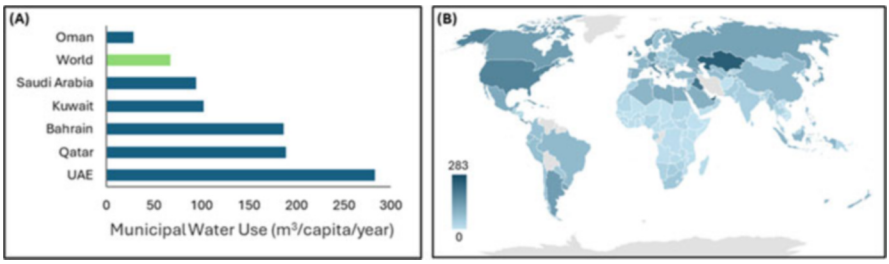

Fig. 1 Illustration of the per capita municipal water use rate in 2020 for the GCC countries and globally. (**a**) Comparison of the per capita municipal water use rates of GCC countries with the global average. (**b**) Display of a world map highlighting the 2020 municipal water use, measured cubic meters per capita, and patterns across different regions (FAO Aquatat Database)

al., 2017; Damkjaer & Taylor, 2017). The more challenging one, which is prevalent in the cities of the Gulf Cooperation Council (GCC) region (Al-Rashed & Sherif, 2000), is physical water stress, where freshwater sources such as lakes and rivers are limited, and water use rates are high (see Fig. 1) (Ali & Nafees, 2023). Over the past few decades, GCC countries and cities have experienced a significant rise in water usage due to economic expansion, population growth, and urban development (Damkjaer & Taylor, 2017; Ali & Nafees, 2023). To overcome the mismatch in water supply and demand, the GCC has mainly focused on groundwater extraction as a main source of water along with seawater desalination (Al-Rashed & Sherif, 2000; Qureshi, 2020). This has accelerated groundwater depletion in the region and has led to more demand for seawater desalination as the main freshwater source for many cities across the GCC region.

The symptom of a growing water stress condition in cities can induce and reverberate into social, economic, and environmental impacts (Israilova et al., 2023). For example, water stress can affect public health, sanitation, and quality of life in GCC cities, leading to water stress-related diseases, hygiene issues, and conflicts over water access (DeNicola et al., 2015). Worsening water stress conditions can also undermine economic growth and development by limiting agricultural productivity, industrial expansion, and tourism potential in GCC cities (Alrwis et al., 2021). It can also increase water production and distribution costs, putting financial strain on governments and consumers.

GCC cities are also poised to experience climate change as a risk multiplier. The region is experiencing a range of climate change impacts, including rising temperatures, extreme weather events, and sea-level rise (Wehrey et al., 2023). Climate change can exacerbate water stress in the GCC through various mechanisms. Rising temperatures accelerate evaporation rates and increase water demand for irrigation and cooling purposes. Changes in precipitation patterns lead to more frequent and intense droughts, reducing surface water availability. Sea-level rise threatens coastal aquifers and exacerbates saltwater intrusion into freshwater sources. These changes have profound implications for urban areas, leading to increased heat stress, water stress, and coastal flooding (Jägerskog & Barghouti, 2022). Additionally, socioe-

conomic disparities within cities can exacerbate vulnerability to climate change impacts, with marginalized communities often bearing the brunt of environmental risks (Chapter 6: Cities, settlements and key infrastructure, 2024).

These forces are expected to worsen over the coming decades, putting more strain on the climate resiliency of cities in the GCC region. This chapter examines the progress of managing water stress in GCC cities and provides policy recommendations for addressing existing and future challenges and enhancing climate resiliency in GCC cities.

2 Managing Water Stress in GCC Cities

This section examines the water stress management strategies employed by Riyadh, Dubai, Doha, Muscat, and Kuwait. These regions have been selected for their diverse and innovative approaches to addressing severe water shortages exacerbated by arid climates and rapid urbanization. By analyzing the progress and challenges faced by these cities and projects, this chapter aims to provide a comprehensive understanding of effective water management practices in the context of the GCC and neighboring regions.

2.1 Case Studies of Water Scarce Cities Progress and Challenges in the GCC

Riyadh, Saudi Arabia, is the central hub for politics, finance, and administration in Saudi Arabia and is home to a rapidly growing population (Aldegheishem, 2023). According to the Saudi Arabia Census, according to the Saudi Arabia Census, the population in Riyadh was approximately 6.22 million in 2010 and grew to 8.59 million in 2022 (Saudi Census, 2022). However, the city's harsh arid climate, minimal precipitation, and lack of renewable freshwater sources pose several challenges. Due to the lack of freshwater sources such as lakes and rivers, the city relies mainly on groundwater abstraction and seawater desalination to meet its freshwater demands (Al-Juaidi & Attiah, 2019). According to the Ministry of Energy, Water and Agriculture (MEWA) of Saudi Arabia (Ministry of Energy, Water and Agriculture, 2022), domestic water use in Riyadh has increased from 0.663 BCM in 2010 to 1.106 BCM in 2022 (Ministry of Energy, Water and Agriculture, 2022; Saudi Census, 2022). As of a 2010 report, the groundwater level in Riyadh was between 1200 and 1500 m deep (KICP, 2024), making groundwater extraction both energy- and cost-intensive with time, as the depth would continue to increase since the aquifers are nonrenewable. According to MEWA's statistical annual reports from 2014 to 2022, the volume of desalinated water for domestic use in Saudi Arabia increased by 67.1%, while groundwater abstraction decreased by

3.4%. Also, with the advancements in technology for desalinated water, the energy use decreased from 6.5 kWh/m^3 in 2011 to 3 kWh/m^3 in 2018. Utilizing solar energy for desalination plants is growing in Saudi Arabia, allowing desalination to become more sustainable as the country aims to meet its net-zero goals by 2060. This clearly emphasizes how seawater desalination is vital for Riyadh to overcome its freshwater shortage.

In line with Saudi Arabia's Vision 2030, Riyadh is undertaking the Green Riyadh Project, which aims to enhance the city's green areas by planting 7.5 million trees (Abdelrahman, 2024). Given the high costs associated with water procurement in the city, it is essential to recycle and reuse water to ensure both resilience and sustainability. Thus, one of the Green Riyadh Project's key enablers is the construction of a new water treatment network with a daily capacity of one million cubic meters to be used for irrigation (Abdelrahman, 2024), to be both resilient and sustainable.

The Green Riyadh project will significantly enhance Riyadh's preparedness for rainwater management and flood risk mitigation. Also, the adoption of green building techniques, such as green roofs and walls, along with the reduction of the ambient temperature in the summer as a result of planting trees, is expected to reduce annual power consumption by up to 650 gigawatt-hours. As water is used for power production (Abdelrahman, 2024), implementing these techniques could lead to substantial water savings across Saudi Arabia, particularly if applied in other cities.

Dubai, United Arab Emirates, is situated on the southeastern coast of the Arabian Gulf and is known as the vibrant metropolis of the United Arab Emirates and the Middle Eastern region. Dubai is renowned for its ultramodern architecture, bustling economy, and booming tourism sector. Similar to Riyadh, Dubai also suffers from a lack of renewable freshwater sources. Dubai's harsh arid climate, minimal precipitation, and limited natural and renewable freshwater sources necessitate advanced and sustainable water management strategies to support its rapidly growing population and maintain its economic momentum. Annual precipitation in Dubai during the rainy season has shown a decreasing trend in the last century and more significantly in recent decades. According to the World Bank, the average precipitation in Dubai during the rainy season (December, January, and February) from 1901 to 1930 was 35.08 mm, from 1961 to 1990 was 35.26 mm, and from 1991 to 2020 was 31.88 mm (World Bank Climate Change Knowledge Portal, 2024). However, the average temperature in Dubai during the rainy season has shown an increasing trend in the last century and more significantly in recent decades as well. The average temperature in Dubai during the rainy season from 1901 to 1930 was 13.19 °C, from 1961 to 1990 was 13.49 °C, and from 1991 to 2020 was 14.4 °C (World Bank Climate Change Knowledge Portal, 2024). The population in Dubai in 2009 was 1.7 million people, and in 2022, the population reached 3.55 million people, a 50% increase (Dubai Statistics Center, 2022). This increase in population has contributed to the rise in water demand in a city that is already facing water stress issues.

Having groundwater and seawater desalination as the sole freshwater source, Dubai was forced to implement a multifaceted water conservation strategy, focusing on desalination and wastewater reuse. One of the main initiatives taken by Dubai Electricity and Water Authority (DEWA) was the expansion of seawater desalination plants by investing in advanced, energy-efficient, and more environmentally friendly desalination methods such as reverse osmosis. In 2023, the total water requirement in Dubai was 0.657 BCM with 0.655 BCM provided by desalinated water and reverse osmosis plants provided 43% of the city's desalinated water (DEWA, 2023).

Moreover, Dubai is committed to achieving 100% wastewater recycling by 2030 as a part of its sustainability strategy (The National News, 2023). To achieve this, the municipality has implemented stringent regulations aimed at boosting the efficiency of water treatment plants and encouraging the reuse of treated wastewater in irrigation, landscaping, and the industrial sector. This treated water is also essential for sustaining the green spaces and public parks that enhance the city's livability, even in its challenging arid environment.

In addition to these infrastructural projects, Dubai has been actively promoting water conservation through public awareness campaigns and incentive programs to reduce its per capita consumption. The government has been encouraging residents and businesses to adopt water-saving practices, such as using water-efficient appliances and fixtures (DEWA, 2022). To further incentivize water conservation, Dubai has participated in national competitions that reward significant reductions in water usage. One notable competition is the UAE Water Aid (Suqia) award, which honors innovative water conservation and desalination solutions. These competitions not only foster a culture of conservation but also stimulate technological advancements and community engagement.

Through a combination of cutting-edge technology, stringent regulations, and public participation, Dubai is making significant strides in mitigating water stress and working toward sustainable water management. These efforts are crucial for ensuring the city's resilience and long-term sustainability in the face of environmental challenges.

Doha, Qatar, is located along the coast of the Arabian Gulf and is known for its rapid development and modern skyline. Similar to Riyadh and Dubai, Doha faces significant challenges regarding freshwater availability due to its arid climate, minimal rainfall, and the absence of natural renewable freshwater sources. The average annual precipitation in Qatar from 1976 to 2010 over 29 rain stations shows mixed variability but can still be described as decreasing, with the highest recent annual rainfall recorded at only 125 mm in 2006 (Mamoon & Rahman, 2017). The average temperature in Qatar during the rainy season (December, January, and February) from 1901 to 1930 was 17.68 °C, from 1961 to 1990 was 18.09 °C, and from 1991 to 2020 was 18.87 °C (World Bank Climate Change Knowledge Portal, 2024). The total water use for households increased from 279 Mm^3 in 2009 to 293.1 Mm^3 in 2020 and is projected to continue to increase with population growth (Ministry of Development Planning and Statistics 2015; Planning and Statistics Agency (PSA), 2021).

A key component of Qatar's strategy to address water stress is its stringent limitation on groundwater abstraction. Recognizing the critical importance of preserving its nonrenewable groundwater reserves, Qatar has implemented policies to drastically limit the extraction of groundwater. This approach aims to prevent the depletion of aquifers and ensure the long-term sustainability of the country's water resources, by providing the extra demand through seawater desalination and wastewater reuse (Aloui et al., 2023).

In 2010, Qatar had water reserves that could only hold 48 hours of water storage in case of emergencies. This led to significant investments by the state-owned water utility company KAHRAMAA, to enhance drinking water storage capacity. As a result, the Water Mega Reservoirs project was initiated (Dutch, 2019), with the first phase of the project, starting in 2015. It aims to build 24 large concrete reservoirs to reach a capacity of 2300 million gallons to store 7 days' worth of potable water, meeting the expected demand by 2026. The second phase will extend this capacity to 3800 million gallons to meet the forecasted demand by 2036 (The Water Security Mega Reservoirs Project Qatar, 2019). These reservoirs are strategically located along the Qatar National Utility Corridor and interconnected with fully automated pumping stations to ensure security, contingency, and reliability.

To further support its water needs, Doha has heavily invested in desalination plants using advanced technologies. The city is also expanding its wastewater treatment facilities to recycle and reuse water for irrigation, landscaping, and public parks, contributing to the city's greenery and enhancing the overall quality of life (Lawler et al., 2023).

The Doha's government has also been promoting public awareness and participation in water conservation. Various initiatives and campaigns are conducted to educate residents and businesses about the importance of water-saving practices. These programs promote the use of water-efficient appliances and fixtures, encouraging the community to adopt habits that reduce water use (Al-Maadid et al., 2023).

Through a combination of stringent groundwater protection, increased storage capacity, advanced technology, infrastructure development, and community engagement, Qatar is making significant strides in addressing its water stress challenges. The country's proactive approach to water management is essential for its resilience and sustainability, ensuring that it can thrive despite the harsh environmental conditions.

Muscat, Oman, is located on the southeastern coast of the Arabian Peninsula, overlooking the Gulf of Oman and the Straits of Hormu. Oman, as well as the city of Muscat, has been rapidly investing in tourism, infrastructure, and other sectors to modernize the country. Similar to its neighboring countries on the Arabian Peninsula, Oman and the city of Muscat are facing significant water stress challenges due to its arid climate, limited renewable freshwater resources, and the growing demand for water use. The average annual precipitation in Oman is also variable due to the variability in geography and the monsoon season in the southern region. However, studies show that there is a decreasing trend in recent years. The average annual precipitation was 30.6 mm/year in 2022 (Tridwip, 2024), while in 2006, it was 96 mm/year (al-Shukaili, 2011). The annual temperature has increased

about 0.4 °C per decade since 1980, bringing the current average temperature to 27.8 °C. In recent years, heatwaves have become more significant and more common in Oman, with one heatwave lasting almost a month in some locations in June 2021 (IEA, 2024). The total annual water use for the household sector in Oman increased from 106.2 to 180 Mm^3 (GCC Stat, 2020).

The city of Muscat and, more broadly, the country of Oman, more broadly, have taken a multifaceted approach to tackle the water stress issue by managing both the supply and demand sides of the water challenge. For supply management, Oman has been investing in dam construction since 1985, with the total water use retained in 2013 reaching 167 Mm^3 (Al-Shibli, n.d.). Desalination plays a crucial role in Oman's water supply; desalination production has increased from 0.24 BCM per year in 2010 to 0.39 BCM per year in 2020 (GCC Stat, 2020), which allows for a decrease in groundwater use. An interesting concept that is being tested in Oman is fog collection, where nets or mesh structures are set up to collect water droplets as the fog passes through. These water droplets grow larger and are collected in either troughs or containers. They can be used as a renewable water supply with low environmental impact. The water would be mainly used for irrigation and water use for animals (Sultanate of Oman | FogQuest: Sustainable Water Solutions, 2009). Also, cloud seeding, that is, dispersing substances into the air to enhance precipitation, has been recently implemented in Oman. It is estimated that since 2012, there has been an 18.8% increase in rainfall in the areas where cloud seeding stations were built (Oman Observer, 2024). In late 2022, Oman implemented a new water tariff strategy to reduce water demand within the domestic sector, after seeing the success of tariffs within the electricity sector. Currently, there is not enough data to analyze the effects of the water tariff, but similar strategies have been seen to reduce water demand (Oman Power and Water Procurement Co, 2022).

Another implementation of Oman's water strategy was to reduce non-revenue water, which consists of leakage losses, illegal connections, non-working meters, and errors in readings, and they were able to reduce this by 32% from 1976 to 2011 (Al-Shibli, n.d.). For the use of treated wastewater, the Muscat government aims to reach 100 MCM (in 2012, it was at 30 MCM) and by 2025 to provide all towns with more than 10,000 people with piped water supply and wastewater treatment (Al-Shibli, n.d.).

Oman has been actively engaging the public to raise awareness about water use and conservation strategies. For example, Oman Water Week is a weeklong event that brings together policymakers, scientists, and students to learn more about Oman's water situation and what they do to promote sustainable water use (Oman Water Week). The government has been encouraging educational programs within schools throughout the country, including site visits to desalination plants, for example, to allow local students to have an interactive learning experience toward water use (MEDRC | New CSR Initiative Aimed at the Youth of Oman, 2024).

Oman is making significant progress in mitigating its water stress through creative and innovative technologies, policy implementation, and public awareness to reduce water usage. This will go a long way in ensuring the country's continued growth in a sustainable and resilient manner.

The story is relatively the same in the other cities across the GCC, including *Kuwait*. Kuwait, for example, also faces significant challenges due to a lack of freshwater sources (Tariq et al., 2022) and has heavily invested in developing advanced water infrastructure (Al-Otaibi & Abdel-Jawad, 2007). One of the cornerstones of Kuwait's strategy, and similar to Qatar's, is its extensive use of desalination technology to provide fresh water (Hamoda, 2001). Kuwait has also been focusing on wastewater treatment with high standards to be reused in agricultural irrigation, landscaping, and industrial applications. Kuwait has one of the largest treatment plants globally "The Sulaibiya Wastewater Treatment Plant" with a capacity of 600,000 cubic meters per day (Choukr-Allah, 2010). The country is also exploring smart water management systems, employing advanced technologies like sensors and data analytics to enhance water distribution efficiency and reduce losses (Zaher et al., 2021).

3 Policy Recommendations

To tackle water stress effectively, combining innovative technological solutions with comprehensive policy frameworks is essential. By integrating advanced desalination technologies, for example, membrane and green desalination, promoting widespread water recycling, and incentivizing water-saving practices, we can significantly reduce the strain on existing water resources while mitigating the impacts on carbon emissions. Furthermore, strengthening governance structures and fostering a culture of water conservation through public awareness campaigns are critical components of a sustainable water management strategy. The following recommendations outline specific actions that policymakers can take to achieve these goals and ensure the long-term resilience of cities in the GCC region.

Advance Desalination Desalination has become a significant part of the water supply for cities in the GCC region due to the lack of renewable freshwater sources. The GCC should continue to make technological advancements in desalination to allow it to become more environmentally friendly and to lower its operating costs. The introduction of reverse osmosis is an example of technological advancement that can help reduce the negative environmental impact of desalination. Thermal technologies, such as Multi-Stage Flash and Multi Effect Desalination, using natural gas emit from 20.4 to 25.0 $kgCO_2/m^2$ and 11.8 to 17.6 $kgCO_2/m^2$, respectively, while reverse osmosis plants emit from 1.75 to 2.79 $kgCO_2/m^2$ (Moossa et al., 2022). Policies allowing for public–private partnerships encourage collaborations between the government, academia, and industrial leaders to accelerate the development of improved desalination methods. Providing tax incentives and subsidies for desalination plants that utilize renewable energy can encourage desalination plants to become more energy efficient and reduce their carbon emissions as well.

Diversify Water Supply Sources The GCC countries have developed the Unified Water Strategy (UWS) to ensure the continuous improvement of the water sector

for the region, which has 13 key performance indicators. One of them is to have 90% of total treated wastewater to be reused in each GCC country (Moossa et al., 2022). Increasing the reuse of treated wastewater will increase the water supply for agricultural and municipal uses. Creating policies to encourage building more wastewater treatment plants, industries to recycle water, and municipalities to reuse treated wastewater for landscape irrigation and non-potable uses will add another element for the water supply, reducing the amount of desalinated water or groundwater. Thus, GCC cities should invest in diversifying their water sources by promoting water reuse, rainwater harvesting, and wastewater treatment technologies to reduce reliance on desalination and groundwater extraction. Implementing these measures can enhance water security and resilience in GCC cities.

Enhance Groundwater Management Given the high reliance on groundwater aquifers in the GCC (Sherif et al., 2023), implementing stringent strategies for groundwater extraction is crucial to ensure their sustainability. Establishing strict regulations that limit extraction rates and prevent aquifer depletion is imperative. Any excess water demand should be supplemented by alternative sources, prioritizing the conservation of groundwater reserves. Furthermore, substantial investments in groundwater research are essential to improve understanding of aquifer dynamics, recharge rates, and long-term sustainability. By adopting these measures, the GCC can safeguard its groundwater resources for future generations and mitigate the risks associated with overexploitation and depletion of aquifers.

Enhance Water Conservation Measures In addition to improving technological advancement and diversity of its supply sources, cities in the GCC should also invest in promoting water reuse, rainwater harvesting, and wastewater treatment technologies to reduce reliance on desalination and groundwater extraction. For example, policies to implement real-time monitoring and leak detection technologies in the water distribution system will help reduce water losses due to leakages and inefficiencies. Implementing such measures can enhance water security and resilience in GCC cities by improving their water use efficiency.

Improve Irrigation Water Use Efficiency In the GCC region, more than 80% of the water demand comes from the agricultural sector and groundwater is exploited to meet the agricultural water demand (Alotaibi et al., 2023). Thus, the GCC region should explore enacting policies to promote drip irrigation and other water-saving irrigation methods to help reduce the demand from the agricultural sector. Also, drought-resistant crops require less water, and policies can be used to encourage their use. Hydroponics, growing plants without the use of soil, can also help produce high-quality crops in controlled environmental conditions year-round and can increase the yield by 40 times as much per acre planted (Fiaz et al., 2018). Currently, greenhouses in Qatar, the United Arab Emirates, and Saudi Arabia use hydroponics to produce food items with similar prices as those grown in the field. Seawater greenhouses, using seawater instead of fresh water, have been implemented along the coast of the Red Sea within KSA and have been successful as well (Fiaz et al., 2018).

Promote Awareness Public awareness and education are also critical to educating citizens on water conservation methods and policies to help integrate water conservation topics into the school curricula can help build this awareness from a young age. An awareness campaign should also promote the broader implications of inefficient water use with respect to their social impacts, environmental impacts, as well as their economic impacts. For example, water saving might be a more effective energy-saving and emissions abatement option. Informational campaigns to educate citizens on their water and environmental footprints and how they compare with their more efficient peers and neighbors could help offer important nudging and behavioral changes.

Employ Integrated Water Management Strategies Embracing integrated water management strategies is essential to address the interconnected challenges of water supply and demand, along with how they are also impacted by climate change. Systems thinking and integrated approaches that take a holistic view of the entire water cycle can ensure that while reducing stress on one water source, it does not increase on another source. For example, Saudi Arabia's Vision 2030 emphasizes the integration of desalination, wastewater recycling, and efficient irrigation while reducing groundwater use to create a balanced water management system (MEWA, 2024). The UAE's Water Security Strategy 2036 aims to optimize desalination, groundwater use, and recycled water through planning and advanced technologies (Almheiri, 2023). Qatar has implemented a National Water Act that emphasizes the reuse of treated sewage effluent for landscaping and industrial purposes (Jasim et al., 2016). These strategies highlight the importance of the holistic approach in mitigating water stress while supporting the sustainable development of cities in the GCC region. As for the demand side, implementing campaigns similar to Dubai's initiatives to reduce water consumption, along with investing in improving irrigation water use efficiency as previously discussed, could seamlessly integrate with supply strategies and significantly impact the water cycle.

Devise Climate Change Adaptation Strategies Climate change is continuing to negatively impact the world and the GCC countries are recognizing the urgency in needing to address climate change by implementing various strategies to help mitigate the impacts (Climate Futures Report, 2023; KAPSARC, 2024). Equally important is the need to establish national and city-scale climate change adaptation strategies. The GCC regions should develop climate change adaptation strategies and infrastructure projects such as seawater desalination powered by renewable energy sources, water-efficient irrigation systems, and drought-resistant crops to mitigate the impacts of climate change on water resources in GCC cities. These strategies can enhance the resilience of water supply systems and minimize the adverse effects of climate variability on water availability.

Promote Collaboration and Knowledge Exchange Regional collaboration and knowledge exchange are important strategies to help combat climate change within the GCC region due to the similar challenges they face, the shared climate conditions, and, in some cases, shared water resources. Through various platforms,

such as the GCC Water Cooperation Committee and regional conferences, countries within the GCC are sharing best practices, technologies, and policy frameworks. The Unified Water Strategy mentioned previously is a result of the GCC's collaboration and exchange of knowledge. The annual Gulf Water Conference serves as an important forum for experts and policymakers to coordinate sustainable water management practices. The GCC-STAT center for statistics has become an important tool in exchanging data and helping facilitate research on water resources and climate impacts, increasing the ability to develop effective strategies. Strengthening these collaborations will be crucial for building resilient water management systems and effectively adapting to climate change (World Bank, 2024).

4 Conclusions

Water stress is a complex challenge facing cities in the GCC region, with far-reaching social, economic, and environmental implications. The case studies of Riyadh, Dubai, Doha, Muscat, and Kuwait highlight the diverse approaches these cities are employing to address water stress, including advancements in desalination, wastewater reuse, and public awareness campaigns. Despite their unique contexts, these cities share common goals: enhancing water security, ensuring sustainable growth, and mitigating environmental impacts. Addressing water stress requires a holistic approach that combines policy interventions, technological innovations, and community engagement efforts. By following the policy recommendations outlined in this chapter, GCC countries and cities can significantly enhance water security, promote sustainable development, and safeguard the well-being of their citizens for generations to come. Regional collaboration, integrated water management, and continued investment in research and technology will be crucial in overcoming the multifaceted challenges of water scarcity and ensuring a resilient future for the GCC region.

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Climate-Resilient Cities—Priorities for the GCC Countries Resilient Power Systems

Muhammad Adnan Hayat and Moamar Sayed Mouchaweh

Abstract Historically, power generation and transmission systems remained centralized and less prone to extreme events. However, with many countries aiming to achieve net-zero emissions including in the power sector. The future power system brings new challenges for the power system security, reliability, and resiliency. The emerging power grid is comprised of a greater mix of inverter based intermittent renewable generation resources which are heavily reliant on weather conditions. Additionally, the electricity sector is becoming more and more digitized and integrated with other sectors like health, transport, and industry. Therefore, even a short blackout can disrupt the whole city and halt emergency services which makes the resilient power system more important than ever. Gulf Cooperation Council (GCC) countries similar to other countries are projecting similar trends in terms of grid transformation and modernization. On top of it, GCC countries are projected to experience significant growth in power demand driven by urbanization, industrial activities, and population growth. This chapter discusses in detail how emerging power systems can be made more resilient against severe weather events and digital disasters. This chapter concludes by outlining key considerations for the GCC countries to enable resilient power system.

1 Introduction

A reliable and secure power system remains the core of social and economic activities. Historically, a power outage can cause the disruption of economic activities and halt day-to-day activities. However, this reliance on reliable and secure power systems is greatly enhanced with the digitalization and integration of every sector with electricity. In modern cities, all the major sectors are linked to the power system, from transportation (traffic lights, electric trains) to critical

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services (hospitals, police stations, other emergency services) to communications systems; all sectors rely on the constant supply of electricity without interruption. Additionally, in modern cities, the citizens are not used to outages, and it is normal to expect that power is available securely all the time. Even a couple of hours of outage can halt emergency services, disrupt the flow of traffic, close shopping malls and offices, pause the transportation and communications system, and literally stop the city. This immense reliance on secure and stable electricity makes it a key pillar to build resilient cities.

A conventional power system remained centralized and less prone to extreme events. However, with many countries aiming to achieve net-zero emissions economy-wide including in the power sector, the emerging power system brings new challenges. The emerging power grid is comprised of a greater mix of intermittent renewable generation resources which are heavily reliant on weather conditions. These emerging renewable technologies are localized[1] and small scale and come with a different response rate. Moreover, the emerging power grid is digitalized with bidirectional energy and information flows. This emerging power grid involves consumers in energy generation and management through decentralized decision-making and coordination. These transitioned power systems require power grid designers, planners, and operators to anticipate, prepare for, and adapt to changing grid conditions. Furthermore, it requires additional monitoring, control, and communication requirements. Similar to the global trend, Gulf Cooperation Council (GCC) countries are projecting similar grid transformation and modernization. Moreover, GCC countries are projected to experience significant growth in power demand driven by urbanization, industrial activities, and population growth.

This chapter discusses what is a resilient power system and why it is important. It further discusses how the conventional power system is transitioning to a relatively fragile digitalized future power system. Strategies to improve the resilience of emerging power systems are then discussed. Further resilience metrics and planning for digitalization resilient power grid are discussed. Finally, this chapter concludes by outlining key considerations for building resilient power systems and recommendations for the GCC countries.

2 Power System Resilience

2.1 What Is a Resilient Power System?

A resilient power system withstands, responds to, and recovers rapidly from events causing major power disruptions. Power system resilience overlaps with operational reliability and resource adequacy. However, resilience covers several unique aspects that typically include more extreme that go beyond reasonable

[1] Localized implies that it is pertaining to the local weather conditions.

outages considered under resource adequacy and operational reliability (AEMO, 2021). Therefore, power system resilience comes in the context of low probability and high consequences in terms of power disruptions and outages (Eric Vugrin & Silva-Monroy, 2017). Power system resilience planning prepares the grid for extreme events such as thunderstorms, winter weather, hurricanes, or human threats such as cyberattacks. This enables the power system to absorb shocks related to failure in the operation of generation or transmission assets as a result of an event to enable it to quickly recover and operate again.

Resilient power systems are critical to building modern resilient cities. Historically, power systems were centralized, and generation systems were not exposed to extreme threats. There were only challenges like technical operational issues or economic issues like fuel shortage which could disrupt the power system. Most of the challenges could be addressed by proactive planning and maintenance. It was mainly transmission lines that were exposed to greater risk in terms of being exposed to extreme weather conditions such as storms, hurricanes, and bushfires. However, modern cities are much more fragile when it comes to power system resilience. There are three main reasons why the power system resilience in the modern cities is very important:

1. First, localized weather-dependent intermittent renewable energy sources like wind and solar are more sensitive and exposed to extreme weather conditions.
2. Second, in modern resilient cities, the power system is integrated with sectors such as health, transportation, and communication systems. Therefore, electricity outage severely impacts all aspects of the day-to-day activities of the modern city.
3. Third, emerging digitalized power systems are more exposed to human-caused failures, for example, digital disasters and cyberattacks.

Historically, for conventional power systems, metrics of power system reliability and power system resource adequacy were sufficient for the secure and reliable delivery of electricity under all credible and non-credible contingencies. However, for emerging power systems, there is a growing need for power system resilience to cope with future challenges and threats.

2.2 Conventional and Emerging Digitalized Power System

Power grids are at the center of a huge transformation to enable the transition toward sustainable and low-carbon emission energy systems. They are upgraded from a conventional one-direction energy flow system to a complex cyber-physical system with bidirectional energy and information flows. They are enabling a shift toward integrating small-scale renewable energy generation. Moreover, they are involving consumers in energy generation and management through decentralized decision-making and coordination. Table 1 shows a comparison between a conventional power grid and a digitalized emerging power grid. The latter is the future power

Table 1 Comparison between conventional power grid and digitized power grid

	Conventional power grid	Digitalized emerging power grid
Generation	Centralized based on large power plants/large share of fossil energy	Decentralized small-scale power plants ignoring boundaries between generation and demand/large share of variable renewable energy
Transmission	One directional power flow (generation to demand) and information (demand to utility) based on large power lines	Bidirectional power and information flows based on widespread and localized transmission lines with utility-scale battery storage
Demand	Passive consumers only paying, demand driven	Producer and consumer (Prosumer) participating actively in the power grid operations, weather/season/time of the day dependent
Market	Utility-driven/power providers	Customer-driven/more volatile/smaller/shorter supply periods/service providers
Grid operations	Centralized	Centralized and decentralized/emergence of new players
Grid operators	Large energy supply actors	Smaller energy supply actors, private individuals, and actors from outside of the electricity system
Information and communication technology (ICT)	Separated Information Technology (IT) from Operational Technology (OT)	Integration of IT and OT together and sharing data between them

grid required to meet the objectives of energy transition in terms of decarbonization, energy efficiency, and variable renewable energy integration into the main grid.

In a conventional power system, controllable generation tends to support the power system in remaining stable following system disturbances. However, in an emerging power system, the proportion of controllable generation is declining which accentuates the system resilience risks (AEMO, 2021). This emerging power grid continues to test the boundaries of the power system (AEMO, 2020). In terms of generation, intermittent renewable generation is unable to assist or prevent the collapse of the power system as a result of extreme weather events. Rather, it is increasingly prone to extreme weather events due to the localized and weather-dependent nature of these resources. Therefore, the resilience of emerging power systems should be one of the key considerations for building resilient power systems

and ultimately resilient cities. The following section reviews some of the key strategies that are proposed to improve the resiliency of emerging power systems in the literature.

2.3 *Strategies to Improve Resilience of Emerging Power Systems*

There are various studies that proposed different measures to improve the resilience of emerging power systems. Australian Energy Market Operator (AEMO) in its Integrated System Plan proposed that fuel diversity, geographic diversity, and strategic redundancy can improve power system resilience. The AEMO report further recommends that battery storage and transmission network can increase power system resilience (AEMO, 2022). AEMO also recommends consideration of diversity of transmission lines, increasing physical robustness of assets, and increased monitoring for early alerts of potential severe events to improve the resilience of the power system (AEMO, 2020).

There are also some studies that recommended some actions based on the investigation of weather-related events that caused widespread outages. The National Association of Regulatory Utility Commissioners (NARUC) of the United States in its investigation of the power system outage from Superstorm Sandy that left 1.5 million customers without power in the City of New York in 2012 observed that none of the installed rooftop PVs were configured to provide backup power in the event of power interruption. Following Superstorm Sandy, a more resilient distributed energy system was developed by integrating rooftop solar PV with battery storage (NARUC, 2019). Another weather-related event occurred in September 2016 in South Australia where tornadoes with wind speeds in the range of around 260 km/h caused failure of transmission lines and nine wind farms. AEMO analysis showed that significantly low inertia[2] due to a lower number of online firm power generators was one of the key reasons for blackout (AEMO, 2017). There are various utilities that have recommended actions to enhance the resilience of power systems. One is investing in black start[3] capacity to ensure reliable fail-safe backup power which can become available during extreme events. Another recommendation was restructuring regulatory flaws impacting dispatchable generation. Mitigating growing interdependence between infrastructure sectors (ASCE, 2022), power systems tend to be less resilient in highly urbanized cities with large populations, and a more distributed population is a better design in terms of achieving higher power system resilience in urban planning (Shen et al., 2021). Therefore, urban city resilience planners should work closely with utilities and power system planners to build energy-resilient cities.

[2] Inertia in power systems refers to the energy stored in large rotating generators.

[3] Black start enables the restoring of electric power to recover from a blackout.

Another growing challenge is the impact of high penetration of renewables on the techno-economic viability of conventional controllable power generation. Subsidized non-dispatchable intermittent renewable generation diminishes the participation margin for dispatchable power generation[4] (ASCE, 2022). This non-dispatchable generation negatively impacts the economics of dispatchable generation critical for a reliable and resilient power system. There is a tremendous resilience and reliability difference between intermittent renewable and firm dispatchable power[5] generation. Policy guidelines and incentive mechanisms need to reflect this difference. In this regard, the objective should be to remain technology agnostic where power system resilience is a concern. Some of the studies have identified traits and attributes of a resilient power system. A resilient power system constitutes physically stronger infrastructure configurations and institutional resourcefulness to adapt and skillfully respond to operational challenges as a result of an extreme event (NREL, 2024). Some of the key attributes for power system resilience are robustness, resourcefulness, adaptability, and recoverability of the power system after an extreme event (NREL, 2024). In addition to the recommendation made in the literature to build resilient power systems, there are some other aspects in terms of planning an orderly and smooth transition to an emerging power system. The following section presents some of the key recommendations that can enable the transition to a resilient emerging power system with a high share of renewable energy sources.

2.4 Power System Resilience With High Renewable Energy Share

One of the key aspects of a resilient emerging power system with a high renewable share is managing the transition where the resiliency aspect is well considered. This requires the right policy incentives and policy guidelines. For example, in the case of wind, generally, there is an increased tendency to build wind farms in locations with high wind profiles such as near the coast as this will increase return on investment with the maximum electricity generation potential. However, if there is not the right incentive to bring variability in the generation profile, it is likely that wind farms are clustered toward high-wind profile regions or where an electricity transmission network is readily available. This cluster of wind farms in the same region would expose them to similar weather events. In order to build a resilient grid, it is vital that prime generation sources such as wind farms bring the required variability by considering the resiliency aspects in consideration. Investment signals that can improve power system resiliency for wind farms can be brought by measures such

[4] Dispatchable generators are available when required and are able to adjust their power output.

[5] Firm dispatchable power can become available at all times when required.

as policy interventions encouraging diversity in wind electricity generation profile, extending transmission network, etc.

Similarly, in terms of increasing generation mix from solar generation, there are two options: one is encouraging small-scale rooftop PVs and the other is building utility-scale solar farms. As with rooftop PV, although feed-in tariff can incentivize the installation of rooftop PVs, it cannot be fully managed at which part of the grid there is over or under the concentration of rooftop PVs. Some countries have tried to link it with the hosting capacity and variable feed-in tariff which come with additional complexities of implementation and billing aspects. A policy to encourage utility-scale solar farms is better suited for a resilient future power system, as it brings flexibility in terms of choosing the optimal location, size, management, and curtailment of this renewable energy source when required.

Similarly, a tendency to encourage household battery storage comes with additional challenges of monitoring and management when installed by individual households. An emerging resilient power system would ensure that the right size and location of battery storage is available to firm the intermittent renewable power. Policy incentives can advise availability hours of battery storage which are usually based on the peak energy demand hours. In this regard, community battery storage or utility-scale battery storage can contribute more to the grid resilient rather than small-scale residential storage batteries. Although small-scale residential batteries can also be regulated, in such a case utility does not have direct control over the design, performance, and operational aspects.

Electrification of the transportation sector particularly electric vehicles (EVs) constitutes a major transformation for modern cities. However, very early adoption of EVs would not bring the resultant benefits in terms of decarbonization targets when the grid is not fully or significantly decarbonized. This is an important aspect as early adoption may bring some power resilience challenges to the grid, whereas a smooth and orderly transition can buy more time without impacting net-zero emissions targets. Additionally, with regard to EV deployment policies that can enable and continue to support a resilient grid, EV charging time is important. A convenient timing would be charging the EVs after getting back from work during evening hours or early mornings. However, this timing coincides with the peak demand periods of most of the modern cities and could result in further stressing the grid. Policy intervention to encourage overnight charging after the peak period would help to increase the resilience of the grid and make it stronger to be able to cope with extreme events. Additionally, day charging should also be encouraged as it coincides with solar generation. However, for remote locations, the charging station should specifically be powered by a fail-safe backup power source as the outage of a charging station in a remote location may put the safety and security of the passengers traveling at risk.

In the case of emergency and critical services such as hospitals and police stations, there should be power backup options available for the secure supply of electricity during extreme events. This may include battery storage to firm the power from renewables and backup supply of electricity with diesel generators that are regularly maintained. Furthermore, additional monitoring and control equipment

using advanced digitalization techniques can also keep the power system resilient. However, despite all the measures, there can be instances where backup power fails to work for some reason. For example, during Superstorm Sandy in New York, two major hospitals lost power due to the failure of backup diesel generators (CleanEnergyGroup, 2015). Therefore, additional measures such as staff training to prepare for emergency power outages should always be ensured.

2.5 Planning for a Resilient Power System

Power system reliability and resilience is a societal expectation, particularly for critical infrastructure. The resilience of the power system is not a performance outcome that is only audited occasionally. However, resilience should be measured, planned, and investigated for the current and emerging power system regularly. Additionally, key takeaways and recommendations should be implemented via policy, technical, and regulatory guidelines. Moreover, power system resilience should be modeled and analyzed to see the impact of policies and measures and adapt it to the changing grid and power system conditions.

Planning and modeling for the resilience of emerging power systems require a wide range of input and assumptions. These inputs and assumptions need to be thoroughly investigated so that they can show the realistic projected threat to the power system. The selection of appropriate metrics that represent the resilience of emerging power systems is important. Reliability metrics such as System Average Interruption Duration Index (SAIDI), and System Average Interruption Frequency Index (SAIFI) are widely accepted for demonstrating power system reliability under normal operating conditions (Eric Vugrin & Silva-Monroy, 2017). However, in the case of resilience metrics, it is important that forward-looking estimates capture the disruptions to the emerging power grid with reasonable accuracy while considering the projected power generation mix. Projecting the performance of a power system on such attributes requires significant data such as computer models for future grid operations and disruptions.

Another important aspect of planning resilient power systems is that resilience metrics capture information on a broad range of threats and hazards, for example, capturing the right likelihood of occurrence of the event, for example, in case of hurricane, heat wave, earthquake, flooding, and storm, fuel supply shortage or cyberattack is important. These events can cause the failure of power system generation, transmission, distribution, or protection and control systems. Planning for resilience for projected heat waves and the resultant increase in peak demand requires a projected demand profile. For such conditions, the projected peak demand should be carefully forecasted as an over-exaggerated demand may result in a significant cost increase whereas an underestimated demand projection may even cost more by collapsing the grid during extreme event conditions. Table 2 shows a range of attributes to measure the resilience of emerging power systems (Eric Vugrin & Silva-Monroy, 2017; Paul et al., 2024), starting with the baseline and state of

Table 2 Attributes for measuring and modeling emerging power system resilience

Input and assumptions				Output and recommendations	
Event	Exposed assets	Data/model	Event consequence resilience matric	Planning and improvement	Resilience management
Hurricane	Solar farms	Retrospective data of events	Normal customer outage hours	Technical measures: Adding more generation, storage, transmission lines, etc.	Prevention: avoid the event: Advanced metering, enhancing infrastructure resilience, etc.
Cyberattacks	Wind farms	Projected data based on emerging generation mix and future potential events	Critical service outage hours: hospital, fire stations, police stations	Policy measures: Renewable policy, EV policy, etc.	Reacting to event: sensing and controlling, communicating, repair and resource allocation, etc.
Storm	Transmission lines		Time to power recovery	Regulatory measures: measuring and communicating system status communication and protocols, etc.	Recovery: event forecast, load prioritization, etc.
Flooding, etc.	Control equipment		Cost of power recovery		
	Protection equipment		Loss of revenue		
	Data risks, etc.		Damage to power infrastructure		
	Fossil fuel generation				

resiliency of the current power system based on which the power system resilience planning and investment efforts can be made to improve the resilience of the power system to future events and hazards.

Another key risk to the resilience of power systems is the availability and reliability of communication systems. The communication system interacts with a range of other schemes and protection settings across the power system (AEMO, 2020). Features such as isolating equipment during extreme events to avoid cascading failure depend on a reliable communication system (Eric Vugrin & Silva-Monroy, 2017). Similarly, during extreme events, reporting and alarming of the system risk to the stakeholders rely on the digitalization of the power system. Further evaluation of such risks during credible and non-credible contingencies is important. While increased use of advanced sensors and communication systems mitigates the risks and potential damage from extreme events, it further enhances the risks associated with cyberattacks and digital disasters. Such risks and their mitigation options will be discussed in the coming section.

3 Resilient Digitalized Power System of Future

3.1 Digitalization of Emerging Power Systems

Digitalized emerging power grids (Brand et al., 2022) leverage advances in Information and Communication Technology (ICT) to allow increased communication among devices and facilitate remote monitoring, control, and management of all generation and storage resources to meet the varying electricity demands of end-users. ICT is divided into Information Technology (IT) and Operational Technology (OT). IT focuses on business transactions (accounting), administration, and customer management, while OT focuses on the control and management of physical equipment and devices.

Digitalized power grids combine physical and cyber domains. The physical domain comprises digital technologies to generate, transmit, store, and consume the power flow at different points of the grid. It includes power generators, transmission lines, substations, charging infrastructure of EVs, inverters, appliances, heaters, energy storage equipment, etc. The cyber domain includes processing units, sensing instrumentation, and communication equipment to monitor, manage, and control the power flow over the grid to improve its efficiency, reliability, flexibility, security, and environmental friendliness. It contains digital technologies for Internet of Things (IoT) and Industrial IoT (IIoT) connectivity/communication, sensors, meters, switches, thermometers, home or building energy management systems, automated monitoring and decision support tools, grid planning and asset management, etc. Figure 1 shows a general structure of the digitalized power grid as a cyber-physical system.

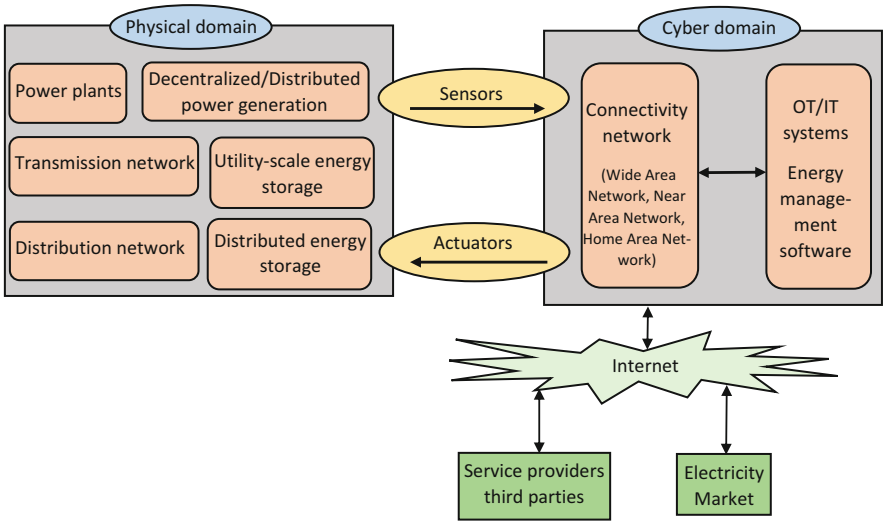

Fig. 1 Digitalized power grid as a cyber-physical energy system

Therefore, digitalized emerging power grids are complex cyber-physical systems composed of generation, transmission/distribution, storage, and demand sides. Power generation is based on flexible low-emission firm power (gas, nuclear, etc.) and renewable energy generators (wind, solar, hydroelectric, biomass, etc.). Power generators are large power plants and distributed/decentralized small renewable power plants. Generation and transmission/distribution sides are equipped with sensors and automated control on circuit breakers and load breaker switches. The storage is utility-scale and distributed with short-term (batteries) or long-term (hydrogen) storage capacity. The demand side is composed of residential, commercial, and industrial sectors. They are equipped with smart meters, remote-controlled heaters, air conditioning, distributed renewable energy resources, and storage capacity including bidirectional electric vehicles. Hydrogen is produced using electrolysis (power to gas), and this hydrogen may be used to fuel vehicles or it could be turned back into electricity or heat. Electricity is converted into heat for industrial heating applications (e.g., heat pumps, large electric boilers, electric vapor compressors) or to increase no longer usable low-temperature or pressure to a higher and technically usable temperature level.

There are many benefits of the digitalization of emerging power systems (Turovets et al., 2021; Ninomiya et al., n.d.; Sayed-Mouchaweh, 2020). These benefits are obtained by unlocking the value of real-time measurements about the grid state and electricity flow dynamics. These measurements are generated by sensors and advanced metering infrastructures distributed throughout the modern power grid. Figure 2 summarizes the major benefits of the digitalization of emerging power grids.

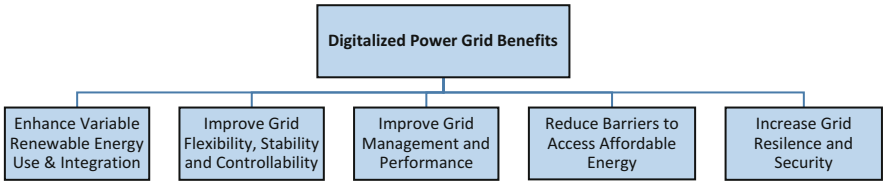

Fig. 2 Major benefits of a digitalized power grid within the context of energy transition

Advanced analytics and high-performance computing are used to transform data into valuable insights, recommendations, and actions. This transformation is obtained through prediction and optimization. The objective of prediction is to predict the future value of a target variable within a time horizon in response to a set of input variables. Predicting, in different time horizons, the electrical energy consumption or demand, the produced energy by a renewable energy resource such as solar and wind, and the health state of transformers, generators, or transmission lines are examples of the use of prediction in power systems.

Optimization aims at defining a set of actions to minimize cost or optimize an objective function. The latter is a mathematical representation of a set of criteria to be optimized while satisfying a set of conditions or constraints. For instance, optimization can define the set of actions to adjust energy consumption/generation while maximizing the use of variable renewable energy (solar, wind) output with respect to grid congestion, peak loads, and electricity price signals. The actions can be recommendations executed manually by end-users or automatically by controllers. For instance, optimization determines the periods to turn on or off consumers' high-consumption appliances with respect to an online electricity price signal. The goal is to turn on these appliances during the lowest electricity price to reduce electricity bills. Then, an automatic controller turns on or off these appliances with respect to these periods.

3.2 Disturbances and Behavior of Resilient Digitalized Power Grids

Grid resilience indicates its ability to resist disturbances and recover with minimal downtime or disruptions. Disturbances refer to any event that leads to a power outage or energy supply interruption. These disturbances are classified into three main categories.

1. The first category refers to disturbances caused by natural disasters and extreme weather events such as blizzards, hurricanes, and heat waves. Their severity and

occurrence frequency are increasing due to climate change. They account for 58% of power outages observed in the United States since 2002[6].

2. The second category of power grid disturbances is caused by man-made disasters due to malicious cyberattacks. Their number is small compared with natural disasters, but their impact on the power grid availability may be worse and their scale could be wider. For instance, a cyberattack against the western Ukraine power grid in 2015 resulted in 30 electricity substations going offline and 225,000 people losing power.[7] The power was manually restored after six hours entailing the loss of over 130 MW of load.
3. The third category of disturbances is the consequence of adding large quantities of variable renewable energy sources (wind and solar). Indeed, as wind and solar energy resources are weather-dependent, the demand may not match the generation creating power grid instability. For instance, during a dark and still day, the generated renewable energy is not enough to charge the batteries to their full capacity. Therefore, the stored energy is not enough to satisfy the peak demand in the evening. Therefore, conventional firm generation may need to ramp up very quickly to supply the evening peak demand. Usually, conventional firm power plants are not designed for frequent switching on and off. This is both expensive and comes with a time delay. Therefore, conventional plants must run at a minimum stable level as a backup to supply power and ramp up immediately when needed. Thus, a resilient future grid requires a combination of firm conventional generation and intermittent renewable generation. Managing such a diverse mix of generations with varying characteristics in real time is an emerging challenge that can be mitigated by the digitization of the emerging power grid.

Power grid resiliency must be evaluated to determine its vulnerability and if investments are required to reinforce it. Figure 3 identifies the key parameters that contribute to the vulnerability of the emerging digitalized power grid. These parameters impact the power grid's resiliency as they introduce more uncertainty and complexity to manage the grid stability, intensify the bad consequences of an outage, and increase cyberattack space and entrance points. Several measures can be used to quantify the resiliency of a power grid (Leddy et al., 2023) to a major power outage. Examples of these measures are customer outage time in hours, loss of utility revenues, load not served in kilowatt-hours, number of customers impacted by an outage, number of critical services impacted by an outage, time to recovery in hours, cost of recovery, and cost of damage due to an outage. A major power outage affects a region with at least 500,000 customers and lasts several hours (Brand et al., 2022). Therefore, centralized generating plants and aggregated decentralized generating or storage units with a net nominal capacity of more than 420 MW and behind-the-meter devices that consume or deed in more than 420 MW

[6] https://www.energy.gov/articles/economic-benefits-increasing-electric-grid-resilience-weather-outages

[7] https://www.iea.org/reports/power-systems-in-transition/cyber-resilience

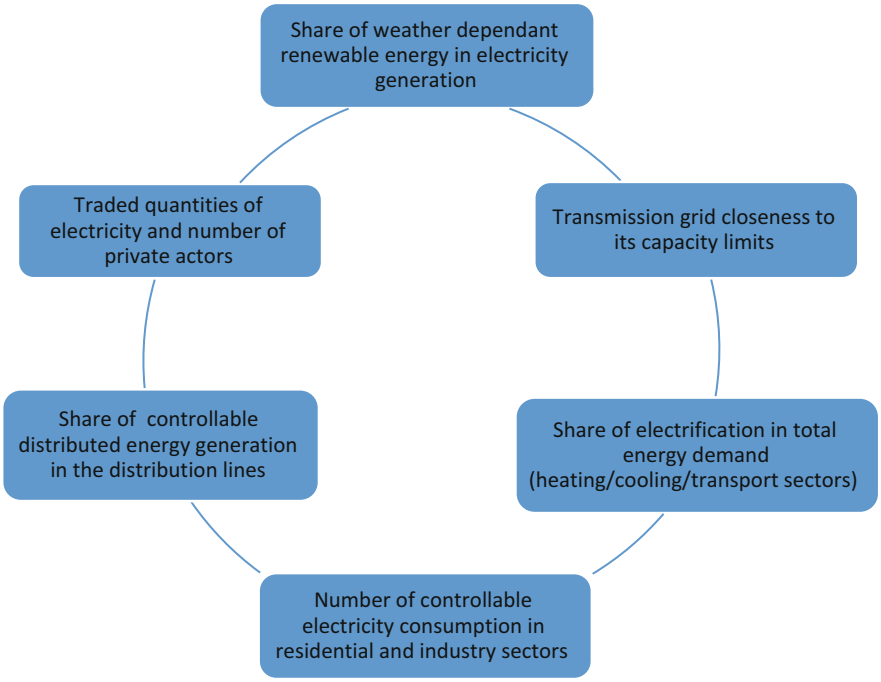

Fig. 3 Key parameters contributing to the vulnerability of the future digitalized power grid

are considered critical electric power supply infrastructure (Brand et al., 2022). A power outage in the latter is a serious threat, and hence resilience measures must be developed for this kind of infrastructure.

The behavior of a resilient power grid is based on five phases to quickly restore power in the wake of extreme weather events (e.g., major storms) or cyberattack (Brand et al., 2022; Leopoldina et al., 2021).

1. The first phase corresponds to normal operation where loads are supplied, and power grid parameters are within their operational limits. The n−1 criterion could be used to enable the power grid to operate in the normal state in case of losing one generating unit, transmission line, or transformer.
2. The second phase is the disruption absorption. It occurs when the application of the n-1 criterion does not allow to supply all the loads. The aim of this phase is to prevent cascading and escalating failures. For instance, an outage in 11 transmission lines in India in July 2012 evolved into a large-scale failure cascade leading to a blackout (Ratha, 2013). Soltan et al. (2018) simulated a transmission line failure initiated by a 1% increase in the demand in the Polish grid in 2008 by an adversary. This initiated failure caused failures in 263 transmission lines and 86% outage of the power grid. The stabilization phase aims at gaining full control over frequency and voltage to prevent further triggering of protection

equipment. The restoration phase aims to bring back the power grid from a stable but degraded state to full performance by reconnecting all loads that have been disconnected.
3. The last phase is the optimized normal operation. It aims at improving the power grid resiliency to the occurrence of similar incidents in the future.

3.3 Targeting Power Grid Resilience with Digitalization

Digitalization can enable and accelerate a successful transition toward more low-carbon, reliable, and economically efficient power grids. However, it would also entail new vulnerabilities to failures, software bugs and human errors, and cyber-attacks. For instance, an undetected software bug in the alarm system caused a major power blackout in the Northeast of the United States and parts of Canada on August 14, 2003.[8] The operators in the control room were unaware of overhead transmission lines. Therefore, they did not redistribute the load and the overhead lines drooped into foliage causing a cascading outage throughout the grid. This blackout lasted 2 days and left 55 million people without electricity. An example of a cyberattack on the power grid is the 2015 Ukraine power grid cyberattack (Rajkumar et al., 2023). Hackers used malware to remotely control circuit breakers and shut off power to 225,000 customers for several hours. In addition, the number of behind-the-meter distributed energy resources, EVs, and smart appliances connected via IoT to the power grid is increasing at a high pace. The potential for cyberattacks, for example, manipulation of demand via IoT attacks (Shekari et al., 2022), to cause significant disruption in the electricity supply would grow if these connected devices are intentionally switched on or off at the same time. For instance, hackers can remotely shut down EV charging stations.[9] This could cause significant disruptions to local power supply.

Therefore, it is necessary to develop a resilience strategy to manage the vulnerabilities of the emerging power system within the context of climate change and digitalization. The goal is to withstand any sudden extreme weather or human attack on the power grid infrastructure and resist power blackouts and their damaging consequences on economy and society. The cost of a 1-hour power outage at noon on a winter weekday in Germany is estimated to be EUR 600 million in 2010 (Piaszeck et al., 2013). With the electrification of the demand, the power grid blackout would entail the disruption and even the collapse of other critical infrastructures, such as transport, healthcare, and water supply. A resiliency strategy is based on four steps (Song et al., 2022).

[8] https://en.wikipedia.org/wiki/Northeast_blackout_of_2003

[9] https://www.saiflow.com/blog/how-mishandling-of-websockets-can-cause-dos-and-energy-theft/

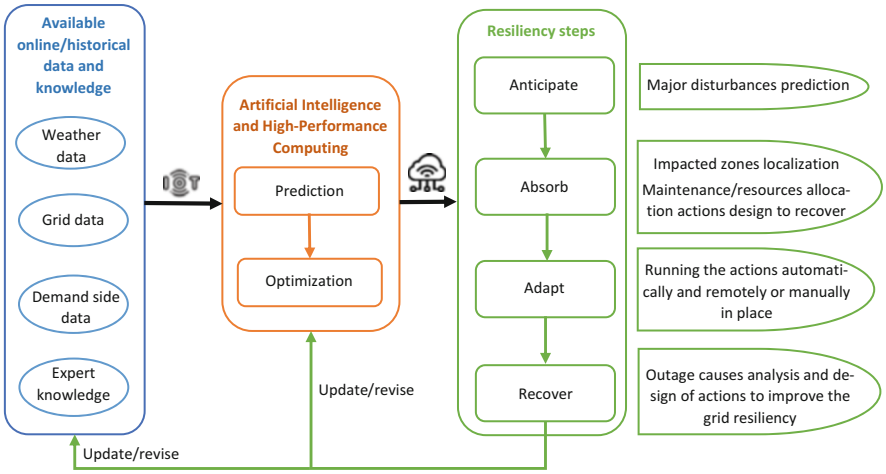

Fig. 4 Resilient digitalized power grid

1. The first step (anticipate) aims at forecasting the occurrence of a major disruption in the power grid caused by an extreme weather event or a cyberattack.
2. The second step (absorb) is the detection of an outage as a consequence of the disruption, identification of impacted zones, and design of actions to recover from a power outage.
3. The third step (adapt) aims at running these actions remotely or by a team to quickly restore the power.
4. The fourth step (recover) aims to analyze the causes of this outage and perform actions to improve the resilience of the power grid in the face of the occurrence of this outage in the future (Fig. 4).

The digitalization of emerging power grids allows the generation of extensive high spatial and temporal resolution data about weather, grid status and dynamics, demand consumption, and flexibility. This data is used by high-performance computing and artificial intelligence (machine learning and deep learning) to extract actionable insights. The latter is used to provide real-time, high-resolution, and shared situational awareness among the different operators and actors of power grids and to perform coordinated actions and optimize the use of grid resources to absorb, adapt, and recover from a major disruption.

The digitalization of the emerging power grid allows taking the benefit of the diversity of distributed energy resources, utility-scale and distributed storage units, virtual electricity lines and plants,[10] and controllable connected consumer

[10] Virtual electricity lines and plants are networks of decentralized generation combined with flexible loads and storage systems. They can be managed remotely and automatically by power grid operators to maintain grid balance and stability.

appliances to design and implement an efficient resiliency strategy for power grids. These resources can be considered sustainable and low-carbon additional operating resources that can take over their function when main operating resources fail. For instance, decentralized grid operations and governance allow to isolate the outage or cyber-physical attack in the affected area without disruption to the power generation and ICT systems in other sections of the grid. In addition, to absorb an outage, utilities could use decentralized/distributed storage sites close to impacted communities to supply power during outages until the underlying problem could be fixed. Outage absorption and power restoration are instantaneous and automated using artificial intelligence and high-performance computing. The blackout absorption and power restoration are achieved by finding the cheapest and quickest grid resources.

4 Power System Resilience in GCC Countries

The GCC states—Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates—are the Middle East's most important source of energy supplies, as well as an emerging economic hub of global significance. GCC region has an installed capacity of around 173 GW, and Saudi Arabia is the region's largest electricity producer with an installed capacity of around 84 GW as of 2022. As of 2022, the country has around 477 generation units with a maximum load demand of 65 GW. The electricity demand is projected to increase by 120 GW by 2030 (Soummane & Ghersi, 2022). Saudi Arabia pledges to reach net-zero emissions by 2060 and increase its share of renewable generation to 50% by 2030. Moreover, Saudi Arabia has targeted at least 30% of its cars to be electric-powered by 2030 (IRENA, 2023). Owing to a greater mix of gas-fired power generation, currently, power grid of Saudi Arabia is capable of coping with extreme weather events and other hazards. However, the future power system with a greater mix of renewable and digitization is likely to bring additional challenges.

Power outages are a serious concern in the GCC countries, particularly during hot days in summer, when temperatures could be up to more than 50 °C. These high temperatures cause a surge in electricity demand due to wider and greater use of air conditioning units. In addition, higher temperatures can reduce the efficiency of some generation assets and the transmission capacity of power lines. Dust storms, extreme heat waves, and thunderstorms are more likely events that are able to disrupt the power system in the GCC countries. Similar to other countries, Saudi Arabia is taking various steps to improve the resilience of future power systems.

- The Saudi Arabian Government has put forward an ambitious plan for the deployment of smart grid technologies with real-time monitoring, control, and data analytics. These smart grid technologies include advanced metering infrastructure, distribution automation, and grid optimization solutions (Techsci,

2022). These innovative solutions enhance power system resilience by making it more agile and responsive to transitioning future power systems.

- Digitalization of energy services is another transformative trend in Saudi Arabia. This trend aligns with the broader digital transformation goals outlined in Saudi Vision 2030. The digitalization of energy services improves the operational efficiency and resilience of power systems. Furthermore, the integration of artificial intelligence in energy management systems can enable more accurate demand forecasting and proactive maintenance and thereby improve the resilience of power systems (Techsci, 2022).
- Saudi Arabia is also taking conventional measures such as the deployment of mobile substations that support the weaker and critical parts of the transmission network and make them capable of withstanding extreme events (ArabNews, 2017).
- A case study that allows designing of climate-resilient digitalized power grids in the GCC countries is power exchange and trading through GCC interconnection grids. The interconnection of GCC power grids allows them to respond to sudden demand surges by sharing spinning reserves, generation, and transmission resources. The use of the GCC interconnection grids strengthens the power grid resilience as it takes benefit of the technological and geographical diversity of generation and transmission resources of the GCC countries. Digitalization allows more efficient coordination and synchronization of energy exchange between GCC countries in case of extreme weather events or cyberattacks. This coordination is based on more accurate and reliable forecasting of:
  - The occurrence of extreme weather events with early warning systems to help energy suppliers in the GCC countries to activate emergency plans in a timely manner;
  - The maximum transmission capacity of power lines to maximize the exchanged electrical energy between the GCC countries while ensuring grid dependability;
  - The renewable energy generation to maximize their penetration and use as well as the power grid's sustainability.

Moreover, power system resilience metrics as discussed in previous sections and some other recommendations about the smooth, orderly, and manageable transition to renewables are also relevant for the GCC countries to enable resilient future power systems.

5 Discussion and Recommendation

Power system resilience is the core for building modern resilient cities. One of the key measures to transition to a resilient emerging power grid is introducing policy guidelines that encourage the smooth, orderly, and manageable transition to intermittent renewable energy resources. Wind farms should be located at various

locations offering a range of wind profiles, and this poses less risk to grid instability during extreme weather events and increases the resilience of the grid. In terms of solar generation, preferring solar farms over small-scale residential rooftop PVs makes the management of this intermittent energy source conveniently possible. Similarly, encouraging utility-scale battery storage and incentivizing battery storage to remain available during the peak demand period can increase power system resilience. Some other policy recommendations are to remain technology agnostic by valuing the resilience of the power system brought by different generation sources. Future power system models and studies should capture a wide range of resilience metrics so that they can reflect the potential threat to the power system by major events. Power system planners and utilities in the literature mainly proposed stronger infrastructure of transmission and generation assets, battery storage, reasonable share of firm dispatchable power at all times, black start, and fail-safe capabilities to keep the power system resilience intact under potential threats.

In order to develop a resilient emerging digitalized power grid, it is important to increase incentives for grid operators to strengthen resilience by developing and promoting security standards to prevent problematic simultaneous activities that could destabilize the power grid. In addition, operators of power grids must have mandatory training to cope with unexpected blackouts to improve the grid resilience against their occurrence in the future. Moreover, the diversity of the energy mix must be maximized by using different renewable sources, such as wind, solar, and hydro, as well as other reliable and flexible energy resources, such as nuclear and natural gas. This allows grid operators to absorb and recover the power grid from major disturbances by exploiting the diversity of these resources. For instance, a disruption in gas supplies that coincides with periods of high demand in very hot or very cold weather, or dips in the wind or solar generation could entail a grid blackout or severe supply shortages. The energy mix diversity can absorb these disturbances by using stored solar power (e.g., utility-scale and distributed storage), virtual power lines and plants, or increased wind energy from elsewhere in the power grid. These options are sustainable and low carbon. Other flexible and reliable low emissions options such as natural gas would still be required to maintain the resilience of the power grid.

Global strategies to build resilient future power systems mainly depend on the current and projected generation mix, available renewable energy resources, and relevant potential threats to the power system. Since many countries have committed to phasing out coal (E. o. C. i. S. a. COP26, 2021), countries with a high share of coal in their generation mix such as China, the United States, and Australia would need to explore other firm generation options to keep the power system resilient. For example, Australia is projecting to rely on increased natural gas-fired generation with carbon capture, renewables with battery storage, and increased network of transmission lines (AEMO, 2022). One key opportunity for GCC countries is that these countries are not heavily reliant on high-emitting power generation sources like coal. In the case of GCC countries, gas is one of the major sources of power generation which is considered a relatively low-emission power generation

option which is considered a technology that would be needed for transition to the resilient emerging power grid. Additionally, these countries also have high renewable generation potential with high solar, wind, and geothermal potential. By enabling the orderly transition to renewable energy technologies and planning for a resilient grid based on future generation mix and threats, GCC countries are well placed to cope with the challenges of emerging power systems to build resilient cities.

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Proactive Distributed Renewable Energy Resources (DRER) for Powering Tomorrow

Luis Gautier and Mahelet G. Fikru

Abstract The production and consumption of cleaner energy by distributed renewable energy resource (DRER) owners, sometimes referred to as prosumers, is expected to increase over the next few decades. With energy storage still remaining a costly investment, DRERs are actively looking for ways to match their peak onsite renewable generation with increased consumption to enhance their self-consumption rate. Despite a growing economics literature presenting energy production–consumption decisions by prosumers, there are not many studies characterizing DRER owners that proactively manage their energy accordingly. Building on past studies, we present a model of a DRER owner that maximizes utility to determine her rate of self-consumption after making energy production and consumption decisions. Our results suggest that a proactive DRER owner exhibits a relatively higher level of self-consumption if she cares enough about the carbon footprint coming from her energy consumption decisions. This points to the need for designing customized policy interventions based on how DRER owners view carbon emissions, ranging from no intervention with higher degrees of carbon disutility to using price incentives to encourage production and consumption of energy by the DRER owner.

JEL Classification Q4, Q2

Keywords Carbon emissions · Utility · Energy policy · Smart cities · Green electricity · Energy management

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1 Introduction

Distributed renewable energy resource (DRER) owners are decentralized energy producers that invest in renewable energy technologies such as rooftop solar photovoltaic (PV) and small-scale offshore wind turbines to primarily satisfy their demand for *locally produced cleaner* energy. DRERs are often referred to as *prosumers* to highlight their role in energy production and consumption (Fikru, 2019). In addition to the availability of a reliable two-way electric flow infrastructure and system, feed-in-tariffs and net-metering provisions incentivize DRER owners to export their excess electricity (if any) to the electric grid for some credit or compensation. The production and consumption of renewable energy by DRER owners is expected to increase over the next few decades, in part due to favorable policy incentives designed to achieve climate change goals, and in part due to consumer preferences for alternative energy-generating options featuring attributes such as reduced grid dependency, energy independence, and local generation (EEA, 2022). Related to this, energy storage or batteries are proposed as the most technically feasible approach to achieving objectives related to grid resiliency and energy independence.

Energy storage also plays an important role in strengthening the resilience of communities that rely on renewable energy by addressing the variability and intermittent nature of renewable energy generation, providing backup power, stabilizing the grid, and offering a sustainable and decentralized energy solution. However, the adoption of energy storage systems with renewable energy technologies (e.g., bundle solar purchase with batteries) faces significant cost barriers. For example, the initial capital investment for purchasing and installing energy storage technologies can be substantial, posing challenges for DRER owners, especially those with limited financial resources. As a result, prosumer communities need to adopt other proactive strategies in energy management through behavioral changes (Frederiks et al., 2015; Hafner et al., 2019). For instance, previous studies suggest that prosumers could actively match onsite generation with consumption patterns to reduce electricity bills or load shifting (Wittenberg & Matthies, 2016; Fikru, 2020), adopt energy-saving behavior, or invest in energy-efficiency improvements with solar installations to lower energy needs (Fikru, 2021).

A *proactive DRER owner* is an energy producer who not only consumes some of the energy she generates locally (self-consumption) but also actively participates in energy management, matching generation to direct consumption. She takes on a proactive role in managing her energy resources, including renewable energy generation and consumption. For instance, she may adjust her energy usage based on real-time data, optimizing energy consumption when renewable energy generation is high and reducing consumption during periods of low renewable energy availability. Despite the important role of proactive DRER owners in building resilient prosumer communities and facilitating energy transition and decarbonization goals, the economic literature offers little insight into the self-consumption decision of proactive DRER owners.

We address this gap by using the production–consumption model of the prosumer featuring the double optimization procedure (Fikru, 2020; Sanstad, 2011) to characterize the utility-maximizing rate of self-consumption of locally produced cleaner energy by the proactive-DRER owner. We define a proactive DRER agent as one that proactively manages self-consumption with utility maximization objectives, in addition to optimally choosing energy consumption and production levels (by maximizing utility and net revenue functions, respectively). The study addresses the following research questions: (1) What is the relationship between the rate of self-consumption on site and the percentage of energy demand offset by renewable generation? (2) To what extent should proactive DRER owners match their local generation with direct consumption (optimal self-consumption rate)? (3) How is the self-consumption rate, either exogenously given or optimally chosen (endogenous), affected by the degree to which a DRER owner cares about her carbon footprint?

The double optimization framework (i.e., maximizing two objective functions by the same agent or decision-maker) is a fast-growing approach to modeling energy-related decision-making (Fikru & Awuah-Offei, 2022). For instance, Fikru and Gautier (2023) argue that prosumers decide on energy consumption level by maximizing a utility function and decide on renewable energy generation by maximizing a net revenue function, where the relationship between energy consumption and generation is nonlinear. Due to feed-in tariffs or net-metering/billing requirements, prosumers typically earn credit or compensation by exporting their excess generation into the grid, which in turn incentivizes a lower self-consumption rate. Thus, depending on the extent of their energy management or self-consumption rate, which is assumed exogenous in previous studies such as Fikru and Gautier (2023), their optimal rate of onsite generation may increase (large marginal revenue gains) or decline (small marginal revenue gains) with the self-consumption rate. We add to this line of the literature by explicitly characterizing the utility-maximizing rate of self-consumption.

By explicitly characterizing the utility-maximizing rate of self-consumption as endogenous, this study draws implications for proactive prosumer behavior, such as load shifting and demand-response participation. A proactive prosumer goes beyond the basic role of producing and consuming energy by actively engaging in optimizing their energy practices. This includes adopting practices and strategies to enhance energy efficiency, adjusting consumption patterns to align with renewable energy availability, and potentially investing in energy storage solutions. The term *proactive* implies a conscious effort to optimize energy usage and contribute to a more sustainable and resilient energy ecosystem. Furthermore, this study explicitly factors in the role of disutility from carbon emissions (or environmental damage) from energy production, which is absent from existing works. The results have implications for understanding the additional benefits of the proactive-DRER owner model and designing policies to incentivize it accordingly.

Our results suggest that a proactive-DRER owner who maximizes utility to choose self-consumption rate exhibits relatively higher rates of self-consumption when she cares sufficiently about her carbon footprint. This result points to two potential types of DRER owners with different views on their carbon footprint,

which gives rise to different optimal rates of self-consumption and onsite production. This implies that to achieve a smooth energy transition, policymakers could benefit from designing customized policy prescriptions depending on the extent of disutility or preference for reducing one's energy carbon footprints (Stanley, 2022). For instance, if a community cares enough about their energy carbon footprint, then active policy intervention may not be needed since DRER owners are proactive enough and also willing to consume a large portion of their own energy produced onsite. However, if a community does not care too much about its energy carbon footprint (e.g., only a small disutility from carbon emissions), then policy intervention may be needed to encourage the consumption of energy produced onsite by DRER owners.

To achieve energy independence, we explore the role of the financial compensation rate (e.g., dollar per kilowatt hour) at which the DRER owner exports excess energy. We show that this policy prompts the DRER owner to increase her consumption *and* production of her own energy, if she cares enough about her carbon footprint. A higher financial compensation rate prompts the DRER owner to increase the production of energy, which raises her demand for energy coming from the grid. But if the DRER owner cares enough about her carbon footprint, then she will be willing to substitute grid energy demand for the energy she produces onsite. Finally, as a case study, we discuss model implications in the specific context of member nations of the Gulf Cooperation Council (GCC). The GCC States, namely Bahrain, Kuwait, Oman, Qatar, Kingdom of Saudi Arabia (KSA), and the United Arab Emirates (UAE), are in a prime position to capitalize on distributed renewable generation. Their abundant solar resources, coupled with rising residential energy demand and progressive net-zero emissions policies, present an ideal opportunity for significant investment and growth in the DRER sector.

Section 2 presents the prosumer model along with energy consumption and production decisions when the onsite self-consumption rate is treated as exogenous. Section 3 discusses results when self-consumption rate is endogenous and determined by maximizing utility. Section 3 also presents additional analysis to highlight the role of the solar compensation rate and draw lessons for GCC States. Section 4 concludes with some policy implications.

2 The Prosumer Model

Consider a representative DRER owner or prosumer who owns the technology to generate renewable energy (e.g., using solar panels). The energy generation per period, q megawatt hours (MWh), represents a fraction $\phi \in (0, 1)$ of total energy demand or load, D, where $q = D\phi$ per period as in Fikru (2020) and Fikru and Gautier (2023). $\gamma \in (0, 1)$ denotes the percent of renewable energy generation that is used for onsite or self-consumption, and $1 - \gamma$ the excess (cleaner) energy exported back to the electric grid. Hence, energy exported to the grid is given by $\phi D(1 - \gamma)$ in MWh. We assume the government determines the compensation

rate for excess clean energy (dollars per MWh), P_b, through which the prosumer is compensated for her excess generation.

The DRER owner fulfills her net demand by buying energy from the local utility where the electric utility is assumed to offer both fossil-fuel-based energy, D_f, and greener energy, D_c (e.g., sourced from large-scale renewable energy projects). Thus, the total MWh of energy demand for the DRER owner is $D = D_c + \gamma\phi D + D_f$; that is, energy bought from the electric utility (fossil-based and greener) and self-consumption of DRER generation, $\gamma\phi D$.

The DRER owner perceives D_c and D_f as imperfect substitutes in consumption, where the parameter d denotes the degree of product differentiation and the degree to which the two products substitute each other in the function of providing electric services such as heating/cooling building spaces. If $d = 0$, then green and fossil-based energy are viewed as completely differentiated, and as d increases, the degree of substitutability between green and fossil-based energy increases.

According to the double optimization procedure presented in Sanstad (2011), the decision-making problem consists in first deciding what percent of energy demand or load the DRER will offset by onsite (renewable) generation, ϕ (based on maximizing a net revenue or net return function); and second, deciding how much energy to buy from the grid (by maximizing utility subject to a budget constraint). We solve the model via backward induction. That is, for a prosumer or DRER owner, we first solve for optimal D_f and D_c by performing a constrained utility maximization problem (given ϕ) and then solving for optimal ϕ by maximizing a net revenue function. For a proactive DRER owner, we first solve for optimal D_f, D_c, and γ by performing a constrained utility maximization problem (given ϕ) and then solving for optimal ϕ by maximizing a net revenue function. Figure 1 presents an illustration of the first- and second-stage decisions made by the proactive prosumer.

2.1 Energy Consumption Decision

The DRER owner chooses energy consumption levels, D_f, D_c, by maximizing the following utility function subject to budget constraints:

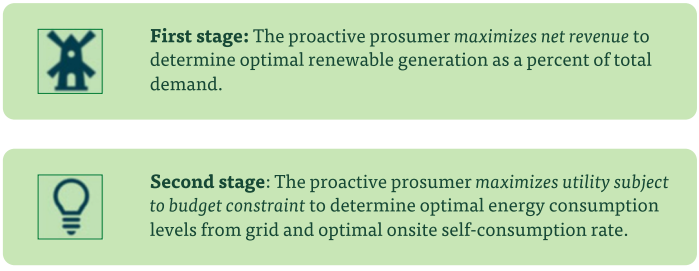

Fig. 1 Decision-making stages for proactive-DRER owner (Source: Authors' own elaboration)

$$\max_{D_c, D_f} U(D_c, D_f) = a_c D_c + a_f D_f - [(\beta_f D_f^2 + \beta_c D_c^2)/2 + d D_c D_f] + q_o - \frac{sE^2}{2} \tag{1}$$

where q_o is a numeraire good with price normalized to one, $\beta_f > d$ and $\beta_c > d$. Disutility from carbon (or greenhouse gas) emissions is captured by the term, $sE^2/2$, where the parameter s denotes the extent of the disutility from carbon emissions. We define net carbon emissions as E that affects the prosumer's utility where $E = D_f - D_c - \phi D$. That is, carbon emissions are proportional to consumption of fossil-fuel-based energy less greener energy bought from the grid, minus cleaner energy produced onsite. The presence of $s > 0$ captures the case of a DRER owner who cares about her net energy carbon footprint.

The prices of fossil-fuel-based energy, P_f, greener energy, P_c, and the compensation rate for excess energy, P_b, are assumed to be exogenous and given. The DRER owner maximizes Eq. (1) subject to her budget constraint, $M = P_c D_c + P_f D_f - (1 - \gamma) P_b \phi D$, where M is wealth or income. Solving the problem yields solutions for energy consumption levels (that is, amount bought from the electric utility) as follows: $D_c(\gamma, \phi, P_b, s, P_f, P_c)$, $D_f(\gamma, \phi, P_b, s, P_f, P_c)$.

2.2 Energy Generation Decision

Using solutions from the constrained utility maximization problem, $D_c(.)$ and $D_f(.)$, the DRER owner chooses optimal ϕ (renewable generation as a percent of demand) by maximizing the following net revenue function:

$$\max_{\phi} P_b(1 - \gamma)\phi D - C(q) - F \tag{2}$$

$C(q)$ and F denote variable and fixed costs of renewable generation, respectively, and the first term represents the revenue the DRER owner receives from selling excess energy produced onsite. The solution to Eq. (2) yields $\phi^*(\gamma, P_b, s, P_f, P_c)$, where substituting $\phi^*(.)$ back into energy consumption levels derived from constrained utility maximization gives equilibrium values such as $D_c^*(\gamma, \phi^*, P_b, s, P_f, P_c)$, $D_f^*(\gamma, \phi^*, P_b, s, P_f, P_c)$.

As a benchmark case, Fig. 2 presents the relationship between ϕ^* and γ when $s = 0$ and when D or total energy is not changing with ϕ ($dD = 0$) to avoid any solar rebound effects (see Appendix for a derivation of solutions). The benchmark case is for an exogenous or given γ and hence not (yet) capturing proactive measures undertaken by the prosumer.

The figure traces out what the optimal ϕ^* (renewable energy generation as a percent of total load) would likely be for different levels of γ (e.g., the ϕ^* could represent optimal PV sizing decision of the prosumer). The $\hat{\gamma}$ represents the level of onsite self-consumption that is consistent with the maximum renewable generation

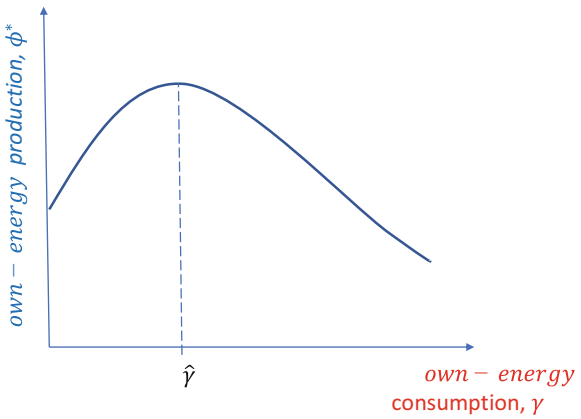

Fig. 2 Benchmark case: The impact of self-consumption rate on ϕ^* when γ is exogenous, $s = 0$, and $dD = 0$ (Source: Authors' own elaboration)

size as a percent of demand. As onsite self-consumption increases, the optimal renewable generation as a percent of demand initially increases (due to increasing net marginal benefits earned from compensation of excess generation), reaches a maximum, and then declines (due to lower volumes of generated energy available for compensation). The nonlinear relationship presented in the figure is consistent with prosumer models presented in previous studies (Fikru & Gautier, 2023). If $\gamma < (>)\hat{\gamma}$, the DRER owner consumes too little (much) of her own energy produced onsite. As a result, the marginal net revenue gains from producing onsite energy are large (small) enough, which prompts the DRER owner to produce more (less) energy onsite with increases in the self-consumption rate. In this benchmark case, γ is exogenous, and so the DRER owner is not necessarily proactive in matching generation with consumption to maximize utility.

3 A Proactive Approach for Prosumers

This section delves into the optimization of self-consumption rates by DRER owners, starting with a model where a proactive DRER owner determines the optimal rate of onsite self-consumption, considering both the utility derived from energy consumption and the disutility from pollution. The second subsection explores the role of the solar compensation rate, examining how changes in this rate influence the DRER owner's decisions about energy production and consumption. The section concludes with a discussion of lessons for GCC States illustrating how insights gained from the model presented in this study could inform policymaking.

3.1 Utility Maximization and Carbon Footprint

The proactive DRER owner maximizes utility to determine the optimal rate of onsite self-consumption, γ, in the presence of disutility from pollution, $s > 0$,

simultaneously with demand for energy coming from the grid, D_c and D_f. That is, in addition to maximizing utility to determine energy consumption levels, the proactive prosumer also maximizes utility to choose optimal onsite consumption rate subject to budget constraints as before:

$$\max_{\gamma, D_c, D_f} U(D_c, D_f, \gamma) \tag{3}$$

From Eq. (3) we obtain D_c, D_f, γ as functions of ϕ and prices. To solve the model, we substitute these into Eq. (2) and obtain the equilibrium ϕ as a function of prices. To complete the characterization of the equilibrium, we substitute ϕ back into D_c, D_f, γ, which gives these as functions of prices and exogenous parameters of the model.

The utility-maximizing rate of onsite self-consumption is represented by γ^u. We compare the $\hat{\gamma}$ presented in Fig. 2 with the case where the proactive DRER owner chooses γ via utility maximization in the presence of disutility from pollution, $s > 0$. In particular, we characterize the γ that maximizes utility, $dU/d\gamma = 0$, and evaluate it at $d\phi^*/d\gamma$ in Fig. 2. If the sign is positive (negative), then $\hat{\gamma} > (<) \gamma^u$, where γ^u is optimal self-consumption rate. The Appendix formally derives this result.

We find that the DRER owner's utility-maximizing rate of self-consumption, γ^u, is greater than $\hat{\gamma}$, if the prosumer cares sufficiently about her carbon footprint coming from grid energy consumption, i.e., s is large enough, $s > \bar{s}$. In this case the higher percent of consumption of own energy reduces the demand for energy coming from the grid (i.e., D_c and D_f fall) and, as a result, the production of own energy falls. That is, we do *not* see the DRER owner increasing her production of own energy, rather she just increases her self-consumption rate. Because she cares enough about her carbon footprint (s is large enough), she is willing to consume more of her own renewable energy and at the same time give up the extra income coming from selling energy back to the grid.

Similarly, if the DRER owner cares little about her carbon footprint coming from energy consumption (i.e., s is small enough, $s < \bar{s}$), then her utility-maximizing self-consumption rate is less than $\hat{\gamma}$. This is because of two reasons. First, by consuming less of her own energy, she is able to sell a larger share of the energy she produces onsite and, therefore, generate extra income to afford additional energy from the grid. It is noteworthy that in this case the DRER owner is willing to consume less of her own energy because by doing so she can generate sufficient extra income by selling a larger share of energy back to the grid instead of increasing own energy production. Second, in this case, the DRER owner exhibits little disutility from emissions, and so she is willing to consume more energy from the grid even as this means a higher carbon footprint. Results are summarized in Fig. 3.

These results suggest that there are two types of proactive DRER owners for which two policy recommendations may be prescribed: one where no policy

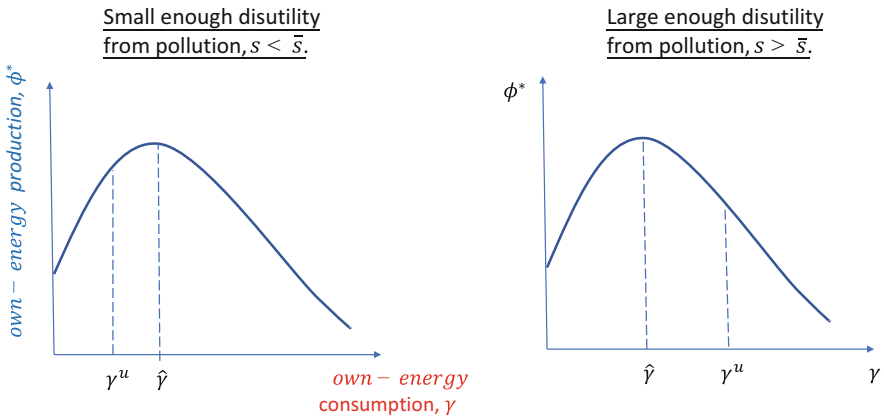

Fig. 3 Utility-maximizing self-consumption rate, γ^u, for relatively large or small disutility from carbon emissions (Source: Authors' own elaboration)

intervention is needed since DRER owner cares enough about her carbon footprint, and another where policy is needed to encourage consumption of onsite energy.

To further elaborate on the relevance of s, we argue that the DRER owner raises her utility-maximizing share of own energy consumption, γ^u, if she cares enough about her carbon footprint from grid energy consumption. In this case the DRER owner's gains from increasing own energy consumption to lower emissions more than offsets the reduction in income from selling energy back to the grid (DRER owner consumes more and therefore sells less of her own energy). There are two effects at play. First, if the DRER owner cares enough about her carbon footprint, then an increase in s lowers (raises) the consumption of default (clean) energy from the grid, where total grid energy consumption falls. This reduction in grid energy consumption leaves room for the DRER owner to increase the consumption of her own energy, γ^u.

Second, an increase in s prompts the DRER owner to increase her own energy production, ϕ, because doing so compensates for the reduction in grid energy consumption and enables the consumption of additional onsite renewable energy. In the Appendix we formally show that $d\gamma^u/ds > 0$, if the disutility from emissions, s, is large enough; we also show the case where the disutility from emissions is small enough and so $d\gamma^u/ds < 0$. The result differs from the analysis in Fig. 3. While Fig. 3 compares the exogenous and endogenous utility-maximizing share of own energy consumption ($\hat{\gamma}$ and γ^u), here we focus on the change in the endogenous utility-maximizing share of own energy consumption given a change in the disutility from emissions.

3.2 The Role of Compensation Rates in Prosumers Decisions

In this subsection, we comment on the extent to which DRER owners could enable grid independency by looking at the role of the compensation rate for excess clean energy, P_b, on ϕ^* and γ^u. The analysis indicates that an increase in the compensation rate induces the DRER owner to increase her own energy production, but this also prompts additional grid energy consumption (both default and clean energy). The additional grid energy consumption comes from the extra income the DRER owner generates by producing more onsite energy and selling any excess. In the absence of the rebound effect (i.e., total energy demand remains constant), the increase in default and clean grid energy consumption prompts the DRER owner to reduce the consumption of own energy (γ) since now she is consuming more energy from the grid. This result suggests that the compensation rate may not be entirely consistent with a policy approach aimed at reducing grid dependency. In the Appendix we formally show this result.

We combine the results from the preceding paragraphs to characterize changes in the share of total energy demand met by the energy consumed onsite, $\phi^*\gamma^u$, in terms of the elasticities of onsite energy production and consumption. Since ϕ^* and γ^u are functions of P_b and s, total differentiation gives (dropping the $*$ and u superscripts)

$$\frac{d(\phi\gamma)}{\phi\gamma} = \left[\epsilon_{\phi_{P_b}} + \epsilon_{\gamma_{P_b}}\right]\frac{dP_b}{P_b} + \left[\epsilon_{\phi_s} + \epsilon_{\gamma_s}\right]\frac{ds}{s} \tag{4}$$

where $\epsilon_{\phi_s} = (s/\phi)(\partial\phi/\partial s) > 0, \epsilon_{\phi_{P_b}} = (P_b/\phi)(\partial\phi/\partial P_b) > 0, \epsilon_{\gamma_s} = (s/\gamma)(\partial\gamma/\partial s), \epsilon_{\gamma_{P_b}} = (P_b/\gamma)(\partial\gamma/\partial P_b) < 0$. Intuitively, the share of total energy demand met by the energy consumed onsite depends on how sensitive the DRER owner is when it comes to producing (ϵ_{ϕ_s}, $\epsilon_{\phi_{P_b}}$) and consuming (ϵ_{γ_s}, $\epsilon_{\gamma_{P_b}}$) energy onsite. If the DRER owner is relatively more sensitive to changes in the production of energy onsite (that is, if changes in $\phi\gamma$ are driven primarily by changes in ϵ_{ϕ_s}, $\epsilon_{\phi_{P_b}}$), then an increase in the compensation rate ($dP_b > 0, ds = 0$) raises the share of total energy demand met by the energy consumed onsite. Similarly, for a DRER owner who becomes more concerned about her carbon footprint ($dP_b = 0, ds > 0$), the share of total energy demand met by the energy consumed onsite also increases. But Eq. (4) also captures the trade-off between higher/lower levels of the compensation rate for a DRER owner who becomes more ($ds > 0$) or less ($ds < 0$) concerned about her carbon footprint; that is, setting Eq. (4) equal to zero gives

$$d(\phi\gamma) = 0 \Leftrightarrow dP_b/P_b = -\left[\frac{\epsilon_{\phi_s} + \epsilon_{\gamma_s}}{\epsilon_{\phi_{P_b}} + \epsilon_{\gamma_{P_b}}}\right] ds/s \tag{5}$$

where the term in brackets is positive as long as the DRER owner is relatively more sensitive to changes coming from the production of energy onsite. This result says that for a DRER owner who becomes more (less) concerned about her carbon

footprint a proportional decrease (increase) in the compensation rate keeps the share of total energy demand met by the energy consumed onsite, $\phi\gamma$, unchanged. This illustrates the trade-off between a DRER owner's disutility from emissions and the compensation rate with implications on the design of effective compensation rate policy which we discuss below.

Now, if the DRER owner is relatively more sensitive to changes coming from the consumption of energy produced onsite (that is, if changes in $\phi\gamma$ are driven primarily by changes in $\epsilon_{\gamma_s}, \epsilon_{\gamma_{P_b}}$), then a myriad of cases arise: The denominator in Eq. (5) is negative and the sign of the numerator is ambiguous. This is because changes in γ depend on the level of the disutility from emissions, s. A large (small) enough s means $d\gamma^u/ds > (<)0$ and therefore $\epsilon_{\gamma_s} > (<)0$.

If the DRER owner does not care enough about her carbon footprint (in the sense that a small enough s means $\epsilon_{\gamma_s} < 0$), then the consumption of own energy falls even as the DRER owner becomes more concerned about her carbon footprint ($ds > 0$). In this case the term in brackets in Eq. (5) is positive (numerator is negative and denominator is negative), and so we still see the trade-off between the compensation rate and the DRER owner's disutility from emissions.

But if the DRER owner cares enough about her carbon footprint (in the sense that a large enough s means $\epsilon_{\gamma_s} > 0$), then the consumption of own energy rises as the DRER owner becomes more concerned about her carbon footprint ($ds > 0$). As a result, the term in brackets is negative indicating that the trade-off between the compensation rate and the DRER owner's disutility from emissions no longer holds. In this case, a DRER owner who cares enough about her carbon footprint and who also becomes more concerned about it raises her own energy consumption. This type of DRER owner can only offset her own energy consumption with a higher (not lower) compensation rate in order to keep constant the share of total energy demand met by the energy consumed onsite, $\phi\gamma$. This is because a higher compensation rate reduces the DRER owner's own energy consumption. More formally, the DRER owner who cares enough about her carbon footprint ($\epsilon_{\gamma_s} > 0$) and who becomes more concerned about it ($ds > 0$) increases her consumption of own energy (thereby raising $\phi\gamma$). But the same DRER owner decreases her consumption of own energy with a higher compensation rate (thereby reducing $\phi\gamma$) in order to keep $\phi\gamma$ unchanged.

Our analysis points to two policy-relevant results. First, policymakers may want to know how sensitive DRER owners are with respect to the production of energy onsite and the consumption of said energy. If DRER owners are sensitive to changes in the production of onsite energy, then a clear trade-off between the compensation rate and DRER owner's disutility from emissions arises. This result has implications for the design of the compensation rate: Those DRER owners who become less (more) concerned about their carbon footprint may need (not need) to see a higher compensation rate in order to raise the share of onsite energy consumed. But if DRER owners are relatively more sensitive to changes in the consumption of onsite energy, then this trade-off may not always hold thus pointing to a potentially different policy design when it comes to promoting energy consumption from onsite energy sources.

3.3 Lessons for GCC States

There is a growing number of studies analyzing the economic and environmental impacts of renewable energy generation in GCC States. For example, Alazemi (2017) finds that solar PV has a financial and environmental benefit in Kuwait; the study by Ramli et al. (2017) highlights the role of distributed generation in lowering dependence on fossil fuels for the Kingdom of Saudi Arabia; Salimi et al. (2022) examine solar energy development options for the United Arab Emirates (UAE) highlighting the need to move away from fossil fuels, and a related study by Sgouridis et al. (2016) examines the financial feasibility of renewable energy sources such as solar. Bhutto et al. (2014) argue for the potential role of renewable energy sources such as geothermal, solar, and wind power in facilitating sustainable energy in GCC States.

Table 1 presents energy statistics for GCC States based on data compiled from ESMAP (2020), IRENA (2019), and REN21 (2023). Solar potential is represented by the global horizontal irradiation which is measured in kilowatt hours (kWh) of solar energy per square meter per day. This metric measures the theoretical potential for the availability of solar resource at a given location and allows for comparing the natural conditions that allow for implementing any PV technology (ESMAP, 2020). Cumulative installed PV capacity is measured in megawatt peak (MWp) and describes the maximum output that a PV system can produce for the year 2018 (IRENA, 2019). Cumulative installed PV capacity per capita is measured in watt peak per population, and electric power consumption per capita (2014) is measured in kilowatt hours. The economic potential of PV is measured by using the levelized cost of energy-LCOE (US dollars per kilowatt hour, 2018) which measures the lifetime costs associated with construction and operation of the solar generation divided by electricity produced during this lifetime. The lower the LCOE the higher the economic potential. Each of the six countries have an average LCOE of $0.08–$0.09 per kilowatt hour, while the world average is at $0.10 per kWh.

Table 1 shows that although GCC nations have higher solar potential, lower cost of PV and a higher per capita electric power consumption rate compared to world averages, the cumulative installed PV capacity (total and per capita) is significantly lower than world averages. Currently, the use of renewable energy in GCC States is minimal, where renewable production represents less than 1% of final energy consumption. However, a shift is potentially underway as GCC nations demonstrate commitment to combating climate change and supporting international efforts to build a more sustainable future by making progress toward reaching net-zero emissions. For example, Bahrain aims to increase its renewable energy usage to 10% by 2035, reducing its reliance on fossil fuels. The country is actively adopting regulations such as feed-in tariffs and premium payments and is considering governmental financial sources and tax incentives to support renewable generation targets. Saudi Arabia, a key player in the region, plans to source 50% of its energy from renewable sources by 2030 supported by several policy and regulatory frameworks such as feed-in tariffs, premium payments, and a mandate for

Table 1 Energy statistics for GCC States (Source: compiled from ESMAP, 2020; IRENA, 2019, and REN21, 2023)

Country	Solar potential	PV capacity	PV capacity/capita	Electric consumption/capita
Bahrain	5.8	5.0	3.2	19,597
KSA	6.2	89.3	2.6	9401
Kuwait	5.7	30.5	7.4	15,591
Oman	6.3	8.2	1.7	6446
Qatar	5.9	5.1	1.8	14,782
UAE	6.1	493.	51.2	11,088
World	4.9	2350.6	41.7	3829

renewable heat. The UAE is making progress, with the aim of increasing renewable energy use from 1% in 2020 to 31% by 2025, where government funding and tax breaks are expected to play a crucial role in the advancement of renewable energy projects. Similarly, Qatar has a renewable energy target supported by public finance mechanisms and fiscal incentives (REN21, 2023). Other nations such as Kuwait and Oman, although they do not have specific renewable targets, have some policies related to renewable energy use in power generation but lack a specific target.

Despite the low usage of renewable energy, GCC's ambitious goals reflect a growing recognition of the importance of transitioning to cleaner energy sources for long-term energy security and environmental sustainability (REN21, 2023). The high solar potential of GCC States (Table 1) suggests that DRERs can be a promising way toward achieving energy resilience. To encourage more investment in DRERs and decentralized generation, GCC states could consider several strategies. First, implementing policies that promote investment in DRERs, such as tax incentives, feed-in tariffs, or renewable portfolio standards, could provide a supportive environment for growth. Second, fostering public–private partnerships can help share the risks and benefits of investing in DRERs, making it a more attractive proposition for private entities including households. Third, increasing public awareness about the benefits of DRERs and decentralized generation through educational programs and public campaigns can drive demand and acceptance. Finally, upgrading the infrastructure of the grid to accommodate more decentralized generation, possibly through the use of smart grid technologies, can facilitate the integration of DRERs. While the transition to more decentralized generation will take time and strategic planning, these steps can help increase the use of DRERs in GCC states. Once DRERs are in place, GCC nations could encourage a proactive energy management approach as presented in this chapter.

The proactive DRER owner model presented in this chapter emphasizes the importance of self-consumption and proactive energy management, which could be beneficial for GCC nations striving for energy system resilience. For instance, the model suggests that DRER owners who care about their carbon footprint exhibit a higher level of self-consumption. This insight could guide GCC nations in designing customized policy interventions that encourage self-consumption and reduce carbon emissions. Policies could range from no intervention for those with higher degrees

of carbon disutility to using price incentives to encourage energy production and consumption by the DRER owner.

Moreover, the model highlights the role of energy storage in achieving grid resiliency and energy independence. While the adoption of energy storage systems faces significant cost barriers, the model suggests that prosumer communities can adopt other proactive strategies in energy management through behavioral changes. These strategies include actively matching onsite generation with consumption patterns to reduce electricity bills or load shifting, adopting energy-saving behavior or investing in energy-efficiency improvements with solar installations to lower energy needs. By understanding and applying these strategies, GCC nations can enhance their energy system resilience, reduce their carbon footprint, and move toward a more sustainable and decentralized energy solution. This approach would not only align with the global trend toward cleaner energy production and consumption but also cater to the specific context and needs of GCC nations.

4 Concluding Remarks

We present an extension of the prosumer model in Fikru and Gautier (2023) by considering a proactive prosumer that actively matches onsite generation with real-time consumption via utility-maximizing goals. We refer to such prosumers as proactive DRER owners and show that depending on the degree to which such decision-makers care about energy carbon footprint, they would have a relatively higher or lower rate of self-consumption rate. While previous prosumer models (Fikru & Gautier, 2023) present the impact of exogenous self-consumption rates on optimal DRER sizes, we characterize the optimal self-consumption rate which is consistent with utility maximization goals. This new element allows us to characterize two different types of proactive DRER owners, namely, one who cares about the impact she has on the environment from consuming energy from the grid and that who does not care much. Hence, we propose two different types of policy recommendations based on these two types of proactive DRER owners. Overall, when it comes to energy consumption, we argue that a less aggressive policy approach should take place if the DRER owner cares sufficiently about her carbon footprint coming from consuming energy from the grid. We also argue that a compensation rate for excess clean energy can be an effective policy to promote energy independence (i.e., higher share of consumption of energy coming from the DRER owner's onsite energy). Our analysis sheds light to the growing literature on prosumer behavior.

The model presented in this study has several policy implications. First, the study suggests that there is a need for designing customized policy interventions based on how DRER owners view carbon emissions. Depending on the extent to which a community cares about their energy carbon footprint, policymakers could consider different levels of intervention. Related to this, the results indicate that there are potentially two types of proactive DRER owners with different views on

their carbon footprint, leading to different optimal rates of self-consumption and onsite production. This suggests that policy interventions might need to be tailored to the preferences and behavior of different DRER owner groups. Second, to achieve a smooth energy transition, policymakers could benefit from understanding the level of disutility or preference for reducing energy carbon footprints within a community. If a community cares enough about their energy carbon footprint, active policy intervention may not be needed, as proactive DRER owners are willing to consume a large portion of their own energy produced onsite. Overall, the framework presented in the study can serve as a foundation based on which future studies can empirical examine to what extent and in what scenarios policies can be designed to take into account the attitudes of DRER owners toward carbon emissions and energy consumption patterns.

In the context of GCC, adopting the DRER model can help the nations to move toward a more decentralized and decarbonized energy system. It can also align with their specific regional context and energy needs, contributing to their broader goals of sustainability and climate change mitigation. However, it is important to note that the successful implementation of this model would require supportive policies and incentives, as well as a shift in consumer behavior toward more proactive energy management.

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Appendix

Solutions When Self-Consumption Rate Is Exogenous and Endogenous

Benchmark Case: Exogenous Self-Consumption Rate

We first characterize the equilibrium and derive closed-form solutions in the presence of disutility from carbon emissions, s. In the first stage, the prosumer maximizes Eq. (1) by choosing D_c and D_f subject to the budget constraint $M = P_c D_c + P_f D_f - (1-\gamma) P_b \phi D$. So,

$$\max \mathcal{L} = U(D_c, D_f) + \lambda \left(M - P_c D_c - P_f D_f + (1-\gamma) P_b \phi D - q_o \right)$$

whence

$$a_c - \beta_c D_c - d D_f + sE \left(1 + \frac{\phi}{1 - \phi\gamma} \right) = P_c + P_b (1-\gamma) \partial q / \partial D_c$$

$$a_f - \beta_f D_f - dD_c - sE\left(1 - \frac{\phi}{1-\phi\gamma}\right) = P_f + P_b(1-\gamma)\partial q/\partial D_f$$
$$M - P_c D_c - P_f D_f + (1-\gamma)P_b\phi D - q_o = 0$$
$$1 = \lambda$$

where $D = (D_c + D_f)/(1-\gamma\phi)$, $q = \phi D$, and

$$E = D_f - D_c - q = D_f\left(1 - \frac{\phi}{1-\phi\gamma}\right) - D_c\left(1 + \frac{\phi}{1-\phi\gamma}\right)$$

Hence, closed-form expressions for D_c and D_f are given by

$$HD_c = \left(a_c - P_c + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[\beta_f + s\left(1 - \frac{\phi}{1-\phi\gamma}\right)^2\right] - \left(a_f - P_f + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[d - s\left(1 - \left(\frac{\phi}{1-\phi\gamma}\right)^2\right)\right] \tag{6}$$

$$HD_f = \left(a_f - P_f + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[\beta_c + s\left(1 - \frac{\phi}{1-\phi\gamma}\right)^2\right] - \left(a_c - P_c + P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\left[d - s\left(1 - \left(\frac{\phi}{1-\phi\gamma}\right)^2\right)\right] \tag{7}$$

where $H > 0$ is the determinant of the coefficient matrix of the system.

Next, we use these values for D_c and D_f and maximize the net revenue function given in Eq. (2), where the first-order condition is given by

$$P_b(1-\gamma)(1-\gamma\phi) = \phi(D_c + D_f) \tag{8}$$

whence we obtain the equilibrium renewable generation as a share of demand, $\phi^*(\gamma, s, P_C, P_f, P_b)$.

Substituting back this expression into (6) and (7) yields $D_c^*(\gamma, s, P_c, P_f, P_b)$ and $D_f^*(\gamma, s, P_c, P_f, P_b)$.

Next, differentiation of (8) gives

$$\frac{d\phi}{d\gamma} = \frac{\phi\left[\frac{\partial D_c}{\partial\gamma} + \frac{\partial D_f}{\partial\gamma}\right] + P_b\left[(1-\gamma)\phi + (1-\phi\gamma)\right]}{-P_b(1-\gamma)\gamma - D_c - D_f} \tag{9}$$

This expression gives Fig. 2 when $s = 0$. This is consistent with Fikru and Gautier (2023)'s nonlinear relationship between ϕ^* and γ when $s = 0$.

Endogenous or Optimal Self-Consumption Rate

We differentiate equation (1) with respect to γ and set it equal to zero; this characterizes the γ which maximizes utility, γ^u:

$$\begin{aligned}\frac{dU}{d\gamma} = 0 \Rightarrow &\left(P_c - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\frac{\partial D_c}{\partial \gamma} \\ &+ \left(P_f - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)}\right)\frac{\partial D_f}{\partial \gamma} \\ &= -sE\frac{\phi^2}{1-\phi\gamma}D \end{aligned} \tag{10}$$

Substituting (10) into (9) gives

$$\rho\frac{d\phi}{d\gamma} = \phi\left[\frac{\partial D_f}{\partial \gamma}\left(1-\tilde{P}_f/\tilde{P}_c\right) - sE\frac{\phi^2}{1-\phi\gamma}D\right] + P_b\left[(1-\gamma)\phi + (1-\phi\gamma)\right] \tag{11}$$

where $\rho = -P_b(1-\gamma)\gamma - D_c - D_f < 0$, $\tilde{P}_f = P_f - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)} > 0$, $\tilde{P}_c = P_c - P_b(1-\gamma)\frac{\phi}{(1-\phi\gamma)} > 0$. And $\tilde{P}_c > \tilde{P}_f$. Then, the comparative statics give

$$\frac{\partial D_f}{\partial \gamma} = s\left[\left(1+\frac{\phi}{(1-\phi\gamma)}\right)\frac{\partial E}{\partial \gamma} + E\frac{\phi^2}{(1-\phi\gamma)^2}\right] - P_b\frac{\phi(1-\gamma)}{(1-\phi\gamma)^2} \tag{12}$$

Substituting (12) into (11) and collecting terms and simplifying give

$$\begin{aligned}\rho\frac{d\phi}{d\gamma} = s&\left[\left(\frac{\phi}{\eta}\left(1+\frac{\phi}{1-\gamma\phi}\right)\frac{\partial E}{\partial \gamma} + \frac{E\phi^3}{(1-\gamma\phi)^2\eta}\right)\frac{\tilde{P}_c - \tilde{P}_f}{\tilde{P}_c} - \frac{E\phi^3 D}{(1-\gamma\phi)\tilde{P}_c}\right] \\ &- \frac{\phi^2 P_b(1-\phi)\left(1-\tilde{P}_f/\tilde{P}_c\right)}{\eta(1-\gamma\phi)^2} + P_b\left((1-\gamma)\phi + (1-\gamma\phi)\right) \\ = &\frac{E\theta_1}{\gamma}\left(\epsilon_{e_\gamma} + \alpha\right) - \frac{\phi^2 P_b(1-\phi)\left(1-\tilde{P}_f/\tilde{P}_c\right)}{\eta(1-\gamma\phi)^2} + P_b\left((1-\gamma)\phi + (1-\gamma\phi)\right)\end{aligned} \tag{13}$$

where

$$\epsilon_{e_\gamma} = \frac{\partial E}{\partial \gamma}\frac{\gamma}{E} < 0$$

$$\frac{\partial E}{\partial \gamma} = -\frac{\phi^2}{(1-\gamma\phi)}D + \frac{\partial D_f}{\partial \gamma} - \frac{\partial D_c}{\partial \gamma} - \left(\frac{\phi}{1-\gamma\phi}\right)\left(\frac{\partial D_f}{\partial \gamma} - \frac{\partial D_c}{\partial \gamma}\right) < 0$$

$$\alpha = \theta_1/\theta_2 > 0$$

$$\theta_1 = \Psi \frac{\tilde{P}_c - \tilde{P}_f}{\tilde{P}_c} + \frac{E\phi}{\tilde{P}_c} > 0$$

$$\theta_2 = \frac{\phi^3}{(1-\gamma\phi)^2\eta}\frac{\tilde{P}_c - \tilde{P}_f}{\tilde{P}_c} > 0$$

Next, from (13), we obtain

$$\rho\frac{d\phi}{d\gamma} = 0 \Leftrightarrow s = \frac{-P_b\left((1-\gamma)\phi + (1-\gamma\phi)\right) + \frac{\phi^2 P_b(1-\phi)}{\eta(1-\gamma\phi)^2}}{\frac{E\theta_1}{\gamma}\left(\epsilon_{e_\gamma} + \alpha\right)} = \bar{s}$$

$$\rho\frac{d\phi}{d\gamma} < 0 \Leftrightarrow s > \bar{s}$$

$$\rho\frac{d\phi}{d\gamma} > 0 \Leftrightarrow s < \bar{s}$$

where $\rho < 0$.

The Effects of s on γ^u

Consider the expression for total demand, $(1-\gamma^u\phi)D = D_f + D_c$, where in equilibrium γ^u, D, D_f and D_c are functions of s. Differentiating (dropping the $*$ superscript) and imposing the no rebound effect assumption ($dD = 0$) gives

$$0 = \frac{dD_f}{ds} + \frac{dD_c}{ds} + \phi D\frac{d\gamma^u}{ds} + D\gamma^u\frac{d\phi}{ds} \tag{14}$$

where the first and second terms are negative and positive, respectively. That is, an increase in s induces the prosumer to decrease (increase) default (clean) energy from the grid to reduce emissions and thus the disutility from emissions. The fourth term is positive: An increase in s prompts additional energy production onsite by the prosumer.

Next, consider

$$\frac{dD_f}{ds} + \frac{dD_c}{ds} < 0 \Leftrightarrow s > \tilde{s}^* \tag{15}$$

That is, the reduction in default energy consumption and the associated increase in clean energy consumption from the grid leave room to the prosumer to raise own energy consumption as long as the prosumer's disutility from emissions is large

enough. In this case the prosumer is willing to raise her own energy consumption, γ^u, to address the higher disutility from emissions. In the context of (14), this means that the sum of the first, second, and fourth terms is negative and, therefore, the third term must be positive ($d\gamma^u/ds > 0$) for (14) to hold. A similar logic applies to the case of small disutility from pollution, $s < \tilde{s}^*$.

From (15) we have

$$\begin{aligned}\frac{dD_f}{ds} + \frac{dD_c}{ds} &= \mu_1 - \mu_2(D_f + D_c) - \frac{2(D_f + D_c)\phi^3}{(1-\gamma\phi)^3}s \\ &< 0 \Leftrightarrow s > \frac{\mu_1 - \mu_2(D_f + D_c)}{\frac{2(D_f+D_c)\phi^3}{(1-\gamma\phi)^3}}\end{aligned} \tag{16}$$

where

$$\begin{aligned}\tilde{s}^* &= \frac{\mu_1 - \mu_2(D_f + D_c)}{\frac{2(D_f+D_c)\phi^3}{(1-\gamma\phi)^3}} \\ \mu_1 &= 2(a_c - \eta_c)\left(1 - \frac{\phi}{1-\gamma\phi}\right) + (a_f - \eta_f)\left(1 + \frac{\phi}{1-\gamma\phi}\right) \\ \mu_2 &= \beta_c\left(1 - \frac{\phi}{1-\gamma\phi}\right)^2 + 2d\beta_f\left(1 + \frac{\phi}{1-\gamma\phi}\right)^2 \\ \eta_c &= \eta_f = P_b(1-\gamma)\frac{\phi}{1-\gamma\phi}\end{aligned} \tag{17}$$

The Effects of P_b on ϕ and γ^u, and Role of s

From (6) and (7) we obtain

$$\frac{\partial D_f}{\partial P_b} = \frac{(1-\gamma)\phi}{(1-\gamma\phi)}\left[\beta_c - d + 2s\left(1 - \frac{\phi}{(1-\gamma\phi)}\right)\right] > 0 \tag{18}$$

$$\frac{\partial D_c}{\partial P_b} = \frac{(1-\gamma)\phi}{(1-\gamma\phi)}\left[\beta_f - d + 2s\left(1 - \frac{\phi}{(1-\gamma\phi)}\right)\right] > 0 \tag{19}$$

where $\beta_c > \beta_f$ means that the increase in default energy is greater than the increase in clean energy from the grid.

Consider total energy demand $(1 - \gamma^u\phi)D = D_f + D_c$ in equilibrium, where differentiation and imposing the no rebound effect assumption ($dD = 0$) give

$$0 = \frac{dD_f}{dP_b} + \frac{dD_c}{dP_b} + D\gamma^u\frac{d\phi}{dP_b} + \phi D\frac{d\gamma^u}{dP_b} \tag{20}$$

where the first three terms are positive since an increase in the compensation rate prompts the prosumer to increase energy production onsite, which generates additional income and thus demand from the grid (default and clean). As a result, in the absence of the rebound effect (20) suggests that the fourth term is negative meaning the prosumer lowers her consumption of own energy since now she is consuming more the grid.

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Digital Resilience in Smart Cities: A Dynamic Capability Approach

Boumediene Ramdani

Abstract Cities worldwide are not immune from a vast array of threats from natural hazards to man-made and health-related disasters. Smart cities have become more vulnerable to new forms of risks due to digital vulnerabilities. In order to make smart cities more secure, smart cities need to embed digital resilience as one of the cornerstones of overall urban resilience. This chapter will explore concepts such as resilience, smart cities' architecture, and threats facing smart cities. Using the dynamic capabilities approach, this chapter will explore how smart cities can be more digitally resilient by building specific dynamic capabilities. Three dynamic capabilities were found to make cities digitally resilient, namely, anticipating, withstanding, and adjusting. Strategies to help smart cities build these dynamic capabilities will be explored with relevant actions to be undertaken.

Keywords Digital · Resilience · Smart · Sustainable · Cities · Dynamic · Capabilities

1 Introduction

Cities face ongoing challenges from urban growth to inequality and climate change. Making cities livable, smart, and sustainable is one of the top priorities for governments around the world. According to the International Telecommunication Union (ITU), "A smart sustainable city is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects" (ITU, 2014, pp. 1). The IESE Cities in Motion Index (2024) ranks world-class cities using several criteria, namely, the economy;

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human capital; social cohesion; environment; governance; and urban planning, international profile, mobility, transportation, and technology.

The advancement of Information and Communication Technologies (ICTs) such as Internet of Things (IoT), artificial intelligence (AI), smart grids, digital twins, and robotics is supporting the development of smart and sustainable cities around the world (Belaid et al., 2024; ITU, 2021; Ramdani & Kawalek, 2024). These technologies have the potential to transform smart cities by improving citizens' quality of life (Garau & Pavan, 2018), providing more efficient services, facilitating collaboration among stakeholders, and promoting innovative business models (Marsal-Llacuna et al., 2015). The promise of smart cities is a more responsive and adaptable urban environment (WEF, 2023). However, emerging and new technologies come with potential risks that could include natural hazards, accidental hazards (e.g., human error and software corruption), or deliberate hazards (e.g., cyberattack and terrorism) (Cañavera-Herrera et al., 2022).

To be able to cope and respond to any risks, cities need to be resilient. Urban resilience is "the capacity of individuals, communities, and systems to adapt, survive, and grow in the face of stress and shocks, and even transform when conditions require it" (Arup and Rockefeller Foundation, 2024). Since 2013, the Cities Resilience Index has helped more than 100 cities worldwide to become more resilient. An integral part of urban resilience is digital resilience, which is "the capabilities developed through the use of digital technologies to absorb major shocks, adapt to disruptions, and transform to a new stable state" (Boh et al., 2023, pp. 344).

The aim of this chapter is to explore how smart cities can become digitally resilient. To accomplish this aim, this chapter will first explore the concept of resilience in general and in urban design and planning in particular. Then, it will look into the smart cities architecture to explore the layers of smart cities. After that, it will outline the existing threats that could jeopardize the basic functioning of smart cities. This chapter will develop a framework of digital resilience using the dynamic capabilities approach. It will highlight the key dynamic capabilities needed for digitally resilient smart cities. Finally, practical strategies for embedding these capabilities will be explored.

2 Resilience

Before exploring how a smart city can develop digital resilience, we need to know the concept of resilience in general and what is known about this concept so far. Linnenluecke (2017) conducted a comprehensive literature review on the concept of resilience in the broad business and management field and identified resilience as the ability "to respond more quickly, recover faster or develop more unusual ways of doing business under duress than others" (pp. 4). She found that resilience can be viewed as:

- *Response to threats*: Resilience here is viewed as how to avoid the threat-rigidity effect, which is the negative framing of situations that usually lead to risk avoidance and harmful outcomes (Meyer, 1982).
- *Reliability*: Resilience is viewed here as how to maintain error-free operations and avoid small failures that could lead to major disasters (Perrow, 1984).
- *Employee strengths*: Resilience is viewed here as a psychological capital that can be developed where individuals are much more prepared to face catastrophes (Coutu, 2002).
- *Business model adaptability*: Resilience is viewed as how to configure business model components by constantly adjusting activities in order to respond to internal and external challenges (Ramdani et al., 2022).
- *Supply chain design*: Resilience is viewed here as the capabilities needed to design strong supply chains and mitigate any disasters such as access to information, speed, collaboration, and flexibility (Juettner & Maklan, 2011).

Another review by Conz and Magnani (2025) found that the concept of resilience is related to time:

- *Before disruption*: Resilience is viewed as a proactive attribute.
- *During disruption*: Resilience is viewed as an absorptive and adaptive attribute.
- *After disruption*: Resilience is viewed as a reactive attribute.
- *Before, during, and after disruption*: Resilience is viewed as a dynamic attribute.

In urban planning and design literature, urban resilience is captured through five dimensions (Ostadtaghizadeh et al., 2015; Ribeiro & Gonçalves, 2019):

1. *Physical*: infrastructure and land use
2. *Natural*: ecological and environmental
3. *Economic*: economic development and society
4. *Institutional*: governance and mitigation strategies
5. *Social*: people and communities

However, a sixth dimension is missing, which is *digital* (software, hardware, and data). This dimension crosses all of the five dimensions mentioned above.

According to Ribeiro and Gonçalves (2019), urban systems can be more resilient if they acquire the following characteristics:

- *Redundant*: availability of multiple components performing the same task. If one fails, the system automatically switches to the one that is still working.
- *Diverse*: availability of multiple functionally different components to absorb different threats.
- *Efficient*: ability to adapt for many years at low cost.
- *Robust*: ability to predict future failures and resist them.
- *Connected*: availability of support through connected components.
- *Adaptable*: ability to respond based on previous experiences.
- *Resourceful*: availability of resources to quickly replace any displaced resources.
- *Independent*: ability to operate independently for a prolonged period of time after that shock without the need for physical interventions.

- *Innovative*: ability to restore the functionality of critical systems under abnormal circumstance.
- *Inclusive*: ability to include most vulnerable communities in the development of plans and processes.
- *Integrated*: ability to exchange information between systems for a quick and common response.

However, cities face several financial, social, political, and structural constraints making it very difficult to design systems that incorporate these essential characteristics.

3 Smart City Architecture

Academics and practitioners have different interpretations of the layers within a smart city. This is critical because these layers will have corresponding measures for resilience. According to Silva et al. (2018), there are four layers in the smart city architecture:

- *Sensing layer*: Sensors are connected to various devices that collect data on several parameters such as temperature, humidity, light, and pressure.
- *Transmission layer*: This layer is responsible for transmitting data collected by the sensing layer through wired, wireless, and satellite technologies.
- *Data management layer*: This layer is in charge of organizing, analyzing, and storing data for decision-making purposes.
- *Application layer*: This layer performs decision execution transferred from the data management layer. Citizens of smart cities are able to interact with smart city architecture through community development, smart transportation, etc.

Each of the above layers includes security modules to help protect sensitive data. Moreover, a recent review by Canavera-Herrera et al. (2022) suggests that smart cities have three layers:

- *The physical city layer*: This layer includes the traditional physical infrastructure (roads, water systems, buildings, etc.) as well as the urban communities and the natural system (rivers, parks, green space, etc.)
- *The digital "smart" technologies layer*: This layer includes all technologies that make a city "smart" such as IoT and AI as well as technologies that are embedded within other infrastructures to make them smarter such as smart roads and smart grid.
- *The data layer*: This layer includes data collected, analyzed, and communicated to other devices as well as data management technologies helping to process the data.

As outlined above, technology is an integral part of smart cities making them more vulnerable to cyberattacks, data breaches, and IoT exploitation among others.

In the next section, this chapter will delve into these threats as well as other hazards that could jeopardize the safety of smart cities.

4 Threats

Cities worldwide are not immune from a vast array of threats. These threats can be categorized into natural, man-made, and health-related hazards (Meyer and Kunreuther, 2017; Cañavera-Herrera et al., 2022).

- *Natural hazards*: These include hurricanes, earthquakes, floods, wildfires, and tsunamis. The occurrence of these disasters has intensified due to the impact of climate change.
- *Man-made hazards*: These include deliberate man-made hazards such as cyberattacks and terrorism as well as accidental man-made hazards due to human error, which include industrial accidents such as chemical spills and nuclear accidents such as the Fukushima disaster.
- *Health-related hazards*: These include widespread health crises and pandemics such as COVID-19.

These disasters bring cities of all kinds on their knees. Adding to this complexity, smart cities suffer from digital vulnerability, which is "a condition of susceptibility to harm that stems from the use of digital technologies" (Ransbotham et al., 2016, p. 1). The digital vulnerabilities of smart cities include the following:

- *Technological vulnerabilities*: These include hardware (e.g., IoT devices with weak security protocols), software (e.g., software bugs and glitches), and data vulnerabilities (e.g., surveillance and monitoring data)
- *Technological obsolescence*: Smarter technologies are always being developed making existing smart technologies outdated and requiring constant investments to upgrade existing technologies.

Kitchin and Dodge (2020) claim that technologies are making smart cities more vulnerable to new forms of risks instead of making them more resilient. According to these authors, smart cities are much more vulnerable due to new forms of cyberattacks and IoT vulnerabilities. They identify five forms of digital vulnerabilities in smart cities:

1. *Weak software security and data encryption*: Smart cities lack proper security measures and deploy new technologies without cybersecurity testing. Moreover, most sensors that exist in the market have limited computing power to establish end-to-end encryption for IoT devices.
2. *Insecure legacy systems and poor maintenance*: Cities transitioning to be smarter bring new technologies into outdated software built two to three decades earlier that cannot be updated or secured.

3. *Complex and interdependent systems*: Smart cities are made up of numerous complex and interdependent systems, which makes it difficult to identify components, assess risk levels, and secure the entire system.
4. *Human error and deliberate misconduct*: Hackers are actively deceiving smart city citizens into sharing sensitive information or performing tasks that compromise systems' security. This can be due to human error such as downloading bugs or deliberately installing systems with unauthorized access.
5. *Security accountability and inadequate funding*: The complexity of smart city systems makes it difficult to assign clear responsibilities for system security due to the involvement of multiple companies and stakeholders. In addition, smart cities are under constant pressure to make savings, which pushes them to outsource services to other vendors leading to fragmented accountability.

These forms make smart cities digitally vulnerable to cyberattacks making it impossible to eliminate security vulnerabilities in smart cities. Thus, digital resilience is critical to make smart cities more secure. The next section will develop a framework for building digital resilience in smart cities.

5 Digital Resilience for Smart Cities

Unlike traditional cities, where the resilience focus is mainly physical, smart cities require digital resilience due to digital vulnerabilities. Using the dynamic capabilities theory (Schoemaker et al., 2018; Teece et al., 1997; Teece, 2009), we propose a framework for developing digital resilience to secure smart cities. As highlighted in Fig. 1, this framework combines the timeline of different states of disruption, the overarching dynamic capabilities, and digital resilience dynamic capabilities needed for each state.

Timeline Viewing resilience as a dynamic attribute (Conz and Magnani, 2020), we will use three states (before, during, and after disruption). The timeline describes

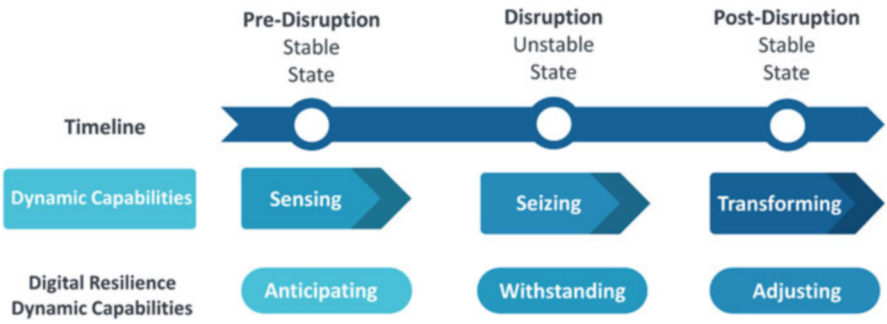

Fig. 1 Building digital resilience in smart cities framework

the three states (pre-disruption "old stable state"; disruption "disrupted state"; post-disruption "new stable state").

Dynamic capabilities "*ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments*" (Teece et al., 1997). These capabilities include the following:

- *Sensing*: ability to assess threats in the environment
- *Seizing*: capacity to mobilize resources to respond to identified threat
- *Transforming*: proficiency in reconfiguring the resource base to maintain a stable state as threats and technologies evolve

Digital resilience dynamic capabilities These are the different capabilities needed for each state in order for a city to respond to any threats and maintain a stable state. According to Conz and Magnani (2020), "a *dynamic* adaptation to a shock, meaning the ability to anticipate, to withstand, to cope with and to adjust to shocks by recombining existing resources to emerge strengthened and more resourceful" (p. 407). These capabilities are as follows:

- *Anticipating*: the ability to proactively identify, assess, and be ready for any potential threats in the environment.
- *Withstanding*: the capacity to remain operational with essential functions and structure despite adverse shocks.
- *Adjusting*: the ability to make the necessary changes behavioral or otherwise to better fit new conditions.

Cities are meant to emerge strengthened and more resourceful in the new stable state ready for any new disruptions with much more alertness and anticipation. Thus, we can identify digital resilience as "the digital capabilities developed to anticipate risks, withstand disruptions, and adjust to a new stable state."

6 Digital Resilience Strategies

Considering the digital vulnerabilities surrounding smart cities' systems, a novel approach must be adopted to ensure the security and safety of smart cities. Traditionally, smart city systems have been secured through technical mitigation solutions such as encryption, firewalls, security protocols, and software updates (Kitchin & Dodge, 2020). However, these solutions alone are necessary but not sufficient, and securing smart cities requires building dynamic resilience strategies by embedding dynamic capabilities for more digitally resilient smart cities.

In the pre-disruption phase, one of the critical actions to be undertaken by smart city governors is to form a dedicated security team. This team must be fully trained and aware of the complexities surrounding the security system within a smart city. They should perform continuous auditing of system components. They are tasked with continuous risk assessment, scenario planning, testing and monitoring devices, and making sure that they are secure. The team must have clear responsibilities on

which part of the system they need to secure and must be accountable for it. They should be able to deploy rapid detection systems including analytics to uncover any anomalies or predict future risks before they occur. The security team must engage smart cities' citizens and community organizations and empower them to be alert and ready for any crises. Conducting security simulations could be one way to prepare them for future attacks.

During the disruption phase, the security team must isolate affected systems to prevent the spreading of failure to other systems and networks. When a component of the system is identified to be risky, it needs to be isolated, updated, and even decommissioned without tempering with the functionality needed for a normal stable state. As in security simulations, the security team should be prepared to engage with technology vendors and urban administrators in order to respond in a coordinated manner. Technology vendors can assist with any software updates and patches to keep the system functional. Urban administrators should be involved in communicating disaster management responses to their superiors for building business cases for the safety of smart cities. For (almost) every scenario, the security team should be able to implement security measures planned for specific threats to recover quickly from adverse effects.

In the post-disruption phase, the security team with the help of urban administrators, citizens, and community organizations should mobilize the resources to the affected areas to adjust back to a stable state. Security teams should be able to quickly acquire hardware resources such as communication networks, sensors, and IoT devices. Technology vendors should be able to respond quickly to cyber-attacks with software updates or patches. Emergency responders, technical experts, volunteering citizens, and city officials should be on standby and engaged when required by the security team. After every disaster, the security team should update the security standards based on lessons learned and communicate these standards to citizens, technology vendors, government officials, and community organizations. Another critical action for the security team is to work with technology vendors on the system characteristics needed to withstand future attacks. Implementing a security-by-design approach (Kitchin & Dodge, 2020) will prevent future disasters. Finally, after a major shock, the security team must update security training to include the lessons learned and provide capacity building to citizens, emergency responders, and city officials. A summary of the dynamic capabilities and related actions are listed in Table 1.

7 Conclusion

From the above discussion, it is evident that smart cities suffer from a vast array of digital vulnerabilities due to possessing many technological layers. Surprisingly, urban resilience includes five dimensions, namely, physical, natural, economic, institutional, and social, but excludes the digital dimension. Moreover, cities face several financial, social, political, and structural constraints making it very difficult

Table 1 Digital resilience's dynamic capabilities and related actions

Digital resilience dynamic capabilities	Actions
1. Anticipating	Forming a dedicated security team with urban administrators that have clear responsibilities for securing specific components Performing continuous auditing of system components, risk assessment, scenario planning, testing, and monitoring Deploying rapid detection systems to uncover any anomalies or predict future risks before they occur Engaging citizens and empowering them to participate in crisis response Conducting security simulations to prepare for unexpected system failures
2. Withstanding	Isolating affected systems to prevent the spreading of failure to other systems and networks Responding to threats in a coordinated manner with the involvement of technology vendors and urban administrators Implementing security measures to recover quickly from adverse effects
3. Adjusting	Mobilizing the necessary resources to the affected areas to accelerate the recovery process Adopting new security standards and communicating them to citizens, technology vendors, government officials, and community organizations Working with technology vendors on designing new components that withstand future attacks Providing (updated) security training and capacity building to citizens, emergency responders, and city officials

to design systems that incorporate the characteristics of resilient urban systems. Thus, we need to know how smart cities can develop digital resilience. This chapter uses the dynamic capabilities approach to propose a framework for building digital resilience in smart cities. This is a practical framework that takes a dynamic view of urban resilience by incorporating three dynamic capabilities necessary to build digital resilience in smart cities. Digitally resilient smart cities are those that develop digital capabilities to anticipate risks, withstand disruptions, and adjust to a new stable state. Critical enablers to building these capabilities include forming a dedicated security team; engaging citizens, technology vendors, and urban administrators; and continuously updating security measures.

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Weaving Resilience: The Enduring Threads of GCC Communities

Mashael Saud AlShalan and Noura Turki Al-Saud

Abstract In this chapter, the focus is on building social resilience to confront climate change. It examines how GCC countries can adapt to and mitigate climate risks weaving deep-rooted community bonds into evolving urban landscapes.

This chapter discusses balancing strong communal ties with rising individualism due to global urbanization. Emphasis is placed on policies and infrastructure that support changing dynamics while reinforcing communal values.

This narrative highlights how climate change can exacerbate global challenges such as pandemics and economic fluctuations, providing strategies to manage these issues within the GCC context. A framework for adapting international resilience practices to the GCC's unique sociocultural and environmental landscape is introduced.

This chapter serves as a resource for policymakers, urban planners, academics, and community leaders in the GCC, providing insights into fostering resilient urban systems to address both immediate and broader challenges posed by climate change.

Keywords Social resilience · Climate resilience · Urban resilience · Community engagement · Social cohesion · Cultural heritage integration · Economic diversification

1 Background

In an era where climate change is no longer a distant threat but a pressing reality, the resilience of our societies is put to the test. This chapter delves into how the rich tapestry of community bonds and the dynamic urban landscapes of the Gulf Cooperation Council (GCC) can be harnessed to build robust infrastructures, policies, and, most importantly, resilient societies. By weaving together socioeconomic factors

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and environmental pressures, we spotlight the urgent need for social resilience in the face of escalating climate impacts.

The Arabian Peninsula, a region deeply intertwined with its environment, is warming at a rate significantly higher than the global average. Imagine a future where a 3 °C rise globally translates into a staggering 4.4 °C increase regionally (McCabe et al., 2023). Such a scenario intensifies heat-related stress, potentially rendering some areas uninhabitable during peak heat periods. This is not just a statistic; it is a looming reality that we must confront with innovative and adaptive strategies.

Projections also suggest a 15% increase in annual rainfall, leading to more frequent and intense extreme rainfall events, heightening the risk of flash floods, particularly in urban areas with inadequate drainage (McCabe et al., 2023). These changes will be felt the most in the southwestern regions, where a warmer atmosphere's increased moisture capacity will exacerbate rainfall extremes.

The impact on our ecosystems is profound. The terrestrial landscapes of the GCC, from sabkhas to wadis, are highly vulnerable to temperature shifts, changes in rainfall, and increased aridity. Overgrazing, unsustainable groundwater use, and poaching further stress these ecosystems, leading to shifts in vegetation, land degradation, and a heightened risk of extinction and desertification (Al-Obaid et al., 2017; McCabe et al., 2023). Similarly, our marine ecosystems, particularly in the Red Sea and Arabian Gulf, face significant threats from intensive dredging, pollution, and overfishing, which are only exacerbated by a warming climate (McCabe et al., 2023).

However, the implications extend beyond nature. Climate change poses substantial challenges to human societies within the GCC. Increased migration to wealthier Gulf countries due to climate impacts could strain resources, create social and political tensions, and potentially lead to instability (Norman et al., 2024; Abubakar et al., 2018). Changes in temperature, humidity, and precipitation patterns also have profound implications for disease transmission and food security. Increased heatwaves, especially during large gatherings such as Hajj and Umrah, pose significant health risks (Aeon Collective and Community Jameel, 2022; McCabe et al., 2023).

Our energy sector, predominantly driven by oil and gas, faces significant hurdles. Rising temperatures can diminish energy production efficiency and increase cooling demands, leading to higher energy consumption. Erratic precipitation patterns and extreme weather events can disrupt operations and infrastructure, necessitating robust long-term planning and investment in resilient technologies. Moreover, the global shift toward decarbonization requires us to transition to clean energy sources and diversify our energy portfolio (IPCC, 2022; McCabe et al., 2023).

Urban, rural, and coastal infrastructures are particularly vulnerable. Rising sea levels, projected to rise by up to 1 m by 2100, threaten coastal infrastructures, increase saline intrusion into freshwater resources, cause erosion and inundation, and potentially displace communities. Major cities in the GCC are also at risk from flash floods, extreme heat impacts on agriculture and infrastructure, and extreme weather events like cyclones (Salimi & Al-Ghamdi, 2020).

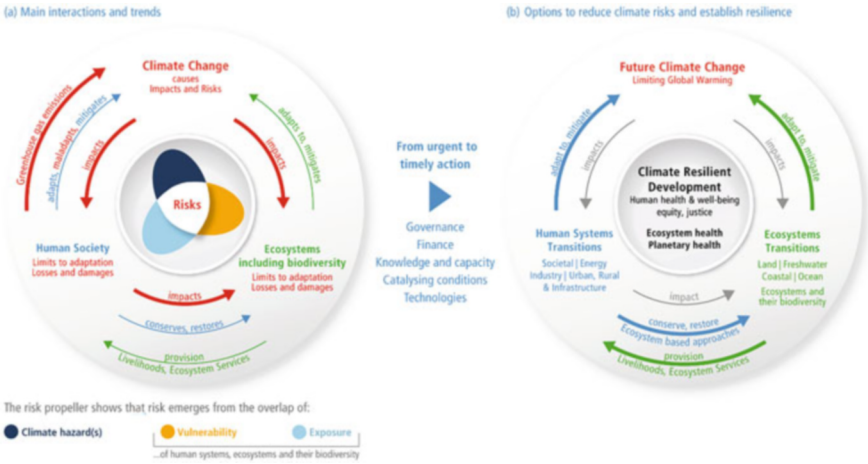

Fig. 1 From climate risk to climate resilient development: climate, ecosystems (including biodiversity), and human society as coupled systems from IPCC (2022)

These challenges underscore the critical need for the GCC nations to adapt their social, economic, and environmental policies to effectively mitigate the risks posed by climate change (IPCC, 2022). To address these challenges, we turn to the framework illustrated by the IPCC (Fig. 1). This model is pivotal in understanding the intricate interplay between human society and ecosystems and highlights the importance of strategic interventions to foster climate-resilient development.

By embracing this comprehensive framework, we aim to ensure that sustainable urban development and community well-being are consistently maintained, even in times of climate uncertainty. This chapter serves as a guide for policymakers, urban planners, academics, and community leaders in the GCC, providing insights into fostering resilient urban systems to address both immediate and broader challenges posed by climate change.

2 Section 2: The Social Fabric of GCC Communities: Historical Roots and Emerging Challenges

2.1 Historical Overview of Communal Bonds in GCC Societies

The GCC region is woven with an intricate tapestry of strong communal bonds and shared values that have historically underpinned its social structure and resilience strategies. These bonds, deeply embedded within extended family systems and tribal affiliations, have governed social and economic interactions for centuries. They

offer a robust framework against socioeconomic stresses, providing stability as communities rally to support one another in times of need (Alsharekh & Springborg, 2008).

Imagine the bustling souqs of old Riyadh, where traders, families, and neighbors engage in daily interactions, their lives intertwined in a web of mutual support. This vibrant tapestry of social interactions, rooted in tradition, now faces the encroaching forces of modernity. As cities like Riyadh and Dubai undergo rapid urbanization, the delicate balance between preserving traditional communal spaces and integrating modern urban environments becomes increasingly complex. This transformation is not just physical but also represents a profound shift in the societal fabric, testing traditional support systems against the backdrop of modern urban pressures (Elsheshtawy, 2019).

In recent decades, these traditional structures have faced significant challenges due to modernization and globalization. As new urban forms emerge, traditional communal bonds are strained, yet their resilience remains crucial. They act as a buffer against the socioeconomic impacts of environmental crises like climate change. Despite these pressures, communal networks continue to play a pivotal role in ensuring community cohesion and continuity.

For example, during the severe flooding event in Jeddah in 2009, local communities quickly activated informal networks to provide essential support and aid to affected families. This response highlighted the potent role of community ties in compensating for urban planning and disaster preparedness shortcomings. Such instances underscore the importance of maintaining these rich communal traditions even as the GCC adapts to a rapidly changing world.

The sustainability of traditional social support mechanisms is a central concern in urban planning and policymaking. This balance is vital for social stability and fostering resilience in the face of environmental and socioeconomic changes. As the GCC navigates the dual challenges of preserving communal traditions and embracing modernization, the region must integrate the best of both worlds, ensuring that modern advancements do not erode the very fabric that has held these societies together for centuries.

By weaving historical anecdotes with contemporary examples, this section sets the stage for a deeper exploration of how modernization impacts these traditional bonds and highlights the enduring strength and adaptability of communal networks in the GCC.

2.2 Urban Resilience in GCC Cities: Historical Perspectives

Urban resilience in GCC cities is woven into their historical and cultural fabric. Traditional communal spaces have long shaped resilient communities. This legacy dates back to the Prophet Mohammad (pbuh), who established the first Jum'a mosque in Al-Madinah al-Munawwarah, around which homes were built. Commerce and trade

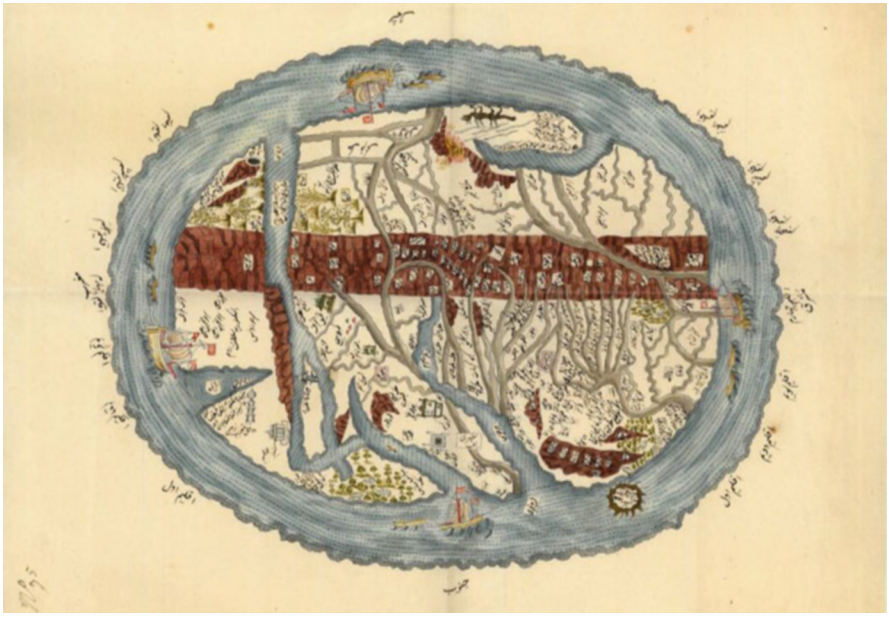

Fig. 2 World Map centered on Arabian Gulf, showing mosques or minarets by Anonymous (1790)

flourished, leading to the establishment of souqs around mosques, creating vibrant, interconnected urban centers. Cities thrived based on their proximity to potable water, fertile land, or natural barriers against enemies. Public libraries, hammams, public gardens, and stables for travelers further enhanced civility. By understanding these elements, we can draw lessons to inform modern urban resilience strategies, ensuring that our cities remain robust and connected (Fig. 2).

Jum'a Mosques

Jum'a Mosques have traditionally been more than just places for worship; they are central hubs for community gathering, legislation, jurisprudence, and support. Historically, during crises such as natural disasters or communal strife, these mosques have often transformed into centers for coordination and relief, distributing aid and providing shelter. This multifaceted role exemplifies how such religious institutions are embedded within the social fabric, offering not only spiritual guidance but also practical support in times of need. Modern urban resilience strategies could benefit from reinvigorating such multifunctional communal spaces while ensuring that they comply with contemporary regulations. This includes maintaining cleanliness, enhancing educational outreach, and integrating cultural initiatives to foster community ties and social cohesion. By adapting the historical role of mosques to meet today's community needs, we can ensure that these spaces

Fig. 3 A Town Map of Riyadh, Chief Town of the Nejd, Arabia 1866 AD. Revised by Abdulrahman Al-Rowaishid (n.d.). (Originally drawn by William Palgrave. Available at [https://www.loc.gov/item/17020697/])

enhance the capability to manage emergencies effectively and support the holistic development of urban environments (Fig. 3).

Proximity of Houses in Old Towns

The traditional urban design within older GCC towns, characterized by closely packed houses, is a strategic adaptation to the harsh climate. This layout creates narrow, shaded pathways that significantly reduce the ambient temperature. Historically, these houses were typically constructed with thick mud walls and sometimes featured wind towers (barjeels), which naturally cooled buildings before the advent of modern air conditioning. Historical Riyadh was a small fortified settlement strategically located near Wadi Hanifah, providing essential water and fertile land for agriculture. This proximity not only supported agricultural productivity but also influenced the settlement's compact design. Moreover, rooftops played a significant role in social cohesion, serving as communal spaces where families and neighbors gathered in the evenings to socialize and enjoy the cooler night air, thus reinforcing community bonds and resilience (La Tansoon, 2024).

Fig. 4 Photo of Falaj Alin Al Jabal al Akhdar from Metz (1994)

The architectural closeness of Riyadh's houses facilitated a strong sense of community and mutual aid, as neighbors could easily interact and support one another. Regularly repairing homes and building new ones further strengthened communal bonds. By revisiting these traditional building practices and materials, contemporary urban development can harness these sustainable and community-oriented design principles. This approach fosters both environmental resilience and a robust social fabric, ensuring that modern urban growth respects and incorporates the rich cultural heritage of the past. For instance, integrating green building codes and community-centric layouts in new developments could mirror the historical efficiency and social cohesion seen in old Riyadh (Fig. 4).

Water Infrastructure as Social Spaces

Traditional water infrastructure in older GCC towns, such as aflaj irrigation systems and saqiyas (water wheels), was crucial for both agriculture and community gatherings. In Oman, the aflaj systems, recognized by UNESCO, utilized gravity-fed channels to distribute water, supporting both agriculture and social interaction (UNESCO World Heritage Centre, 2006). Similarly, in Asir, the mountainous terrain necessitated innovative water management like terraced agriculture with intricate canal systems. These terraces not only supported farming but also served as social

hubs, fostering community interaction and cooperation (UNESCO World Heritage Centre, 2015).

By integrating these traditional approaches with modern technology, contemporary urban development can create resilient environments that address water scarcity and promote social cohesion. Revitalizing historic water infrastructure in modern settings, with careful adaptation to contemporary contexts, can mitigate urban heat and enhance community bonds, blending heritage with innovation for sustainable development.

Souqs (Markets) (Fig. 5)

Souqs are not merely economic centers but pivotal social hubs within GCC cities. Their intricate design—a labyrinth of alleyways and stalls—encourages not only commerce but also social interaction, playing a key role in maintaining the socioeconomic and cultural vitality of urban centers. Modern enhancements to these markets, such as incorporating traditional architectural elements with modern facilities, help preserve their historical charm while improving functionality. For example, the renovation of the Souq Waqif in Qatar or Souq Muttrah in Oman exemplifies how these markets, which have always historically held great significance, can evolve

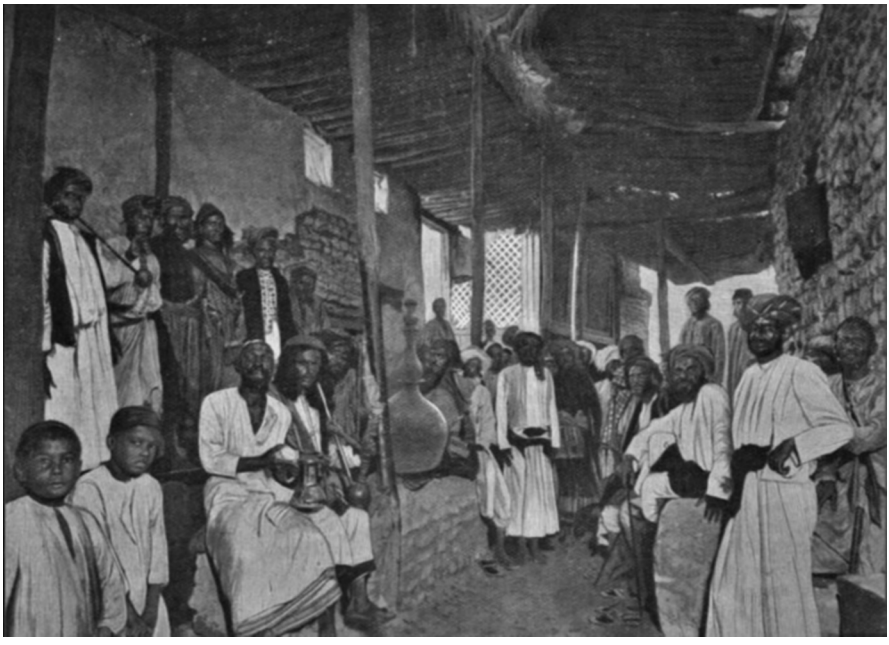

Fig. 5 Photo of the Souk of Muscat from Alleman (1901). Oman. Ombres Blanches

into vibrant cultural and commercial centers that remain deeply integrated into the city's social life, thus contributing to a dynamic, resilient urban environment.

Public Spaces and Rubats (Inns) (Fig. 6)

Public spaces have historically been vital to the social fabric and resilience of GCC cities, offering areas for commerce, relaxation, and social interaction. Public libraries, hammams, public gardens, and stables for travelers enhanced civility and cohesion. These communal spaces not only provided essential services but also fostered a sense of community and cultural continuity. Public libraries promoted education and intellectual growth, while hammams served as centers of hygiene and socialization. Public gardens offered leisure and reflection spaces, contributing to urban well-being, and stables ensured safe travel and trade.

Rubats, a notable example, served as waypoints for travelers and traders. These inns offered more than accommodation; they were centers of commerce, social interaction, and safety. Rubats provided free lodging to those in need, including widows and single women. Typically designed with a central courtyard, they facilitated interaction and cooperation among diverse groups.

Fig. 6 Rubat Al Khunji. (Photo courtesy of Saudi Ministry of Culture (2020))

A prime example is the Rubat Al Khunji in Jeddah, built in 1813 by Sheikh Mahmoud Kassim Alkhunji. Located in Jeddah's historical district, Al Balad, Rubat Al Khunji now serves as a cultural hub under the Art Residency Program, part of Saudi Arabia's Vision 2030 (Al-Jaber, 2017).

Reintroducing and modernizing these traditional public spaces, including Rubats, can create multifunctional areas that support modern needs while echoing the past. This approach aligns with sustainable urban development principles, ensuring that the historical legacy of these public spaces contributes to the dynamic and resilient cities of the future.

Communal Squares and Event Spaces (Fig. 7)

Communal squares (fina'a and baraha) and shared event spaces in GCC cities have historically been centers of social, cultural, and economic activity. These spaces, whether they are designated squares, courtyards within marketplaces, or multipur-

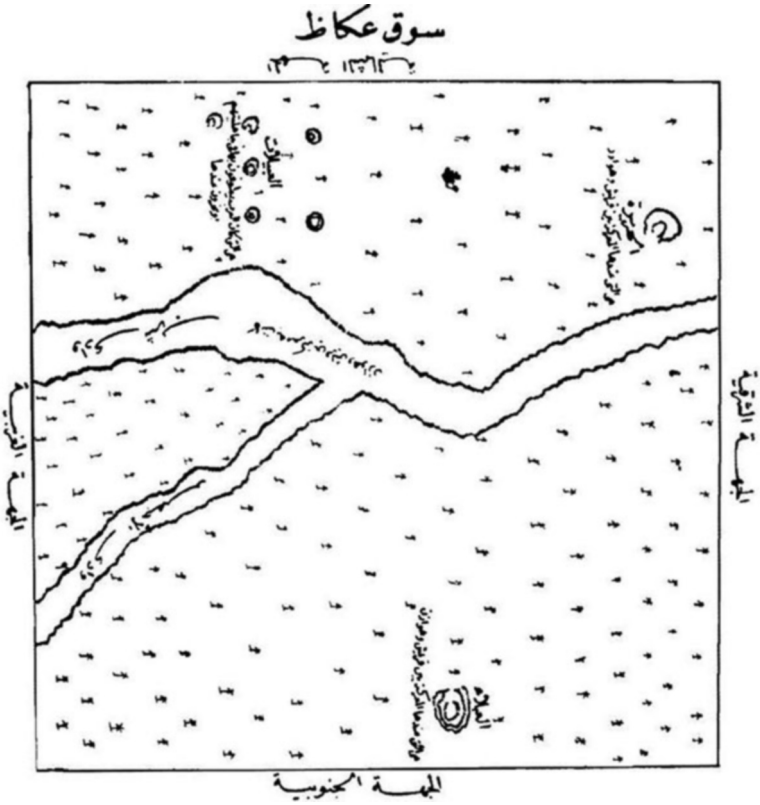

Fig. 7 Map of Souq Okaz from Ibn Balīhad al-Najdī, M. ibn 'A (1951)

pose areas, have facilitated public discourse, public and private celebrations, cultural festivals, markets, and communal gatherings. These spaces can be revitalized to strengthen community bonds and enhance social resilience by highlighting their multifunctional nature and strategic importance in urban planning. A prime example is Souq Okaz in Taif, a historic market established in 501 AD, which served as a cultural, social, and economic hub. Souq Okaz was a media platform for tribes, a venue for political activities, and a stage for poets, strategically linking trade routes from the east and south of the Arabian Peninsula. After a 13-century hiatus, Saudi Arabia revived Souq Okaz in 2006, transforming it into a festival that celebrates its rich history with cultural and literary events. Visitors enjoy folk songs, dances, plays, poetic recitations, local foods, and green spaces, making it a vibrant communal space that attracts various interest groups. The festival also involves young people in its design, construction, and operation, contributing to youth employment, skills development, and wider cultural and societal integration. By rejuvenating historical spaces like Souq Okaz, cities can harness cultural values, norms, and traditions while meeting modern demands and comforts, thereby creating dynamic communal spaces that foster stronger community ties and celebrate cultural heritage. Modern adaptations, such as cultural festivals in Hofuf, showcase how these areas continue to serve as vital hubs for community engagement and cultural preservation.

Intangible Heritage: Spoken Word, Poetry, and Music (Fig. 8)

The intangible heritage of spoken word, poetry, and music has historically played a crucial role in fostering communal bonds within the Arabian Peninsula. Practices such as poetry have been a cornerstone of Arabian culture, serving as a medium for storytelling, history-keeping, and moral instruction. Poetry gatherings in "majlis," were venues where poets recited their work, engaged in intellectual debates, and reinforced community bonds. Similarly, traditional music like Samri, where people gather around a fire and engage in rhythmic drumming and chanting, exemplifies the cultural richness of the region. These gatherings not only provided entertainment but also strengthened social ties and conveyed cultural values. For instance, in traditional settings, people in Najd and Ta'if would warm their drums (tar) and sing together, creating a shared cultural experience. Traditional music also had therapeutic benefits, as illustrated by historical practices where music was used to entertain and heal communities, such as the elderly in Bahrain (Bahrain News Agency, 1976).

Revitalizing these practices in modern urban settings can enhance social cohesion and cultural continuity. Community centers can host poetry readings, music nights, and storytelling sessions, fostering a sense of belonging and continuity. Integrating these intangible heritage elements into contemporary urban planning ensures that cultural practices that once brought communities together continue to do so, enriching the social fabric and contributing to overall well-being.

Fig. 8 Bahrain News Agency (BNA). (1976, February). Bahrain News Agency. https://www.bna.bh/en/FolkmusicentertainstheelderlyFebruary1976.aspx?cms=iQRpheuphYtJ6pyXUGiNqjemu5F

2.3 Traditional Resilience in the GCC: Case Studies from Bedouin and Agricultural Communities

Traditional resilience practices of the GCC region are deeply rooted in the nomadic and agricultural lifestyles that have thrived in its arid environment for centuries. These practices, passed down through generations, are a testament to the ingenuity and adaptability of the region's inhabitants. By examining these traditional methods, we can glean valuable insights into sustainable community engagement and environmental stewardship.

Case Study 1: Sustainable Rangeland Management in the Arabian Peninsula
Historical Context and Cultural Roots:

Rangeland management in the Arabian Peninsula is deeply rooted in its inhabitants' nomadic and semi-nomadic lifestyles, particularly the Bedouin tribes. These communities have honed sustainable practices over centuries, underpinned by a profound understanding of their arid environment's ecological limits and potential.

1. Bedouin Practices: Hema System
   The Bedouins have historically implemented the *hema* system—a traditional form of environmental conservation, where certain areas are designated as protected zones to allow vegetation to regenerate. This practice demonstrates an early form of community-based resource management, ensuring the sustainability of pastures and water resources which are critical for the survival of livestock, the mainstay of Bedouin livelihoods. The *hema* system not only preserved the ecosystem but also facilitated a fair distribution and responsible use of scarce resources among tribes. Tracing its origins to pre-Islamic times, the *hema* was initially a tool of oppression used by powerful chieftains as private reserves. However, with the advent of Islam, it underwent a transformative shift toward a community-centered resource, reflecting its integration into the legal and religious frameworks and adapting to diverse environmental management needs through various applications—ranging from strict grazing prohibitions to regulated seasonal usage (Gari, 2006).
2. Camels: Vital to Sustainable Management
   Camels have long been integral to the Bedouins' sustainable rangeland management. Bedouins organize camels into herds according to size, each overseen by a herdsman. The herdsman leads the herd to the pasture, intoning praise to guide them along ancient paths so as to not impact the pasture along its sides. Camels strategically graze on diverse vegetation, essential for managing the arid rangelands sustainably. They follow specific grazing routines that align with traditional ecological knowledge, optimizing resource use and supporting the hema system. The herdsman's intimate connection with the herd ensures optimal care, driving efficient grazing practices that preserve resources for future generations (Musil, 1928).
3. Tribal Territories and Seasonal Migrations
   Tribal rights to specific territories, including rangelands, have historically been well-defined, with different tribes holding established claims to certain areas. Seasonal migrations, dictated by climatic variations and the availability of resources, were a hallmark of traditional rangeland management. These migrations prevented overgrazing and ensured the sustainable use of resources. The routes and timing of these migrations were based on ancestral knowledge, which minimized conflicts and optimized the use of the landscape.
4. Community Regulations and Agreements
   Local customs and informal agreements, often enforced by tribal elders or community leaders, were pivotal in managing the rangelands. These agreements ensured compliance with sustainable practices and mediated disputes over resource use, reflecting a sophisticated system of local governance centered on sustainability and collective well-being.
5. Ancestral Wisdom and Oral Traditions
   Ancestral wisdom, transmitted through oral traditions, included extensive knowledge about the land, such as understanding seasonal cycles, identifying plant species beneficial for grazing, and locating water sources. This oral

tradition ensured that valuable ecological knowledge and sustainable practices were passed down through generations, embedding environmental stewardship within the cultural fabric of the community.

6. Adaptation to Environmental Challenges
   The harsh desert environment of the Arabian Peninsula necessitated the development of various adaptive strategies. Among these were sophisticated water conservation techniques such as the establishment of wells along critical routes like Darb Zubaidah, the ancient pilgrim road from Kufa to Mecca (Rāshid, 1980). These wells, strategically placed along the arduous journey, provided essential water resources for travelers and their livestock, showcasing the ingenuity of the time. The construction and maintenance of these wells were critical for the survival and prosperity of the Bedouin tribes and other inhabitants, allowing them to manage their ecological footprint while sustaining their livelihoods in one of the most arid regions on earth.

Case 2: Sustainable Water Management and Agricultural Practices in the Arabian Peninsula

Historical Context and Cultural Roots:

Sustainable agriculture in the Arabian Peninsula has evolved from ancient techniques devised to conquer the harsh, arid climate. Rooted in the ingenuity of early civilizations, these practices were shaped by an intimate understanding of the local environment and the critical scarcity of water resources. This rich heritage continues to influence contemporary agricultural strategies, intertwining ecological wisdom with modern innovations.

1. Agricultural Land Ownership Structures
   In the Arabian Peninsula, agricultural land ownership intertwines with cultural norms and environmental adaptations. Traditionally, land is kept within families and often not divided through inheritance to prevent fragmentation and maintain sustainable farming practices. This communal management approach is vividly demonstrated in the Asir and AlBaha region, where owning multiple farms signifies social prestige and carries substantial communal responsibilities. These farms, frequently managed by family members who remain to cultivate the land, employ traditional techniques suitable for mountainous and plain terrains (King Abdulaziz Public Library, 2007).
2. Oasis Agriculture and Crop Layering
   Historically, the strategic use of fertile lands within oases has been pivotal in desert agriculture. These oases employed multi-layer farming techniques that maximized the utility of limited water resources and arable land. For instance, in the lush oases of the AlAhsa region, date palms served as canopy layers, under which farmers cultivated a variety of understory crops like vegetables and herbs. This method created a beneficial microclimate and enhanced soil moisture retention, key for agriculture in arid zones.

3. Water Management Systems
   The construction of micro-dams and terracing systems in the mountainous terrains of Asir are prime examples of ancient hydrological innovations called *AlRakeeb* (King Abdulaziz Public Library, 2007). These systems slowed water runoff during the rare but intense rainfalls, allowing more water to seep into the ground and replenishing underground aquifers essential for local agriculture. Similarly, the sophisticated water management seen at Marib, with its grand-scale dam constructions, and in Al Faw, where a network of wells provided a consistent water supply, illustrates a deep understanding of local hydrological conditions and needs. The traditional water cisterns of Jeddah exemplify an adaptive strategy for the region's water scarcity. These cisterns, crucial for the storage and distribution of rainwater, underpinned the city's socioeconomic fabric, ensuring access to water during arid periods and serving as a testament to the historical resilience and ingenuity of the local communities (Blin, 2007).
4. Ingenious Water Harvesting and Irrigation Techniques
   The *falaj* (*singular of aflaj*) system, an ancient aqueduct technology, highlights the ingenuity of early hydro-engineering in the Arabian Peninsula. These aqueducts efficiently, in some cases (*as mentioned in Sect. 2.2*), transported water from mountain springs to distant agricultural fields, using gravity and the natural topography to maintain a steady flow of water, which was crucial for irrigation and community water supplies. In contrast to the sophisticated *falaj* system, some regions within the Arabian Peninsula, such as Asir, relied on simpler, yet effective, rain-dependent agricultural practices. Known locally as *Athra*, these methods involved farming primarily based on the seasonal rainfall patterns. This variance in techniques highlights the adaptability and resourcefulness of the region's inhabitants in leveraging their specific environmental conditions for agriculture and water management (King Abdulaziz Public Library, 2007).

Modern Integration and Conservation Efforts

In contemporary settings, there is a growing recognition of the value of these traditional practices, leading to their integration into modern rangeland management strategies. This fusion of traditional knowledge and modern science forms a cornerstone of sustainable development efforts in the region, aiming to rejuvenate degraded lands and promote ecological balance.

2.4 The Impact of Modern-Day Urbanization and Globalization on Social Structures

The rapid urbanization and globalization transforming cities such as Riyadh, Dubai, and Doha profoundly impact social structures within the GCC. As urban landscapes evolve, traditional communal living arrangements give way to more individualized

urban dwellings, challenging conventional social support systems and introducing diverse cultural dynamics. These changes pose risks, as inequalities can lead to weaker social structures and reduced social cohesion.

Significant demographic shifts in Bahrain and the UAE illustrate how the influx of international businesses and expatriate workers reshapes local norms and lifestyles, creating a complex social fabric that blends traditional and modern elements (Gardner, 2013). Studies on the Indian community in Bahrain highlight the cultural influence of expatriates on local social dynamics. Similarly, Saudi Arabia's labor policies, influenced by oil economics, have historically shaped urban growth and continue to impact social structures (Hertog, 2011).

Viewing urbanization in the GCC through the lens of the "urban growth machine" concept reveals cities as economic engines prioritizing development, often at the expense of social equity (Molotch, 1976). This perspective helps explain the socioeconomic stratification and spatial segregation accompanying urban growth, posing significant challenges to social cohesion. The cyclical nature of the oil market has led to economic booms and recessions, affecting the sustainability of growth, modest diversification, labor market imbalances, low productivity, and distortions in incentive systems. Recognizing these challenges, Saudi Arabia has coupled economic development with social sustainability through initiatives such as Vision 2030 and its Quality of Life Program (Vision 2030, 2017; Al-Moneef, 2022). Such programs aim to promote social equity and enhance quality of life, mitigating the risks associated with rapid urbanization.

However, these challenges also present opportunities. Addressing them requires resilient strategies that balance infrastructural development with inclusive social policies. By respecting heritage while embracing new cultural influences, cities can foster a cohesive social environment amidst rapid urban growth. As GCC cities continue to expand, integrating sociological, political, economic, and cultural perspectives will be crucial in developing resilient urban systems capable of withstanding twenty-first-century socioeconomic pressures and turning risks into opportunities for sustainable development.

2.5 Analysis of Current Balance Between Community Ties and Individualism

The intricate interplay between traditional community ties and rising individualism is reshaping the sociocultural fabric of GCC cities. Urbanization introduces lifestyles and housing patterns that emphasize personal space and privacy over communal living. This shift is evident in the increasing preference for apartment complexes over traditional extended-family homes. These trends highlight a broader cultural transition influenced by globalization and economic strategies aimed at diversification.

Table 1 Community and official response to the 2009–2011 Jeddah floods

Aspect	Community response	Official response	Official remediation
Emergency response	High degree of spontaneous volunteerism and local aid initiatives	Criticized for poor coordination and delayed actions	Implementation of stricter disaster management protocols and increased investment in emergency services
Infrastructure impact	Local knowledge utilized to navigate compromised urban terrain	Exposed inadequate flood management and infrastructure planning	Initiated major infrastructure upgrades, including the overhaul of drainage systems to prevent future flooding
Recovery and rebuilding	Community efforts were pivotal in the initial recovery phases	Long-term rebuilding efforts required substantial government intervention	Launched reconstruction projects and offered financial aid to rebuild affected areas and support displaced families

Data adapted from Alrehaili (2021), Atif et al. (2020), Youssef et al. (2016), and author's analysis based on oral interviews from reliable media sources

However, community bonds continue to provide social stability and resilience in times of crisis. For instance, the severe flooding event in Jeddah in November 2009 not only tested the city's infrastructure but also its social cohesion. Local communities quickly mobilized informal networks to support affected families, highlighting the enduring strength of communal ties. This response showcases the potent role of community ties in compensating for urban planning and disaster preparedness shortcomings, where the community's rapid response was critical in complementing later governmental actions. Detailed assessments of such events, like M. AlSaud's evaluation of the 2009 Jeddah flood, underscore the need for targeted mitigation strategies to prevent future catastrophes (Saud, 2010).

Table 1 contrasts the community and official responses to the Jeddah floods, illustrating the significant role that community networks play in resilience.

This example provides a deep dive into how community ties and individualism interact during crises. While individualism fosters personal freedom and aligns with global urban trends, communal ties act as a safety net that bolsters societal resilience. By understanding such dynamics, policymakers can better design urban spaces that support both individual and communal resilience. This theme is revisited in subsequent sections (see Sects. 4.2 and 4.3 for detailed discussions on social cohesion and resilience strategies).

As GCC cities continue to evolve, balancing communal values with individual aspirations remains crucial. This balance will be increasingly important as climate change intensifies, acting as a catalyst for social transformation. The next section explores how climate change is reshaping social dynamics in GCC cities, highlighting the interplay between environmental pressures and sociocultural changes.

3 Section 3: Climate Change as a Catalyst for Social Transformation

3.1 Climate Change Effects on GCC Cities

Climate change is not just an environmental issue but a profound disruptor for GCC cities, catalyzing significant social transformations. The region's unique geographic and climatic conditions amplify the impacts, necessitating urgent and targeted responses.

The relentless rise in temperatures across the GCC is reshaping urban living. Unlike the global average, these increases make outdoor conditions during peak periods nearly uninhabitable, pushing urban centers such as Dubai, Riyadh, and Doha to the brink (McCabe et al., 2023). This intensifying heat not only jeopardizes public health but also strains energy systems and tests the limits of urban infrastructure. Addressing this requires innovative urban planning that prioritizes heat mitigation and sustainable design.

Water scarcity, already a critical concern, is worsening. Climate change is stretching the limited water resources of the GCC, impacting agriculture, daily living, and overall economic stability (Al-Saidi & Saliba, 2019). This exacerbates existing vulnerabilities and highlights the necessity for integrated water management strategies that combine technological advances with rigorous conservation policies.

The socioeconomic fabric of GCC cities is under strain. The traditional economic pillars of oil and tourism are increasingly susceptible to climate variability. This vulnerability underscores the imperative for economic diversification. By investing in sustainable industries and clean energy, GCC cities can not only adapt to climate impacts but also create resilient economic structures that offer new employment opportunities and foster long-term stability.

This confluence of challenges—extreme heat, water scarcity, and economic vulnerability—underscores the urgent need for resilience strategies. These strategies will be further explored in subsequent sections, examining how extreme weather events and broader socioeconomic fluctuations driven by climate change shape the social dynamics in GCC cities.

3.2 How Extreme Weather Events Have Influenced Social Dynamics

Extreme weather events, magnified by climate change, profoundly impact the social dynamics within the GCC cities. These events test the resilience of physical infrastructures and influence community behaviors, policies, and long-term strategic planning. Exploring specific case studies allows a deeper understanding of the multifaceted impact of these events on the sociocultural and economic frameworks of GCC societies.

Case Study: The 2024 Dubai Floods (Fig. 9)

In April 2024, Dubai experienced an unprecedented rainfall event, the heaviest since records began in 1949, causing significant disruptions. This intense storm disrupted major highways, residential areas, and even the operations at Dubai International Airport, the world's busiest for international travel. On a single day, the city received more than 142 mm (5.59 inches) of rainfall, which is about 150% of its average annual rainfall (AP News, 2024). The flooding resulted in serious infrastructural challenges and human casualties, highlighting the vulnerability of urban systems to extreme weather. Waterlogged streets and inundated homes brought daily life to a standstill, impacting residents' safety and causing widespread disruption (Bloomberg, 2024).

Authorities mobilized swiftly, deploying advanced technologies such as mobile command centers and live cameras to manage the crisis in real time. These measures were part of a broader strategy initiated earlier in the year to enhance the city's capability to handle such extraordinary weather events (Gulf News, 2024). The floods also sparked debates about the UAE's cloud seeding program, with experts clarifying that the severity of the flooding resulted from a combination of atmospheric conditions rather than cloud seeding alone (WIRED ME, 2024). This event illustrated the complexities involved in managing weather patterns and reinforced the need for robust policy and environmental management strategies.

Fig. 9 People walk through floodwater caused by heavy rains, in Dubai, United Arab Emirates, April 17. REUTERS/Amr Alfiky. https://www.reuters.com/pictures/pictures-uae-begins-cleanup-after-deadly-rain-floods-2024-04-17/3BF6I7ZH3JJ2LDJS3HXBF6APEU/

Fig. 10 Strong waves hit the shore as Cyclone Shaheen makes landfall in Muscat Oman, October 2, 2021. (Picture taken October 2, 2021. REUTERS/Sultan Al Hassani. https://www.reuters.com/world/middle-east/cyclone-shaheen-approaches-oman-flights-delayed-2021-10-03/)

Case Study: The 2021 Cyclone Shaheen in Oman (Fig. 10)
October 2021 saw Cyclone Shaheen batter Oman with fierce winds and torrential rains, testing the resilience of both infrastructure and community preparedness. The cyclone inflicted extensive damage on roads, bridges, and homes, particularly along the coast, causing significant economic disruptions. Local businesses and industries, especially tourism and fisheries, suffered heavy losses (Almufarji & Husin, 2022). The Omani government responded rapidly, activating the National Emergency Management Centre, issuing timely weather warnings, and coordinating relief efforts. Community response teams, including volunteers and nongovernmental organizations (NGOs), played crucial roles in providing emergency aid and supporting evacuations.

Post-cyclone, the cleanup was substantial, especially in areas where oil spills and debris had polluted beaches and marine habitats. Socially, the cyclone fostered a spirit of cooperation and resilience among communities, reinforcing the importance of improved urban planning and stronger infrastructure to withstand future events (Almufarji & Husin, 2022).

Case Study: The 2019 Heatwaves and Labor Policies in Qatar (Fig. 11)
In response to rising temperatures and severe heatwaves, Qatar introduced labor policies to protect outdoor workers. Regulations restricting work hours during peak

Fig. 11 A worker is seen inside the Lusail Stadium during a stadium tour on December 20, 2019, in Doha, Qatar. (Francois Nel/Getty Images. https://www.cnn.com/2022/11/17/football/qatar-2022-world-cup-migrant-workers-human-rights-spt-intl/index.html)

heat periods were designed to mitigate health risks associated with heat exposure. These policies, particularly impactful in the construction sector, reduced cases of heatstroke and other heat-related ailments (Gourzoulidis et al., 2023).

Qatar's Ministry of Labor implemented these measures to ensure worker safety and uphold international labor rights commitments, especially with the FIFA World Cup on the horizon. Research and technological investments aimed at developing sustainable practices and equipment further supported these regulations. Despite the challenges to project timelines and productivity, the policies heightened awareness about labor rights and welfare, fostering a shift in public and corporate attitudes toward worker conditions in Qatar (Gourzoulidis et al., 2023).

Case Study: The 2015 Riyadh Dust Storms (Fig. 12)

Riyadh's severe dust storms in April 2015 dramatically affected public health and the local economy. High concentrations of airborne dust particles led to a sharp increase in respiratory issues among residents, with hospitals reporting numerous cases of asthma and other respiratory problems during and after the storms (Al-Dabbagh & Lyles, 2016). The storms also caused economic disruptions, reducing visibility, affecting transportation, and halting construction activities.

The Saudi government responded by issuing health advisories and implementing emergency health services to address the increase in respiratory cases. This event

Fig. 12 Major Dust Storm Hits Riyadh, Making the Sky Turn Orange Riyadh, Saudi Arabia. (Credit: Twitter/@alicemargi)

highlighted the need for better urban planning and air quality monitoring, underscoring the importance of proactive measures to mitigate such environmental challenges (Al-Dabbagh & Lyles, 2016).

Historical Case Study: The1917 Fire of Nakato Village, Jeddah (Fig. 13)
The summer of 1917 brought devastation to Nakato, a large settlement characterized by its round huts made from branches and mud. A catastrophic fire ravaged the village, yet the community displayed remarkable resilience, reconstructing Nakato to its former state by the following spring. This event illustrates the robustness of traditional community bonds and the collective capacity to recover from environmental disasters (Blin, 2007).

Nakato, located near present-day Al-Hindawiyaa and Al-Sabil in Jeddah, was a significant settlement composed of 200–300 huts. The fire, documented in photographs by André Alexandre, demonstrated the village's ability to rebuild swiftly, relying on traditional construction knowledge and strong social support systems. The Nakato case provides valuable insights into the intrinsic capacity of communities to self-organize and respond to crises, emphasizing the importance of preserving traditional practices and community structures in modern urban planning and social policies (Blin, 2007).

By examining these events, we see that extreme weather significantly influences social dynamics in GCC cities. The responses to these crises highlight the critical

Fig. 13 Fighting the Fire in Nakato Village, Jeddah. End of June 1917, André Alexandre. (Blin, 2007)

role of government actions, community resilience, and the need for improved infrastructure and adaptive policies to protect vulnerable populations. As climate change continues to amplify the frequency and intensity of such events, the GCC must prioritize strategies that integrate social, technological, and environmental considerations to safeguard its communities.

3.3 Pandemics, Economic Fluctuations, and Linkages to Climate Change

Climate Change and Public Health Impacts: The GCC region's interplay between climate change and health outcomes is particularly pronounced. Rising temperatures and altered precipitation patterns influence the distribution and intensity of vector-borne diseases such as malaria and dengue. Studies indicate an expansion in the habitats suitable for vectors due to warmer climates, increasing the risk of disease outbreaks. This emerging public health challenge necessitates robust health infrastructure and proactive disease surveillance systems to manage the increased risk of pandemics under shifting climate conditions (Paz et al., 2021).

Economic Resilience and Sustainability: Climate change significantly impacts economic stability in the GCC, a region heavily reliant on oil revenues. As global

energy markets evolve toward sustainability, the GCC's economic vulnerability to fluctuations in oil prices is exacerbated. The research underscores the necessity for economic diversification and investment in sustainable practices, including clean energy sectors that promise job creation and economic renewal. This shift is crucial for reducing the region's economic dependence on fossil fuels and enhancing long-term economic resilience (Beni et al., 2021).

Pandemics and Human Security Integration: The COVID-19 pandemic has reinforced the critical need to integrate human security into the broader security framework within the GCC. Effective pandemic response strategies highlight the importance of resilient public health systems that are well-integrated with economic and environmental policies. This integration helps prepare for and mitigate the impacts of multifaceted crises, ensuring that public health resilience is maintained alongside economic and environmental stability (Soubrier, 2020; Chen et al., 2024).

Adaptive Policy Frameworks: The complex interdependencies between climate change, economic shifts, and pandemics require adaptive and integrated policy responses. Strategies that couple economic diversification with enhancements in public health infrastructure can provide a foundation for sustainable development and resilience against future shocks. Policies must therefore be dynamic, incorporating continuous learning and flexibility to adjust to new data and changing circumstances in climate and health sciences.

These interconnected challenges underscore the critical need for a holistic approach to resilience that integrates public health, economic stability, and adaptive policies. As we delve into the building blocks of social resilience in the next section, we will explore how these strategies can be effectively implemented to create resilient and sustainable communities in the GCC, equipped to navigate the complex landscape of climate change and its associated impacts.

4 Section 4: Building Blocks of Social Resilience

4.1 Key Components of Resilient Social Systems

Resilient social systems are fundamental to navigating and adapting to the myriad challenges posed by climate change, economic fluctuations, and social transformations. In the GCC, where rapid urbanization and significant environmental stresses test traditional social structures, developing resilient social systems is critical. This section explores the key components that contribute to the resilience of social systems in the GCC, emphasizing the integration of technological, ecological, and community-driven approaches.

Community Engagement and Empowerment: The transformation from urban planning to community sustainability highlights the vital role of community engagement in urban resilience within the GCC. As urban strategies evolve, there is a growing emphasis on involving local populations in the planning and resilience

processes to ensure that solutions are precisely tailored to meet the specific needs and vulnerabilities of the community. This participatory approach is critical as it empowers residents and leverages their local knowledge to enhance the effectiveness of resilience strategies, thus fostering a more cohesive and responsive urban ecosystem (Zaidan, 2023; Jha et al., 2013). For instance, as highlighted in Sect. 3.3, proactive disease surveillance systems and robust health infrastructure are essential to manage health risks exacerbated by climate change. Community health programs and local engagement are pivotal in building resilience against public health crises.

Diverse and Inclusive Policy Frameworks: Addressing the socioeconomic diversity within the GCC necessitates the adoption of diverse and inclusive policy frameworks. These frameworks are essential for encompassing the needs of all community segments, particularly vulnerable and marginalized groups. By fostering inclusive development, these policies strengthen community resilience against socioeconomic disruptions and environmental challenges, thereby enhancing the overall adaptive capacity of the region to global changes (Zaidan et al., 2019; Brunetta et al.2019).

Robust Infrastructure and Technology: In the face of climate change, the development of robust infrastructure and the integration of advanced technology are paramount. These elements are crucial for sustaining urban growth and resilience, enabling cities in the GCC to withstand and quickly recover from various climate-induced and socioeconomic stresses. The strategic focus on sustainable urbanism not only supports resilience but also ensures that urban developments are future-proofed against an array of potential disruptions (Zaidan & Abulibdeh, 2021; Stone, 2012).

Enhanced Public Health Strategies: As noted earlier, the intricate relationship between climate change and public health in the GCC necessitates a robust health infrastructure and proactive disease surveillance systems. These systems are critical for managing the increasing risks of pandemics influenced by climatic changes, thereby safeguarding public health amidst shifting environmental conditions (Tambo et al., 2019).

Economic Diversification: Economic resilience in the GCC hinges on reducing dependency on oil revenues through diversification into more sustainable sectors. This shift is crucial for enhancing economic stability and mitigating the impacts of global market fluctuations on the region's economy. Diversification strategies include investing in clean energy and other emerging sectors that foster economic growth and job creation, thereby reinforcing the economic foundation of the GCC (Zaidan et al., 2019).

Environmental Stewardship and Education: Promoting environmental stewardship through ongoing education and awareness programs is essential for building a resilient community capable of facing climate challenges. These initiatives enhance community knowledge and engagement, which are vital for the effective implementation of resilience strategies and for fostering a proactive response to environmental changes (Zaidan & Abulibdeh, 2021).

4.2 Infrastructure and Policy in Its Role in Sustaining Communal Ties

The infrastructure and policies of a region play a crucial role in sustaining communal ties, which are pivotal for social resilience. In the GCC, where traditional social structures are deeply ingrained yet challenged by rapid modernization, the careful crafting of infrastructure and policy becomes essential to preserving the social fabric while accommodating new dynamics.

Infrastructure That Fosters Community Interaction: Infrastructure is not merely about physical buildings and roads but also about creating spaces that promote social interaction and community bonding. Urban parks, community centers, and accessible public spaces are examples of infrastructure that can help sustain communal ties by providing venues for social activities and cultural celebrations. These spaces serve as critical platforms for intergenerational communication and cultural exchange, reinforcing community networks and fostering a sense of belonging and mutual support among residents.

Policies Promoting Social Cohesion: Policies aimed at promoting social cohesion are vital in ensuring that the benefits of economic growth and urban development are equitably distributed among all community members. This includes housing policies that prevent spatial segregation by income, education initiatives that promote cultural understanding and tolerance, and social welfare programs that provide support to vulnerable segments of society. By ensuring that all individuals have access to resources and opportunities, these policies help maintain a cohesive society where communal ties are strengthened rather than weakened by urbanization and economic change.

Integrating Technology with Community Needs: The integration of technology in urban planning can also enhance communal ties if directed toward community-oriented solutions. For example, digital platforms that facilitate neighborhood initiatives or apps that streamline access to community services can enhance engagement and participation in local governance. These technologies can help bridge the gap between government and citizens, making urban management more inclusive and responsive to the needs of its residents.

Environmental Policies Enhancing Communal Spaces: Environmental sustainability policies can also play a significant role in sustaining communal ties. Initiatives aimed at preserving local green spaces not only contribute to environmental health but also promote community well-being by providing natural settings for social interaction. Policies that encourage community gardening, green rooftops, and the preservation of public parks are examples of how environmental considerations can be harmoniously woven into the fabric of community life.

Cultural Heritage and Identity: Finally, policies that protect and promote cultural heritage play a critical role in maintaining communal ties. These policies help ensure that despite the rapid pace of globalization and modernization, the cultural identities and traditions that define and unite communities are not lost. This might include support for cultural festivals, museums, and art programs that celebrate and perpetuate the unique heritage of the GCC countries.

4.3 Preserving Cultural and Social Norms in the Face of Change

In the context of the rapidly changing environments of the GCC countries, preserving cultural and social norms is crucial for maintaining social cohesion and identity. This preservation is essential not only for fostering a sense of belonging and continuity among community members but also for enhancing the overall resilience of social systems to external shocks and stresses.

Valuing Cultural Heritage: Cultural heritage in the GCC is a rich tapestry that includes traditions, languages, rituals, and arts that have been passed down through generations. Preserving these elements helps maintain a strong cultural identity that can provide psychological comfort and stability in times of rapid change or crisis. Policies that support cultural festivals, traditional arts, and crafts, and the teaching of history and languages in schools are vital in keeping these traditions alive and relevant.

Adapting While Preserving: While it is important to preserve cultural norms, it is equally important to adapt them in the face of globalization and modernization to ensure that they remain relevant and meaningful. This might involve modernizing certain cultural practices without stripping them of their essence or finding ways to integrate traditional customs into the fabric of contemporary urban life. For example, architectural designs can incorporate traditional motifs, and urban developments can include spaces for traditional community gatherings.

Role of Education: Education systems play a pivotal role in preserving cultural and social norms by imparting values and traditions alongside modern curricula. Schools and universities can serve as conduits for cultural transmission, embedding respect for traditional practices in the next generation while also equipping them with skills to navigate global cultures. Integrating cultural studies into the education system helps young people appreciate their heritage and understand the importance of its preservation.

Inclusivity and Shifting Demographics: In addition to valuing and preserving traditional cultural heritage, it is imperative to embrace the increasing diversity within the GCC due to shifting demographics. As the region becomes more cosmopolitan, integrating the customs and traditions of incoming populations into the broader cultural framework is essential for maintaining social cohesion. Policies need to ensure that cultural preservation activities are inclusive, not only reflecting the heritage of native populations but also acknowledging and incorporating the cultural contributions of expatriates and newer residents. This inclusive approach not only enriches the cultural tapestry but also strengthens community ties, ensuring that all members feel valued and integrated within the social fabric. Education systems and media play pivotal roles in this integration, promoting a shared cultural identity that respects diversity while fostering unity.

Community Involvement in Governance: Engaging communities in governance processes in the form of consultative boards or utilizing participatory approaches

to placemaking ensures that development policies and projects respect and reflect local cultural norms. This involvement can help mitigate the alienation that often accompanies rapid urban development, ensuring that new initiatives receive community support and actively contribute to strengthening social bonds.

Leveraging Media and Technology: Media and technology also play a crucial role in preserving cultural norms. Traditional music, dance, poetry, and storytelling can be promoted through modern media channels to reach broader audiences, including the younger generation. Social media platforms can be used to celebrate cultural events, share stories, and discuss the relevance of traditions, helping to keep them alive in the digital age.

Cultural Diplomacy: Internationally, cultural diplomacy can help GCC countries showcase their cultural richness and diversity, promoting understanding and appreciation on a global scale. This not only enhances the region's soft power but also strengthens internal cohesion as citizens feel proud of their cultural contributions to the world stage.

By emphasizing the preservation of cultural and social norms, GCC countries can ensure that their societal evolution in response to external pressures does not erode the fundamental aspects of their identity. This preservation is key to maintaining resilience, as it supports social stability, promotes intergenerational continuity, and enriches the collective life of the community.

5 Section 5: Adapting International Practices to GCC Context: Preserving Cultural and Social Norms in the Face of Change

5.1 Adapting Effective Global Practices for Social Resilience

Adapting international practices to enhance social resilience within the GCC requires a strategic approach that aligns global strategies with the region's unique sociocultural and environmental context. Effective global practices, such as community-based approaches, integrated urban planning, public-private partnerships (PPPs), technological innovations, and cultural adaptation programs, can be tailored to meet the specific needs of GCC cities.

Community-based resilience programs worldwide have demonstrated the importance of involving local populations in planning and resilience-building processes. For instance, participatory budgeting in India empowers communities to make decisions about local expenditures, while Chicago's community centers and emergency response systems protect vulnerable populations during extreme heatwaves (Klinenberg, 2002). In the GCC, these models can be adapted by leveraging existing communal ties and tribal structures, which are integral to the region's social fabric. Initiatives such as local disaster response teams and community health ambassadors can be established, drawing on traditional communal bonds and tribal

loyalties. Developing robust social infrastructure and emergency response systems can significantly bolster resilience to extreme weather events (Sharifi, 2016; Keck & Sakdapolrak, 2013).

Integrated urban planning is another critical area where international practices can be beneficial. Cities such as Copenhagen and Singapore have successfully implemented green infrastructure and mixed-use developments to promote sustainability and resilience. Copenhagen uses parks and green roofs for stormwater management and urban cooling, while Singapore integrates residential, commercial, and green spaces to create a balanced urban environment. The GCC can incorporate these principles by focusing on creating shaded, walkable areas with sustainable cooling solutions such as green walls and water-efficient landscaping. Additionally, integrating traditional architectural elements like wind towers with modern green infrastructure can enhance both ecological and social resilience (Magis, 2010).

Public-private partnerships (PPPs) have facilitated significant advancements in infrastructure resilience and healthcare worldwide. The Thames Tideway Tunnel in London, developed through a PPP, addresses critical infrastructure needs, and Germany's healthcare partnerships have improved access to medical services through efficient resource utilization and advanced technologies. In the GCC, PPPs can focus on enhancing infrastructural resilience to climate impacts, such as developing heat-resistant roadways and advanced water management systems. Furthermore, PPPs can support economic diversification and technological innovation by targeting renewable energy, healthcare, and smart infrastructure sectors, aligning with the region's goals of reducing dependence on oil and fostering sustainable development (Brown, 2014).

Technological innovations, particularly the use of smart city technologies and data analytics for disaster risk management, represent a global trend that can be adapted to the GCC context. Cities such as Tokyo and Amsterdam utilize IoT sensors and advanced data analytics to improve predictive capabilities and enhance urban system efficiencies. Implementing similar technologies in GCC cities can improve real-time monitoring of urban systems such as water and energy networks, providing valuable data for disaster preparedness and response. Advanced data analytics can also be used to predict climate impacts, allowing for proactive measures to mitigate risks.

Cultural adaptation programs that address the challenges faced by migrant populations, such as Australia's approach to multiculturalism, can also be adapted for the GCC. Australia encourages immigrants to maintain their cultural heritage while integrating into the broader society through supportive policies and community programs that foster inclusiveness and mutual respect (McKell Institute, 2024). For the GCC, which hosts a significant number of expatriates, developing culturally adaptive programs can improve integration and contribute to overall social cohesion.

Incorporating these international best practices into the GCC's unique context requires a deep understanding of local conditions and a flexible approach to policy implementation. By selectively adapting these practices, the GCC can enhance its social resilience, preparing it to face future challenges while maintaining its cultural integrity. This strategic adaptation not only promotes sustainable development but

also strengthens the sociocultural fabric of GCC societies, ensuring that resilience-building efforts are both effective and culturally coherent.

5.2 Challenges and Opportunities in Customizing These Practices for GCC Cities

The adaptation of international practices for enhancing social resilience within the GCC involves a strategic blend of global insights and local nuances. This section delves into both the inherent challenges and the potential opportunities that customization presents, aiming to maximize the effectiveness of resilience strategies in the region.

Challenges in Customization:

1. Political Landscape: The predominantly centralized political systems in the GCC may limit the adoption of practices that are predicated on decentralized governance. Adapting international models to align with local governance structures requires thoughtful reconfiguration to ensure alignment with the region's political framework (Kamrava, 2012).
2. Resource Allocation: While GCC countries possess considerable economic resources, these are primarily channeled toward infrastructure and economic development. Repurposing these investments to support long-term resilience, particularly beyond the oil sector, remains a substantive challenge. Balancing economic growth with sustainability initiatives is crucial (Woertz, 2013).
3. Integration of Expatriate Populations: The significant expatriate demographic in the GCC complicates the uniform application of resilience strategies. Tailoring these strategies to accommodate the diverse cultural backgrounds and needs of both local and expatriate communities is essential for effective implementation (Gardner et al., 2013).
4. Sociocultural Dynamics: Deep-rooted cultural traditions necessitate careful adaptation of international resilience practices. Community participation and public engagement initiatives must respect and integrate these cultural norms to be effective. This requires a nuanced understanding of the hierarchical and family-oriented social structures prevalent in the region (Hertog, 2010).

Opportunities for Customization:

1. Leveraging Economic Resources: The substantial financial capabilities of the GCC offer unique opportunities to pioneer advanced resilience technologies and infrastructures. Investments can be directed toward innovative projects like smart cities and clean energy solutions that align with both economic and environmental objectives (Krane, 2019).
2. Public-Private Partnerships (PPPs): The dynamic private sector in the GCC is a valuable asset in the resilience-building process. Strengthening PPP

frameworks could catalyze significant advancements in resilient infrastructure and public services, enhancing the region's capacity to manage and mitigate crises (Hvidt, 2013a, b).

3. Educational Reforms: Ongoing reforms in the education sector provide a pivotal platform for embedding resilience and sustainability into academic curricula. Educating the next generation about these concepts from an early age will cultivate a populace that is well-prepared to tackle future challenges (Romanowski & Nasser, 2012).
4. Cultural Revitalization: Embracing the rich cultural heritage of the GCC in resilience strategies offers a pathway to sustain cultural identity while fostering ecological sustainability. This approach encourages the preservation of traditional knowledge and practices, which are inherently adaptive to the local environment (Al-Nakib, 2016).

Moving Forward:

Effective adaptation of international practices in the GCC necessitates a nuanced understanding of the region's unique cultural, political, and economic landscape. By fostering a conducive environment for innovation and inclusive policymaking, the GCC can craft resilience strategies that are not only effective but also culturally coherent and sustainable. This forward-looking approach will ensure that resilience-building efforts are robust, comprehensive, and aligned with the GCC's long-term development goals.

5.3 Framework for Integrating International Practices into Local Contexts (Fig. 14)

The effective integration of international best practices into the GCC regions must consider unique sociocultural and environmental factors to enhance social resilience while upholding local traditions and economic goals. This framework provides a structured approach for adapting and implementing these practices tailored to the needs and nuances of the GCC.

Step 1: Assess Local Needs and Conditions

Initiate with a comprehensive assessment of local needs, cultural norms, environmental conditions, and infrastructural capabilities. Utilize culturally tailored communication strategies and emerging technologies for interactive stakeholder feedback. Engage government bodies, community leaders, and the private sector to identify specific local challenges and opportunities, ensuring that the planning process is detailed and context-sensitive.

Step 2: Customize and Localize International Models

Adapt international practices to align with local governance, cultural values, and economic conditions of the GCC. For instance, incorporate advanced smart grid technologies to manage the region's arid climate and energy demands or modify

Fig. 14 Framework for integrating international practices into local contexts

community-based programs to reflect the family-oriented and hierarchical social structures prevalent in GCC societies. Tailor these models to maintain cultural integrity while fostering economic and environmental sustainability. The customization should also consider integrating traditional building techniques with modern technologies to ensure cultural continuity and sustainable development.

Step 3: Pilot and Scale

Implement pilot projects to test the adapted practices on a manageable scale. Use these pilots to gather insights and validate the effectiveness of international models within local contexts. This approach allows for real-world adjustments and scaling based on feedback, ensuring that the practices are both feasible and impactful. Pilots should serve as a platform for iterative learning and adaptation, reflecting the dynamic nature of urban and social environments.

Step 4: Monitor, Evaluate, and Iterate

Establish a continuous monitoring and evaluation mechanism to measure the impact of implemented practices. Use data-driven insights to refine and optimize strategies over time, allowing practices to evolve in response to new challenges or shifts in the socioeconomic landscape. This iterative process should include regular feedback from community stakeholders to ensure that the interventions remain aligned with local needs and expectations.

Step 5: Foster Public and Private Partnerships

Strengthen collaborations between the public and private sectors to enhance resource allocation, innovation, and implementation capabilities. Define clear roles where private firms drive technological innovation and governments provide the necessary regulatory framework and support. Such partnerships are vital for mobilizing investments, expertise, and technology.

Step 6: Promote Education and Public Awareness

Develop educational programs and public awareness campaigns to build a culture of resilience. Integrate resilience topics into school curricula and leverage media platforms to disseminate information about effective resilience practices. Foster partnerships with academic institutions for resilience research and conduct public workshops to address local environmental challenges. Educating the public not only empowers citizens but also ensures community involvement in resilience-building efforts, enhancing the overall efficacy of these strategies.

By focusing on culturally integrated, environmentally sustainable, and community-focused approaches, this strategy promotes a cohesive and resilient society capable of navigating the complexities of modern urban development while preserving the region's cultural heritage and advancing its economic ambitions.

6 Section 6: Strategies for Inclusive Resilience Building

6.1 Inclusive Approaches and Mechanisms in Resilience Building

The pressing challenges of climate change necessitate an inclusive approach to resilience building. According to the Human Development Report 2020 by the UNDP, fostering inclusivity is not only a moral imperative but also a strategic necessity for effective resilience (UNDP, 2020). This section integrates the importance of inclusivity with practical mechanisms for involving all societal segments in resilience planning.

1. Policy Integration and Stakeholder Engagement: Develop resilience policies that integrate the views and needs of diverse community segments. Form inclusive policy development committees that include representatives from various social strata, including vulnerable populations, experts, and local leaders. This representation helps to incorporate a wide range of insights and needs into policymaking, enhancing their relevance and effectiveness (UNDP, 2020; World Bank, 2019).
2. Capacity Building and Education: Implement targeted educational programs to raise awareness and understanding of resilience and climate adaptation strategies. Tailor these programs to different community groups to equip them with the necessary skills and knowledge, empowering them to actively contribute to resilience efforts (World Bank, 2019). Conduct widespread education and awareness campaigns that inform all community members about resilience strategies and the importance of their involvement.
3. Economic Inclusion: Promote economic policies that ensure equitable access to resources and opportunities. This includes supporting sectors critical to resilience such as sustainable agriculture and clean energy, and fostering the

development of small- and medium-sized enterprises and community-based initiatives (Adger et al., 2005).

4. Cultural Competence in Resilience Planning: Adapt resilience measures to align with local cultural practices and social norms. This involves respecting and integrating traditional knowledge and practices into modern resilience strategies (IPCC, 2022).
5. Universal Design in Infrastructure: Advocate for and implement universal design principles in infrastructure development to ensure that resilience-related facilities are accessible to all, including those with disabilities and the elderly (Pelling, 2003).
6. Social Safety Nets: Strengthen social safety nets to provide critical support during climate-induced and other related emergencies. These should be readily available and accessible to all segments of the population, providing necessary support such as healthcare and emergency housing (World Bank, 2014).
7. Community Consultation Forums and Digital Participation Platforms: Establish regular community consultation forums that provide a platform for all societal segments to voice their concerns and suggestions. These forums should be accessible to different demographics, including marginalized groups, to ensure a diversity of viewpoints are gathered. Leverage technology to create digital platforms where community members can participate in resilience planning. This approach facilitates broader and more effective participation, especially from those who cannot attend in-person meetings due to physical, economic, or social constraints (Pelling, 2003).
8. Feedback and Evaluation Mechanisms: Implement transparent mechanisms for feedback and evaluation where community members can critique and suggest improvements to resilience plans. This feedback should be taken seriously and used to make necessary adjustments to strategies (Schlosberg & Collins, 2014).
9. Youth Engagement Strategies: Engage youth through educational institutions and youth organizations to harness their unique perspectives and innovations. Youth engagement can be particularly effective in promoting sustainable practices and pioneering new technologies in resilience building (Sharifi, 2016).
10. Partnerships and Legal Support Structures: Develop partnership programs with local organizations, NGOs, and private sectors to drive community-focused resilience initiatives. Establish legal support structures that assist underrepresented groups in navigating the planning process, ensuring their rights and interests are protected and their voices are heard (Adger et al., 2005; World Bank, 2019).

By integrating the importance of inclusivity with practical mechanisms for involving all societal segments in resilience planning, we ensure that resilience strategies are well-rounded, culturally sensitive, and sustainable.

6.2 Successful Community-Led Resilience Initiatives

Community-led initiatives are critical for fostering resilience, especially in regions like the GCC where traditional knowledge and local engagement play a significant role in adapting to climate challenges. This section highlights successful examples of community-led resilience initiatives, emphasizing their outcomes and impacts.

Case Study 1: "Ehsan" Platform, Saudi Arabia
The Saudi government launched the "Ehsan" platform to facilitate charitable donations and support for those affected by the pandemic.

Community Involvement: The platform enabled individuals and organizations to contribute to various charitable causes, supporting those in need during the crisis.
Key Achievements:

1. Financial Aid: Facilitated direct financial support to low-income families, unemployed individuals, and small businesses impacted by the pandemic.
2. Resource Allocation: Donations were used to provide essential supplies, including food and medical equipment, to affected communities.
3. Transparency and Trust: Ensured transparency in the distribution of funds, building trust and encouraging widespread participation.

Impact: The Ehsan platform significantly mitigated the economic and social impact of COVID-19 on vulnerable groups in Saudi Arabia, showcasing the power of digital tools in community resilience.

Case Study 2: Al-Ahsa Oasis Restoration, Saudi Arabia
The Al-Ahsa Oasis, one of the world's largest natural oases, has long been a cornerstone of sustainable agricultural practices in Saudi Arabia. This initiative underscores the successful integration of traditional knowledge with modern agricultural techniques to enhance resilience against climate variability.

Community Involvement: Local farmers, supported by government bodies and NGOs, have spearheaded efforts to restore and maintain the oasis. This includes the rehabilitation of traditional irrigation systems (qanats) and the adoption of sustainable water management practices.
Key Achievements:

1. Water Conservation: The reactivation of ancient qanats has improved water efficiency, ensuring a reliable water supply for agriculture amidst increasing aridity.
2. Sustainable Agriculture: Implementation of crop rotation and organic farming techniques has boosted soil fertility and crop yields, contributing to food security.
3. Economic Empowerment: By fostering community-led agricultural cooperatives, the initiative has enhanced local economic resilience, providing livelihoods and sustaining traditional agricultural practices.

Impact: The Al-Ahsa Oasis restoration has not only preserved a vital ecological and cultural heritage site but also demonstrated the effectiveness of community-driven approaches in achieving sustainable development and climate resilience.

Case Study 3: Mangrove Restoration in Ras Al Khaimah, UAE
The mangrove restoration project in Ras Al Khaimah represents a successful effort to combat coastal erosion and enhance marine biodiversity through community-led environmental stewardship.

Community Involvement: Local communities, particularly fisherfolk and youth groups, have been actively involved in planting and monitoring mangroves. This initiative has been supported by partnerships with environmental NGOs and government agencies.
Key Achievements:

1. Coastal Protection: The restored mangroves act as natural barriers against storm surges and coastal erosion, protecting inland areas from extreme weather events.
2. Biodiversity Enhancement: The mangroves have created habitats for various marine species, boosting local biodiversity and supporting fisheries.
3. Environmental Education: Community involvement in mangrove restoration has fostered environmental awareness and stewardship, particularly among the youth.

Impact: The project has significantly enhanced the resilience of coastal communities in Ras Al Khaimah, demonstrating the power of community engagement in environmental conservation and climate adaptation.

6.3 Leveraging Technology and Innovation for Social Resilience

Technological innovations play a vital role in enhancing social resilience by providing tools and solutions that help communities better prepare for, respond to, and recover from various challenges. This section highlights specific examples of how technology has been leveraged to enhance resilience, focusing on practical applications and their direct impact on communities.

Digital Platforms for Community Engagement

Case Study: Kuwait's "Kuwait Finder"
Overview: "Kuwait Finder" is a digital platform developed by the Public Authority for Civil Information (PACI) in Kuwait. It provides a range of services that enhance community engagement and public service delivery (PACI, 2023).

Technological Innovations:

1. Geolocation Services: Offers precise location services and navigation, allowing residents to find government services, businesses, and facilities easily.
2. Real-Time Updates: Provides real-time traffic information, weather updates, and emergency alerts, ensuring that residents are well-informed about their surroundings.
3. Public Feedback: Includes features for residents to provide feedback on public services and report issues such as road conditions and public facility maintenance needs.

Community Impact:

1. Increased Accessibility: Enhances the accessibility and usability of public services for all community members, including those with mobility challenges.
2. Enhanced Public Participation: Encourages active participation from residents in governance and community maintenance, fostering a sense of ownership and responsibility.
3. Improved Response Times: Facilitates faster response times from public services by streamlining the reporting and feedback process.

Impact: "Kuwait Finder" demonstrates how digital tools can enhance community involvement and resilience through better service delivery and real-time information sharing, contributing to more responsive and resilient urban management.

Big Data and Predictive Analytics

Case Study: Saudi Arabia's Climate Change Center
Overview: The Climate Change Center, inaugurated at King Abdullah University of Science and Technology (KAUST), is part of the Middle East Green Initiative (MGI) launched by Saudi Arabia. This center is a strategic initiative aimed at enhancing environmental performance and supporting regional climate action.

Technological Innovations:

1. Real-Time Data Collection: Continuous collection of climate and meteorological data through a network of advanced sensors and satellites.
2. Predictive Analytics: Utilizes advanced algorithms to analyze climate data, predict extreme weather events, and assess their potential impacts.
3. Information Dissemination: Provides real-time climate information and alerts to policymakers and the public, ensuring timely preparedness and response.

Community Impact:

1. Improved Disaster Preparedness: Enhances the ability of communities to anticipate and prepare for extreme weather events, reducing their impact.
2. Reduced Vulnerability: Increased public awareness and preparedness measures help mitigate the risks associated with natural disasters.

3. Efficient Resource Allocation: Better allocation of resources and emergency services in response to climate predictions, ensuring effective management of climate-related events.

Impact: The Climate Change Center plays a crucial role in strengthening Saudi Arabia's and the region's ability to manage and mitigate the effects of climate change, thereby enhancing community resilience (KAUST, 2023; Middle East Green Initiative, 2023).

Innovation in Environmental Sustainable Practices

Case Study: UAE's Estidama Program

Overview: Estidama, which means "sustainability" in Arabic, is a program developed by the Abu Dhabi Urban Planning Council to promote sustainable building and development practices in the UAE. It focuses on the four pillars of sustainability: environmental, economic, social, and cultural.

Technological Innovations:

1. Pearl Rating System: Estidama features the Pearl Rating System for buildings, villas, and communities, which evaluates sustainability performance across several criteria, including water and energy usage, indoor environmental quality, and material selection.
2. Energy-Efficient Systems: Integration of energy-efficient HVAC systems, solar panels, and smart lighting.
3. Sustainable Landscaping: Use of native and adaptive plants to reduce water consumption and promote biodiversity.

Community Impact:

1. Reduced Carbon Footprint: Significant reduction in carbon emissions from buildings.
2. Improved Energy Efficiency: Lower energy consumption leading to cost savings for residents and businesses.
3. Enhanced Living Conditions: Healthier indoor environments and better living conditions for occupants.

Impact: The Estidama program has significantly advanced the UAE's efforts in sustainable development, making it a leader in green building practices in the region. It serves as a model for integrating sustainability into urban planning and development (Department of Municipalities and Transport, 2023).

As we transition into the final section of this chapter, we will explore specific policy recommendations and future directions for fostering resilient urban systems in the GCC.

7 Section 7: Policy Recommendations and Future Directions

7.1 Policy Recommendations

1. Integrate Social Resilience Into National Planning Frameworks
   - Mandate Social Resilience: Embed social resilience explicitly within national development plans, ensuring that all new urban projects incorporate climate adaptation and social cohesion measures.
   - Cross-Sectoral Coordination: Establish a coordinating body to facilitate collaboration among government agencies, private sectors, and civil society for cohesive resilience strategies.
2. Enhance Community-Based Resilience Programs
   - Localized Approaches: Tailor resilience programs to specific community needs and sociocultural contexts, leveraging traditional knowledge.
   - Capacity Building: Invest in training local leaders and community members in disaster preparedness, sustainable practices, and adaptive technologies to empower grassroots resilience.
3. Promote Inclusive Economic Policies
   - Economic Diversification: Implement policies to diversify the economy, focusing on sectors such as clean energy, technology, and sustainable agriculture to reduce oil dependency and boost economic resilience.
   - Support for Vulnerable Populations: Design economic policies that provide targeted support to vulnerable groups, enhancing their participation in and benefits from resilience-building initiatives.
4. Preserve and Adapt Cultural Heritage
   - Cultural Preservation: Support policies that protect and promote cultural heritage, including festivals, traditional arts, and the teaching of history and languages in schools.
   - Adaptive Practices: Encourage the modernization of cultural practices to ensure their relevance, such as incorporating traditional architectural motifs in new urban developments.
5. Promote Inclusive Governance, Environmental Sustainability, and Communal Spaces
   - Governance Structures: Establish consultative boards and participatory approaches to ensure that development policies reflect local cultural norms and receive community support.
   - Community Involvement: Engage communities in governance processes to mitigate the alienation that accompanies rapid urban development.

- Green Spaces and Community Hubs: Promote the preservation of local green spaces and communal gardens to enhance community well-being and social interaction. Reinvigorate communal spaces such as mosques, souqs, and public gardens to serve as hubs for social interaction, education, and emergency coordination.

6. Develop Robust Infrastructure Resilience
   - Climate-Resilient Infrastructure: Prioritize investments in infrastructure that can withstand extreme weather events and other climate impacts and promote social resilience, emphasizing green infrastructure solutions such as urban green spaces and natural flood defenses.
   - Smart Technologies: Incorporate smart city technologies to improve urban system monitoring and management, enhancing responsiveness to environmental changes and emergencies.
7. Strengthen Legal and Regulatory Frameworks
   - Environmental and Social Legislation: Enact and enforce laws that protect natural resources and promote sustainable urban development.
   - Regulatory Oversight: Create strong regulatory bodies to ensure compliance with sustainability standards and resilience policies.
8. Encourage Community-Led Innovations
   - Support Grassroots Initiatives: Provide funding and technical support for community-led projects offering innovative resilience solutions, encouraging participatory research and innovation hubs.
   - Scaling Successful Models: Identify and scale successful community-led resilience models, adapting them to various local contexts within the GCC.
9. Foster Public-Private Partnerships
   - Collaboration for Innovation: Foster partnerships between government, private sector, and academia to drive innovation in resilience technologies and sustainable practices.
   - Funding Mechanisms: Establish funds and incentives for private sector investments in resilience-building initiatives that align with national sustainability goals.
10. Promote Education and Awareness
    - Curriculum Integration: Include climate change, sustainability, and resilience topics, utilizing when appropriate a cultural relevance lens, in national education curricula to foster a culture of resilience from an early age.
    - Community Engagement: Promote educational programs that engage the community in preserving cultural norms and adapting them to contemporary contexts.

- Public Awareness Campaigns: Launch nationwide campaigns to raise awareness about resilience, emphasizing the role of individuals and communities in building resilient societies.

11. Leverage Data and Technology for Decision-Making
    - Data-Driven Policies: Use big data and predictive analytics to inform policy decisions, improving the ability to anticipate and respond to climate risks and social vulnerabilities.
    - Open Data Platforms: Develop open data platforms to provide accessible climate and social data, fostering transparency and community engagement in resilience planning.
12. Advance Regional Cooperation
    - GCC-Wide Initiatives: Promote regional cooperation within the GCC to share best practices, resources, and technologies for resilience, addressing transboundary climate impacts.
    - Integrated Response Systems: Develop integrated response systems for regional climate emergencies, ensuring coordinated actions across borders.[1]
13. Institutionalize Resilience Planning
    - Permanent Resilience Units: Create dedicated units within government agencies for resilience planning and implementation, ensuring long-term commitment to resilience goals.
    - Continuous Learning and Adaptation: Foster a culture of continuous learning and adaptation in resilience planning, ensuring that policies evolve based on new knowledge and changing conditions.

7.2 Vision for the Future of Resilient Urban Systems in the GCC

The future of resilient urban systems in the GCC envisions cities that are adaptable, inclusive, and sustainable. These cities will be characterized by their ability to:

1. Withstand Climate Impacts: Urban systems that effectively manage and mitigate extreme weather events, land degradation, sea-level rise, and other climate challenges.
2. Promote Social Cohesion: Inclusive and cohesive communities with strong social networks and support systems that enhance collective resilience.

[1] Saudi Arabia, through the Middle East Green Initiative, has already initiated regional efforts like the Regional Center for Early Storm Warning to address future risks, effective collaboration key to the success of such efforts.

3. Drive Sustainable Development: Economies diversified and sustainable, reducing fossil fuel dependency and embracing clean energy, green technologies, and circular economy principles.
4. Foster Innovation and Learning: Societies valuing innovation and continuous learning, leveraging technology and data for informed decision-making and adaptation.
5. Uphold Cultural Integrity: Urban development respecting and integrating cultural heritage and traditional knowledge, ensuring that modernization does not erode cultural identities.

By implementing these policy recommendations and pursuing future directions, GCC nations can build urban systems that not only survive but thrive in the face of climate change, setting a global example for resilience and sustainability.

8 Conclusion

The Gulf Cooperation Council (GCC) stands at a critical juncture in its pursuit of sustainable development and climate resilience. The intricate weave of our historical, cultural, and social fabric provides a unique foundation upon which to build resilient communities capable of withstanding the myriad challenges posed by climate change and rapid urbanization. Our journey is not merely about adapting to change but about thriving in the face of it, guided by the enduring values that have defined our societies for generations.

By fostering collaboration across sectors and borders, we can ensure that our resilience-building efforts are robust, comprehensive, and sustainable. The future of our cities lies in their ability to integrate modern resilience practices with our rich cultural heritage, creating urban systems that are not only adaptable and sustainable but also deeply rooted in our shared identity.

This vision for the future is one where GCC cities are exemplars of resilience and sustainability, setting a global standard for urban development in the face of climate uncertainty. By embracing this vision, we can ensure that our communities are not only prepared for the challenges ahead but are also empowered to seize the opportunities that arise from them.

By weaving resilience into the very fabric of our societies, we can create a legacy of sustainability and strength for future generations. Together, we can build a future where our cities thrive, our cultures flourish, and our people prosper in harmony with the environment. The journey ahead is complex and demanding, but with unwavering commitment and collaborative action, we can achieve a resilient and sustainable future for the GCC.

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Fostering Social Cohesion in Multicultural Societies of the Gulf Cooperation Council

Sara Lechtenberg-Kasten

Abstract The global pandemic has highlighted the importance of social cohesion in responding to traumatic events. While developing physical infrastructure that can withstand the effects of climate change is crucial, equal attention should be given to the social component of resilience in disaster mitigation strategies. Communities with strong social networks are better equipped to respond to immediate threats and recover after a disaster, but what factors contribute to social cohesion, and how can they be fostered in dynamic and multicultural societies in the Gulf Cooperation Countries (GCC)? This chapter reviews the foundational literature on social cohesion, explores the unique aspects related to the Gulf, and highlights opportunities to strengthen community bonds in the post-COVID era.

Keywords Social cohesion · Multicultural societies · Community bonds · Diversity and inclusion

1 Introduction

Great cities are known for their reliable services and modern infrastructure, but they also owe their greatness to social connections and a feeling of belonging. The COVID-19 pandemic reminded us of the importance of communities coming together during a crisis. While policymakers focus on reinforcing critical infrastructure and essential services, investments related to social infrastructure also need attention. This chapter was drafted during the pandemic, with the preliminary research initiated from Riyadh and conclusions formulated upon the author's return to the United States. The experience with a socially cohesive response in Saudi Arabia and a starkly different situation in the United States served as the motivation for this chapter. This chapter aims to answer the question of what factors contribute to social cohesion in multicultural communities and what actions can be taken to

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strengthen strong social ties. It will cover foundational concepts related to social cohesion from Western social science perspectives and highlight thought leaders who have analyzed social aspects of resiliency in a GCC context. The chapter will discuss two critical enablers of social cohesion, trust and security, and provide best practices for promoting strong, socially cohesive, and inclusive societies.

2 Framing the Issue: Social Cohesion Definition

Social cohesion has been framed as "soft resilience" due to the intangible nature of the concept. In the most basic of terms, social cohesion is the fabric of a society, which binds a community together during "normal" times and plays a role in risk reduction, relief, and rebuilding after a crisis. A more nuanced definition comes from the OECD (2021), which describes a cohesive society as one promoting the well-being of all its members, combating exclusion, and fostering a sense of belonging and trust.

A good foundation from which to build knowledge on social cohesion and social infrastructure is Putnam's foundational work on reciprocity and social capital (Putnam, 2000). The concept suggests that community members' altruistic actions contribute to a collective safety net.

Putnam's seminal work formalized the understanding of the need for connectedness in communities. Putnam frames social cohesion as rooted in generalized reciprocity, which means that a community member will do a good deed for another without directly or immediately expecting the return of help. In sum, individuals do not tally good deeds; instead, people exchange kind acts in a socially cohesive community. Putnam characterizes generalized social capital as being in line with living life with the Golden Rule aphorism, "Do to others as you would want to be done to you." A similar Arabic proverb would be "Do Good and Let it Fall Where it Falls/ افعل الخير وليقع حيث يقع " Both guiding principles highlight the societal need to care for one another, but without expecting an immediate personal reward. Generalized reciprocity helps promote strong communities in good times and creates response capacity within a community during a tragedy.

Another foundational work on social cohesion comes from Daniel Aldrich's work, which underscores the value of social connections in disaster recovery, proposing that communities with strong social ties exhibit better outcomes than those relying solely on physical infrastructure. Aldrich contends that cohesion develops through bonds formed through social relations, task relations, perceived unity, and emotions. Aldrich writes about the complicated nature of social capital and categorizes it into bonding, bridging, and linking connections. Bonding social capital remains the most common and involves strong ties between people who are family and tribal members and close friends. (Aldrich, 2012) In contrast, bridging relationships create connections with individuals and groups with demographic differences, often through institutions such as workplaces, schools, or clubs. While

bonding and bridging connections are essential at a community level, an overarching system needs linking connections, referring to the relationship with the larger power structure, such as government officials or a ruling family member. Aldrich highlights that the concepts are nuanced, and indicators and manifestations of social capital may play out differently across different cultures, countries, and eras.

Aldrich looked at communities around the globe and argued that rather than fleeing a disaster zone and never returning, communities with strong social connections will rebound after the shock. Residents who are tied to each other and have trust and regular interaction will work collaboratively to move from the initial relief phase through reconstruction. He contends that social networks provide private funding and valuable self-help from a community level, which builds into national security and stability (Aldrich, 2017, 2019). Aldrich argues that based on extensive case studies, communities with strong social connections can promote resiliency in a way that investment in physical infrastructure alone will not.

Scholars in the GCC have contributed to thought leadership on the role of social cohesion and public open spaces in rapidly growing and multicultural communities. Perspectives on social trust in Abu Dhabi's multicultural urban areas are detailed by Yang et al. (2021). The concept of public open spaces and the opportunities and obstacles to creating understanding between Bahrain's citizens and temporary works add insights into the nuances of social infrastructure (Al-Madani, 2018, 2022). Al-Hathloul and Aslam Mughal Nahiduzzaman et al. highlight the importance of gathering places in multi-ethnic societies in Saudi Arabia. Addas and Rishbeth (2018) highlight the need to understand culture in designing social infrastructure, focusing their research on multicultural communities in Jeddah, Saudi Arabia, and the need for inclusive public policies that address the diverse needs of all residents. Al-Maamari highlights the role of schools and education in building understanding between ethnic groups in Oman (2016). These authors reiterate the role of social cohesion in multicultural communities and provide nuanced policy proposals for both public investment and communications strategies to explain cultural differences and increase understanding. An overarching theme that all authors touch upon is the importance of a culturally sensitive approach to urban planning that considers the social norms of different communities and the need to create public spaces that foster cultural exchange.

3 What Are the Critical Enablers of Social Cohesion?

The theoretical foundation on social cohesion helps to provide a baseline from which to understand the concepts, but equally important in policy formation is the need to consider the unique challenges that communities in the GCC face, including rapid urbanization, demographic diversity, and expatriate labor dynamics. While these factors are a formidable barrier to achieving social cohesion, reframing the challenge as an opportunity to build inclusive and socially resilient communities is possible.

The literature review from Western and Gulf academics indicates no single step-by-step "recipe" to create a socially cohesive community that can withstand a traumatic event or challenge. Resiliency researchers should consider two issues present in Gulf countries that have been declining in the United States: trust and security.

Trust in governmental leaders and heads of state creates conditions favorable for nurturing social relations. Social scientists draw a connection between transparent and trusted governance and a community's well-being. International organizations and research centers that study trust globally contend that populations in the GCC hold public institutions, elected officials, and governmental officials in high regard.

The Edelman Trust Barometer conducts an annual survey globally to measure trust and credibility between citizens and their governments, and the 2024 report provides some initial insights. Within the GCC, the United Arab Emirates ranked highest for citizen trust in government, scoring 74, and Saudi Arabia was also at the top of global trust in government rankings, scoring 72.[1] This high rank is notable compared to a decline in trust in public institutions in the West. For example, the United States trust ranking told a very different story, with a significantly lower score of 46, falling into the "Distrust" category.

During the COVID response, the Edelman Trust Barometer on public trust evaluated government, businesses, non-governmental organizations, and media during the pandemic. The report discusses the role of trust during a crisis and how to emerge from the crisis with a strong social contract. The report also shows that respondents in Saudi Arabia greatly value a governmental response, from the immediate need to contain the virus to providing information to the public and helping rebuild economic livelihoods. One fundamental limitation of the Edelman data set is that only two of the six GCC countries are studied; thus, avoiding the inference that other GCC countries did not have positive rankings is essential.

A second critical element of thriving communities is security. Building cities that have strong social resiliency is more challenging for communities fractured by gun violence and crime. Whereas American communities struggle to combat ever-frequent mass shootings at schools and in communities, gun violence within the GCC countries is so rare that it is difficult to find data on this type of violence. With regard to violent crime, the most recent reporting from the United Nations indicates striking differences between the low crime rate in the region as compared with the United States. While communities in the United States face approximately 7 homicides per 100,000 in 2021, countries of the GCC had zero of such crimes per 100,000 within a similar time frame (World Bank Group, 2021).

[1] Edelman Trust Institute, 2024 Edelman Trust Barometer.

Scholars of resiliency indicate that a high level of crime before a disaster is strongly connected to mortality levels during an event. They propose the theory that urban areas with high crime share less information, do not trust government warnings, and participate less in "collective action" (Aldrich, 2012).

4 The Way Forward: Best Practices to Leverage to Reinforce Social Fabric

While countries in the GCC have some of the foundational elements of trust in public institutions and security, the pandemic has stress-tested the social fabric in dense multicultural communities. The following section provides some initial observations of actions and policies that helped reinforce social ties during the pandemic. These options range from grassroots initiatives to strategic investments to create public open spaces and investments in social infrastructure.

Gulf Leaders and Culture Looked to the Past to Reduce Risk Historical memories of overcoming a crisis play a role in creating resiliency at an individual, community, city, and national level and creating a cultural narrative. For example, public health authorities in Saudi Arabia understood the potential impacts of COVID-19 due in part to their recent experience with the 2012 Middle Eastern Respiratory Syndrome (MERS-CoV). Governmental leaders created various lines of effort to reduce risk, including a command-and-control center, a government lead to study pandemic (the Saudi Center for Disease Control and Prevention), a National Health Laboratory, and a surge capability for isolation and treatment of virus victims throughout the country. These capabilities were in place (Algaissi et al., 2020), allowing health officials to leverage lessons learned from the MERS outbreak to invest in personal protective equipment stockpiles (Saudi Gazette, 2020) and inform the need for protective policies such as border closure and strict enforcement of quarantine and social distancing rules.

In addition to quick governmental responses, the role of elders as a source of knowledge also played an essential part in creating a cohesive risk-reduction strategy. Learning from the past at a policy level provides one layer of risk reduction, and combining strategic actions with elders' historical memories provides an additional, yet difficult-to-measure, component of social resiliency.

Envision a Future with Inclusive Social Infrastructure While trust in government and security are foundational elements, investment in social infrastructure plays a role in risk reduction and resiliency (Oldenburg, 1999). Whereas home is considered the "First Place" and work the "Second Place," vibrant communities feature opportunities for a "Third Place"—such as a neighborhood café, a shopping mall, or a beauty shop where opportunities to meet up with friends and neighbors brings richness to life that is hard to quantify in social terms.

In recent years, GCC communities have witnessed an expansion of Third Spaces, with private investment growth in food truck scenes and art spaces. One of the more important social venues in the Gulf is coffee shops, which provide a venue for social, business, and cultural exchange. Serving coffee has long been a part of generous hospitality in the region, and T.E. Lawrence writes about the ceremonial aspect of serving coffee before a meal (Lawrence, 1935). While chain coffee shops have long served as a Third Place, there is a new trend for local shops that offer opportunities to build appreciation for coffee traditions. Local shops include traditional design elements, Arabic coffee, and experiences rooted in local traditions.[2] The international chains and the newer start-ups serve as a "Third Place" and ultimately can help build social fabric and create conversations, but these venues may not be accessible to many, due to either cost or perception that the businesses cater to a certain demographic or social class. They also provide a space where newcomers to the region can build informal social connections.

While private investment in the development of social infrastructure is promising, policies that focus on public investment in social infrastructure should be a priority. Eric Klinenberg highlights the role of public social infrastructure as an enabler of bridging networks in diverse communities. Klinenberg broadly defines social infrastructure as public open spaces, places, meetings of civic organizations, and places of worship. He states that public spaces such as libraries, public parks, public transportation, and informal social clubs can help connect communities and build connections, which in turn help reinforce willingness to work together to reduce risk and respond when disaster strikes.

Additionally, Kleinenberg highlights the role of faith-based social infrastructure during hurricane relief and reconstruction and advocates for more significant linkages between religious leaders and elected officials to create a greater community vision for the intersection between physical and social infrastructure. In the post-pandemic era, there is an opportunity for more significant research and introspection on the role of religious leaders and places of worship as first-line responders to human needs and to play a role in reconstruction after the pandemic.

Reinforcing social infrastructure development is essential, but one must be cognizant of cultural context. Policymakers have internalized the need for public open spaces, and there are several key examples of successes in the region. The strategic policy statements across the GCC highlight the need for investment in social infrastructure such as parks and community gathering areas. For example, Abu Dhabi Vision 2030 speaks to the need for public open spaces and envisions urban spaces built upon the National Park System. The Open Space Framework Plan integrates a hierarchy of formal and informal open areas throughout the city. It connects them to City parks, community recreation areas, green boulevards, and public plazas, which will form the green backbone of the city and link the people of

[2] https://www.nytimes.com/2020/01/15/world/middleeast/saudi-women-coffee-shops.html

Abu Dhabi to the need to protect current public parks and create public spaces that provide shade for walking and gathering. Other social infrastructure, such as plazas in front of governmental buildings, mosques, and train stations, is included in the vision.

More recent governmental strategies seek to increase the availability of public outdoor space, and the Saudi Arabian National Transformation Program has set a target to improve the quantity and quality by 2030. Specifically, the Green Riyadh program seeks to increase the total green coverage in the city from 1.5% to 9% by 2030 to plant trees and create green, open spaces. Meanwhile, The Green Middle East program, championed by Saudi Arabia, seeks to plant 50 billion trees and increase the amount of environmentally protected land from 17% to 30%. Increasing the availability of public spaces has the role of building social connections in diverse communities and is especially important in an era where social distancing is essential.

Consider Multiculturalism and Diversity While social cohesion can help create positive outcomes, the concept has a downside. Aldrich highlights that in communities with strong bonding social capital, not all community members will benefit, and strong bonds can create an "us-them" dynamic that reinforces inequality. He presents the paradox that social cohesion is vital for the well-being of a community but can also have a downside if the powerful social group leverages its position against a less powerful demographic (Aldrich, 2012).

How does one promote social cohesion in communities where expatriates outnumber nationals? While this creates multiculturalism, it also invites challenges during turbulent times. Reinforcing bonding relationships while opening avenues for bridging social interactions is possible, especially through sports.

Putnam writes about the importance of bowling leagues in creating social connections in the United States, and there are similarities with the sport of cricket in the GCC. For example, the Riyadh Cricket Association, which serves as a sporting club and a civic organization for temporary South Asian workers, is bridging social relations. The cricket pitch allows expatriates to set aside political rivalries, and sportsmanship binds the community and helps to provide a social support system for individuals in the clubs.

Similarly, there is growing interest in Rugby among Saudi Arabian youth (Arab News, 2019). Most recently, Rugby has become popular in the Gulf, and inclusive values associated with that sport have allowed clubs to flourish that bring together different demographic groups.[3] Bridging social capital allows relationships between different ethnic groups and sets conditions for social groups to become a more cohesive community. As urban areas are rapidly developing, the spaces that were once used for informal matches are quickly disappearing. Putting public investments into sporting facilities that are inclusive is one solution. While sports and civic clubs

[3] https://rugby.sa/

Source: https://www.shutterstock.com/image-photo/busaiteen-manama-bahrain-oct-27-2017-750619381. Is it possible to get rights to this photo for use?

can provide opportunities for bridging social capital to grow, building cohesion in communities where temporary/non-residents outnumber nationals is a topic that deserves more analysis.

Creating opportunities to develop public open spaces that are inviting and accessible to both citizens of the Gulf and newcomers requires intentional efforts (Al-Madani, 2018, 2022). Creating spaces that all can use and building an understanding of cultural differences can help in the long term to create cohesive communities. Recognizing the tension between creating open public spaces welcoming to all and reinforcing cultural norms in diverse communities is challenging. However, doing so with a vision of an inclusive society could help policymakers better understand the costs and benefits of inclusive public open spaces.

5 Further Research

The countries of the Gulf are fundamentally different from Western societies, with culture, political, and economic conditions influencing social cohesion and investment in social infrastructure. Additional research on the GCC response to COVID-19 and whether and how socially cohesive communities were better able to reduce suffering and rebound from the pandemic could inform both domestic policies and provide insights to others in leadership roles on ways to reinforce social relations. The specific areas of research indicated in this section seek to build upon

the work of the foundational work on social cohesion profiled in this paper and dive deeper to understand where knowledge gaps exist on the intersection between social cohesion in large urban areas in the Gulf and opportunities to strengthen bonds.

Proactively Measure Vulnerabilities Susan Cutter's research on socially created vulnerabilities in the United States has helped stakeholders understand how inequalities in communities hit by the 2005 Hurricane Katrina and informed risk reduction specialists on the need to understand better the intersection between social vulnerability and the capacity to "bounce back" after a traumatic event. Other methodologies that leverage publicly available data can inform social capital indices that can help policymakers understand at a zipcode level where social capital is high (Kyne & Aldrich, 2020). Leveraging existing frameworks on social indicators and adapting to the Gulf's cultural aspects, demographic considerations, and other unique factors could help policymakers understand where to create policies and investments to strengthen social cohesion and proactively plan to support communities that are at risk.

Investigate the Role of Culture, Social Contract, and Religion Western social scientists provide insights on how social cohesion is developed and why it is essential. However, greater research on this topic from a Gulf perspective would be valuable. First, foundational work on the role of the social contract in the Gulf, the role of trust in government, and the role of culture in creating cohesion would provide policymakers with insights into why some communities struggle with cohesion while others thrive. Of note, initial observations and literature indicate that social contracts in Gulf states are distinctly different from communities in the West. Generally, the social contract is a set of formal and informal agreements between societal groups and the government on rights and obligations. The concept of trust is a critical part of the social contract. It relates to relationships between neighbors at a community level and reaches up to trust between citizens and their government. According to Markus Loewe, the Gulf Cooperation Council's social contract originates in the Quran. The foundation upon which citizen–government relations are built is the relationship between God and believers. Andreas Krieg highlights that Sharia law defines rights and duties. The role of leader and citizen reflects the requirement to uphold fundamental religious tenets and promote solidarity of the larger community of believers.

A large part of the religion and culture in the GCC focuses on collective responsibilities. While individualism is celebrated in the West, Karen Armstrong states that Islam influenced the creation of a collectivist culture, which puts community before the individual, with practical compassion at the foundation. She explains that overindulgent self-focus is not favored and that putting community well-being before individual whims takes precedence. In sum, the Western focus on individual rights differs from the cultural concept of collective responsibility in GCC countries. It plays a role in creating the social contract and influences the development of cohesion.

Religious leaders and places of worship play a crucial role in creating strong community bonds and often play a role in the relief phase of a crisis. Religious teachings and the faith community can strengthen a community and build capacity in risk mitigation, relief, and recovery. From a prevention and mitigation standpoint, religious leaders and texts provide insights into the teachings on risk reduction and influence cultural response and social resilience. Islamic teachings reminded the citizenry of the rules for limiting the spread of disease. The Hadith states: "If there is a plague in a town, no one should leave it or go into it." Other passages speak more generally of the need to remain strong during a challenge and remind communities that life is difficult. However, the difficulty is temporary in the whole scope of life.

6 Conclusion

While social aspects of resiliency are hard to measure precisely, cohesion and public spaces play a key role in preparing communities to withstand traumatic times. The COVID-19 pandemic served as a reminder of the importance of human connections in our communities and that the virus has affected all, but not all equally. Revisiting foundational work on soft resilience from noted thought leaders in the West provides a starting place to consider social infrastructure. Equally important is the need for additional understanding of how Gulf countries leveraged social cohesion during COVID-19 and the development of risk reduction strategies both in the GCC and globally that bolster the role of social elements of resiliency.

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Globalization, Climate Change, and Compound Health Risks in the Era of COVID-19 Pandemic: The Case of the GCC

Fateh Belaïd and Razan Amine

Abstract COVID-19 served as a stark reminder of the economic devastation caused by poor preparedness for systemic risks. This lack of preparation triggered a domino effect, leading to an economic downturn, soaring debt, and supply chain disruption. The unprecedented global scale of this pandemic has accentuated multiple challenges with risk reduction and capacity to respond, both in the developed world and in the least developed countries. This chapter delves into the interconnectedness of globalization, public health risks, and climate change. First, we review the relationship between globalization and health risks. Subsequently, we explore the potential link between climate change and pandemics. Then, leveraging this understanding of interconnected global challenges, we analyze the response of GCC countries to the COVID-19 pandemic. The analyses show that the COVID-19 pandemic is an unprecedented test of policymakers' ability to handle composite risks as climate uncertainties disrupt global epidemic responses. Although short-term measures can play a role in minimizing climate-induced loss of life, climate adaptation necessitates a long-term strategy toward pandemic preparedness as well. In the wake of the pandemic, leading economies should shift their focus away from short-term economic benefits that could undermine ecosystems and their services to society. On the contrary, this pandemic can serve as a starting point for a transformation to achieve sustainable development that merges environmental, economic, and social considerations.

Keywords Climate change · COVID-19 · Globalization · Health risks · GCC

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1 Introduction

On March 11, 2020, the World Health Organization (WHO) classified COVID-19 (Severe acute respiratory syndrome-coronavirus 2 or SARS-CoV-2) as a pandemic. The outbreak's origins can be traced back to December 31, 2019, when the WHO was notified of a cluster of pneumonia cases with unknown etiology (cause) in Wuhan, China (Gostin & Gronvall, 2023). As the virus spread, so did the recognition that some countries were better prepared than others to protect their population.

In some regions, public reactions to COVID-19 were decisive and aggressive, especially compared to other contemporary economic and environmental crises, which are sometimes labeled as "existential threats" due to the difficulty of recognizing the risks at hand. Decisive response included stringent containment measures in China, Japan, Italy, France, Germany, Morocco, New Zealand, South Korea, and Australia. In these countries, most businesses and schools shut down, and individuals adopted rigorous hygiene practices, social distancing, and self-quarantine, all of which carry high personal, economic, and other social costs (Wang et al., 2021). GCC countries implemented a unified approach to public health measures. This strategy, coupled with a positive public response to government mandates, proved instrumental in mitigating risks during the pandemic's initial wave.

The COVID-19 pandemic served as a stark wake-up call, exposing the devastating consequences of inadequate preparation for systemic risks. A single health shock triggered a domino effect—crippling the global economy, ballooning debt burdens, and disrupting vital supply chains (Zhang et al., 2022). These cascading impacts further exacerbated existing vulnerabilities, leading to diminished incomes and setbacks in progress toward global development progress (Belaid et al., 2022).

Climate change, however, presents an even more significant threat. Unlike the pandemic, it is not a single event but a continuous and multifaceted phenomenon. The physical manifestations of climate change, such as extreme weather events and rising sea levels, are poised to trigger a cascade of interconnected disruptions across various global systems (Hui-Min et al., 2021; Belaïd & Cretì, 2021).

This chapter delves into the factors that allowed COVID-19 to evolve and spread globally. It then offers valuable insights for international audiences by examining the pandemic response in the GCC countries. We analyze both government policies and public reactions to understand what enabled the GCC to recognize the threat and implement effective prevention measures. While directly replicating these strategies in other regions might not be feasible, a close examination offers valuable lessons for risk analysts worldwide. By understanding the GCC's approach, we can explore how regional-level responses can inform public policies on risk reduction in diverse geographical contexts.

This chapter is organized as follows: Section 2 examines the interconnectedness of globalization, climate change, and pandemics. Section 3 analyzes the GCC's pandemic response, exploring both government policies and public reactions.

Section 4 focuses on lessons learned from COVID-19 that can be applied to developing environmental conservation solutions. Section 5 concludes this chapter with a summary of key takeaways.

2 Overview: Globalization, Climate Change, and Pandemic

The COVID-19 emergency has revealed distinct yet overlapping challenges that are connected to climate change. While globalization has been the gateway to health improvements in poverty alleviation, hunger reduction, and trade of goods and services, it has also contributed to widespread infectious diseases (Daulaire, 1999). Traders exchanged goods and ideas, religion and art; but also exchanged germs and diseases like bubonic plague, smallpox, measles, and tuberculosis.

In the context of the Arabian Peninsula, communities witnessed similar benefits of trade and the global growth of Islam. For example, UNESCO's Silk Roads Program details the importance of Jeddah as a port city along the Red Sea for both trade and entry for pilgrims on the way to Mecca. Similarly, port cities along the coast of Oman played a critical role in trade and allowed for the entry of viruses. During the fourteenth century, it is estimated that the Black Death killed approximately one-third of the population in the region; much of this loss is attributed to religious pilgrims.

While historians have documented the role of global trade in the spread of disease when drawing a direct connection between climate change and pandemics is not so simple, in sum, leading academics indicate that science is still under construction and provides guidance on understanding risks. Dr. Katharine Heyhoe, Director of the Climate Center at Texas Tech University, suggests that the proper way to frame the inquiry is with the following question: "Did climate change make COVID-19 worse?" She argues that it is too much of a stretch to frame the discussion in terms of direct causation and instead draws attention to how global warming opens Pandora's Box of risk. Climate change creates the perfect conditions for vector-borne diseases to spread more rapidly from ticks, mosquitoes, and other parasites. Climate change is causing longer summer seasons and creating a broader geographic reach for insects, increasing the chances of humans getting vector-borne illnesses such as dengue fever and Lyme disease. Health implications from the changing environment and extreme weather result in the following: respiratory infections, cholera, cryptosporidiosis, campylobacter, leptospirosis, malnutrition, malaria, etc.

Other academics also caution against assuming a causal link. According to the Harvard T.H. Chan School of Public Health, the direct causal link between climate change and COVID-19 is yet to be established (Coronavirus and Climate Change, 2020). Similar to Heyhoe's framing, they emphasize that climate change impacts the dynamics between different species on earth, bringing humans in contact with animals and pathogens that previously were separated. Loss of habitats due to large-scale agricultural developments and climate change increases the probability of humans coming into contact with viruses that originate in wild animals and

Fig. 1 Interaction between human and wildlife increase the probability of virus transmission. (Source: Author's design)

dangerous pathogens. Human interventions, especially those that affect the climate, can foster an environment where human–animal-borne vectors overlap.

Human expansion into animal ecosystems brings an increased chance of exposure to zoonotic viruses, resulting from humans meeting wildlife such as primates, bats, pangolins, or domesticated animals that contracted the virus from wildlife. According to Dr. Yanthe Nobel, spillover risk has been present for some time, but the global community is just recently "waking up" to reality (Hook, 2020). At the same time, the unintentional overlap between wildlife and domesticated animals is a serious concern; another source of zoonotic viruses concerns public health experts. Wildlife trafficking is known to be a risk factor in the spread of zoonotic viruses and is thought to be the source of the COVID-19 virus (Fig. 1).

A part of this equation is the modern approaches to agriculture. Large-scale agriculture has eradicated sections of forests and jungles to make way for concentrated livestock and agricultural operations. Monoculture farms are near wildlife, which increases the risk of wildlife viruses jumping into livestock (LA Times, 2020).

Addressing key research gaps is essential to minimizing risks during future pandemics. One key research question is the role between population density and pandemic spread. While those in affluent areas of the world exited cities to have more space during the height of the pandemic, a sophisticated understanding of why dense cities might have performed better in reducing risk is still in its infancy. Social class and economic means to relocate to avoid pathogens are nothing new. Dating back to early Roman times, aristocracy understood the nexus between weather and seasonal illnesses and left the city during hot summer months in part to avoid mosquito-borne diseases.

Initial findings are that densely populated cities have better infrastructure to respond to pandemics. Some of the literature from the media indicates that poor housing conditions for laborers stimulated the spread of the virus in certain cities. Additional research is needed to determine if living in dense conditions, often associated with temporary workers and laborers, made it impossible to isolate socially. Access to financial resources has allowed many to socially isolate or work from home, while those in unskilled jobs cannot stay away from work and may not have funds for living spaces that allow for social distancing.

3 GCC Pandemic Response

Here, we focus on the response of GCC countries to the recent COVID-19 pandemic. While new variants and surges may arise, it is important to acknowledge the past successes in containing the virus and flattening the curve in the GCC region. There is a chance that global leaders still struggling with economic and social impacts might not have the chance to consider the successes in the GCC, and academics are focused on other geographies; there is a risk that approaches in the GCC will not be documented. Additionally, there is a danger that uninformed individuals will discount the success of the GCC with a hand wave—economic strength in the GCC allowed the counties to access the vaccine early, and that alone accounts for the success in limiting suffering. The truth is far more nuanced, and this section will provide insights into the timeline and decisive actions GCC countries took to reduce risk.

From a timeline perspective, Awaidy et al. (2021) indicate that the first five cases of COVID-19 in the GCC member states were reported in the United Arab Emirates (UAE) on January 29, 2020 (Fig. 2). The UAE was the first GCC country to report the virus from travelers from Wuhan City, China. In less than a month, the virus was then detected in Bahrain, Qatar, Kuwait, and Oman. The first known case of COVID-19 was reported in Saudi Arabia on March 2, 2020.

To begin with, we first display graphs (Fig. 3) for the six countries that show the confirmed COVID-19 cases, total recovered, deaths, and total COVID-19

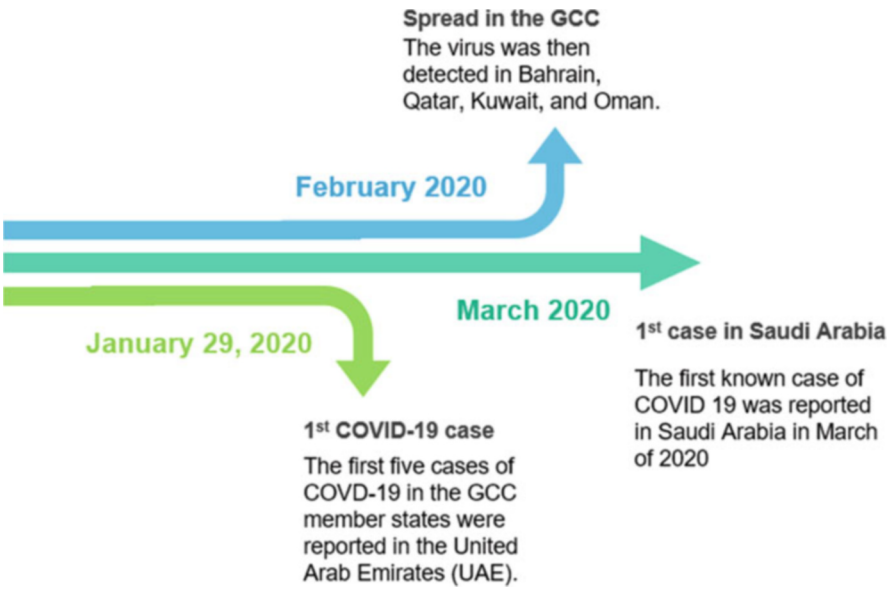

Fig. 2 Chronology of COVID-19 propagation in the GCC. (Source: Author's design)

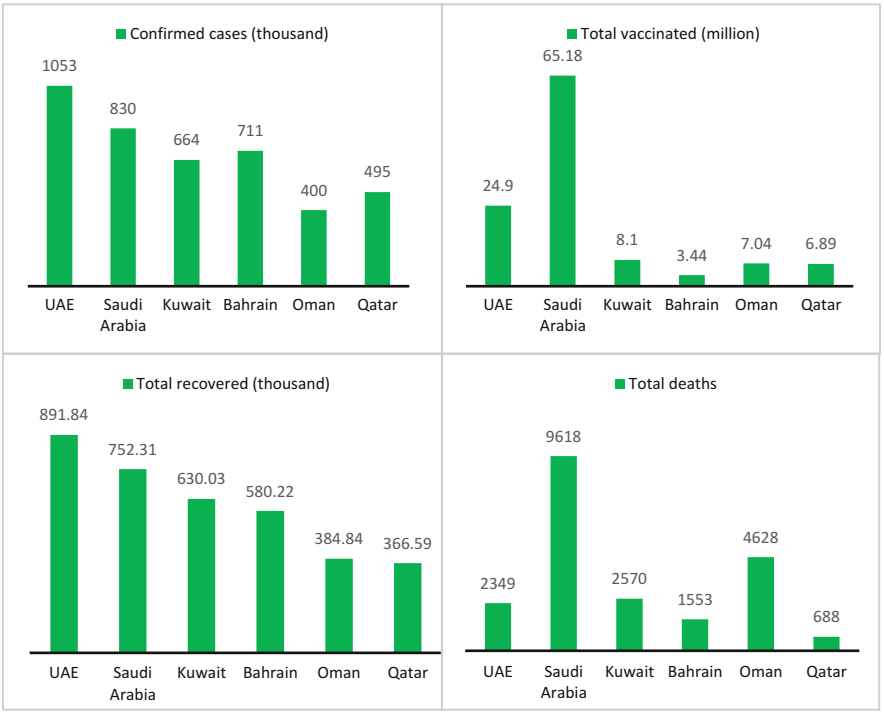

Fig. 3 COVID-19 key statistics in GCC: confirmed cases, total vaccinated, total recovered, and deaths in GCC. (Source: Source: Author's design using GCC stat: https://geogcc.gccstat.org/portal/apps/dashboards/26472504a44342e3beb7d5cb0e9db93f)

vaccinated), according to the last GCC statistics portal. This allows us to understand the trends and progress toward handling the COVID-19 pandemic impacts. We can see that Oman and Qatar had relatively the lowest cases among the GCC countries.

More broadly, GCC countries have demonstrated a successful response to the pandemic. They have achieved a high vaccination rate, effectively "flattened the curve" by reducing new COVID-19 cases, and experienced a lower death toll compared to other regions. These positive outcomes highlight the effectiveness of the implemented strategies.

What were the factors that allowed GCC countries to achieve this end state? First, governmental mandates for quarantine were announced throughout the region, and publicly available data indicates a high level of compliance. GCC nations deployed record-breaking fiscal and monetary stimulus to combat the crisis's impact (Al Awaidy et al., 2021). There are several indicators that show how populations responded to governmental and self-imposed social distancing. These indicators include the policies announced, the restrictions imposed, and the lockdowns announced.

To best understand population response, compliance, and behavior of people in the six different countries from the start of the pandemic until the time of writing this

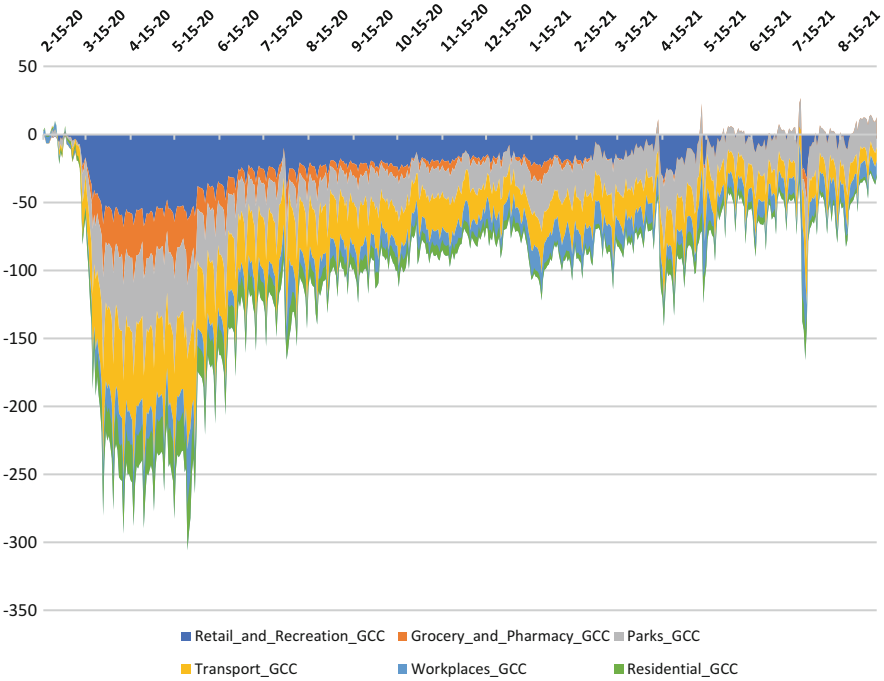

Fig. 4 The trend of the six mobility variables from the start of the pandemic to summer 2021, overall in the GCC. (Source: Author's design)

chapter, we resort to using data that depicts the movement of the people during the pandemic. The analysis of this data could give us an idea of whether the policies set by the different countries were enforced sufficiently and whether the people have conformed strictly to them. The data used to elaborate on this is the Google mobility data.[1] The Google mobility data, structured as a country–day panel, has six mobility variables, which represent a percentage change of the movement relative to a specific baseline, which is the median value for the corresponding day of the week during the 5-week period from January 3 to February 6, 2020.[2] The data is available between February 2020 and August 2021. The six mobility variables demonstrate the movement of people in six areas: retail and recreation, grocery stores and pharmacies, parks, transit stations, workplaces, and residential areas. Figure 4 shows an aggregate[3] of the movement to depict the regional trend of the six mobility variables in the GCC. Overall, we can notice that the greatest

[1] Data Reference: https://www.google.com/covid19/mobility/

[2] Reference: https://www.nature.com/articles/s41562-021-01181-x#Sec21

[3] This aggregation is computed by taking the average of each of the six variables for the six countries.

reduction in the mobility of people in various areas has been peaked at the start of the pandemic when most countries started announcing lockdown policies. The change of the movement of people relative to the baseline has been reduced over 2021, as restrictions started to ease, but we can still see points in time where the restrictions arise again, correlating with a decrease in the mobility of the people. Qatar is a country that stands out in terms of the linearity of the change in the movement of people across time.

To further provide a description of the above graph, the table shows the minimum and the maximum percentage change of the movement (for the six mobility variables for the six GCC countries) relative to a specific baseline (baseline is the median value for the corresponding day of the week, during the 5-week, period from January 3 to February 6, 2020) (Table 1).

Another data source that informs public compliance with governmental mandates is a series of surveys that have been conducted in GCC countries that express people's mental health during the lockdown and their perception of the pandemic's severity. In the United Arab Emirates, a survey by Vally (2020) reports that 44.8% of the 634 participants adhered to the government rules and mandates. Similarly, in Qatar, Abdelrahman (2020) shows that 87.3% of 405 respondents to a survey preferred to stay at home during the peak times of the pandemic, and 95.8% reported that they adhered to personal hygiene rules. 73.5% reported that they think COVID-19 is a dangerous virus. In Bahrain, Alsalman et al. (2020) report that 30% of the people surveyed (sample of 1115) said they suffered from depression during the pandemic. These comparative studies show the differences in perception between people regarding the severity of the pandemic and its impact on their mental health.

How Did GCC Countries Achieve This Result?

First, in certain cases, it is possible to "learn lessons" from previous traumas and create sound public policy to reduce risks in the future. Specifically, Saudi Arabia's experiences combatting the MERS helped create risk reduction policies that effectively saved lives during the first wave of the pandemic. El-Saharty et al. (2020) explain the GCC's overall preparedness to face the pandemic. Countries implemented the "detect, test, isolate, and contact trace," aiming to flatten the pandemic cases curve. On the other hand, countries also wanted to implement measures to deal with the rising recessions. Algaissi et al. (2020) elaborate on prior experience with large-scale events like Hajj and lessons learned from combatting the MERS virus, which helped countries in the GCC to mobilize strategic response plans. Saudi Arabia has put in place a set of rules like never before, which may be attributed to the Kingdom's previous experience with pandemics, particularly MERS-Cov (Pétriat, 2020). That also explains the ability of Saudi Arabia to contain the virus, for example, by preventing the entrance of about 2.5 million internationals who wanted to perform Hajj. Adly et al. (2020) add that these measures helped reduce COVID-19 death rates in Saudi Arabia by 27%. The International Monetary Fund's country report on Saudi Arabia outlines its preparedness for the COVID-19 pandemic, where Saudi Arabia's economy was bolstered with non-oil growth as the pandemic started, maintaining positive progress for reforms under Vision 2030. The

Table 1 Descriptive statistics of the mobility factors in GCC countries

Country		Retail and recreation	Grocery and pharmacy	Parks	Transit	Workplaces	Residential
Qatar	Min	–72	–47	–70	–69	–74	–2
	Date	4/10/20	4/10/20	4/24/20	4/24/20	5/24/20	3/2/21
	Max	4	50	49	14	7	34
	Date	3/1/20	5/12/21	12/18/20	12/18/20	3/7/20	5/24/20
UAE	Min	–80	–60	–86	–84	–77	0
	Date	3/27/20	3/27/20	4/10/20	3/27/20	5/24/20	2/29/20
	Max	9	57	31	1	5	36
	Date	5/12/21	5/12/21	12/2/20	2/17/20	2/29/20	5/24/20
Bahrain	Min	–61	–32	–66	–56	–64	0
	Date	3/27/20	3/27/20	3/27/20	3/27/20	5/24/20	2/17/20
	Max	5	23	11	17	7	25
	Date	7/18/21	7/19/21	12/16/20	7/18/21	2/16/20	5/24/20
Kuwait	Min	–90	–81	–83	–83	–83	–2
	Date	5/11/20	5/11/20	5/15/20	5/15/20	5/24/20	2/24/20
	Max	5	13	21	14	8	46
	Date	2/24/20	3/11/20	2/21/20	2/24/20	2/16/20	5/14/20
Oman	Min	–91	–89	–78	–83	–88	–6
	Date	7/20/21	7/23/21	7/23/21	7/22/21	7/20/21	9/5/21
	Max	3	41	4	2	11	33
	Date	2/29/20	7/19/21	2/22/20	2/28/20	3/1/20	7/22/21
Saudi Arabia	Min	–84	–72	–81	–88	–79	1
	Date	5/24/20	5/24/20	4/24/20	5/24/20	5/24/20	2/6/21
	Max	22	63	48	–2	11	35
	Date	7/18/21	5/12/21	7/20/21	2/27/20	7/16/21	5/24/20

The table shows the minimum and the maximum percentage change of the movement (for the six mobility variables for the six GCC countries) relative to a specific baseline (baseline is the median value for the corresponding day of the week during the 5-week period from January 3 to February 6, 2020)

government also supported the private sector by allocating 13.9% of non-oil GDP for fiscal and employment support programs; more generally, SAR 116.5 billion, or 5.8% of non-oil GDP, was allocated for the COVID budget (International Monetary Fund, 2021).

Next, we look at public policy that creates interagency collaboration as another factor that helped reduce risk in the GCC. Due in part to Saudi Arabia's role in hosting the annual Hajj, a sub-specialty called "mass gathering medicine" has played a role in helping communities in the GCC identify pandemic risks and create policies to mitigate the risk of illnesses spreading during the Hajj season. The annual Hajj pilgrimage is considered to be one of the largest annual mass gathering events globally, with upward of two million pilgrims from around the globe congregating in Mecca to participate in the fifth pillar of Islam. Both the close contact during the religious procession and the living conditions in temporary housing provide ample opportunities for the spread of public health problems. Lessons learned from managing infectious diseases like MERS-COV during the 2012 Hajj pilgrimage have significantly advanced the field of mass gathering medicine (Pétriat, 2020). These learnings have been applied to other large-scale religious and cultural events. A crucial factor in creating sound public health policies for the Hajj is the close collaboration between the Ministry responsible for Hajj and the Ministry of Health. This interagency cooperation allows for better risk identification and informed decision-making, ensuring a safe pilgrimage experience "in normal times" and during pandemics.

Transparent Communications Between GCC Leadership Helped Transparency and collaboration proved pivotal for GCC nations navigating the COVID-19 pandemic. Open information sharing and joint efforts fostered a unified front against the virus. The interconnectedness highlighted by the Qom, Iran, case (a pilgrimage city attracting diverse regions) demonstrates why transparency is crucial. Many initial cases in the Middle East stemmed from pilgrims returning from Qom, emphasizing the need for regional cooperation. Effective pandemic response requires both national and regional transparency and collaboration, allowing GCC leadership to implement robust containment strategies.

Health Infrastructure Availability Combatting COVID-19 effectively hinged on early detection. Recognizing the catastrophic potential of the virus, GCC countries made strategic investments to secure testing equipment and provide free testing for all.[4] This proactive approach enabled them to identify cases quickly and implement isolation measures, thereby curbing the spread of the virus. The robust medical infrastructure of the GCC also played a crucial role in their response. Awaidy et al. (2021) highlight how advanced healthcare systems and comprehensive government

[4] https://www.newarab.com/analysis/geopolitics-vaccine-diplomacy-middle-east; https://insights.omnia-health.com/saudi-arabia/prompt-action-defines-saudi-arabias-success-story-emerging-covid-19

efforts, including investments in testing and treatment facilities, contributed to lower mortality rates.

Medical researchers from across the GCC collaborated on an analysis of the early response of public health infrastructure in June 2020 to help gain an understanding of the effectiveness of the early response phase. Awaidy et al. (2021) measured GCC preparedness using the WHO priority areas, which included several elements. First, country-level coordination, planning, and monitoring indicate the GCC countries' preparation level to respond to the COVID-19 pandemic. Other factors include infection prevention and control, operations support and logistics, national laboratories, surveillance, rapid-response teams, case investigation, risk communications, and community engagement. Their study of the early phase of pandemic response in the GCC found that the GCC countries enhanced existing medical infrastructure and rapidly implemented policies to control the spread of the virus.

From an economic and social perspective, GCC leadership adopted policies to reduce the human impact while seeking to protect economic growth in the region. Most GCC countries resorted to closing borders, suspending flights, shutting down schools, enforcing quarantines, and banning social events and gatherings. However, the GCC strategies that have been implemented do not mean the MENA region did not face any challenges in combating the pandemic. In particular, Baloch et al. (2020) elaborate on the challenges that the Middle East faced. These challenges include a combination of underdeveloped healthcare systems, religious gatherings, political instability, and regional conflicts. So, how prepared was the GCC to face the pandemic?

Indeed, insights on how various vulnerable segments of the population report experiencing the pandemic can offer valuable information to shape future resource provision, investigation, and clinical interventions to optimize outcomes and mitigate COVID-19 adverse effects as they persist, particularly during periods of social restriction or containment.

To sum up, while the pandemic continues to wreak havoc across the globe, the GCC strategies have helped protect lives and reduce economic impact. While governments have taken decisive actions to help curb the impacts of COVID-19 pandemic, challenges remain in continuously adapting to the changing economic, political, and health environments. Governments ought to be specific in implementing their various policies to help businesses survive and aid households' employment (OECD, 2020). Creating fiscal policies that bolster economies against shocks is definitely a goal to be achieved by all countries, especially fragile ones.

4 What Can We Learn from COVID-19: Emerging Approaches and Environmental Conservation Solutions

The natural resources that modern society has relied on to develop the world's growing food supply build cities, and manufacture elaborate devices and pharmaceuticals

are diminishing rapidly. The consequences of this are now being observed, such as loss of biodiversity, climate change, land-use changes, the environmental burden of products, and climate change. These challenges are not only exacerbating current health risks but generating substantial new ones. The current pandemic of COVID-19 has proven that the plague era is still not over and that viruses persist in surprising and threatening humans. It has also provoked a rethinking of globalization, its meaning, and impacts on the environment, health, and well-being.

While vaccination rates for COVID-19 are booming around the world, the social, economic, and ecological legacy of the pandemic will endure. Some experts even speculate that the pandemic's containment impacts will have persistent shortfalls on environmental protection and monitoring policies (Bates et al., 2021). Further, this ongoing pandemic has emphasized how human activities and behavior changes in types, scope, and scale may impact the environment. Accordingly, the COVID-19 policy response, including lockdowns and mobility restrictions, offered tangible insights into how human activities affect the ecological system. The ongoing COVID-19 pandemic is an incredible stress test of global governments' preparedness to deal with compounded risks, as the vagaries of climate perturb the worldwide response to epidemics. This experience offers valuable opportunities to explore the relationships between globalization, nature, and humans. While short-term measures can be taken to mitigate climate-related fatalities, climate adaptation necessitates a long-term commitment to support pandemic preparedness.

Therefore, plans and policies need to break down agency silos. If climate change and pandemic response are kept compartmentalized, there will not be an accurate risk assessment and inadequate response planning. Subject matter experts and academics need to collaborate on developing cohesive risk mitigation strategies. Professor Martin Seigert, Co-Director of Grantham Institute, highlights the possible lessons learned on the COVID-19 connection to climate change action. The world can collectively take action, with ample funding available to address major issues. By relying on scientific evidence, significant problems can be alleviated through decisive actions. Science magazine provides great cost-benefit analyses on reducing the risk of future outbreaks and how these initiatives would be a win for climate change mitigation. Moreover, Andrew Dobson, Princeton University Professor of Ecology and Evolutionary Biology, and coauthors help frame pandemic prevention from a cost savings perspective. Policies should focus strategically on what can "de-multiply" the risk and seek international support to reduce deforestation and wildlife trafficking.

Strong public policies are essential for effectively confronting future pandemics and mitigating their severe impacts. Such policies not only help prevent the occurrence of additional pandemics but also reduce the likelihood of their emergence in the first place. An optimal policy would account for both protecting the people's health as well as the economy's health. The way to start this is for countries to evaluate their previous policies, like travel restrictions and quarantines, to see if they worked or if they were counterproductive. This evaluation would consider that there is a human cost to quarantine and social distancing. This, in turn, has a series

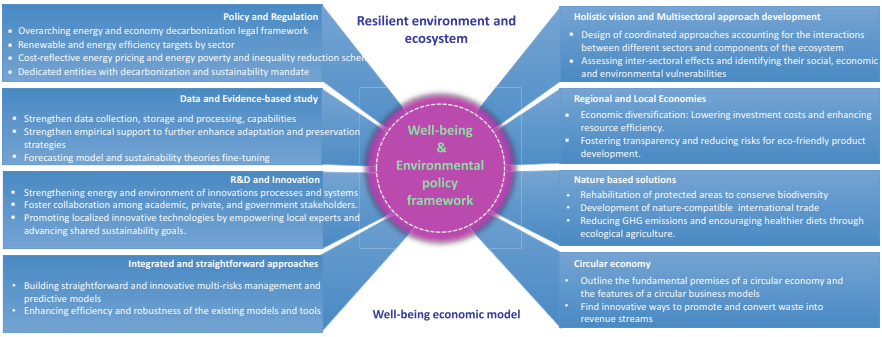

Fig. 5 Policy framework to leverage the insights of COVID-19 as a pivotal point for promoting economic sustainability and building social and climate resilience. (Source: Author's design)

of impacts on people's productivity and mental health, which has underestimated impacts on the economy. In short, nations should react early and build "natural insurance" to deal with pandemics (Vehkalahti, 2013).

The entire world has been impacted and reacted strongly to stop the spread of COVID-19. Accordingly, various strategies to drive positive economic and sustainability impacts are identified. We observed how individuals changed their lifestyles and activities profoundly and the extent to which businesses are transformed by the accelerated adoption of digital technologies, highlighting that profound societal and technological change is feasible. It is evident that many of the underlying causes of this health crisis are the same ones exacerbating the current biodiversity and climate change challenges. As humanity continues to learn and adapt to pandemics, the technological and societal transformation opportunities that could change the world and strengthen the resiliency of natural systems are essential to take into consideration.

More than ever, a holistic vision is necessary to emerge from this pandemic and find solutions to expand well-being economies and sustainability (Belaïd et al., 2021a, b; Tiba & Belaid, 2020, 2021). Figure 5 summarizes the most prominent measures to optimize lessons learned in controlling the COVID-19 pandemic and leverage them as the backbone of a resilient and well-being economic model.

5 Conclusions

In our interconnected world, the COVID-19 pandemic reinforced the understanding that viruses do not respect territorial borders, and international organizations have called for a greater unity of effort around the globe to create early warning, response, and capacity building in developing countries.

The urgency of managing COVID-19 has seriously distracted attention from the climate crisis in the public arena. This chapter elaborates on a straightforward

analytical framework to examine the globalization–climate change–health nexus. The scope of the analysis is to elaborate on how aggressive policy responses to COVID-19 may be used to promote the mitigation of future economic and health crises and the ever-present global environmental crisis. First, we review the relationship between globalization and health risks. Then, we elaborated on the linkage between climate change and pandemics and discussed how to enhance countries' capabilities to mitigate health and climate change impacts. Finally, we discuss the response of GCC countries to the COVID-19 pandemic.

This analysis has many implications for the policy-making process and policy choices, considering the looming problem of climate change and its devastating impacts on society, the economy, and the environment. Overall, in many situations, a very well-coordinated, rapid, and forceful public response to the COVID-19 pandemic was undertaken, especially during the initial stages of the crisis.

Throughout this chapter, we have sought to explain this solid public commitment to these rather draconian mitigation actions, with a focus on the GCC region. Further, we have focused on understanding the insights of this experience and how they can be harnessed to promote actions to mitigate the effects of future potential pandemics and similar pressing global threats necessitating proactive social action, namely, the global climate crisis.

The COVID-19 pandemic is an unprecedented test of policymakers' ability to handle composite risks, as climate uncertainties are disrupting global epidemic responses. Although short-term measures may be implemented to minimize climate-induced loss of life, climate adaptation also necessitates a long-term strategy toward pandemic preparedness.

In the wake of the pandemic, we suggest that leading economies shift their focus away from short-term economic benefits that could undermine ecosystems and their services to society. On the contrary, this pandemic lesson can be used as a starting point for a socioeconomic transformation aiming to enhance cities' long-term economic and environmental sustainability (Belaïd & Arora, 2024). There is scientific evidence that the alteration of ecosystems and heavy exploitation of wildlife enhance the likelihood of pandemics, indicating that proactive environmental efforts have the potential to mitigate future pandemics (Dobson et al., 2020). A comprehensive assessment of potential trade-offs and synergies is crucial to ensure effective mitigation programs. This analysis should prioritize the identification and implementation of synergistic mitigation actions, minimizing the occurrence of trade-offs.

Further, there are urgent calls to examine the relationships between the factors modulating pandemics' impacts on individuals' well-being and mental health. These factors include mainly the following: social networks, demographic aspects, pre-existing mental health conditions, character traits, and occupational and financial context. Understanding these mechanisms is critical in informing healthcare and policy decisions.

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Grey Carbon—A New Nature-Positive Carbon Removal Technology for the Built World

Ralph Chami, Thomas Cosimano, Nathalie Hilmi, Dinah Nieburg, and Rebekkah Swisher

Abstract Humanity is in a race to reduce carbon dioxide levels in the atmosphere. Emissions must be reduced while also accelerating net carbon dioxide removal (CDR). Historically, carbon removal has been shouldered by "green" and "blue" nature—land, coastal areas, and ocean. With the world's growing population, impacts from climate change, and increasing urbanization, it is clear nature cannot handle all the CDR needed. Natural systems are under threat, risking their ability to maintain the same rate of carbon sequestration. Man-made technology must deliver more. The IPCC Assessment Report 6 (AR6) highlights a mix of nature- and technology-based CDR solutions that will be needed. Here, we look at a new CDR solution for the construction industry, which is responsible for 38% of global CO_2 emissions. Since climate change is only increasing demand for construction, we must reimagine how and what we build with. We need building technologies that can help keep their own industry's emissions in check while also reducing CO_2 from the atmosphere. This is where "grey carbon" comes in. Like its blue and green cousins, grey carbon offers net carbon removal from man-made technology and presents a pathway that delinks pollution and development. Here, we use a case example of how the Bahamas is turning to a grey carbon building product to respond to housing demand and climate adaptation. We describe the science behind this CDR technology and apply financial valuation techniques to calculate the monetary value that could be derived from the grey carbon credits. We show how

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grey carbon delivers climate, nature, and community benefits from the following: CO_2 avoidance and removal during production, longer-term carbon removal as the materials continue to weather, ocean protection through reduced brine waste, and social benefits from the sale of grey carbon credits. We show that a 1250 ft^2 home built with this cement can deliver 170.94 tCO_2e credits over 20 years for a present value of $38,145 per home and $57.22 million for 1500 homes. We conclude that grey carbon can mitigate emissions from the built world while also helping to deliver a future in which the biosphere and Technosphere, blue, green, and grey climate solutions, coexist as allies for human well-being and climate stabilization.

Keywords Grey carbon · Carbon-negative concrete · Carbon dioxide removal · Built environment · Green cement · Eco-disaster risk reduction

1 Introduction—Grey Carbon Is Needed Along with Green and Blue

Humanity is in a race to reduce carbon dioxide levels in the atmosphere, reverse biodiversity loss, and restore the biosphere's capacity to deliver life services. This requires reducing emissions as quickly as possible while also accelerating carbon dioxide removal (CDR) from the atmosphere through nature-based solutions and man-made technology. Current estimates put CDR levels at 2 $GtCO_2$/year, primarily through nature-based solutions on land, whereas at least 8 $GtCO_2$/year CDR is projected to be needed by mid-century (Smith et al., 2023). While climate mitigation must happen as quickly as possible, countries also face the challenge of developing and adapting to climate impacts without making matters worse. For example, Small Island Developing States (SIDs) on the front lines of climate change need to rebuild after hurricanes and deliver climate-resilient housing. Thus, to achieve the CO_2 reduction targets needed to stay below the 1.5 °C ceiling, there is a need not only to enhance the capacity of natural systems, green and blue, to absorb CO_2 from the atmosphere but also to create a circular "Technosphere"—the man-made world—that absorbs CO_2 and creates long-term storage.

This is where "grey carbon" comes in. Like its green and blue cousins, grey carbon offers net carbon removal and presents a pathway that delinks pollution and development. Grey carbon offsets, meanwhile, are easy to accurately monitor and quantify. Here, we provide an example of a new technology—a new material for the built world—that delivers CDR in two ways. First, the material—cement—is produced using wastes and other minimally processed materials rather than materials derived from combustion or clinkering processes, thereby avoiding process CO_2 emissions and emissions otherwise produced from heating. Second, this new material absorbs CO_2 directly from the atmosphere—initially during curing and over a period of 20 years, again, through a geochemical process. Unlike some CDR technologies, which require carbon capture technology and then propose to inject CO_2 back into the lithosphere, this material requires no carbon capture or injection

equipment and securely stores CO_2 into the built environment itself. Both avoidance and removal carbon credits can then be created based on this technology. We call these credits "grey" carbon.

In this chapter, we use the case of the Bahamas to demonstrate the contribution of grey carbon to their portfolio of climate solutions, which leads both to climate mitigation and nature-positive economic development. The Bahamas has already moved forward with its goal to create blue and green carbon markets to bring in financing for conservation. They have passed carbon trading legislation and are enacting conservation measures—both needed as the foundation for bringing investment into their natural capital economy. With these investments, jobs around environmental conservation can grow, contributing to a nature-positive economic base. However, demand for the built world is also growing, partly due to climate change's impacts, such as hurricanes and rising sea levels. We show that by relying on grey carbon technology, countries needing to grow their built environment can do so in a climate and nature-positive way while also delivering multiple social benefits.

In sum, this chapter describes innovation in concrete building materials that are now available for countries to meet their construction needs using a climate-friendly negative cement product. In Sect. 2, we outline the opportunity available to transform the concrete building industry to be climate positive. In Sect. 3, we describe the science which underpins the grey carbon outcomes. We calculate the financial flows that can be derived from both avoidance and removal credits derived from the production process of the cement, from the home construction, and from the long-term continuing carbon sequestration of the built structure. Finally, we show how these innovations deliver benefits to society, climate adaptation, and sustainable development goals. We review the benefits to the Small Island States, as well as highlight the potential for this construction technology in the Gulf Region, particularly due to the potential for repurposing the brine waste produced by desalination. In Sect. 4, we close by emphasizing the multiple benefits that come when an innovation, such as this new material needed for the built world, can be applied within a broader systemic lens to mitigate GHG emissions while also bringing benefits to society and to the natural world.

2 The Built World—A New Era of Climate and Nature-Positive Grey Carbon

Climate Change Is Only Accelerating Building Demand With the world's growing population and impacts from climate change and increasing urbanization, the demand for delivering the built environment continues to grow. However, to keep global warming below 1.5(C), the building and construction (B&C) industry, which accounts for 38% of global emissions, must be transformed. Construction rebounded after the 2020 COVID downturn, resulting in a growing gap in the decarbonization

pathway for this industry (UNEP, 2022). The demand for housing comes not only from population growth but also from increasing disasters displacing populations and damaging existing structures. In the Bahamas alone, Hurricane Dorian in 2019 destroyed 60% of the homes in northern Abaco Island. Other island countries face similar threats, and there is growing awareness and commitment from countries to take urgent action. As of 2021, 80% of countries included buildings in their NDC action plans (UNEP, 2022).

Climate Change Is Constraining Freshwater Supplies Meanwhile, the effects of climate change are also placing ever-increasing constraints on freshwater supplies in regions that are most vulnerable (Parmesan et al., 2022). As a result, both drought-prone areas, such as the Middle East, and low-lying island nations like the Bahamas are increasingly forced to turn to desalination to meet their freshwater demands. Although desalination offers a solution to the freshwater supply problem, it is inefficient and creates large volumes of waste brine that are typically discharged into the ocean. Unless the brine is thoroughly dispersed upon injection, this high-salt solution settles on the ocean floor and essentially suffocates the ocean life that is there. What is needed is a holistic systems design in which the built environment reduces and captures carbon dioxide without polluting or harming the natural environment.

We Need to Rethink What We Build With The IPCC AR6, WGIII (IPCC, 2022; Cabeza et al., 2022a, Buildings Supplementary Material) advises that the B&C industry can deliver significant mitigation and adaptation potential, including through decarbonizing building materials (Cabeza et al., 2022a). In 2019, global greenhouse gas (GHG) emissions from buildings were 12 $GtCO_2$-eq, equivalent to 21% of global GHG emissions that year, out of which 57% were indirect emissions from the offsite generation of electricity and heat, 24% were direct emissions produced onsite and 18% were embodied emissions from the use of cement and steel (Cabeza et al., 2022b, Buildings). Other reports estimate that between 2020 and 2050, new buildings will produce around half of their emissions from embodied sources and half from operational sources of the whole lifecycle (Architecture 2030, 2020). "Operational carbon" is defined as emissions produced during the use phase of the building, whereas "embodied carbon" is defined as "carbon emissions associated with materials and construction processes used throughout the whole lifecycle of a building or infrastructure" (World Green Building Council, 2021). Life cycle analysis of GHG emissions indicates that while "operational" emissions are dropping, relative and absolute emissions due to embodied carbon are on the rise (Röck et al., 2020). In other words, the way we build is inefficient and wasteful and needs to be reimagined. This presents an opportunity to help address climate change by developing new materials in building construction.

With regard to reducing embodied carbon emissions, cement (the binder component of concrete, which includes the addition of aggregates and water) is perhaps the lowest-hanging fruit in the building industry, primarily because of the vast amounts of CO_2 generated in simply obtaining the raw materials. The production of Portland

clinker, which acts as the binder, is a critical step in making ordinary Portland Cement (OPC). Limestone ($CaCO_3$) is calcinated at high temperatures in a cement kiln to produce lime (CaO), leading to the release of waste CO_2. This decarbonation reaction accounts for approximately 50% of the produced CO_2 emissions, with 40% of emissions coming from burning fossil fuels to heat kilns to the high temperatures needed for this calcination process and 10% of emissions from fuels required to mine and transport the raw materials. Every ton of Portland Cement produced contributes about a ton of CO_2, both directly through the heat of decomposition of calcium carbonate to produce lime and CO_2 and indirectly through burning fossil fuel to heat the calcium carbonate in the kilns.

Over the last several decades, the cement industry has focused on reducing embodied emissions. The industry has implemented energy-efficient kilns, lower-emission fuels, and increased clinker substitution. Meanwhile, several new cement technologies have emerged that mechanically capture, bottle, and reinject CO_2 into the cement as it cures. None of these measures, however, has been able to create a concrete product that offers a net removal of CO_2 from the atmosphere.

Here, we describe a whole new category of green building materials and methods where the embodied carbon is "net negative"—namely, instead of emitting carbon, it is stored in the cement while also being nature-positive. We also calculate the economic value of capturing this grey carbon and present a new social paradigm for affordable, climate-resistant housing that enables climate adaptation while also chipping away at the causes of climate change itself. Similar to Blue and Green "Nature-Based Solutions"—where carbon dioxide is reabsorbed into ecosystems through photosynthesis, this grey carbon is an example of a "technology-based" solution in which CO_2 is absorbed through geochemical processes into man-made products while also delivering other positive social and nature co-benefits supported by carbon financing mechanisms.

3 Case Study—Bahamas' Grey Carbon Home Construction Provides Climate Adaptation and Finance

There is a dire need for building technologies to help keep their industry's emissions in check. Partanna, the solution that is described here, ushers in a new field of Grey Carbon, carbon captured from the atmosphere using sustainable building materials. Like blue and green carbon, Grey Carbon offers net carbon removal and presents a pathway that delinks pollution and development. Here, we show how to develop carbon credits that can provide financing for sustainable development. First (Sect. 3.1), we describe the science leading to carbon avoidance and removal. Then (Sect. 2.3), we provide a valuation framework assuming 1500 houses being built in the Bahamas. Finally (Sect. 3.3), we show how the new technology and additional carbon credit cash flows lead to and finance multiple sustainable development goals.

3.1 The Science—Grey Carbon Stocks Sequestered in Concrete

Partanna is the world's first building material that not only avoids carbon emissions from traditional processes but also removes carbon from the atmosphere. The binder components in Partanna gain strength and improve quality by consuming CO_2 through a chemical reaction called carbonation. Carbonation results when carbonate ions ($CO^{2-}{}_3$) from dissolved carbon dioxide react with the positive ions and precipitate various solid carbonates.

The technology relies on an alternate, patented method of activating the siliceous/aluminous material that would be found in a pozzolan. Partanna can use almost any source of pozzolanic materials—slags, volcanic ashes, or natural pozzolans. There is no need for the clinkering process, which is the main culprit for the staggering 9% of global CO_2 emissions that are attributed to Portland cement.

The technology uses a brine activator, which is a combination of various salts that can be found in seawater. As that material becomes soluble, carbon dioxide from the air begins to dissolve into the water until it reaches equilibrium. As that CO_2 is dissolved in the water, various solid carbonates are formed, consuming CO_2 in the reaction.

As these materials solubilize, dissolve, and react, a skeleton begins to form. Instead of calcium silicate hydrate, which is the glue that derives from Portland cement, these reactions form *calcium alumina silicate hydrate* and *magnesium alumina silicate hydrate*. These new materials perform the same binding function as traditional cement.

Partanna makes positive environmental impacts and achieves typical 28-day strength requirements in as little as 24 hours. In practice, these strengths are sufficient for a number of applications without requiring the use of any Portland cement.

It is important to note that carbonation reactions also occur in concrete made with Portland cement, but these occur more slowly and cannot overcome the embodied carbon dioxide that is emitted in the raw material processing. In contrast, Partanna's solution starts with raw materials with very low embodied carbon that does not require such energy-intensive processing and does not depend on clinkering/decarbonation (CO_2 release) to get to the raw binder materials. The solution is inspired by nature itself, using waste materials (brine) to create a circular Technosphere[1] that can help society respond to the effects of climate change, while also working together with the regenerative biosphere to bring the climate back into balance (Fig. 1).

[1] https://mcdonough.com/william-mcdonough-helps-articulate-circular-carbon-economy-framework/

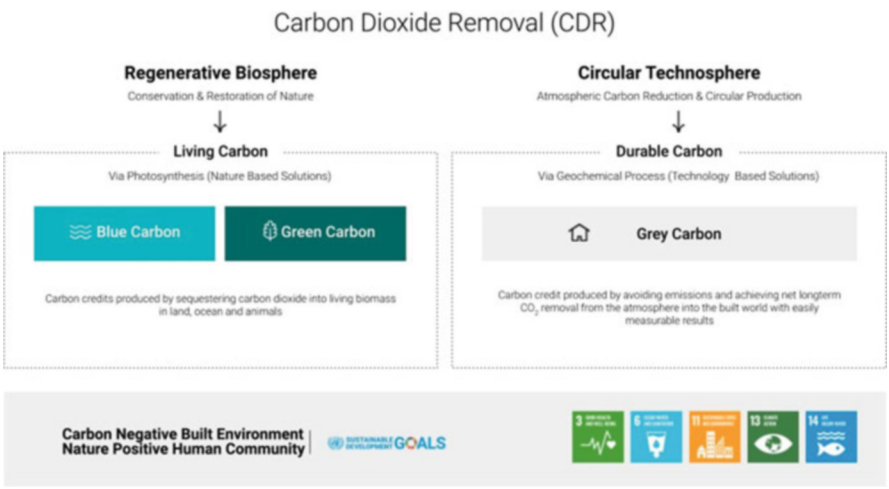

Fig. 1 The concept of grey carbon shifts the burden of carbon removal to a more balanced paradigm, where building technologies keep their own industry's emissions in check and support the efforts of blue and green carbon at the same time. (Source: Developed by Blue Green Future and Partanna. Circular technosphere from McDonough. https://mcdonough.com/william-mcdonough-helps-articulate-circular-carbon-economy)

3.2 The Finance—Valuing Grey Carbon Credits

Through the new carbon-negative building materials, Partanna produces two revenue streams—from the sale of the homes and from the sale of carbon credits that can generate cash flows to benefit the builder, buyer, and community. Partanna's products deliver both avoidance and removal credits.

Avoidance Credits Partanna's innovative carbon-negative building material is just as affordable, versatile, and durable as traditional cement. However, its manufacturing process completely eliminates the use of Portland cement, which is made from an alternative binder that uses natural or recycled ingredients, including materials reclaimed from brine and pozzolans. This binder is mixed with natural, recycled stones and cured at ambient temperature. There is no need for clinker, which avoids the use of traditional kilns and associated emissions. Thus, the technology enables Partanna to generate avoidance credits from the displacement of cement. A number of other "green" cements achieve avoidance credits by limiting their use of Portland cement.

In addition to rethinking the materials we build with, we must also rethink *how* we build in the context of climate change. Consider an interior wall, for example. In typical US construction, for instance, each wall is built using a layered process that starts with wood studs and then adds on various layers of insulation, paper, wallboard, screws, and a finish of choice, which could be wallpaper, paint, plaster,

and so on. Not only is this process inefficient, but many materials also contain high levels of embodied carbon.

With this in mind, Partanna has reinvented the way a home is put together and simplified the wall construction so that it does not require multiple layers of carbon-intensive building materials. The material has insulative properties and achieves a desirable finish on its own without applying external finish layers common throughout the USA and much of the developed world. This building process is quicker, simpler, more cost-efficient, and far less carbon-intensive. At least 10 tons of CO_2 per house can be avoided by simply sidestepping the materials in that layered process.

Removal Credits The unique advantage of Partanna's concrete technology is that it generates removal credits through its absorption of CO_2—both at production and *throughout the life of the concrete*. Approximately 20% of the removals occur during the initial curing period, and then the concrete continues to absorb carbon significantly over the next 20 years. Concrete with this technology captures CO_2 directly from the air and mineralizes it in the concrete. The first project using this technology involves the construction of 30 hurricane-resistant homes in the Bahamas in 2023. Upon successful completion of these homes, Partanna will have the option to use its technology to construct between 100 and 1000 homes per year in the Bahamas.

The company's estimates—confirmed by lab tests—is that for every masonry unit (block) produced, 14.3 kg of CO_2 are reduced. Almost 80% of that reduction is from removal (CO_2 absorption) and 20% from avoidance (reduction in Portland cement usage). This is by far the highest ratio of removal to avoidance known today.

These blocks are used as construction materials, and they also include Partanna concrete poured for the foundation, driveway, porch, sidewalks, roof tiles, and other features. When added all together, Partanna estimates one 1250 ft^2 house would reduce 200 tons of CO_2 reductions, with about a 2:1 removal-to-avoidance ratio. Thus, when complete, the 1000 homes will have reduced close to 200,000 tCO_2eq, the majority being high-value carbon removal offsets. This is equivalent to the annual emissions of approximately 21,500 passenger vehicles or the carbon footprint of roughly 11,000 American households.

Homes that reduce CO_2 either through avoided emissions and/or carbon dioxide reduction (CDR) can be sold as carbon credits. The value of these credits can be delivered as additional cash flows to the builders and/or the buyers of the houses. The avoidance credit is assumed here to be worth $\$85/tCO_2e$ following the average price of the EU ETS 1-month future contract from March 2022 to February 2023.[2] The removal credit is more valuable but varies depending on the parties involved in the transaction. Here, the price of one metric ton of removal credit is assumed to be

[2] Investing.com/commodities/carbon-emissions-historical-data.

Table 1 Benefits from grey carbon homes (Assuming \$85/ton of Avoided CO_2e and \$400/ton of removal CO_2e)

	CO_2–Grey carbon (avoided/reduced per home)	Valuation per house	Valuation of carbon credits for 1500 homes in US$ millions
1. Production of cement (avoided)	41.63 tCO_2e	\$3539	\$5.31
2. Production of cement (removal)	8.31 tCO_2e	\$3324	\$4.99
3. Construction methods (avoided)	9.92 tCO_2e	\$800	\$1.20
4. CDR during first 5 years (removal)	5.01 tCO_2e	\$2005	\$3.01
5. CDR during remaining 14 years (removal)	27.19 tCO_2e	\$10,876	\$16.31
6. Longer-lasting houses (avoided and removal)	78.88 tCO_2e	\$17,602	\$26.40
Total carbon credits	170.94 tCO_2e	\$38,145	\$57.22

\$400/tCO_2e.[3] The production of 1500 homes over 5 years is assumed based on an initial assembly line production rate of 100 homes per year.

Partanna homes have achieved carbon emissions reductions throughout the life cycle of the buildings, particularly in terms of embodied carbon. Here, we calculate the financial valuation of carbon credits created through five mechanisms: (1) avoided and (2) removal of CO_2e in cement production; (3) avoided CO_2e in house construction; (4) initial CO_2 removal and (5) drawdown of CO_2e over 20 years (carbon dioxide removal credits); and (6) avoided CO_2e in the long-term durability of the homes. (Valuation methodology provided in Annex)

Table 1 shows the relative contribution to climate mitigation from the six mechanisms, with the curing and long-term durability of the homes having the greatest impact on carbon sequestration.

The value of avoiding and removing CO_2 just in cement production amounts to carbon credits worth \$3539 and \$3324 per house, respectively. Construction methods for walls provide an additional avoided credit worth \$800 per house. Beyond the construction process, concrete carbonation in the first 5 years delivers additional credits worth \$2005 in the first 5 years and \$10,876 over the next 15 years.

[3] Removal credits are rare relative to avoidance credits, since there are few production processes which extract carbon. Direct air capture (DAC) costs between \$600 and \$2000 per Mt CO_2 equivalent per year, but there is an expectation that the cost would fall. See www.wri.org/insights/US-carbon-removal

Table 2 Carbon dioxide avoided and removed: from materials and home construction over 5 years

	Homes built	Avoided/reduced tCO_2e	Cash flows[a]
Year 1	100	6474	$895,146
Year 2	200	13,167	$1,877,869
Year 3	300	20,079	$2,948,170
Year 4	400	27,211	$4,106,049
Year 5	500	34,561	$5,351,506
Total	1500	101,492	$15,178,741

[a]The cash flow accounts for the difference in price of carbon credit based on whether avoided or reduced

Finally, the longer duration of housing (row 6) yields avoidance and removal credits worth an additional $17,602 per house. The sum of all these processes estimates 170.94 CO_2 credits per house, which is valued at $38,145 per house. This leads to a present value of $57.22 million for the 1500 houses produced over the 5 years.

AR6 report, WGIII (Cabeza et al., 2022b, Buildings), along with studies focused on the decarbonization of the building and cement industry within Saudi Arabia (Belaid, 2022), lays out policies and technological innovations needed to decarbonize the building industry, including information, financing, markets, and behavioral mechanisms. In this instance, the combination of technological solutions (carbon-negative cement) and carbon market mechanisms are in place and can incentivize governments to subsidize the building of carbon-negative homes as part of their NDCs, fulfilling both GHG emissions reduction pathway in the built industry while also contributing to multiple SDG targets.

Table 2 considers the cash flows and carbon credits that track the 5-year development project just in the production and construction of the 1500 homes without accounting for the duration of the homes and the extended carbonation of the concrete beyond the 5 years. A total of $15.18 million worth of avoided and removal carbon credits were produced during the initial 5-year period. Again, these credits can be sold, produce cash flows for the builder and the homeowner, or fund community projects contributing to the community's health, well-being, and sustainable development.

Additional co-benefits can be valued based on market price discovery and new science. For example, desalination plants avoid having to mitigate 12,041,944 gallons of brine waste over 5 years from the production of the 1500 homes by such approaches as evaporation ponds, estimated at a cost of $10.04 per cubic meter of brine. We calculate this translates into $433,741 in cost savings to the desalination plant from using brine as feedstock for 1500 homes. Further, as science can demonstrate the negative impact of brine on ocean productivity and climate mitigation, additional monetary values can be calculated. For now, science can confirm the toxicity and harm from brine dumping to the ocean habitat and biodiversity, providing an additional "co-benefit" that companies can claim in their SDG and ESG reporting.

3.3 Climate Adaptation and Sustainable Development in Small Island States

The model results confirm that when the principles of a circular economy are paired with the science of carbon-negative building materials to reduce waste and pollution in the ocean, the construction and building industry can respond to the needs of communities in a way that delivers multiple sustainable development goals while mitigating and adapting to climate change.

Reduce Poverty (SDG1) Building storm-resistant homes with additional cash flows from carbon credits can reduce poverty (SDG1) and increase equity by reducing housing costs and the likelihood of home repair or rebuilding. The growing demand for carbon credits means that carbon-negative homes represent not only a safe and healthy place to live but also a source of additional cash flows. This means that government-backed housing could subsidize costs associated with purchasing homes to make them more affordable for local citizens or to create a disaster relief fund. This is especially important in the Bahamas, where housing is scarce, and hurricanes have decimated many traditionally constructed homes. Owners stay out of extreme debt because they do not need to rebuild after every hurricane or other unexpected climate shock. The homes themselves become the "man-made" CDR grey carbon technology.

Greater Health and Well-Being (SDG3) Partanna construction leads to greater health and well-being (SDG3) as air pollution is reduced compared to other construction methods. Globally, more than 10 million people die each year from outdoor fine particulate emissions (PM2.5) generated by fossil fuel combustion (Vohra et al., 2021). Partanna materials avoid noxious NO_2 and particulate emissions since the cement alternative does not involve clinkering and the fossil fuel combustion required to produce the high heat required in Portland cement kilns. Beyond air pollution, Partanna houses are stronger. Because it is made with saltwater, it gets stronger in saltwater and can withstand hurricane-force winds that destroy traditional CMU-constructed homes. Unlike Portland cement, which is susceptible to corrosion, Partanna is resilient in corrosive environments and is not susceptible to sulphate attack. Its alkalinity protects structural steel from corrosion. In fact, it stands up to caustic industrial waste environments, where Portland cement typically fails. All this leads to a healthier, safer, stronger, and more durable home.

Clean Water and Sanitation (SDG6) Partanna changes the risk to clean water and sanitation (SDG6), as it does not tap into freshwater supplies. It gets the water it needs from desalination's concentrated reject brine, conserving water in an already water-constrained country (Monteiro et al., 2017). Concrete production alone is responsible for 9% of industrial water withdrawal (or 1.7% of total global water withdrawal) (Mycoo et al., 2022). In addition, freshwater through desalination can be produced without the resulting toxic effect on the ocean habitat by diverting the "waste" from desalination as a feedstock into the cement production process.

Safe and Affordable Housing (SDG11) Safe and affordable housing, aligned with goals (SDG11) to create sustainable cities and communities, can be funded through public–private arrangements, reducing deaths due to climate disasters, including water-related disasters, and supporting development in LDCs and SIDs using locally sourced sustainable building materials. Sourcing supplies locally where desalination plants are needed, as is the case for SIDs, increases local jobs and reduces transportation costs as well as the associated emissions.

Responsible Consumption and Production (SDG12) "Responsible Consumption and Production" (SDG12), including target 12.4, which achieves sound management of waste products throughout the production cycle, is supported as the "waste brine" from desalination is recycled, reducing the negative impact on the oceans.

Climate Change (SDG13) Most importantly, climate change (SDG13) is mitigated through the avoidance and removal mechanisms created through this innovative building product and process, along with strengthening the resilience and adaptation of communities living in the face of increased hurricane and flood risks. Stronger houses reduce deaths and can be part of natural disaster risk reduction strategies.

Ocean Health (SDG 14) Finally, ocean health (SDG 14) is supported by repurposing brine waste that would typically be dumped into the sea, where it can harm sea life. High salt content is toxic if it is not thoroughly dispersed, so additional equipment and energy are usually required to reduce these environmental impacts. Meanwhile, high salt content disrupts the ocean's water chemistry, and brine includes pretreatment chemicals that are unhealthy for ocean life. By utilizing brine instead of fresh water, Partanna's technology avoids all these challenges.

3.4 Application to the Gulf Region

Beyond small island developing states, this technology is also suited for regions relying on desalination. Sixty percent of the world's global water desalination capacity is situated in the Gulf region, with over 400 plants operating throughout the GCC. The region's desalinators have an opportunity to functionally repurpose brine produced through their industrial activity and prevent it from being released back into waterways.

Saudi Arabia is currently one of the world's leading construction markets, with development activity expected to undergo an unprecedented boom over the next 10 years. The country's leading developers—most of whom are linked to the Public Investment Fund—have significant sustainability KPIs.

Currently, just 2% of the world's annual carbon credit production takes place in the Middle East and North Africa. Building and operating multiple carbon-negative concrete factories in the region has the potential to grow the region's carbon credit production capacity significantly.

The Kingdom has been a vocal advocate of carbon removal technologies as a solution to combatting climate change, and this concrete product currently represents one of the few commercially viable carbon removal technologies that can make a meaningful impact in terms of climate change.

4 Discussion

Climate-vulnerable countries, such as SIDs, face significant challenges in the near term, needing to mitigate climate and deliver adaptation remedies while also growing their economies (Mycoo et al., 2022). We provide a case study in the Bahamas to demonstrate how countries can combine nature-based solutions with technology-based solutions to pivot their economies in a more sustainable direction. While natural capital provides a pathway for developing a nature-positive economy, nature cannot do it alone. Here, we describe how innovations in the Technosphere—the man-made environment—also contribute to climate mitigation and a healthier regenerative environment. Moreover, equity and human well-being can only be enhanced by a Technosphere that also follows nature principles—avoiding waste and embedding equity to deliver resilience and sustainability for the whole community.

Through the introduction of carbon-negative building materials and methods, we show that the building and construction industry can play a significant role in helping countries not only meet their decarbonization goals but also contribute to multiple SDGs. It is well understood that to stay within the 1.5 °C target, both nature-based solutions and technology-based solutions will be needed. Here, we describe the science behind a new "carbon dioxide reduction" technology and differentiate it as "grey carbon" stored in the built environment. Grey carbon, produced through geochemical processes, stores CO_2 into man-made products; just as blue and green carbon can store CO_2 in the biological world.

We show that a 1250 ft^2 home built with this cement can deliver 170.94 tCO_2e carbon credits over 20 years for a present value of $38,145 per home and $57.22 million for 1500 homes. As with high-quality green and blue nature-based solutions, which recarbonize the biosphere while also delivering benefits to people, this high-quality "grey" carbon provides durable long-term storage, carbonizing the built environment while also ensuring benefits for people and nature.

This carbon removal technology avoids the downside of other CDR technologies, such as BECCS and DACCS, which are not yet scalable. For example, grey carbon technology described here does not cause nature or human rights impacts, such as those raised by land-use changes needed for large-scale BECCS deployment (Gunther & Ekardt, 2022); or requires high energy needed by DACCS technology; and is ready to be deployed.

Climate solutions must be systemic in nature—addressing the nexus of climate-biodiversity-equity simultaneously (Nature Climate Change, 2022) as these issues are now global interdependencies. The combination of a carbon-negative product

with a circular production design, joined with financial mechanisms to support communities, can maximize the benefits without creating additional negative externalities. Using valuation methods for the carbon and nature services derived from this grey carbon product makes the positive externalities more transparent and can incentivize governments, communities, and the market to behave differently. While climate policy tends to differentiate nature-based versus technology-based CDR, we demonstrate how future-fit economic development must include both, providing even greater acceleration of the transition to a healthy and climate-stable future. Estimates of how much CDR will be provided by nature vary—with the IUCN and UNEP study estimating as high as 10-18GtCO2e per year by 2050,[4] whereas other studies also highlight the importance of technological solutions to reach net zero GHG (IEA, 2021). By combining green, blue, and grey climate solutions, humanity can begin to design a future in which development and growth can be delinked from pollution and the triple nexus of climate–biodiversity–people are rejoined in a cycle of well-being and regeneration.

Author Contributions RC, TC, NH, DN, and RS contributed to the conception and design. DN and RS wrote the first draft of the manuscript. TC performed the financial analysis. RC and NH reviewed and added to the draft and references. All authors contributed to manuscript revision, read, and approved submitted version.

Conflict of Interest Thomas Cosimano and Dinah Nieburg are co-founders in Blue Green Future, LLC, which was contracted by Partanna to perform the valuation of their carbon credits. They declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Annex: Valuation Methodology and Assumptions

The typical house is 1250 ft^2 which uses 146 cubic yards of concrete per house. This allows for the calculation of concrete in the third column of Table A1. In the production of concrete, 32% consists of cement, which yields column four in Table A1.

Table A.1 Proposed program for production of homes over five years along with quantity of concrete and cement used

Year	Homes	Concrete	Cement
1	100	14,596	4671
2	200	29,193	9342
3	300	43,789	14,012
4	400	58,385	18,683
5	500	72,981	23,354

[4] IUCN and the UN Environment Programme (NBSCCM.pdf (unep.org)).

Table A.2 Implication of proposed production of homes over five years in Table A1 in terms of emissions of tCO_2e, use of electricity, net emissions, and present value following Eq. (A1)

Year	Total emissions of tCO_2e	MW of electricity per year	Electricity emissions per year	Net emissions	Present value per year
1	4413	40	26	4388	$372,967
2	8827	80	51	8776	$731,309
3	13,240	120	77	13,164	$1,075,454
4	17,654	160	102	17,551	$1,405,822
5	22,067	200	128	21,939	$1,722,822

The emission factor for cement is 0.9449 tCO_2e per ton of cement, with a range of [0.8898, 1.0000]. Multiplying this efficiency factor by the last column in Table A1 yields the second column in Table A2. The production of each house uses 0.40 MW per house, with the emission factor of the electric grid being 0.64 tCO_2e per MW of electricity. The third column in Table A2 is found by multiplying 0.4 MW per house by the number of homes in the second column in Table A1. The emission of tCO_2e, because of the use of electricity, is found by multiplying column the third column in Table A2 by the emission factor of 0.64. The result in column 4 of Table A2 is subtracted from column 2 of Table A2 to yield the net emissions of tCO_2e in column 5 of Table A2.

The next step is to find the economic value of the net emissions by multiplying column 5 of Table A2 by the $85 price of tCO_2e to yield the cash flow. To add these cash flows, they must be discounted by

$$PV_i = \frac{1}{(1+r)^i} \quad \text{for } i = 1, \ldots 5, \tag{A1}$$

because $1 in the future is equivalent to PV_i since this amount can be placed in a financial investment at the interest rate of r in the current time period and receive $(1 + r)^i$ in i years. By multiplying the cash flow in each year by PV_i, for $i = 1, \ldots, 5$, the result is the last column in Table A2. These values can now be added since they are in terms of today's value. This yields a present value of $5,308,374. This corresponds to the first number in Table 1 for the avoidance of emissions. By dividing this amount by the 1500 homes, we obtain the next to last term $3,539 in Table 1 for the value of the avoidance of emissions per house. Finally, the avoidance of emission 41.63 per home is found by dividing the previous number by the $85 price of tCO_2e.

The tCO_2e removed in the initial production of Partanna concrete is 6.00% of the concrete. As a result, the third column of Table A1 is multiplied by 6% to obtain the second column in Table A3 for each year. The price for the removal credits is $400, so the third row in Table A3 provides the cash flow from the initial production of Partanna concrete. Equation (A1) is used to convert the cash flow each year into the present value for each year in the last column of Table A3. The sum of these

Table A.3 Removal of tCO_2e from production of Partanna homes over five years along with the corresponding cash flow, and present value following Eq. (A1)

Year	Initial Removal of tCO_2e	Cash flow Initial removal of tCO_2e	*PV* initial removal
1	876	$350,311	$350,311.11
2	1752	$700,622	$686,884.53
3	2627	$1,050,933	$1,010,124.31
4	3503	$1,401,244	$1,320,423.94
5	4379	$1,751,556	$1,618,166.59
Total	13,137	$5,254,667	$4,985,910
Per House	8.76		$3324

Table A.4 tCO_2e from production of Partanna homes using alternative construction methods over five years along with the corresponding cash flow, and present value following Eq. (A1)

Year	Home	tCO_2e	Cash flow	*PV*
1	100	992	$84,289	$84,289
2	200	1983	$168,579	$165,273
3	300	2975	$252,868	$243,049
4	400	3967	$337,157	$317,711
5	500	4958	$421,446	$399,351
Total	1500	14,875		$1,199,673
			Per home	$800

present values is $4,985,910, which corresponds to the last item in the row titled Production of Cement Removal. This amount is divided by 1500 homes to yield the $3324 value of the initial production of concrete per house. Finally, dividing the value per house by the $400 price of a removal credit yields 8.31. However, if the total tCO_2e removed in the initial production is found by adding the first five values in the second column of Table A3, it yields 13,137 tCO_2e removed or 8.76 per house. This number completes the second row of Table 1.[1]

Table A4 provides the calculations for the "Construction Methods Avoided" row of Table 1. These methods include the combination of paint (interior and exterior of the wall), Hardie board, insulation, Gypsum board, and plaster into one wall produced in the factory. In addition, there is a Bitumen roofing system. These methods save 9.92 tCO_2e in avoided credits, which are worth $85 each. These values are used to calculate the total tCO_2e avoided per year, as well as the cash flows. The present value of these cash flows is determined by multiplying the cash flows by Eq. (A1) at an interest rate of 2%. The sum of the present values of these cash flows is $1,199,673 or $800 per house. This completes the numbers in the third row of Table 1 for "Construction Methods Avoided".

The CDR from the carbonation of concrete over its lifetime is calculated using the1.5% of concrete per year for 15 years. In the first year, the tCO_2e removed is 1.5% of 14,596 or 219 tCO_2e from the first year in column three of Table A1. This removal is called Generation 1 of concrete, which lasts 15 years from 2023 to

[1] The 8.31 is smaller, since the discounting reduces future numbers smaller values.

Table A.5 The carbon dioxide removal for the production of homes over 5 years from carbonation of concrete over its lifetime of 15 years using the1.5% of concrete per year

	Generation					Sum
Year	1	2	3	4	5	per year
2023	219					219
2024	219	438				657
2025	219	438	657			1314
2026	219	438	657	876		2189
2027	219	438	657	876	1095	3284
2028	219	438	657	876	1095	3284
2029	219	438	657	876	1095	3284
2030	219	438	657	876	1095	3284
2031	219	438	657	876	1095	3284
2032	219	438	657	876	1095	3284
2033	219	438	657	876	1095	3284
2034	219	438	657	876	1095	3284
2035	219	438	657	876	1095	3284
2036	219	438	657	876	1095	3284
2037	219	438	657	876	1095	3284
2038		438	657	876	1095	3065
2039			657	876	1095	2627
2040				876	1095	1971
2041					1095	1095

2037, in column 2 in Table A5. The homes produced in the second year use 29,143 cubic yards of concrete, which has led to 438 tCO_2e being removed. The amount for Generation 2 lasts for 15 years, from 2024 to 2038. The third through fifth generation tCO_2e removed is calculated following the same procedure. To obtain the total tCO_2e removed per year, the sum across the row for that year is recorded in the last column of Table A5.

Given the amount of tCO_2e removed each year in the last row of Table A5, the cash flow from the CDR per year is found by multiplying this number by the $400 price for the tCO_2e removed. This result is recorded in the second row of Table A6. The present value of these cash flows at the 2% interest rate is found using Eq. (A1) for years $i = 1, \ldots, 15$. For row (4) in Table 1, labeled "CDR During the First Five Years," sum the *PV* from 2023 to 2027 to yield $3,006,837 for the last item in this row. If this amount is divided by 1500 homes, each house has removal credits worth $2005. If this value is divided by the $400 price of CDR, then 5.01 tCO_2e will be removed over the 5 years. These results complete the fourth row of Table 1. Following the same procedure for the years 2028 to 2041 yields the results in the fifth row of Table 1, labeled "CDR During Remaining 14 Years (Removal)."

The last two rows in Table 1 account for the Partanna houses lasting three times the traditional form of construction. If the first five numbers in the last column are added together, then the present value of producing 1500 homes is $30,814,303, which can last up to 90 years. These homes replace Portland cement concrete block homes, which last about 30 years. As a result, the Portland cement homes would

Table A.6 The cash flow per year at a price of $400 for removal credits listed in the last column of Table A5

Year	Cash flow	*PV*
2023	$87,578	$87,578
2024	$262,733	$257,582
2025	$525,467	$515,163
2026	$875,778	$858,606
2027	$1,313,667	$1,287,908
2028	$1,313,667	$1,287,908
2029	$1,313,667	$1,287,908
2030	$1,313,667	$1,287,908
2031	$1,313,667	$1,287,908
2032	$1,313,667	$1,287,908
2033	$1,313,667	$1,287,908
2034	$1,313,667	$1,287,908
2035	$1,313,667	$1,287,908
2036	$1,313,667	$1,287,908
2037	$1,313,667	$1,287,908
2038	$1,226,089	$1,202,048
2039	$1,050,933	$1,030,327
2040	$788,200	$772,745
2041	$437,889	$429,303

Table A.7 Calculation of present value of carbon credits from Partanna which last 90 years which avoids the production of Portland houses over three 30-year periods

***PV*for 1st 30 years**	$30,814,303
2nd @ 30 years:	$17,011,680
3rd @ 60 years:	$9,391,653
Subtotal	$26,403,333
Total valuation:	**$57,217,635**
Per house:	**$38,145**

have to be rebuilt. This means that Partanna concrete homes will avoid or remove the construction of Portland homes in 30 years and 60 years. The replacement of the Portland homes would have a present value of $17,011,680, which is the product of $30,814,303 and Eq. (A1) at an interest rate of 2% and $i = 30$. Similarly, the replacement of the Portland homes in 60 years would have a present value of $9,391,653, which is $30,814,303 and Eq. (A1) at an interest rate of 2% and $i = 60$. These benefits are added together in Table A7 to yield $57,217,635 or $38,145 per house. These are recorded in the last line of Table 1. To obtain the last quantity in the last row of Table 1, notice that the *PV* of the first 30 years is 54% of the total value and 46% follows from the longer-lasting houses. The first 30 years avoids or removes 92.06 tCO_2e, so that the total avoidance and removal is 92.06/0.54 = 170.94 tCO_2e over the entire duration of the Partanna homes. This means 78.88 tCO_2e are attributed to the longer length of the Partanna homes. This completes the last two rows in Table 1, when the same procedure is applied to the value of each home, as well as the 1500 homes.

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Part II
Special Zones

Resilience of Small Islands: Unveiling Nature-Based Solutions for Sustainable Futures

Nathalie Hilmi, Matías Crisóstomo, Angela Bermudo, Ralph Chami, Nicolas Imbert, and Carlos M. Duarte

Abstract This chapter explores the inherent resilience of small islands in the face of multifaceted challenges and examines the pivotal role of nature-based solutions in securing their sustainable trajectories. Small islands, possessing unique ecosystems and cultural heritages, face heightened vulnerabilities due to their size, geographical isolation, and exposure to various environmental, social, and economic stressors. Amid these challenges, the concept of resilience emerges as a beacon of hope, representing the capacity of these islands to adapt, withstand, and transform.

Drawing upon a comprehensive review of literature and case studies, this chapter investigates the diverse dimensions of resilience exhibited by small islands. It examines the intricate interplay between natural systems and human societies, showcasing how nature-based solutions serve as a catalyst for resilience-building. From leveraging ecosystem services to integrating traditional knowledge and innovative technologies, these solutions offer sustainable pathways that bolster the resilience of small islands.

This chapter highlights the significance of nature-based approaches in mitigating the impacts of climate change, biodiversity loss, and socioeconomic vulnerabilities.

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It sheds light on successful initiatives and best practices, elucidating their contributions to enhancing adaptive capacities and fostering sustainable development in small island contexts.

Furthermore, this chapter emphasizes the need for holistic and participatory approaches, engaging local communities, policymakers, and stakeholders in co-designing and implementing nature-based solutions. It advocates for the integration of indigenous wisdom, community-based management, and innovative strategies aligned with local contexts to amplify resilience efforts.

Ultimately, this chapter aims to underscore the importance of nature-based solutions as indispensable tools in fortifying the resilience of small islands. By recognizing and harnessing the intrinsic capacities of ecosystems, societies, and cultures, it advocates for a paradigm shift toward sustainable futures, where small islands thrive in harmony with nature.

Keywords Small Island Developing States · Resilience · Nature-based solutions · Climate change

1 Introduction

The US and European nations have released about 50% of cumulative greenhouse gasses (GHG) responsible for climate change since the Industrial Revolution (Ritchie et al., 2023), followed by China and France (Maizland, 2021). Yet the resulting changes impact across the entire planet. Particularly vulnerable are small island developing states (SIDS), which often have low-lying national territories. Hence, they are at greater risk of flooding with rising sea levels and are particularly vulnerable to climate extremes, such as droughts and cyclones, intensifying with climate change (Mycoo et al., 2022).

At the same time, ocean and coastal areas are massive options for GHG emission reduction and mitigation. Around 93% of the heat produced by GHG emissions is absorbed by oceanic waters (Stocker et al., 2013). The special report "The Ocean as a Solution to Climate Change" (Hoegh-Guldberg et al., 2019) projects that nearly four carbon dioxide equivalent billion tonnes can be reduced by ocean-based climate solutions by 2030 and by 2050 around 11 billion tonnes annually (Stuchtey et al., 2020). Oceanic ecosystems are being modified rapidly due to climate change, causing high risk, which can lead to irreversible changes (Pörtner et al., 2014). "Climate change is a direct driver that is increasingly exacerbating the impact of other drivers on nature and human well-being" (IPBES, 2019). Therefore, climate change has a massive impact on the achievement of the Sustainable Development Goals (SDGs) in a holistic context, especially for SIDS.

It is well known that the marine environment has always been fundamental to life development in SIDS. The world's highest marine biodiversity can be found in the coral triangle, which includes the waters of the Philippines, Papua New Guinea, Indonesia, and Malaysia, integrating a vast range of reef-associated organisms

(Hoeksema, 2007; Burke et al., 2011; Lam et al., 2019). It is well known that coral reefs provide income, food, well-being, and coastal protection to countries around the Indian Ocean and Asia (Lam et al., 2019). The SIDS have limited territories on land but huge states on the ocean, as they are custodians to one-third of the ocean's exclusive economic zone of all nations (UN-OHRLLS, 2020). Climate change mitigation and adaptation options for SIDS are limited due to their small territories and economic capacity, so nature-based solutions are an important option because of their relatively low cost and co-benefits (Pörtner et al., 2023). Because of their limited territory, nature-based climate solutions for SIDS are best deployed in their extensive marine territory, including, for instance, blue carbon strategies (Duarte et al., 2013).

The SIDS are at the frontline with regard to challenges related to the triple crises of pollution, climate change, and biodiversity loss. Anthropic impacts directly affect marine and terrestrial ecosystems, endangering their well-being and survival (Pedersen Zari et al., 2019). Therefore, nature-based solutions (NbS) have been considered an imperative option, as they can provide important benefits that can help mitigate the triple crisis impacts and maintain SIDS and their well-being.

Moreover, regarding the importance of integrating and including indigenous peoples and local communities (IPLCs) and their traditional knowledge, as Pedersen Zari et al. (2019) expresses: "Pacific SIDS, with significant bodies of traditional knowledge and emerging NbS experience, can also inform global responses to both urbanization and climate change."

2 The Significance of Nature-Based Approaches in Mitigating the Impacts of Climate Change, Biodiversity Loss, and Socioeconomic Vulnerabilities

The Organization for Economic Cooperation and Development report (OECD, 2018) describes SIDS as a political and technical term used to identify countries composed of single islands or archipelagos that face increasing and specific challenges due to their remoteness, geographic characteristics, small landmass, high exposure to external economic and environmental impacts, small populations, small size of economy, among others (Hilmi et al., 2021a). Their strong dependence on marine and coastal resources renders them particularly vulnerable to biodiversity loss and degradation (Cherian, 2007), compounded by their geographical isolation and limited landmass, rendering them acutely exposed to environmental perturbations. In addressing these intricately interlinked challenges, the adoption of nature-based approaches emerges as an imperative strategy for supporting the resilience of small islands, grounded in empirical evidence and scientific rigor. Yet, resources and adaptive capacity are usually limited in these States (UNFCCC, 2005). In particular, these SIDS have limited policy and technical tools to identify, measure, adapt, and mitigate the impacts of climate change and the loss of biodi-

versity. The IUCN (International Union for Conservation of Nature) defined NbS as "actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges effectively and adaptively, while simultaneously providing human wellbeing and biodiversity benefits" (Cohen-Shacham et al., 2016; Hilmi et al., 2023b).

3 Outcomes from the Application of Nature-Based Solutions

3.1 Climate Change Resilience

The SIDS rank among the most vulnerable countries to climate change effects (CDKN, 2014) and are highly dependent on marine and coastal ecosystems for income, livelihoods, and well-being (Buckwell et al., 2020; Grantham et al., 2020; Veron et al., 2019; Selig et al., 2019; Hills et al., 2013). However, in most cases their resources are depleted due to pressures from increasing human population and development. For instance, the massive harvesting of fish and other reef animals aggravates the pressure on marine and coastal ecosystems (Blaschke et al., 2017). Also, climate change worsens the risks SIDS face, mainly sea level rise, storm intensity and rainfall, and long droughts, jointly affecting water security (Blaschke et al., 2017). Small islands are, therefore, on the frontline of climate change impacts, facing severe risks from rising sea levels, extreme weather events, lost protection from coral reefs and changing precipitation patterns. Empirical studies underscore the salient role of nature-based solutions in bolstering climate change resilience on small islands. Coastal ecosystems, exemplified by mangroves and coral reefs, have been demonstrated as effective natural barriers mitigating the impact of storm surges and erosion (Alongi, 2015; IPBES, 2019; Spalding et al., 2014). Afforestation initiatives, particularly those focusing on indigenous vegetation, contribute significantly to carbon sequestration, thereby mitigating greenhouse gas emissions (Pan et al., 2011; Chazdon et al., 2016). Robust empirical evidence supports the assertion that conserving and restoring these ecosystems enhances the adaptive capacity of small islands in the face of climate change-induced challenges. Furthermore, in diverse atolls in Pacific SIDS, the ecosystem and natural coastal barriers lost have increased the risk of saltwater intrusions in freshwater aquifers due to storms and wave action, adding pressure to water and, therefore, food security on these atolls (White et al., 2007). This pressure greatly impacts poor individuals, especially those residing in informal settlements (McEvoy et al., 2017). In addition, pollution and destruction of marine and coastal ecosystems can detrimentally affect their biodiversity; consequently, individuals are forced to leave their homesteads and migrate to cities, reinforcing cycles of ecosystem degradation (Pedersen Zari et al., 2019).

By conserving coastal and marine ecosystems, SIDS could experience significant co-benefits from adapting to climate change. Also, NbS mitigate climate change through the carbon sequestration function of marine coastal vegetation, thus

contributing to achieving global climate goals. Hence, NbS can be an effective mechanism for producing beneficial environmental outcomes, especially in the context of developing nations (Techera, 2023).

3.2 Biodiversity Conservation and Marine Protected Areas

The biodiversity of small islands is often exceptionally rich and unique, but, as scientific literature has unequivocally underscored, this biodiversity is also highly vulnerable to various anthropogenic pressures. Sustainable land-use practices have demonstrated their capacity to curb habitat loss and combat invasive species (Arneth et al., 2020; Pörtner et al., 2021; IPCC, 2022). Protection and restoration of marine ecosystems, through measures like the establishment of Marine Protected Areas, are evidenced as effective in preserving the unique biodiversity of small islands (Faiza et al., 2010; Rees et al., 2018).

By prioritizing the protection and restoration of biodiversity hotspots, small islands can enhance their adaptive capacity to environmental changes while simultaneously nurturing the cultural identity embedded in their natural surroundings. Integration of traditional ecological knowledge ensures that conservation strategies are culturally attuned and foster coexistence between human communities and diverse ecosystems (Berkes, 2012).

3.3 Socioeconomic Co-benefits

Nature-based solutions, NbS, offer avenues for diversifying economic activities and fostering sustainable practices. For instance, promoting agroecological approaches, sustainable fisheries management, and eco-friendly tourism practices align with the principles of resilience-building. Instead of building engineered solutions (gray infrastructure), NbS is considered an opportunity and a feasible option through coral reefs, mangroves, and seaweeds that can dissipate oceanic energy, helping to prevent coastal erosion, storm surges, and flooding, among others (Wedding et al., 2022). Also, sustainable fisheries management has proven instrumental in mitigating external market fluctuations and ensuring long-term socioeconomic stability (Costello et al., 2016). The incorporation of traditional knowledge in resource management practices enhances the adaptive capacity of communities, aligning socioeconomic development with the ecological carrying capacity of the islands (Fernández-Giménez, 2000).

It has been defined that NbS most important advantage is to raise the quality and quantity of ecosystem services and decrease the negative impacts of ecosystem loss and climate change. Also, the need for a holistic perspective can produce mutually beneficial situations between the multiple interconnected stakeholders and sustainable systems (environment–economic–social), as NbS require limited

infrastructure and create a cascade of direct and indirect social benefits for the community delivering the actions.

Among NbS benefits include the facilitation of local food resilience and limited usage of fossil fuel reliant resources and imported technology in an environment where the cost of which is tremendously high and the availability can be jeopardized due to borders restrictions, controls, or extreme health or meteorological events, such as the COVID-19 pandemic.

In addition, it is important to consider the potential of NbS to empower vulnerable societies to better adapt to natural disasters and climate change and address trickle-down outcomes such as water, food, and energy security problems in an efficient and culturally appropriate manner (Pedersen Zari et al., 2019). In this regard, there is a need for the creation of proper context to produce a list of socioeconomic benefits and co-benefits within NbS.

One of the key strengths of NbS lies in its ability to generate multiple co-benefits. For SIDS, these co-benefits extend beyond environmental gains to encompass social and economic advantages. Green infrastructure projects, such as reforestation or sustainable land use planning, enhance ecosystem services, support local livelihoods, and simultaneously contribute to climate change adaptation. This integrated approach promotes a harmonious relationship between nature and society, holistically reinforcing small island resilience. Some examples of NbS in Pacific SIDS include estuarine and coastal mangrove restoration; afforestation and reforestation projects; ridge-to-reef river restoration projects; and rehabilitation of urban green spaces; among others. These examples help to overcome challenges in terms of climate change adaptation and mitigation, coastal effective management, biodiversity conservation, food, water and energy security, and disaster risk management, among others (Cohen-Shacham et al., 2016; Pedersen Zari et al., 2019).

In conclusion, NbS offer a comprehensive and adaptive toolkit for SIDS. This empirical foundation supports the proposition that a comprehensive, nature-centric approach aligns with the unique contexts of small islands, embodying a paradigm shift toward sustainable and resilient trajectories. The synergy between indigenous knowledge systems and scientifically grounded strategies constitutes a robust framework for navigating the intricate interplay of climate change, biodiversity loss, and socioeconomic vulnerabilities. By integrating these solutions into sustainable development strategies, small islands can unlock their inherent resilience and pave the way for a future where both their ecosystems and communities thrive in harmony.

Case Studies

The following country case studies highlight successful initiatives and best practices, elucidating their contributions to enhancing adaptive capacities and fostering sustainable development in small island contexts.

1. *Palau—Coral Reef Conservation and Sustainable Fisheries Management*

Initiative Overview: Palau, a Pacific Island nation, has implemented a comprehensive coral reef conservation and sustainable fisheries management initiative. The

Palau National Marine Sanctuary, established in 2015, designates 80% of Palau's maritime territory as a no-take zone, protecting coral reefs and marine biodiversity.

Contributions: This initiative has significantly enhanced adaptive capacities by preserving critical marine ecosystems. The no-take zone acts as a natural buffer against overfishing, ensuring sustainable fisheries and supporting the resilience of local communities dependent on marine resources. The approach aligns with indigenous resource stewardship principles, contributing to ecological and socioeconomic sustainability.

2. *Seychelles—Blue Economy Strategy*

Initiative Overview: Seychelles, an archipelago in the Indian Ocean, has embraced a Blue Economy Strategy that emphasizes sustainable development, marine conservation, and economic diversification. The country has designated a substantial portion of its Exclusive Economic Zone (EEZ) as protected areas and promotes sustainable fisheries practices.

Contributions: Seychelles' Blue Economy Strategy showcases the integration of nature-based solutions in economic development. By prioritizing the sustainable use of marine resources, the initiative contributes to both biodiversity conservation and socioeconomic stability. The approach underscores the importance of holistic strategies that balance ecological health with economic development in small island contexts.

3. *Cuba—Agroecological Practices in Isla de la Juventud*

Initiative Overview: Isla de la Juventud in Cuba has implemented agroecological practices to enhance food security and reduce environmental impacts. Through the promotion of diversified and sustainable agricultural practices, such as permaculture and organic farming, the island aims to reduce dependence on external inputs and foster local resilience.

Contributions: The agroecological initiatives in Isla de la Juventud contribute to sustainable development by strengthening local food systems and by reducing the ecological footprint of agriculture. This approach aligns with the principles of nature-based solutions, leveraging traditional knowledge alongside innovative practices to enhance adaptive capacities in the face of climate variability and economic uncertainties.

4. *Maldives—Sustainable Tourism Practices in Baa Atoll Biosphere Reserve*

Initiative Overview: The Maldives, particularly in the Baa Atoll Biosphere Reserve, has implemented sustainable tourism practices to balance economic development with environmental conservation. This includes strict regulations on construction, waste management, and coral reef protection.

Contributions: The sustainable tourism practices in the Maldives contribute to the resilience of small islands by preserving marine ecosystems and supporting the tourism-dependent economy (Hilmi et al., 2023a). The approach aligns with

nature-based solutions by recognizing the intrinsic value of the natural environment and incorporating sustainable practices to ensure long-term viability and economic stability.

5. *Barbados—Integrated Water Resource Management*

Initiative Overview: Barbados has implemented an Integrated Water Resource Management (IWRM) strategy to address water scarcity issues. This initiative combines nature-based solutions such as rainwater harvesting, watershed management, and reforestation to ensure a sustainable and resilient water supply.

Contributions: The IWRM strategy in Barbados exemplifies the integration of nature-based solutions to enhance adaptive capacities in the face of climate change and increasing water demand. By aligning water management practices with natural processes, the initiative fosters environmental sustainability and resilience in a small island context.

6. *Hawai'i—Ahupua'a Management for Watershed Conservation*

Initiative Overview: In Hawai'i, indigenous communities have revived traditional Ahupua'a land management practices. These practices involve holistic management of watersheds, incorporating community-led reforestation, taro cultivation, and fisheries management to restore and maintain ecological balance.

Contributions: Local engagement in Ahupua'a management empowers indigenous communities to actively participate in conservation efforts. The integration of traditional knowledge ensures sustainable resource use and promotes resilience by aligning ecosystem management with cultural values.

7. *New Zealand—Māori-Led Marine Protected Areas (rāhui)*

Initiative Overview: Māori communities in New Zealand have established marine protected areas known as rāhui. These areas are self-imposed fishing restrictions aimed at preserving marine resources and allowing ecosystems to regenerate.

Contributions: Māori-led rāhui initiatives showcase the importance of local governance in conservation. These community-driven marine protected areas not only contribute to biodiversity conservation but also empower indigenous communities to actively manage and protect their ancestral marine territories.

8. *Vanuatu—Community-Managed Marine Conservation Areas*

Initiative Overview: In Vanuatu, communities have taken a lead role in managing marine conservation areas. These initiatives involve the establishment of locally managed marine areas (LMMAs) where communities actively participate in monitoring and enforcing sustainable fishing practices.

Contributions: The engagement of local communities in the management of marine conservation areas in Vanuatu fosters a sense of ownership and responsibility. By incorporating indigenous knowledge and traditional management systems, these initiatives contribute to both ecological resilience and community well-being.

9. *Jamaica—Community-Based Coral Reef Restoration*

Initiative Overview: Jamaican fishing communities have initiated community-based coral reef restoration projects. These projects involve local fishers actively participating in coral planting and reef rehabilitation efforts.

Contributions: The involvement of local communities in coral reef restoration not only aids in the recovery of marine ecosystems but also provides alternative livelihoods for fishers. This community-based approach aligns with indigenous stewardship perspectives and ensures marine resource sustainability.

10. *Fiji—Traditional Qoliqoli Management*

Initiative Overview: In Fiji, the traditional practice of Qoliqoli management involves indigenous communities in the sustainable use and protection of coastal and marine resources. Local communities actively participate in decision-making processes regarding fishing practices and resource allocation.

Contributions: The Qoliqoli management approach in Fiji illustrates the effectiveness of integrating traditional knowledge into contemporary conservation strategies. By empowering local communities to manage their resources, this initiative enhances both ecological sustainability and community resilience.

11. *Ouvea—Implementation of Local Nature-Based Solutions to Keep Shore Dwellings and Natural Habitats Safe*

Initiative Overview: The Loyalty Islands Province in New Caledonia (four islands—16,000 inhabitants) has launched and codesigned with the civil society their local resilience plan, while the first priority was to protect from seashore level rise and ensure livability for their location populations, keeping housing premises safe, and encouraging the development of food security and resilience, as well as energy autonomy and preservation of species and natural habitats.

Contributions: The Province des Iles Loyauté jointly implemented the proof of concept and prototyping of 100 m of locally-build nature-based solutions from local wood and pruning waste with the customary district governance authority. The methodology to initiate this project relies on an important involvement of local communities, building the solutions from their own forces and exchanging with scientists and customary knowledge to move forward and consolidate their own approach to restoration (Green Cross France & Territories, 2023).

A few months after the proof-of-concept launch, the results are very encouraging, demonstrating economic efficiency, projected benefits for shoreline preservation, and improved safety for nearby dwellings. Additionally, local communities have been recognized and empowered to maintain the installations and replicate them as needed. The initiative also reveals further advantages, such as habitat restoration for juvenile marine species and reduced impacts from extreme events on the surrounding coastlines. The prototyping phase also highlighted the importance of preserving local scientific data and knowledge, ensuring that local communities receive information on outcomes in return for their dedication and investment.

Additionally, it emphasized the need to adhere to circular economy principles, particularly by using wood and pruning waste rather than healthy wood resources as the project scales up.

12. *Bahamas*

Initiative Overview: The discovery of the largest seagrass meadows in the world in the Bahamas, extending up to 92,000 km^2 (Gallagher et al., 2022), led to the development of a national blue carbon project based on the conservation and restoration of seagrass, which had declined due to low intensity, but persistent impacts. A Climate Change and Carbon Market Initiatives Act (https://opm.gov.bs/wp-content/uploads/2022/04/Climate-Change-and-Carbon-Market-Initiatives-Bill-2022-19-April-2022.pdf) was passed by the Bahamas Parliament (a) to enable the Government to create incentives and implement initiatives to support the overall global target of greenhouse gas emissions reduction consistent with its Nationally Determined Contributions, (b) to ensure compliance by the Bahamas of its obligations under the Paris Agreement, and (c) to enable the establishment of a market in the Bahamas to trade in carbon credits. A public company, Carbon Management Ltd., was established to trade the carbon credits, which are currently being assessed through a thorough evaluation of the current and past extent of the seagrass meadow and the scope to create additional carbon sequestration through conservation and restoration measures along with reducing pressures leading to seagrass losses, such as resulting from poor water quality.

Contributions: Small island developing states (SIDS) such as the Bahamas are already experiencing the impact of climate change, such as increased and more powerful cyclones, sea level rise, and ocean warming events impacting fish stocks and species migration. These communities need funding both for mitigation and climate adaptation. Nature-based solutions comprise funding through carbon and, in the future, biodiversity, as well as credits for projects that support communities in taking action to protect and restore natural habitats, such as mangroves and seagrass.

The NbS not only mitigates carbon through its carbon sequestration capacities, drawing CO_2 out of the atmosphere as a "nature-tech" CDR solution but it also ensures better coastal protection and other benefits for sustaining marine species. SIDS such as the Bahamas have blue natural assets—seagrass, salt marsh, mangroves—that can provide climate mitigation through their capacity to absorb and store carbon. The Bahamas has the world's largest known seagrass meadow, with 30% of the global extent (Gallagher et al., 2022), leading to a massive potential for climate finance to come into the country against carbon credits sourced from avoidance of further losses and restoring the extensive seagrass ecosystem. The meadow extends 92,000 km^2 (Gallagher et al., 2022) but has likely experienced a decline, evidence for declines of carbon burial in Bahamian seagrass meadows since the 1980s, suggesting opportunities to enhance carbon sequestration through blue carbon strategies aimed at avoiding further losses and restoring Bahamas seagrass meadows, as well as damaged mangrove forests (Fu et al., 2023). If the Bahamas were to restore the seagrass carbon removal capacity lost, the carbon credits alone could be worth more than US$150 billion. On the other hand, the Bahamas could

choose to implement "avoided loss" of seagrass, thereby implementing protection actions that would involve both legislative as well as enforcement. In either case, the protection and restoration of seagrass meadows would generate other ecosystem benefits, such as enhanced fisheries and coastal protection. Moreover, enhancing the resilience of ecosystems has spillover effects on employment, poverty alleviation, and, ultimately, stabilizing people on their land.

These kinds of nature-based blue carbon projects have potential throughout SIDS as these countries map their coastal habitats and prioritize protecting and restoring these habitats alongside their marine spatial planning efforts that grow their blue economy (Hilmi et al., 2021b). The value of ecosystem services—the services from regulating, structuring, and culture—has now come into the cost-benefit equation for economic development. Through these NbS, a new class of assets is brought into the planning process, recalibrating the balance between economic activity that extracts from nature and economic activity that restores nature and ensures the sustainability of the natural capital.

4 The Need for Holistic and Participatory Approaches

In the face of escalating environmental and socioeconomic challenges, the resilience of small islands hinges on innovative and sustainable approaches. Central to this is the adoption of NbS, which offers a promising pathway to address the unique vulnerabilities of these islands. This chapter emphasizes the critical need for holistic and participatory methods in identifying, designing, and implementing NbS, ensuring they are well aligned with small island ecological, cultural, and socioeconomic contexts.

International cooperation to address climate change through policy and law have been considered a vital topic in the literature (Nwabueze & Techera, 2021; Sands et al., 2018). The legal regime focuses on oceans, with the National Adaptation Plan process, while the Nairobi Work Program focuses on coastal and marine ecosystems (Techera, 2023). The lack of integration of the multiple legal instruments is a challenge that States have to solve. Implementing NbS to climate change adaptation and mitigation offers States a path to achieve development and environmental goals (Techera, 2023).

In 2017, at the launch of the Ocean Pathway, the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP) formed a new alliance with SIDS to develop a unified policy approach for climate response and ocean-focused urban development strategies for islands. In addition, UNESCAP guaranteed its help for building resilience, decreasing GHG emissions and protecting marine health in coastal islands (UNESCAP, 2017). Moreover, the UNFCCC Technology Executive Committee published in 2022 a draft policy brief on NbS which recognizes that climate change effects include other challenges related to biodiversity (UNFCCC, 2022), and provides recommendations for governments to consider integrating adaptation in climate change policies related to marine areas

(NbS Initiative, 2022). Additionally, a section focused on addressing biodiversity loss, its degradation, and climate change through NbS, expressing the interest in NbS to tackle these challenges (Techera, 2023).

5 Nature-Based Solutions Impact on Nationally Determined Contributions and National Climate Plans and Coordination Between States

Considering their role in climate change adaptation and mitigation, coastal NbS are globally recognized due to their diverse benefits to socioecological systems. Nationally Determined Contributions (NDCs), developed within the Paris Agreement, belong to national climate plans and include coastal NbS as an effective action strategy to guide and support countries in the achievement of their biodiversity and climate goals. Nevertheless, the lack of a standardized NDC structure and the absence of guidance about the inclusion of NbS in NDCs could delay and block access to external funding and, as a result, prevent transparency on the progress toward achieving national plans (Châles et al., 2023). Having recognized the value and vulnerability of coastal and marine ecosystems and their vital role in nature-based mitigation and adaptation to climate change impacts, States and institutions should improve their commitments by helping with technical and financial support, enhancing policies, as well as with law and governance. It is expected that raising awareness about NbS will help to evolve the commitments made in NCDs turning the potential synergies into tangible benefits (Techera, 2023).

More than 90 countries around the globe have signed the Leaders Pledge for Nature, a compromise to take immediate action to address biodiversity loss, with the promise to scale up the implementation of NbS. Also, more countries have pledged to include NbS in their NDCs (Lecerf et al., 2021; Seddon et al., 2019, 2020; UNFCCC, 2021). However, the Sustainable Development Goals (SDGs) separate targets related to climate change (SDG13) from those related to living marine resources (SDG14), while just Target 19 recognizes a relationship between SDGs by aiming to optimize "co-benefits and synergies of finance targeting the biodiversity and climate crises," which supports NbS implementation. During December 2022, the Kunming-Montreal Global Biodiversity Framework was adopted, which considers 23 targets and four goals to be accomplished by 2030 (CBD, 2022; Techera, 2023). Nevertheless, NbS properly designed can support in reinforcing the synergies among the 17 UN SDGs (Cohen-Shacham et al., 2019), while on many occasions, low-cost opportunities compared to engineered solutions can create confusion (Gattuso et al., 2019; Hoegh-Guldberg et al., 2019; Seddon et al., 2020; Châles et al., 2023). The NbS strength in delivering climate change adaptation and mitigation results, while maintaining ecosystem services and natural ecosystems, can be affected due to difficulties in measuring their effectiveness, mobilizing funding, and surpassing governance challenges (Seddon et al., 2020).

6 Impediments and Challenges Facing the Adoption and Implementation of Nature-Based Solutions and Approaches Beyond the Community Level

NbS funding needs to understand and consider the cost involved in monitoring and tracking progress and to set measurable and clear targets (Swann et al., 2021). Also, including NbS in NDCs can help to get funding through adherence to the IUCN Global Standard for NbS. Funding can come from different sources, such as the Blue Natural Capital Financing Facility, Global Environment Facility, and the IUCN Global Facility for NbS. However, the Nauru adjusted dataset exposed the main impediments to accessing financial support for SIDS, which are: small projects that do not meet the scaling-up requirement by many international funds, high costs of project per capita, limited institutional capacity, public debt levels, and difficult applications and forms requirements (Châles et al., 2023).

1. *The need for holistic approaches in the implementation of nature-based solutions*

The complexity of challenges faced by small islands requires solutions that are not just environmentally sound but also socioeconomically viable and culturally respectful. Holistic approaches in NbS consider the interconnectedness of ecosystems, human societies, and cultural values. They go beyond traditional environmental management to include broader considerations such as community well-being, cultural preservation, and sustainable livelihoods.

There is an inherent tension between knowledge systems, including validation and the level of importance placed. Both Western and indigenous knowledge systems offer valuable, complementary perspectives that can radically enrich our understanding of solutions and our ability to advance them.

A significant gap persists between traditional ways of knowing and scientific approaches in the collection, usage, and storage of data and information, as well as in knowledge sharing decision-making. This divide often hinders the effective implementation and recognition of indigenous solutions in climate change strategies and environmental management. In addition, a lack of explanations on how scientists and traditional knowledge owners can cooperate may generate mistrust issues, specifically when dealing with measurements, data, usage of gathered material, or restitution to local communities. Bridging this gap requires a paradigm shift in how knowledge is perceived and integrated.

Scientific research and policy-making processes must evolve to acknowledge and incorporate indigenous wisdom (Kaiser et al., 2019). This integration calls for methodologies that respect and understand the value of traditional practices, narratives, and worldviews. Collaborative platforms where indigenous voices are heard and respected in decision-making processes are essential for co-designing and implementing NbS.

2. *Clear differentiation between indigenous communities and local communities*

There is a history of corporations and governments characterizing local communities of migrant workers as indigenous communities, in an effort to preempt indigenous Peoples' sovereignty from their claims to land or exercising their right to be involved in decision-making. Attempts to engage indigenous peoples must recognize and carefully appreciate the history surrounding these terms and their use.

Indigenous peoples possess profound knowledge systems that have developed over countless generations. Their understanding of the interconnectedness between humans and the natural world is intricate and deep-rooted. Indigenous knowledge systems offer invaluable insights into sustainable living and environmental stewardship in small island contexts. This wisdom is not merely a repository of information but a living practice that sustains communities and regenerates the Earth.

Indigenous approaches to natural resource management, for example, have demonstrated remarkable efficacy in preserving biodiversity, enhancing ecosystem services, and mitigating the impacts of climate change. It is thus no surprise that indigenous people inhabit and steward lands that contain 80% of the global biodiversity. Their practices encompass both environmental aspects and intricate social and economic dimensions, contributing to the overall well-being of communities and the planet.

3. *Engaging local and indigenous communities, respectively, in co-designing solutions*

According to UNESCAP (2018), "[NbS] could be an opportunity to revitalize a cultural connection to the ocean, which is weakening in cities due to the process of urbanisation, and to raise awareness, to educate youth, and to engage communities" (Pedersen Zari et al., 2019).

The success of NbS in small islands hinges on participatory and inclusive approaches. Engaging local communities, policymakers, and various stakeholders in the co-design and implementation of solutions ensures their relevance, effectiveness, and sustainability. These participatory processes must recognize and value the contributions of all stakeholders, especially indigenous communities.

In the context of small islands, the success of NbS is significantly enhanced when local and indigenous communities are actively involved in their co-design and implementation. These communities possess invaluable knowledge and experience regarding their natural environments and societal needs. Engaging them in the NbS process ensures that solutions are grounded in local realities and are more likely to be embraced and sustained. This participatory approach empowers communities, builds local capacities, and fosters a sense of ownership and stewardship toward the environment.

However, engagement with indigenous peoples must be conducted at the discovery and development stages rather than the historical practice of bringing in indigenous peoples at the implementation stage. Approaches based on planet boundaries, resilience schemes, and plans are encouraging this early engagement

and co-design and ensuring not only buy-in but also a strong commitment to achieving every stage in the agreed action plan.

Adopting holistic and participatory approaches in the co-design and implementation of NbS is vital for enhancing the resilience of small islands. These approaches ensure that solutions are not only environmentally robust but also socioeconomically and culturally appropriate. As small islands navigate the challenges of climate change and environmental degradation, the integration of diverse perspectives and knowledge systems through participatory processes stands as a cornerstone for sustainable development. Ultimately, this approach paves the way for a future where small islands can thrive in harmony with their natural environments, bolstered by the collective effort and wisdom of their communities and stakeholders.

Case Studies

Integrating indigenous wisdom, community-based management, and innovative strategies aligned with local contexts to amplify resilience efforts.

The integration and use of the term NbS may be new; however, the practice of working with nature to generate successful human settlements while maintaining a healthy ecosystem is not, as it is considered a cornerstone of several indigenous beliefs (Bryant-Tokalau, 2018).

1. *The Māori Coastal Ecosystem Restoration Project, New Zealand*

Overview: This project focuses on restoring coastal ecosystems in New Zealand, utilizing traditional Māori knowledge combined with modern conservation techniques. It aims to enhance biodiversity and resilience against climate change impacts.

Contributions:

While many countries across the ocean and in the global south call for "loss and damage" funding needed to pay for building climate-resilient infrastructure and for relocating communities to higher grounds, some indigenous people and local communities (IPLCs) are seizing the moment and launching their own initiatives. For example, the Māori people of Aotearoa New Zealand and the South Pacific have formed an indigenous-led ocean resilience, conservation, and biodiversity restoration effort. This project called, "Hinemoana Halo Ocean Fund" (H2O), will scale blue carbon coastal projects along with native forests and ocean protection for marine species recovery. With the Pacific making up half of the global ocean, providing 70% of the global fish catch, restoring natural habitats and protecting biodiversity is vital to have any chance to maintain the largest climate regulating system we have—the ocean. This project demonstrates how an indigenous-led project can draw on indigenous wisdom, community management, and benefit sharing. The approach will focus on long-term investments in indigenous natural capital and resources. This approach reflects the indigenous incorporated values. This intergenerational approach by H2O, in particular, and by IPLCs, in general, overcomes the typical problem of "time commitment" encountered in carbon markets (Chami & Merkl, 2022). Another benefit of IPLCs-led projects is the absence of intermediaries, ensuring that the management and recipients of the

project and its benefits go directly to the Māori people. Moreover, the project leverages state-of-the-art digital MRV, AI, and blockchain platforms to ensure fully transparent project data, addressing buyers' and investors' concerns about governance and conservation actions. Technology, be it digital, satellite, or drone, allows investors full access to high-quality data around the performance of natural assets. Another market verification layer has also been added to the project, with top auditing companies signing up to provide another layer of verification to the project, further enhancing the quality of the project and providing assurance to potential buyers and investors of the quality of the product. Finally, the project combines both indigenous wisdom and Western science to ensure the ecosystems are stewarded to optimize resilience, biodiversity, and cultural benefits, along with long-term carbon storage. In short, this program resets the carbon/biodiversity market and brings hope to other IPCL communities looking to accelerate NbS projects.[1]

Approach:

Integration of Mātauranga Māori (Māori knowledge): Incorporating traditional Māori practices in ecosystem management, such as the use of native plants for dune restoration.

Community Engagement: Active participation of local Māori communities in the planning and implementation, ensuring cultural practices are respected.

Scientific Collaboration: Partnership with environmental scientists to blend traditional and modern conservation methods.

Outcomes:

Environmental Impact: Significant improvement in coastal biodiversity and stabilization of dunes.

Cultural Revitalization: Strengthening of Māori cultural identity and practices.

Educational Value: Increased awareness and knowledge sharing between indigenous communities and scientific experts.

2. *The Vanua Levu Mangrove Reforestation, Fiji*

Overview: This initiative in Fiji focuses on mangrove reforestation to combat coastal erosion and provide natural barriers against storms, crucial for island resilience.

Approach:

Community-Based Management: Led and implemented by local Fijian villages, emphasizing traditional land stewardship.

Ecosystem Services Awareness: Educating communities about the benefits of mangroves for fisheries, coastal protection, and carbon sequestration.

Sustainable Livelihoods: Development of ecotourism and sustainable fishing practices around the restored mangroves.

[1] See Takoko and Chami (2023).

Outcomes:

Environmental Benefits: Increased coastal resilience, improved marine biodiversity, and enhanced carbon capture.

Economic Development: Creation of sustainable livelihoods for local communities.

Community Empowerment: Strengthened community management of natural resources.

Moreover, the integration of traditional knowledge into resource management, as demonstrated by Folke et al. (2002), augments the adaptive capacity of communities, aligning socioeconomic development with the ecological carrying capacity of the islands.

7 A Paradigm Shift for SIDS: Toward a Sustainable Future

The resilience of small islands is a subject of increasing importance in the context of global environmental and socioeconomic changes. The integration of indigenous knowledge with scientific approaches in the design and implementation of NbS offers a pathway to more resilient small islands. This synergy goes beyond addressing climate change; it involves holistic social and economic strategies aimed at regenerating and restoring the Earth.

These islands, characterized by their unique ecosystems and rich cultural heritages, are at the forefront of experiencing the impacts of climate change, biodiversity loss, and socioeconomic vulnerabilities. Amid these challenges, nature-based solutions (NbS) emerge as a vital approach to bolster their resilience. It is imperative to integrate holistic and participatory approaches that harmonize indigenous knowledge and scientific methods and engage local communities and policymakers, as well as stakeholders, in the implementation of NbS.

This collaboration underscores the potential for a future where human societies and natural ecosystems coexist in a mutually beneficial and sustainable relationship. The journey toward this future requires a commitment to embracing, respecting, and harmonizing the myriad of voices and wisdom that make our planet diverse and resilient.

8 Conclusion

It is important to recognize nature-based solutions as indispensable tools in fortifying the resilience of small islands by recognizing and harnessing the intrinsic capacities of ecosystems, societies, and cultures.

Damage to and diminishing habitat condition will impact ecosystem function and services, directly affecting their capacity to contribute to human well-being (Arkema et al., 2013; Ali et al., 2018). Aiming to reduce climate change impacts and risks to the populations, NbS are fundamental in tackling disaster risk reduction,

improving resource management, and enhancing resilience in SIDS (Young et al., 2019; Giordano et al., 2020). However, it is important to safeguard that the strategies implemented to enhance resilience are proactive rather than reactive to the present challenges (Pedersen Zari et al., 2019).

The future of nature-based solutions is critical for the survival of climate vulnerable communities in SIDS and other coastal communities especially in the Global South. As the Integrity Council for the Voluntary Carbon Market (ICVCM) and many other bodies have now established the standards and principles needed for ensuring NbS delivers climate mitigation and community benefits, there is now a need for rapid deployment of private capital into these projects. These new standards are part of the solution, but the investor communities and private sector actors also need assurance that their investment in natural assets will perform within their risk tolerance. The private sector, along with the financial sector, is becoming aware of the risks and dependencies of nature. They need to become partners and investors in fortifying the resilience of the ecosystems, communities, and cultures that underpin economic viability and extractive profits. This growing realization of the risks can begin to change behavior in how companies do business given these risks to their resources and supply chains. It is also an opportunity to produce profit from investments in natural capital and shift into a "nature-positive" business paradigm (Chami et al., 2022).

In addition to the ICVCM standards, investing in natural capital requires transparent and quality data that the market can trust. This includes data on the performance of the natural assets as well as on the valuation and projection of flow of ecosystem services. This data is now rapidly becoming available, through environmental data providers, satellite, and AI technology, and due to advancements such as "science-based finance" (SbF) (Berzaghi et al., 2022) that provides the expected projections of ecosystem flows and valuations for living systems. Market players, including the "big four" accounting firms and rating agencies, are moving into this space as well, providing even more confidence in the verification of these projects. Insurance products are also being devised (e.g., the Mesoamerican parametric reef insurance) to protect assets such as reefs and mangroves, bringing quick funding to repair reef damage from cyclones, and compensating communities when economic losses accrue due to interruption in business (tourism, fishing, pandemics) are encountered. The impact of nature and climate threats have now reached the bottom line and board rooms and NbS are a pathway toward transforming the economic relationship between people and nature such that investment in nature and community resilience will be considered good business.

In terms of psychological, physical, and cultural health, marine and terrestrial ecosystem services are closely related to societal and individual well-being (Bryant-Tokalau, 2018). Also, the NbS are related to increased resilience and human well-being through restoring and conserving nature, understanding the ecosystem services and the ecological systems, and considering different contexts such as sociocultural ones (UNESCAP, 2019). The goal is to create multiple economic, societal, and cultural benefits while conserving nature (Pedersen Zari et al., 2019). Additionally, NbS acknowledge that integrating nature can lead to a more

effective solution to current challenges while conserving and restoring nature and its biodiversity.

Finally, evidence has shown that effective coastal management strategies that consider ecological goals and coastal engineering provide several benefits, including disaster resilience (Bridges et al., 2014; Kurth et al., 2020; González-Dueñas & Padgett, 2021). Research has also shown that stakeholders choose to support NbS rather than gray infrastructure (Deely, 2020). Natural resource management efforts are numerous, mainly due to the demands that resilience as an objective imposes. A multi-pronged approach is needed, aiming to ensure that solutions can satisfy all necessary needs. Thus, NbS have to be well planned before implementation to enhance natural resilience to climate change impacts. Solutions need to encompass sustainable actions that consider long-term management and ecological valorization (IUCN, 2020). Also, the policy to scale the NbS process must be holistic and well designed, including diverse stakeholders, local communities (including women and youth), long-term monitoring, and maintaining a proper relationship between individuals and ecological marine and coastal ecosystems.

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Taking off and Navigating Disruptive and Climate Challenges for Building Resilience in Air Transport Infrastructure

Andres Guzman and Abdulrahman Alwosheel

Abstract The growing recognition of the importance of addressing disruptive events and climate change has led to an increased focus on resilience in recent decades. This is due to the escalating effects of changing weather patterns, rising temperatures, extreme events, and other challenges associated with climate change. Resilience has emerged as a pivotal concept in various fields, including air transport infrastructure. It has become evident that the ability of systems, communities, and infrastructure to anticipate, prepare for, respond to, and recover from the negative impacts of climate change is crucial. Resilience provides a crucial framework for developing adaptive strategies and ensuring sustainability in the face of ongoing climate challenges. In the ever-changing world of aviation, air transport infrastructure faces various climate-related challenges that require them to strengthen their infrastructure to maintain connectivity with their surrounding environment and ensure continuous operations.

This chapter explores the intricate interrelation between aviation and the obstacles posed by disruptive and climate change, delving deep into the concept that air transport infrastructure must actively manage resilience. From the challenges presented by rising sea levels to the impact of extreme weather events, this chapter will skillfully navigate through the various strategies airports employ to strengthen their systems against the effects of climate change. By thoroughly analyzing case studies, it will shed light on the innovative technological advancements and sustainable practices that are being utilized to mitigate the risks associated with climate change. Furthermore, it will thoroughly consider how these strategies can be tailored to suit the unique characteristics of the Gulf Cooperation Council (GCC) countries. This exploration aims to unveil a comprehensive blueprint that will enable airports to confidently take off into a future that is resilient to the challenges of climate change.

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1 Introduction

The concept of resilience, which has a rich historical background, gained significant traction across various sectors in the latter part of the twentieth century and continues to be a prominent topic in the twenty-first century. The term resilience was first introduced by Holling (1973) in the context of ecological systems, marking a significant milestone in understanding it by delineating the capacity of ecosystems to assimilate disruptions while upholding their fundamental functions and configurations. Recently, the concept has expanded to various domains, encompassing engineering, sociology, economics, and urban planning, among others, indicating its broad relevance to complex systems and human communities. Presently, there is a proliferation of academic literature and scholarly publications deliberating on and defining resilience from diverse standpoints and within varied contexts, spanning individuals, communities, organizations, or ecosystems (see more details in Bartuseviciene et al. (2023), Jenkins (2022), Pawar et al. (2022), Wolanin et al. (2022), Zeng et al. (2023)). Consequently, these works may present theoretical frameworks, different modeling approaches, empirical research, case studies, or pragmatic applications of resilience principles.

The utilization of resilience in transportation systems is based on historical background principles and involves assessing the ability of these systems to absorb disruptions, adjust to changing circumstances, and promptly recover from interruptions. According to Cascetta (2001), a transportation system can be characterized as a blend of components and their interactions that generate travel demand in a specific area and provide transportation services to fulfill this demand. Similarly, drawing on prior research by Manheim (1979), a transport system is defined as a fusion of transportation (T) and activity (A) systems, leading to the identification of various subsystems. For example, demand and supply play vital roles within the transportation system. The activity system takes into consideration factors like the scale and location of economic activities, while demand encompasses the volume and nature of travel choices individuals make under particular circumstances, considering aspects such as the quality of available transport modes and their costs. Ultimately, the supply element in air transport comprises infrastructure, which includes the number of flights available and the seating capacity provided. Figure 1 illustrates the key components for assessing the significance of the supply of the air transportation system.

As shown in Fig. 1, the infrastructure of an air transport system comprises various elements. This system serves as a vital artery connecting countries (*A* and *B*), regions (*i*, *j*, *m*, and *n*), and cities (*1* to *6*) across the globe, accommodating both domestic (indicated by black and red lines) and international flights (depicted by blue lines). It facilitates rapid travel and promotes trade and commerce activities.

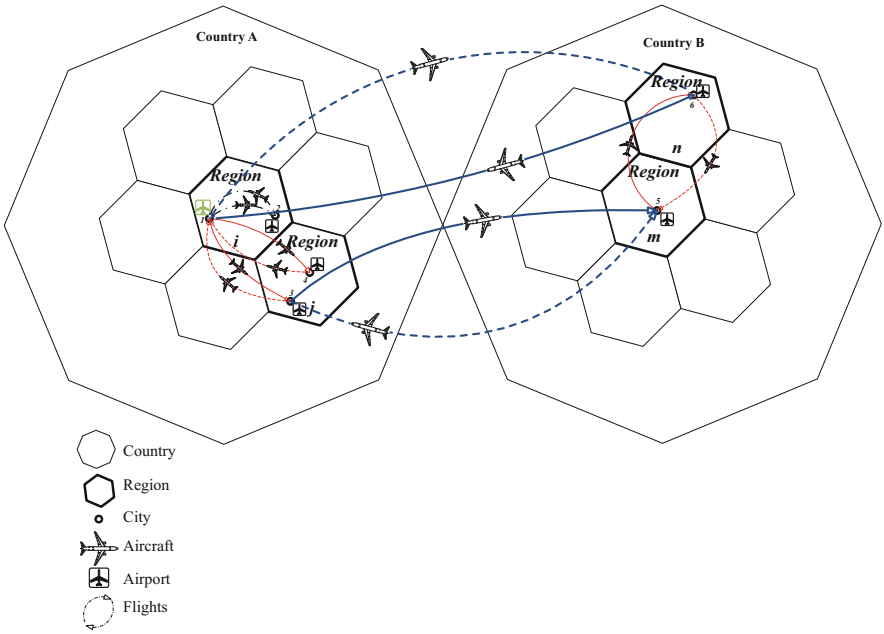

Fig. 1 Infrastructure elements in an air transportation system. (Source: Authors)

At its core are networks of airports, which include multiregion airports situated strategically to serve multiple geographic areas within the same region (Region *i* and *j*). These airports play a pivotal role in facilitating intra- or inter-regional and inter-country connectivity, fostering economic development across diverse territories by facilitating the movement of people and goods. Airports range from bustling international hubs (depicted in green) to smaller domestic and regional terminals (illustrated in black), each playing a crucial role in enabling connectivity. Together, they form the backbone of the air transport system, ensuring efficient movement and exchange on both local and global scales.

International airports serve as primary gateways to the world in major cities, acting as vital hubs in the global transportation network. These large facilities offer diverse amenities catering to travelers' needs. Meanwhile, local airports connect urban centers and remote regions within countries, facilitating both business and leisure travel and promoting economic growth and social cohesion. On the other hand, regional airports provide convenience and efficiency for short-distance flights. These airports are crucial for boosting regional economies and tourism, offering essential connections for communities not served by major hubs.

The diverse fleet of aircraft, including large commercial planes and regional jets, navigates an extensive network of flight paths, swiftly connecting origins and destinations, and includes long-haul intercontinental flights to short-distance trips between nearby cities. Also, landlocked countries face transportation challenges,

relying heavily on air travel due to a lack of direct access to coastal regions, threatening their accessibility and economic growth. Consequently, efficient air transport infrastructure facilitates trade, tourism, and worldwide access to goods and services.

As a result, understanding resilience in an air transportation system must focus on the infrastructure, which is essential for maintaining operational integrity and reliability, rather than being directed toward the demand or the activity system with the intention of making travel decisions that have already resulted from economic activities and characteristics of the transport mode, in this case, air travel.

The remainder of this chapter is organized as follows: In Sect. 2, following the introduction to the significance of resilience in air transportation systems, we provide a literature review on the advancements and developments of resilience in air transportation systems, including identifying key factors for assessment. Section 3 presents a description of the main factors affecting resilience, including climate considerations, among others. Section 4 demonstrates worldwide progress in airport resilience by considering case studies and empirical findings from diverse locations. Section 5 analyzes initiatives and recommendations for pursuing resilience in Gulf Cooperation Countries' (GCC) air transport infrastructure. Section 6 summarizes several practical implications regarding air transportation infrastructure and concludes with policy recommendations.

2 Advancement and Development of Resilience in the Infrastructure of Air Transport Systems

2.1 Overview of Capabilities for Resilience Assessment

In recent years characterized by rapid globalization, heightened connectivity, and evolving environmental challenges, the importance of resilience in air transport systems has significantly increased. Serving as the foundation of global mobility, it is crucial for air transport infrastructure to continuously adjust to both expected and unexpected disruptions in order to guarantee operational continuity, safety, and effectiveness. The enhancement and establishment of resilience in air transport systems entail a multifaceted effort, demanding a thorough comprehension of the intricate interaction among infrastructure, technology, regulations, and environmental elements. This section explores the realm of resilience evaluation capabilities in the context of air transport systems, providing insights into emerging patterns, obstacles, and prospects within this crucial sector.

Resilience in transportation systems is essential for ensuring their ability to withstand and recover from various challenges and disruptions. Therefore, resilience assessment involves understanding and evaluating various key factors that contribute to the system's ability to contribute to enhancing resilience in the performance of air transportation systems. As shown in Fig. 2, these factors encompass a

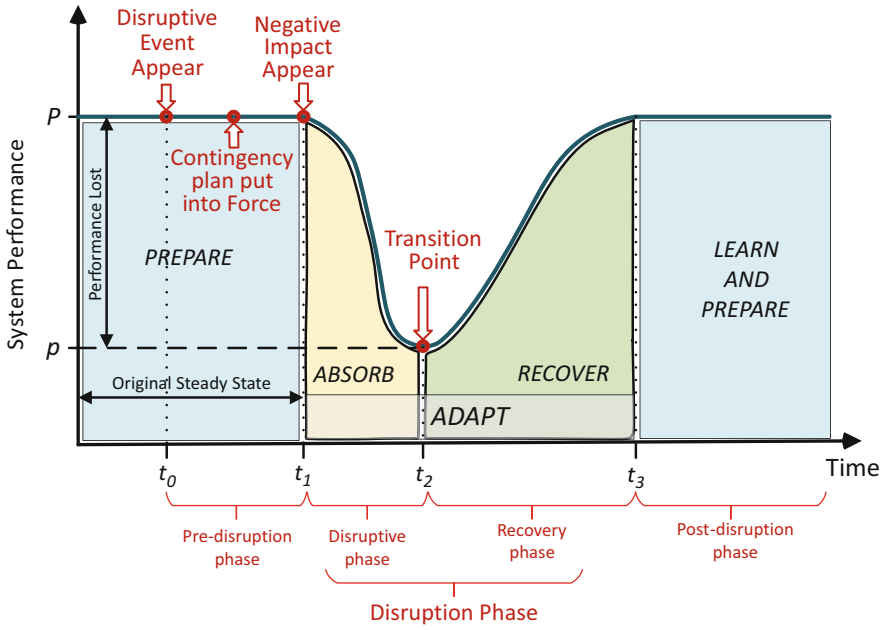

Fig. 2 System performance evolution and resilience capabilities. (Source: Adapted from Malandri (2020), Malandri et al. (2023), Wang et al. (2019), and Zhou et al. (2019))

Pre-Disruption Phase, characterized by the identification of potential risks and vulnerabilities, and preparing the system for unforeseen events, followed by a *Disruptive Phase* during which the system experiences disturbances, testing its readiness and immediate responses. This disruptive phase is then followed by a *Recovery Phase* aimed at restoring normal operations, and finally, a *Post-Disruption Phase* focusing on long-term resilience building. As a result, capabilities in resilience assessment emerge to enhance resilience in transportation systems. In fact, Table 1 shows an overview of the significance of these factors (e.g., absorptive capacity, adaptive capacity, and recovery and resumption) when assessing resilience in transportation systems by highlighting a few case studies.

In the context of resilience, it is essential to consider both the absorptive capacity in times of disruption and the recuperative capacity during the recovery phase to fortify the overall resilience of a system like the air transportation system. Nonetheless, if a choice between the two phases must be made, emphasis should be placed on mitigating the intensity of disruptions in the absorptive phase. Particularly in the absorptive phase, the crucial factor lies in the system's capacity to endure and assimilate the initial shock of a disruption. Strengthening this phase through the implementation of robust risk management strategies, redundant systems, and early warning mechanisms can help organizations mitigate the immediate effects of disruptions and forestall their escalation into more severe crises.

Table 1 Overview of capabilities for assessing resilience

Factor	Definition	Case study	Reference
Absorptive capacity	This refers to the system's ability to endure shocks or disturbances without significant damage. It includes redundancy in infrastructure, strong network connections, and operational flexibility.	Identify critical factors within a framework for assessing the resilience of transportation systems.	Tamvakis and Xenidis (2012)
		Simulation of disruptions at four European airports, finding that the responses of transportation system elements varied depending on factors such as system features and resource utilization.	Malandri et al. (2023)
		The study examines resilience trends across four US airlines. Findings indicate that data-driven methods offer deeper insights into airline resilience compared to traditional network methods.	Wong et al. (2020)
Adaptive capacity	The system's capability to adjust its operations and infrastructure in response to changing conditions or unexpected events. This involves proactive planning, flexible decision-making, and learning from past experience.	This study investigates the resilience of the US air transportation system. It introduces adaptive capacity indices to measure network resilience, gauging how well the system can substitute attacked nodes with neighboring ones.	Yoo and Yeo (2016)
		This research identifies critical airports in the global Air Transport Network (ATN) through simulated attacks. It finds that an adaptive strategy based on betweenness centrality is most effective for detecting critical airports and contributing to the development of contingency plans to address potential airport closures.	Lordan et al. (2014)
		The study suggests formalizing the adaptive capacity of the air transport system, particularly its ability to anticipate disruptions. Findings show that timing adaptive actions can notably mitigate the risk of system saturation, highlighting trade-offs between costs and benefits such as decreased queue saturation risk.	Blok et al. (2018)

Recovery and resumption	After facing inevitable disruptions, resilience in transportation systems involves recovering quickly and resuming normal operations. This includes restoring damaged infrastructure, re-establishing disrupted services, and minimizing the impact on users and stakeholders.	This case study delves into the reaction of the transportation sector to and recuperation from Hurricanes Katrina and Rita, as well as the impact these disturbances exerted on the interstate transportation of goods at a national level.	Grenzeback and Lukmann (2007)
		This study explores the impact of the COVID-19 outbreak on the automobile and airline supply chains, assessing both short and long-term response strategies.	Belhadi et al. (2021)
		Through a Networked Infrastructure Resiliency Assessment (NIRA), the author's findings suggest that road travel times can influence mode choice, leading travelers to opt for alternative transportation modes like rail or air.	Omer et al. (2013)

As a result, the analysis of resilience within transportation systems exposes the intricate and interconnected nature of various factors that impact system performance. This involves the identification of crucial capabilities, evaluation of system responses to disturbances, the formalization of adaptive capacity, and recovery. The findings highlight the need for approaches to assess resilience, integrating diverse methodologies and considering both short and long-term challenges such as climate change, natural disasters, man-made system shocks, and pandemics. Therefore, resilience contributes to making transportation systems better able to withstand disruptions, ensure continuity of services, and ultimately contribute to global connectivity and economic prosperity.

2.2 Advancement and Development of Air Transportation Infrastructure Resilience Assessment

Managing disruptions becomes a significant challenge as the air transport system faces increasing complexity and passenger numbers. Therefore, resilience pertains to how a system reacts to unexpected disruptions and its capacity to sustain the anticipated standards of service provision considering passenger experience, safety, and operational efficiency (e.g., safety, reliability, comfort, accessibility, customer service, punctuality). As a result, resilience assessment in air transportation infrastructure involves evaluating the system's ability to adapt and maintain operational efficiency during disruptions. Understanding the causality relationships within the air transport system and analyzing its consequences could shed light on the management of those situations. According to Teodorović and Janic (2022), resilience assessment in air transportation infrastructure involves analyzing technical, operational, economic, social, and environmental indicators to measure robustness and recoverability under disruptive events. Indeed, resilience metrics, such as robustness, redundancy, resourcefulness, and rapidity, play a key role in assessing and enhancing the resilience of air transportation infrastructure.

First of all, several methodological approaches have been developed for assessing resilience. For instance, Guo et al. (2023) propose a Comprehensive Resilience Assessment (CRA) model to analyze post-pandemic resilience in airport networks. The model considers different epidemic prevention policies and highlights China's more stable resilience level. Similarly, Hoterová and Chovancíková (2021) describe a new methodology for assessing the resilience of transport infrastructure, focusing on unifying approaches for evaluating resilience in the transport sector, including air transportation infrastructure. Other approaches focus on system and node resilience using network diversity characteristics or airport operation systems based on the FRAM[1] Model (see Wang et al. (2020), Guo et al. (2022), among others).

[1] Functional Resonance Analysis Method

Second, following the transportation resilience indicators framework mentioned by Leobons et al. (2019) and Wang et al. (2019), several assessments could be distinguished in previous research, as detailed:

- Robustness assessment in the air transport system involves indicators such as network connectivity/vulnerability, route capacity, mass transportation capacity, demand, and travel time/distance (post-event). See details in Yassien (2020), Paksoy et al. (2022), Janić (2022), Eubank et al. (2010), and Lordan et al. (2014).
- Redundancy considers alternative routes regarding critical points, accessibility levels, and alternative modes. See details in Voltes-Dorta et al. (2017).
- Resourcefulness is based on the time required to start to recover and the availability of people and other resources to act. See, for example, the exploring application of resourcefulness in transport planning was detailed in Verlinghieri (2016).
- Rapidity is characterized as the time required to restore normal operation or near it. The recovery rapidity assessment of different typhoon scenarios is presented by Fang et al. (2022).

Managing disruptions in the air transport system is vital for maintaining service standards. This is achieved through resilience, which involves utilizing various methodological approaches and key metrics. With continuous research and implementation of resilient strategies, we can build a more robust system capable of withstanding future disruptions.

3 Main Factors Affecting Resilience in Air Transportation Infrastructure

In recent years, the resilience of air transportation infrastructure has garnered increasing attention, particularly given the rise in frequency and severity of disruptive events such as natural disasters, pandemics, and geopolitical conflicts, alongside the persistent challenges brought about by climate change. It is imperative to comprehend the key determinants impacting resilience in air transportation infrastructure to guarantee the sustained operability and flexibility of this vital sector amid a range of dynamic threats. Within this framework, the present section delves into the principal factors influencing resilience in air transportation infrastructure, emphasizing both disruptive events and climate change. Through an examination of the intricate interactions among these factors and their ramifications for infrastructure resilience, this section endeavor seeks to offer insights and suggestions for fortifying the resilience of air transportation systems, thereby fortifying them against future disruptions and ensuring the dependable and effective mobility of people and goods.

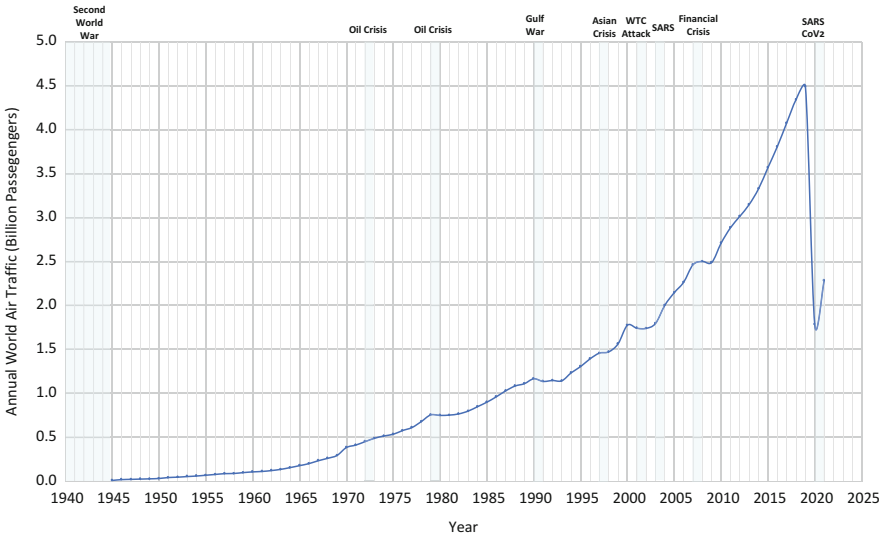

Fig. 3 Global annual passengers and external shocks. (Source*:* Authors based on Airlines for America (2024))

3.1 Disruptive Situations

Aviation has long been recognized as a catalyst for economic development, contributing to job creation, Gross Domestic Product (GDP) growth, and gross value added. It plays a crucial role in facilitating the movement of passengers both domestically and internationally. Moreover, since the Second World War, the aviation sector has demonstrated resilience to external events such as the oil crisis in the 1970s, the Gulf War and the Asian crisis in the 1990s, the September 11, 2001, attacks on the World Trade Center (WTC) in New York in 2001, and the financial crisis in 2008. However, due to its unexpected impacts, the coronavirus (COVID-19 – SARS CoV2) has emerged as a significant challenge for the aviation sector. The industry has experienced significant economic losses and impacts on related sectors due to the overall reduction in global passenger traffic, with a decline ranging from 60%[2] to 66%[3] in global Revenue Passenger Kilometers (RPKs) in 2020 compared to 2019. Figure 3 illustrates the resilience of global air passenger traffic to the previously mentioned external shocks and demonstrates how air traffic collapsed due to the measures taken to contain the spread of the virus worldwide.

As a result, the COVID-19 pandemic has been the most significant disruptor in the air transportation system, unprecedented in its scale and global impact. As

[2] International Civil Aviation Organization (ICAO, 2021)

[3] International Air Transport Association (IATA, 2020a)

countries implemented lockdowns, travel restrictions, and border closures to curb the spread of the virus, the aviation industry experienced an abrupt and severe downturn. Passenger demand plummeted as individuals canceled or postponed travel plans, leading to widespread flight cancellations and route suspensions.

The COVID-19 pandemic profoundly disrupted air travel, affecting every aspect of the industry. Airlines struggled with plummeting revenues, cash flow constraints, and operational challenges due to changing travel restrictions. Many carriers were forced to ground fleets and seek government assistance. Airports, once bustling hubs, became quiet as passenger numbers dropped, leading to closures and job losses for retail and hospitality businesses. The collapse in passenger traffic strained airport infrastructure and resources. Additionally, cargo operations and supply chains were impacted, with reduced capacity for transporting vital goods. The pandemic also highlighted the interconnectedness of the air transportation system with other sectors, disrupting tourism, business travel, international trade, and diplomatic relations and contributing to broader economic downturns and job losses across industries.

Air connectivity, representing the availability of air transport services between destinations, was significantly impacted by the COVID-19 pandemic. It denotes the accessibility of air travel options for travelers, domestically and internationally. Factors influencing air connectivity include the number of airports, airlines, flight frequency, destination variety, and infrastructure efficiency. High air connectivity correlates with enhanced accessibility, economic development, tourism, and global integration. The International Air Transport Association's (IATA) air connectivity index for the Middle East increased by 40% between 2014 and 2019, with the United Arab Emirates (UAE) and Saudi Arabia performing well (see Fig. 4a).

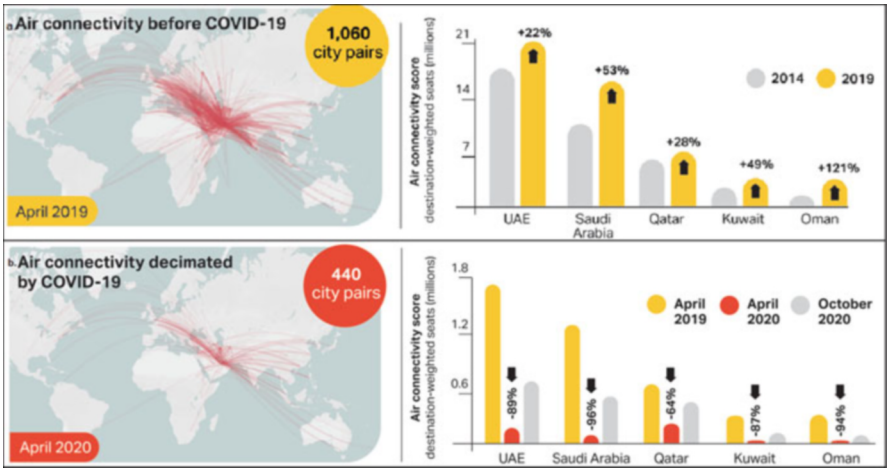

Fig. 4 Air connectivity evolution in the Middle East (2014–2020). (Source*:* International Air Transport Association—IATA (2020b))

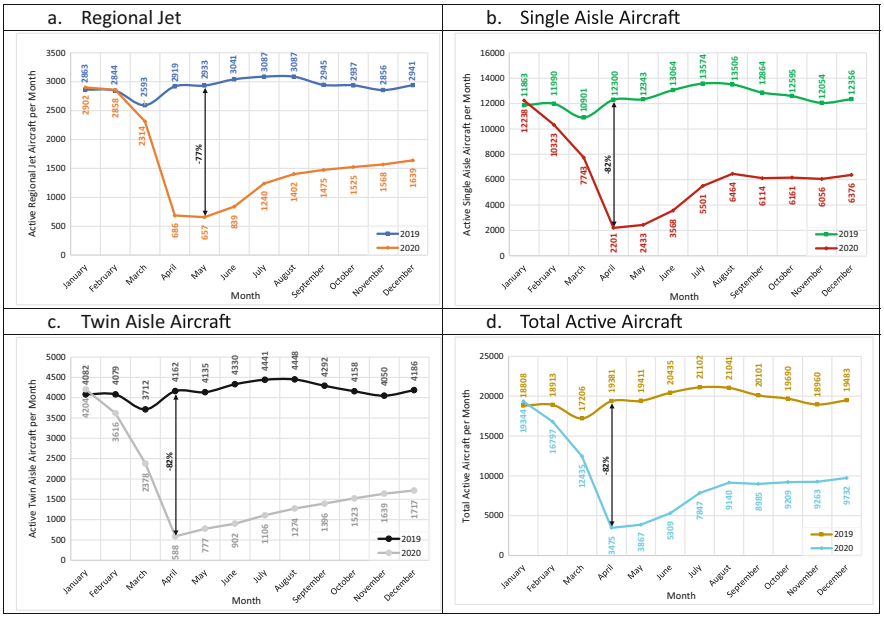

Fig. 5 Aircraft type utilization by month (2019–2020). (**a**) Regional jet. (**b**) Single aisle aircraft. (**c**) Twin Aisle Aircraft. (**d**) Total Active Aircraft. (Source*:* Authors based on the International Civil Aviation Organization—ICAO (2023))

Although the Middle East has achieved significant progress in air connectivity in the pre-COVID-19 pandemic period, the unprecedented consequences of the pandemic affected enormously the index, which decreased from 1060 to 440 city pairs with significant reductions in countries such as UAE with −89% or Saudi Arabia with −96% (see Fig. 4b).

Moreover, the COVID-19 pandemic affected aircraft utilization since rates declined as airlines reduced flight schedules, parked aircraft, and implemented maintenance checks during periods of reduced demand to optimize operational costs. The active aircraft fleet by month, considering regional jets,[4] single aisle,[5] and twin-aisle aircraft,[6] is shown in Fig. 5. As a result, the global active fleet was tremendously impacted by measures to contain the spread of the virus worldwide.

[4] Small aircraft used by airlines operating regional flights up to 100 seats in capacity.

[5] Aircraft are uniquely configured in a linear layout with a solitary aisle, allowing for a seating arrangement of up to 6 seats abreast within a cabin width of fewer than 4 meters (13 ft). These aircraft, also known as narrow-body aircraft, can accommodate a varying number of passengers, ranging from 100 to 295.

[6] Also known as a wide-body aircraft, it has a fuselage wide enough to accommodate two passenger aisles with seven or more seats abreast. The typical fuselage diameter is 5–6 m (16–20 ft).[2] In the typical wide-body economy cabin, passengers are seated seven to ten abreast.

Regardless of whether they were regional, single- or twin-aisle aircraft, most of the fleet was parked, with percentages ranging from 77% to 82% in April and May 2020. Additionally, it is worth noting that after those months, the fleet was parked at around 50%.

In conclusion, the COVID-19 pandemic has severely impacted the air transportation system, causing unprecedented disruptions across airlines, airports, and supply chains worldwide. The drastic reduction in passenger traffic and flight operations has led to significant financial strain, prompting fleet groundings and government assistance. Airports have experienced closures and job losses in retail and hospitality sectors, while cargo operations have faced challenges in maintaining supply chains. Despite these difficulties, the industry has demonstrated resilience by implementing cost-saving measures and adapting to new health protocols. Recovery has required collaboration, investment, and efforts to restore passenger confidence and air connectivity. Ultimately, the industry's resilience will prevail, ensuring its vital role in global connectivity and economic prosperity.

3.2 Climate Change

Climate change poses a significant threat to the airline industry, impacting both its operations and infrastructure. The increasing frequency and intensity of extreme weather events, such as storms, heavy rainfall, and high winds, are disrupting flight schedules and causing flight cancellations. In the Republic of Korea, for example, weather-related cancellations have been on the rise, accounting for more than 80% of total cancellations annually (Kim et al., 2023). This trend is expected to worsen with ongoing climate change.

The impact of climate change on air transport infrastructure is multifaceted. Sea-level rise, for example, poses a risk of flooding and inundation of airport infrastructure, as well as increased storm surge inundation. According to the Fifth Assessment Report and research on Climate Impacts on Aviation by the Intergovernmental Panel on Climate Change—IPCC (2013) depicted in Fig. 6, global sea levels are rising due to ocean warming and ice melting. This can lead to increased flooding, coastal erosion, and permanent inundation in low-lying areas. Sea-level rise also heightens extreme sea levels like storm surges. While regional impacts vary, it is likely that 95% of the world's oceans will experience rising sea levels by the end of the century.

Furthermore, changing wind patterns increases the risk to aircraft operations, potentially leading to aircraft loading and unloading limitations due to strong winds (ICAO, 2018). For instance, a severe winter storm in December 2022 in the United States produced high winds, snowfall, and record-low temperatures, leading to the cancellation of more than 18,200 flights from December 22 to 28. The cancellation led to significant passenger travel disruptions and major operational challenges for the aviation industry (Hsu et al., 2023). Desertification poses further challenges, including soil erosion around runways and water scarcity. Similarly, changes in

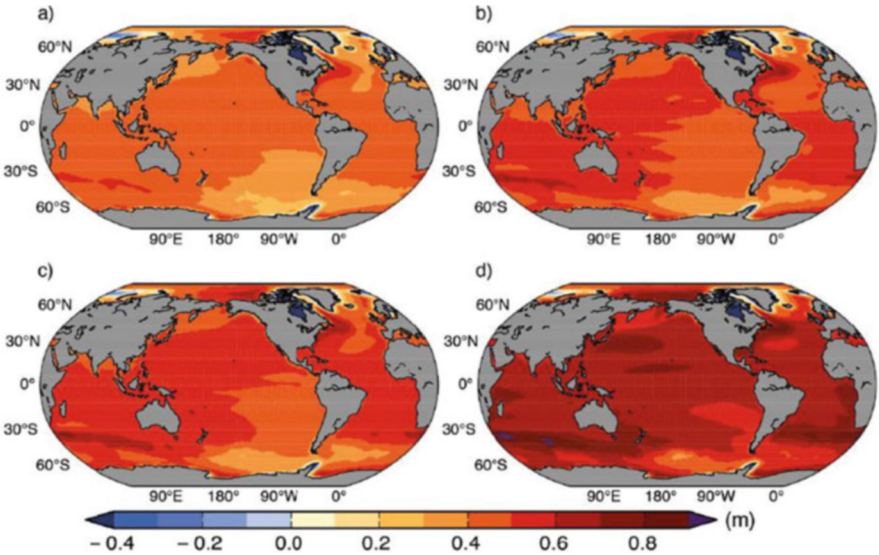

Fig. 6 The average regional relative sea-level change (meters). (Regional sea-level changes (in meters) were assessed using 21 CMIP5 models for RCP scenarios (**a**) 2.6, (**b**) 4.5, (**c**) 6.0, and (**d**) 8.5 between 1986-2005 and 2081-2100. These assessments included atmospheric loading, land ice, glacial isostatic adjustment (GIA), and terrestrial water sources). (Source: Intergovernmental Panel on Climate Change (2013))

biodiversity can disrupt wildlife migration patterns, increasing the risk of wildlife hazards at airports (ICAO, 2018). Changing precipitation patterns require increased airport surface drainage capacity and can lead to flash flooding or infrastructure inundation (ICAO, 2018). These impacts not only affect airport infrastructure directly but also have indirect effects on airport accessibility and ground transport links.

Additionally, changes in average temperatures can exceed design standards, which may lead to damage on airport surfaces and impact aircraft operations. Global average temperatures are rising, with regional variations. The Arctic is warming rapidly, especially in winter. Higher temperatures are expected to bring more frequent and longer heat waves, impacting air density and pollution. A 10 °C temperature increase could double emissions of NOx and VOC (ICAO, 2018). Changes in air density and humidity may affect aviation infrastructure. Projections for temperature increases vary across regions and timescales, with long-term trends dependent on emissions scenarios. The IPCC (2013) predicts more frequent hot extremes and fewer cold extremes globally.

Figure 7 from the IPCC AR5 WG1 Report shows global maps comparing surface air temperature differences between the high-emission RCP8.5 scenario and the low-emission RCP2.6 scenario. The maps depict these differences for two near-term periods (2016–2035 and 2036–2055) and for both winter and summer seasons.

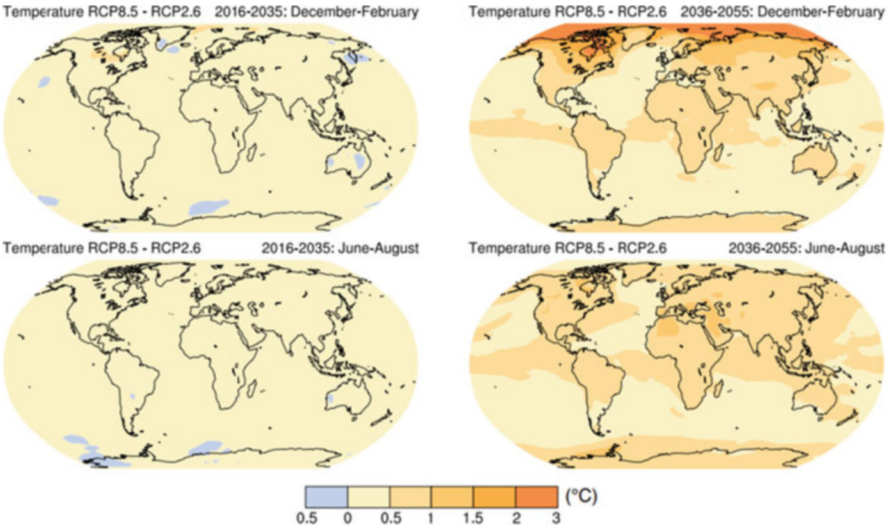

Fig. 7 Global maps of near-future temperature differences under different RCP scenarios. (Source: Intergovernmental Panel on Climate Change (2013))

These weather-related disruptions not only inconvenience passengers but also have economic implications for airlines. Studies have shown that the economic impact of flight cancellations due to weather can be substantial. For example, a significant snowstorm along the Eastern Coast of the US in 2010 led to the cancellation of over 20,000 flights, representing 4.2% of all US flights (Dunn & Wilkinson, 2016). Weather-related delays currently make up about 39% of total flight delays, a number that has been rising steadily over the past few years (Bureau of Transportation Statistics, 2024).

Addressing these climate impacts requires a comprehensive approach that considers the interdependencies of air transport networks. Airports should identify any potential risks to climate and take action to minimize their impacts. This includes investing in climate-resilient infrastructure, developing advanced weather forecasting and monitoring systems, and fostering collaboration among stakeholders in the aviation industry.

4 Worldwide Progress on Air Transport Infrastructure Resilience

4.1 Progress in Climate Adaptation and Resilience

Climate change presents significant challenges to air transport infrastructure globally, necessitating the development of robust adaptation and resilience strategies.

Adaptation and resilience measures suggested or already implemented aim to increase the aviation industry's robustness and flexibility. The rise in severe weather events attributed to climate change has become a major obstacle for aviation system operations (Zhou & Chen, 2020). While transportation planners have endeavored to enhance system resilience through many strategies and technologies for effective risk management, understanding how airport resilience performance varies across different weather events and the factors explaining such variations remains unclear (Zhou & Chen, 2020). Recent studies stress the importance of airports conducting comprehensive climate resilience assessments. Wang and Ng (2021) highlight the significance of considering climate exposure, vulnerability, and adaptive capacity simultaneously.

In areas where projected impacts from sea-level rise are expected in the near to mid-term, specific vulnerabilities and timeframes are being identified, and operational resilience is being improved (San Francisco Bay Conservation and Development Commission, 2017). Sea defenses and other protective measures are being installed for vulnerable areas (Gresham & Marchi, 2015). This involves raising or strengthening infrastructure, such as using salt water-resistant materials or sealants, building or reinforcing sea defenses, maintaining or introducing natural barriers, and tolerating some degree of inundation while ensuring safety. Relocating vulnerable infrastructure and even establishing new secondary airports in safer areas are also options (Gresham & Marchi, 2015). When planning new airports in coastal areas, projections for sea-level rise should be considered. Given that the impacts of sea-level rise will differ by location, there is no one-size-fits-all strategy for the aviation sector.

As the climate changes and storms become more intense, improving our understanding and forecasting of weather events is increasingly important to prepare for them in advance. (Eurocontrol, 2013). To prepare for the anticipated rise in storm intensity, an ACRP synthesis report (2012) outlined the measures taken by two airports in Jackson, Mississippi, situated in the southern United States. These measures include keeping the airfield operational, stocking up on fuel for generators, ensuring the functionality of lights and navigational aids, and mandating staff to clear debris. In cases of forecasted severe storms, some airports or airlines may proactively cancel flights to maintain operational safety and mitigate business disruptions.

In regions where increased temperatures could pose challenges for aircraft take-offs, it may be necessary to reassess future temperature projections and aircraft runway length calculations to ensure adequate runway length. Adaptation and resilience strategies are being implemented in areas impacted by permafrost thaw. These include reinforcing or elevating runways and access roads, as well as relocating facilities (ACRP, 2012).

Airports in colder climates can benefit from studying how airports in warmer climates adapt to higher temperatures while ensuring smooth operations. When airports undergo renovations or changes, anticipated temperature change should be factored into the design process (London Heathrow Airport, 2011). Adaptation strategies for extreme cold weather may involve setting up warming stations in

advance to protect ground support crews during exceptionally cold weather and establishing protocols for servicing frozen equipment and fuel hydrants as needed (Greater Toronto Airports Authority, 2014).

To address snow and ice challenges, ensuring adequate snow and ice removal equipment and available staff is crucial. This can be achieved by using 4 × 4 SUV cars to transport staff to places of work and providing nearby accommodations (NATS, 2011). Specific measures already in place include snow and ice removal strategies at airports like Dallas and Toronto International airports. These strategies involve setting removal targets, keeping a minimum number of runways open, ensuring better access during weather disruptions, and drainage during heavy precipitation events (Palko & Lemmen, 2017).

In contrast, measures for addressing changes in wind conditions are less developed. It is essential to assess the implications of prevailing winds at the local level and identify operational measures to enhance safety and flexibility (Eurocontrol, 2013). Research is ongoing on technologies for aircraft that can assess wind and turbulence changes in real time (Vrancken et al., 2016).These technologies aim to identify Clear Air Turbulence up to 10–15 km ahead, providing sufficient time to alert passengers and crew for safety measures or route adjustments. However, current technology is not yet considered economically viable for widespread use (Vrancken et al., 2016).

The impacts of climate change on air transport infrastructure are multifaceted, requiring a comprehensive approach to adaptation and resilience. While progress has been made in implementing measures to address these challenges, there is a need for further research and investment to effectively mitigate risks and ensure operational continuity. Modal substitution, such as the use of high-speed rail (HSR) as an alternative mode, has proven to be a highly effective resilience tactic for the transportation system. Studies have shown that the speed of air service recovery was 22.9% faster when HSR service was available in the city (Zhou & Chen, 2020). Additionally, Dunn and Wilkinson (2016) proposed an adaptive air traffic network to enhance airport resilience. Through the adoption of cutting-edge strategies and synergistic initiatives, the aviation sector has the capacity to progress toward a future characterized by enhanced resilience and sustainability amid shifting climate trends.

Besides the disruptive and climate challenges imposed on air transportation infrastructure, cyber-attacks, strikes, and labor disputes could affect airport operations, computer systems, air traffic management systems, reservation systems, and communication networks, leading to flight delays and cancellations nowadays more frequently (see more details in Bhatia et al. (2018), Harry and Vivek (2021), and Roy and Sridhar (2016). The occurrences emphasize the growing risk posed by cyber-attacks on airport facilities and systems, necessitating vigilant oversight by airport authorities and airlines to enforce strong cybersecurity practices such as firewalls, encryption protocols, intrusion detection systems, and routine security evaluations.

4.2 Case Studies—Example of Action

Numerous airports have proactively fortified their infrastructure to withstand potential future climate impacts. These efforts are tailored to each airport's unique risk assessment, as there is no universal solution. The approach is contingent upon the specific climate threats each airport anticipates within their chosen timeframe, as well as the acceptable level of risk and economic feasibility of implementing adaptation measures. The following examples illustrate how the air transport sector is addressing climate challenges.

Climate Adaptation in Norway's Air Transport Infrastructure

Norway's climate is undergoing noticeable changes, marked by increasing temperatures, greater volatility, and higher precipitation levels, with significant regional and local variations. Figure 8 illustrates the impact of climate change on Norway over the past 40 years, showing a clear trend toward warmer months and an increase in annual precipitation. These changes are indicative of global warming. These shifts pose considerable challenges for the country's aviation infrastructure, particularly in terms of drainage systems and the ability to withstand extreme weather events. Failing to address these challenges could result in severe physical and financial repercussions.

Avinor, responsible for managing 43 airports across Norway, has been actively engaged in climate adaptation efforts since the early 2000s (Avinor, 2022). Its airports are predominantly situated along Norway's rugged coastline, where several runways lie less than 4 meters above sea level, making them especially susceptible to rising sea levels and extreme weather conditions (ACI, 2018). In response to new legislation introduced in 2006, which mandated the expansion of safety areas around runways at several airports, Avinor undertook practical measures to meet these requirements. This involved complex calculations considering projected sea levels, wind and wave patterns, and underwater topography to ensure the robustness of these safety areas (ACI, 2018). A significant step in Avinor's climate adaptation strategy was a comprehensive risk assessment conducted in 2013. This assessment identified the need for increased drainage system capacity and the relocation of navigation equipment batteries at risk of flooding, highlighting the importance of proactive measures to mitigate climate risks (Avinor, 2022). Avinor has also developed guidelines for low-lying coastal runways and strengthened requirements for potential runways, now stipulating a minimum elevation of at least 7 meters above sea level. These standards are being applied in new infrastructure projects.

Avinor's proactive approach to climate adaptation underscores the importance of early planning and the integration of climate resilience measures in aviation infrastructure. By addressing the challenges posed by climate change head-on, Avinor is ensuring the safety, efficiency, and sustainability of Norway's airports for years to come.

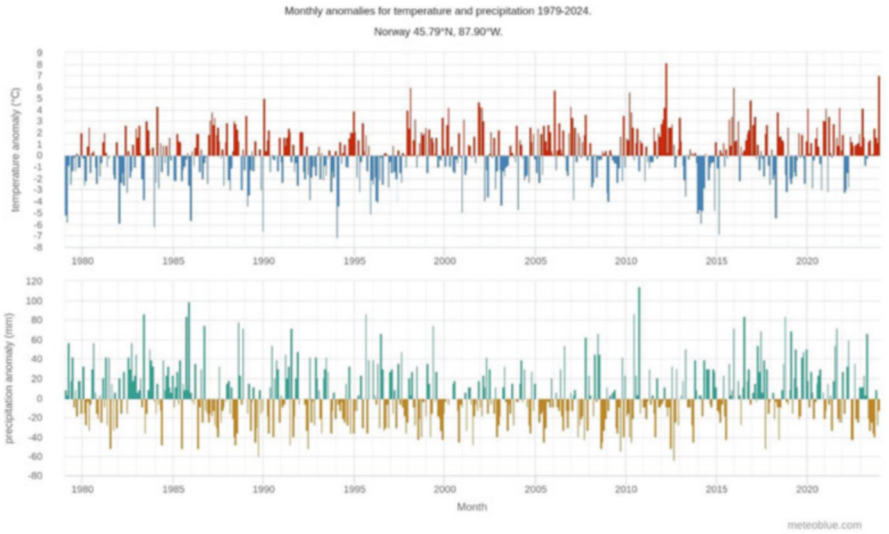

Fig. 8 Monthly temperature and precipitation in Norway (1979–2024). (The top graph displays temperature anomalies since 1979, indicating how much warmer or colder it was compared to the 30-year climate mean of 1980–2010. Red months were warmer, blue colder. The lower graph shows precipitation anomalies since 1979, indicating if a month had more or less precipitation than the 30-year mean. Green months were wetter, brown drier than normal). (Source: meteoblue.com (2024))

Climate Adaptation in Iqaluit International Airport, Canada

Iqaluit International Airport is a critical lifeline for communities in Nunavut, especially due to the region's lack of road access. Constructed in 1942, the airport initially faced challenges related to the underlying permafrost, which were not well understood at the time. Over the years, issues such as runway stability problems caused by the thaw settlement of ice-rich soils have emerged, necessitating a comprehensive improvement plan.

Permafrost, a type of ground that remains frozen for two or more consecutive years, presents unique challenges for infrastructure development in regions like Nunavut. Figure 9 shows an example of permafrost thaw in action. As temperatures rise, permafrost can thaw, leading to changes in the landscape and potentially affecting infrastructure built on top of it. Understanding the dynamics of permafrost thaw is crucial for mitigating its impact on infrastructure.

Recognizing the importance of understanding permafrost degradation, the Iqaluit International Airport Improvement Project was launched in 2013–2014. Several research projects have been conducted using methods like ground-penetrating radar, analysis of permafrost cores, surficial mapping, and remote sensing. These projects aimed to collect detailed, site-specific information about permafrost properties in order to model the interactions between permafrost and airport infrastructure (Palko

Fig. 9 Example of permafrost thaw. (Source: National Geographic (2019))

& Lemmen, 2017). One key finding of the research was that permafrost tends to experience greater warming under pavement compared to natural surfaces. This insight has been instrumental in informing infrastructure decision-making at the airport (Palko & Lemmen, 2017).

The data collected through research has been crucial in guiding infrastructure decisions at the airport. Maps were created to pinpoint areas with potentially challenging conditions for current and future infrastructure, highlighting areas with challenging terrain for construction. In response, a taxiway was relocated and protected with a barrier to minimize the damage, and thick snow cover was recognized as needing removal in key areas (Palko & Lemmen, 2017).

Additionally, thermosyphons were installed beneath airport buildings to help maintain the integrity of the underlying permafrost, and drainage systems were improved to reduce the infiltration of surface water into the permafrost. These measures, along with other informed engineering and operational decisions, have been vital in ensuring the long-term viability and safety of the airport's infrastructure (Palko & Lemmen, 2017).

The case of Iqaluit International Airport exemplifies the importance of understanding and managing permafrost in infrastructure development, especially in regions like Nunavut. Through a comprehensive improvement plan and the integration of research findings into decision-making, the airport has been able to address permafrost-related challenges effectively. This proactive approach serves as a valuable model for other regions facing similar permafrost-related issues.

5 Air Transport Infrastructure Resilience in Gulf Cooperation Council—GCC countries

In recent years, the Gulf Cooperation Council (GCC) countries[7] have made significant strides in the development of air transportation infrastructure, highlighting their strategic position as vital connectors between eastern and western countries regions. However, amid the growing complexities of the aviation sector and the emergence of various disruptive events, ensuring resilience has become a critical concern. This section delves into the unique challenges and opportunities associated with resilience, considering factors such as rapid urbanization, the impact of climate change, geopolitical tensions, and recent global pandemics.

Climate change, along with disruptive events like pandemics, poses a significant environmental challenge globally. While various technologies and methodologies for adaptation exist, they need enhanced scrutiny to demonstrate their potential to foster resilience within the air transportation infrastructure.

5.1 Bahrain

The Kingdom of Bahrain is comprised of an archipelago of 36 low-lying islands. As a coastal region, it faces numerous climate change challenges that can impact its environment and infrastructure, including its air transportation system. Bahrain confronts significant climate challenges, primarily characterized by rising temperatures and the associated environmental and socio-economic impacts. Because of hyperarid climatic conditions, the country has experienced pronounced significant warming trends, particularly during the hotter months, which can impact aircraft performance and airport operations.[8] The highest recorded temperature reveals an alarming warming rate of 0.60 °C per decade (Brown, 2023). Additionally, Bahrain is characterized by high temperatures, erratic and often scanty rainfall, high evapotranspiration rates, and elevated humidity levels due to the surrounding Gulf waters, resulting in inherent water scarcity. This warming trend is part of a broader climate change pattern in the Arabian Gulf area, where temperatures are increasing at a rate of 1.4 °C per 100 years, posing threats to natural ecosystems and human institutions (Elagib & Alvi, 2013). As mentioned by Al-Sayyad and Hamadeh (2014), the environmental challenges are compounded by Bahrain's high

[7] Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE).

[8] Air density changes can diminish thrust and lift capabilities, affecting aircraft takeoff and landing performance and causing runway pavement deterioration. Sandstorms, on the other hand, reduce visibility, pose hazards to aircraft engines, and lead to damage to airport infrastructure and aircraft surfaces due to sand abrasion. As a result, these impacts may disrupt airport operations, resulting in flight delays and cancellations.

per capita carbon emissions, with insufficient data to assess mitigation opportunities in sectors like transportation.

Despite these challenges, Bahrain has taken measures to combat climate change, including the imposition of energy-saving building regulations and the issuance of Sukuk Islamic Green Bonds to fund climate change projects (Alnaser & Merzaa, 2003). Regarding transportation, the measures conducted to combat climate change have been directed mostly to road transport[9] and not explicitly focused on air transport (see more details in Alnaser et al. (2023) and Alsabbagh and Alnaser (2023). The Kingdom of Bahrain has set ambitious renewable energy targets, aiming to achieve 20% of its energy mix from renewable sources by 2035 (Brown, 2023). Solar and wind energy are key components of this strategy, which can reduce the carbon footprint of airport operations. In the same vein, Bahrain's commitment to climate change mitigation encompasses all sectors is evident in its national target of achieving carbon neutrality by 2060, with an interim goal of a 30% reduction in CO2e emissions by 2035 (Alnaser & Merzaa, 2003).

5.2 Kuwait

Kuwait, like other oil-dependent economies, is contending with the potentially destabilizing effects of climate change amid a shifting international energy market that increasingly favors renewables (Nordenson, 2020). However, as highlighted by Al-Dousaria et al. (2021), the harsh and arid environmental conditions of Kuwait exacerbate these challenges. Issues such as deposited dust, increased carbonate and mud percentages in dust, lower solar radiation, high relative humidity, and low wind speed affect the sustainable development of its energy sector, particularly photovoltaic (PV) power stations. Additionally, the extreme summer temperatures, which are expected to increase markedly in the near future (Alahmad et al., 2022; Bhat et al., 2009), often exceeding 40 °C, pose significant challenges for various sectors, including air transportation infrastructure.

These challenges emphasize the urgent need for Kuwait to adapt and mitigate the impacts of climate change through diversified energy sources, improved environmental management, and enhanced public measures. Indeed, Kuwait has adopted a multifaceted approach to combat climate change, focusing on energy transition, technological innovation, policy reform, and stakeholder engagement across various sectors. It also includes policy reforms aimed at enhancing competition, revising energy subsidization, and encouraging energy efficiency to achieve more diversified growth while reducing greenhouse gas emissions (Hilmi et al., 2020). In terms of transportation, Kuwait is promoting the use of public transportation. As highlighted by AlKheder (2021), this initiative has shown potential to reduce traffic congestion

[9] Introduction of fuel economy standards to reduce CO2e.

by about 45% in some areas, alongside notable reductions in fuel consumption and gas emissions, thereby positively impacting the environment. Regarding air transportation infrastructure, Kuwait does not have specific measures to address the climate change challenge in this sector, but the indirect multifaceted measures intended to decrease both CO2 and Greenhouse Gases (GHGs) are evident in its efforts to diversify its economy and reduce reliance on fossil fuels. As a result, Kuwait's approach will significantly reduce GHG emissions, fostering a sustainable future for its various sectors, including air transportation.

5.3 Oman

Oman is highly vulnerable to the impacts of climate change, including increased average temperatures, erratic precipitation patterns, sea-level rise (SLR), and desertification, significantly influenced by its geographical location and economic dependencies (Charabi, 2023). The recent experiences with tropical cyclones, such as Gonu in 2007, Phet in 2010, and Mekunu in 2018, underscore the potential impact of extreme climatic events on urban and coastal areas, highlighting the country's exposure to natural disasters exacerbated by climate change (Charabi, 2013). Additionally, Oman's extensive coastline, stretching 3165 km, is threatened by SLR, with significant portions of the population living in low-lying areas at risk of inundation, storm surge, and flooding. As mentioned by Taylor et al. (2009), this vulnerability necessitates urgent strategic coastal management planning to enhance adaptive resilience and responses due to warming temperatures and sea-level rise.

Integrating climate policies with economic diversification strategies presents both a challenge and an opportunity for Oman. Indeed, Oman has embarked on a multifaceted approach to combat climate change, incorporating strategies from renewable energy adoption to emissions reduction and waste management. The Sultanate is leveraging its solar and wind resources to transition toward Zero Energy Buildings (ZEBs) and Near Zero Energy Buildings (NZEBs), as described in Ninzo et al. (2023) aims to reduce reliance on fossil fuels for power production. Similarly, Oman is exploring mitigation strategies in the hydrocarbon sector despite challenges posed by its hydrocarbon-based economy (see the flaring reduction initiatives, operational excellence, and new technology deployments described in Al Humaimi et al. (2023), Alrawahi et al. (2023), and Muthalaly et al. (2022)).

Regarding the transportation sector, the rapid development and the increase in automobile usage in the Sultanate, including the growth of private car ownership, have led to a commitment by the leadership to cut down greenhouse gas emissions by 2% as part of the United Nations Framework Convention on Climate Change (UNFCCC) commitments (Bernabeo et al., 2018). Specifically in the aviation sector, Oman is likely to align with the global climate goals as part of its broader climate

change mitigation efforts since Oman joined the global commitment to reach net zero by 2050, indicating a broader strategy to reduce CO2 and other greenhouse gases across all sectors, including air transportation (Alrawahi et al., 2023).

5.4 Qatar

As a hot subtropical desert, Qatar experiences extreme heat and humidity in the summer and aridity year-round, posing significant vulnerability to the impacts of climate change challenges. Qatar's challenges include sea-level rises, ocean warming, desertification, and loss of natural diversity, which threaten its environment and sustainable development efforts (Al-Mohannadi & Al-Mohannadi, 2023). Indeed, as mentioned by Alraouf (2022), the coast and waterfronts of Qatar are under threat from climate change, necessitating careful planning and management to ensure resilience. Efforts to mitigate these challenges include the implementation of sustainable development policies and environmental protection legislation (Bilal et al., 2021).

Qatar has made significant investments in renewable energy, such as the construction of solar power stations and plans for the world's largest "blue" ammonia facility (Emerald expert briefings, 2022). Additionally, as mentioned by Walters (2023), Qatar is promoting Green Building Practices (GBP) through the integration of environment-related variables such as sustainable government support and environmental concern. Similarly, in the transport sector, Qatar has been actively working toward climate change through electric mobility, the development of public transportation systems, and the implementation of legal and policy frameworks aimed at reducing carbon emissions (Emerald Expert Briefings, 2022). Legal and policy frameworks, including the Qatar National Vision 2030 and the National Environment and Climate Change Strategy, underscore the country's commitment to sustainable development and climate change mitigation. These frameworks aim to balance social, economic, and environmental development with specific measures targeting the reduction of carbon emissions in the transport sector (see more details in Harmon and Truby (2021), and Al-Thawadi et al. (2020)). Similarly, Qatar has adhered to international standards and initiatives related to the air transportation system toward technological and operational improvements to mitigate environmental impacts.

Resilience in the air transport system has referred exclusively to its transport network considering delay propagation within the broader aviation context, as presented by Xu and Zhang (2022), and with regard to disruptive events, the country handled the economic impacts of the blockade and the pandemic through supporting affected sectors and ensuring business continuity. These measures have indirectly supported the air transport sector by maintaining economic stability and confidence, which are essential for the recovery and resilience of air transport (El-Masri et al., 2021).

5.5 Saudi Arabia

The country's commitment to achieving net zero emissions by 2060 underscores the urgency of addressing its Greenhouse Gas (GHG) emissions, which are significantly impacted by its industrial and energy sectors. In particular, steel and cement industries present substantial hurdles to reducing emissions, highlighting the need for sector-specific mitigation strategies (Al-Sinan et al., 2023; Rahman et al., 2022). In contrast to other GCC countries, Saudi Arabia experiences diverse landforms and a range of climatic conditions, from hot, humid coastal areas to hyperarid deserts and semi-arid climates in the southwestern part of the country.

Saudi Arabia has embarked on a multifaceted approach to combat climate change. The country has pledged to achieve net zero emissions by 2060, a significant commitment given its status as one of the world's largest oil producers through limiting its Nationally Determined Contributions (NDCs) (Gasim et al., 2023; Al-Sinan et al., 2023). In this vein, Saudi Arabia is adopting energy efficiency as a comprehensive strategy toward a more sustainable and resilient energy future through national programs, proposing statutes, issuing technical regulations, and setting appropriate standards.

As mentioned by Al-Sinan et al. (2023), one of the key strategies adopted by Saudi Arabia to achieve its climate goals is the development of mass transit systems and transit-oriented development, particularly in Riyadh. This initiative is expected to reduce energy consumption significantly and GHG emissions by providing a sustainable alternative to private vehicle use. Also, the government is assessing the attitudes toward and the potential impacts of pricing measures on travel behavior to support the shift from private cars to public transportation (Alturif & Saleh, 2023). In air transportation infrastructure, the country has proposed a three-tier process to neutralize carbon emissions, focusing on emission reduction, the promotion of renewable energy, and carbon capture and storage (Turki et al., 2023). These strategies are designed to complement each other, offering a holistic approach to carbon mitigation within the aviation sector.

Saudi Arabia's Disaster Risk Reduction (DRR) endeavors play a pivotal role in bolstering the resilience of its critical infrastructure, including the air transport sector. By focusing on initiatives such as infrastructure enhancement, early warning systems, and emergency response capabilities, Saudi Arabia demonstrates its commitment to safeguarding against potential disruptions and ensuring the continued functionality of essential services (Al-Wathinani et al., 2023).

5.6 United Arab Emirates (UAE)

The United Arab Emirates (UAE) faces significant climate challenges, experiencing rising temperatures and humidity alongside decreasing rainfall, indicating regional climate change impacts (Mokhtar, 2019). Efforts to address these challenges include

initiatives aimed at improving energy efficiency in buildings and targeting net-zero carbon emissions for new and existing structures, particularly in the affordable housing segment (see more details in Kamkar et al. (2022)). However, the effectiveness of these initiatives is hindered by technical and financial challenges, such as variations in construction systems and the quality of construction, as well as the subsidized electricity cost (Friess & Rakhshan, 2017).

The UAE has outlined plans to reduce emissions as part of its broader strategy to mitigate climate change impacts, including investments in renewable energy and technologies. However, as reported by Marei (2022), challenges persist in systematically reporting vehicle emissions, indicating a gap in enforcing mandatory rules for transparency, necessitating proposals for law reform to legitimize climate actions and achieve environmental sustainability in transport. In the air transport system, the UAE has implemented sustainability measures and strategies aimed at reducing Greenhouse Gas (GHG) emissions, aligning with international policies and targets set through international commitments due to the ownership of two major airlines (i.e., Emirates Airlines and Etihad Airways). For instance, Etihad Airways incorporated Sustainable Aviation Fuel (SAF) into its energy mix (Bahman & Shaker, 2023).

Regarding resilience, as mentioned by Bernabeo et al. (2018), the UAE has supported its commitment to sustainability practices within the airline industry, prioritizing government and innovation management to address environmental challenges. For example, the country has focused on network stability and the complementary effects of high-speed rail networks, which enhance the overall resilience of the air transport network (Ajmal et al., 2017; Li & Rong, 2019).

6 Conclusions and Policy Recommendations

Factors impacting resilience include inclement weather, mechanical failures, and human-intended interruptions. The COVID-19 pandemic has highlighted the importance of resilience, with different regions experiencing varying levels of network damage and recovery rates. Resilience has become a significant concern nowadays, and diverse methodological approaches have been designed for tailored situations worldwide, including air transportation.

Global efforts to enhance the resilience of air transport infrastructure in the face of climate change are progressing, albeit with ongoing challenges and the need for further advancements. The aviation sector recognizes the importance of adapting to climate change and has implemented various strategies to bolster resilience. These include improving drainage systems, relocating vulnerable equipment, elevating infrastructure, and integrating climate considerations into infrastructure planning and design. Climate adaptation and resilience strategies are crucial for ensuring the robustness and flexibility of aviation systems in the face of increasing severe weather events. As the aviation industry continues to navigate the complexities of climate change, collaborative efforts, innovative solutions, and further research

will be essential for building a resilient and sustainable future for air transport infrastructure. By learning from successful case studies and embracing adaptive strategies, the aviation sector can mitigate risks and ensure operational continuity in the face of evolving climate patterns.

In the GCC countries, the aviation sector has experienced significant growth in recent years due to a changing pattern of being viewed as a pure stop on their way from America or Europe to East Asia to a hub for both business and leisure travel. This evolution reflects the region's strategic geographic location, which serves as a connecting bridge between various continents. As a result, GCC countries have invested heavily in developing their air transportation infrastructure, including modern airports, expanded fleets, and enhanced services, to meet the growing demand for air travel. However, alongside this growth comes the increasing recognition of the sector's vulnerability to various disruptions, ranging from natural disasters to geopolitical tensions and public health crises like the COVID-19 pandemic. As evidenced in the case of GCC countries, most of the aviation measures to combat climate change follow the broader strategies[10] defined by international commitments rather than adopting country-specific approaches. While GCC countries have made significant strides in aligning with global climate goals, capping aviation CO2 emissions at 2020 levels by adopting international best practices, there remains a need for more tailored and context-specific approaches to address the unique challenges posed by climate change within the region regarding air transportation infrastructure.

Resilience in the air transport of GCC countries necessitates a multifaceted approach encompassing operational, infrastructural, and environmental resilience. To achieve this, GCC countries should prioritize (a) interconnectedness and interdependencies with other infrastructure; (b) comprehensive risk assessment and management strategies; (c) robust contingency planning to effectively respond to disruptions; (d) collaboration among transportation operators, including airlines and airports, and the wider community; and (e) embracing technological innovation, such as predictive analytics, to enhance resilience. As a result, air transportation will develop the ability to adapt and respond effectively to disruptions, such as adverse weather conditions, technical failures, or pandemics, without compromising safety or service quality.

In conclusion, the aviation sector in GCC countries must prioritize resilience-building measures to ensure the continued stability and reliability of air transportation services by analyzing airport and/or airline networks. This includes investing in advanced technology, implementing robust safety protocols, diversifying routes and markets, and fostering stakeholder collaboration. By proactively addressing these challenges and enhancing resilience, the GCC aviation sector can better withstand unforeseen disruptions and continue to thrive as a vital driver of economic growth and connectivity in the region.

[10] Focus on technological improvements, the development of alternative fuels, and regulatory measures.

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A Review Approach to Understanding the Current Status of Port Resilience: Lessons Learned for GCC Ports

A. H. M. Mehbub Anwar and Nora N. Nezamuddin

Abstract Seaborne trade is responsible for the majority of global commerce by volume, and key logistics trade centers are typically located near coastal areas. Ports are fundamental agents of the maritime transportation system, serving as the point of entry and exit for most imported and exported goods. Ports play an important role as key nodes in multimodal transportation systems, making the connection between maritime and hinterland networks. Today, the resilience of ports is increasingly challenged by disruptive and extreme events such as geopolitical strife, adverse weather, pandemics, changing patterns of trade and sea routes, and the rise in sea levels. Achieving resiliency is an important factor for the greater attractiveness of maritime services and port sustainability, which requires infrastructure investments and the adoption of innovative and flexible practices. Currently, the literature surrounding the impacts of extreme events and unforeseen disruptions on maritime transport and ports remains novel. This body of work seeks to contribute to the understanding of resilient ports by reviewing the existing literature and gathering insights on how port resiliency can be applied in the Gulf Cooperation Council (GCC) region by identifying gaps of knowledge that can be explored.

Keywords Maritime · Port resilience · Sustainable ports · Resilient supply chain · Maritime infrastructure · Transport logistics

1 Introduction

Resilience has become increasingly vital for ensuring the sustainability of businesses amid a rapidly evolving landscape fraught with various threats. While traditional hazards like typhoons, earthquakes, and human-related incidents such as ship collisions and labor strikes have historically posed significant challenges to

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port operations, newer threats such as cyber-terrorism and infectious diseases are now emerging as formidable adversaries. The onset of the COVID-19 pandemic serves as a poignant example of this paradigm shift. For instance, in June 2020, the detection of COVID-19 cases among 16 Russian sailors at Gamcheon Port in Busan led to the precautionary self-isolation of 200 port workers, ultimately resulting in a complete suspension of port activities (Kim & Kim, 2021). This episode underscores the realization that infectious diseases like COVID-19, previously overlooked as potential threats to port operations, can indeed pose substantial risks to the port value chain. In essence, the array of factors posing threats to port functionality is becoming increasingly diverse. Consequently, there is a pressing need to enhance the resilience of ports, enabling them to swiftly adapt to disruptive impacts and restore normal operations promptly.

Resilience refers to the capacity to effectively manage and bounce back from the consequences of inevitable events, aiming to either restore the original operational state or progress toward an improved one (Shin & Park, 2019). The exploration of resilience originated with Holling in 1973 and has since been embraced by various disciplines, spanning ecology, psychology, education, architecture, business management, and economics (Chowdhury & Quaddus, 2017). Particularly within the domain of supply chain management, academic attention toward resilience began to surface around 2004, gaining momentum following the supply chain disruptions triggered by the 2011 Tohoku earthquake and tsunami (Kim & Kim, 2021). Infrastructure, including airports, ports, public transportation systems, waterworks, and power plants, represents a major focus area within resilience studies due to the profound societal repercussions associated with their failure.

Ports are essential elements of the global logistical framework, and any disturbance to their key operations can have significant ramifications on the worldwide economy (Kang & Kim, 2017). Therefore, the resilience of ports holds immense significance for both national and global economic stability. However, existing studies on port resilience have not sufficiently addressed the operational and policy aspects of the port industry. To formulate policies aimed at enhancing port resilience, it is essential to delve into the dynamics of port management and operational strategies.

In the ever-changing realm of international trade, the Gulf Cooperation Council (GCC) nations, notably the United Arab Emirates (UAE) and the Kingdom of Saudi Arabia (KSA), stand at the forefront of revolutionizing trade facilitation through the establishment of state-of-the-art smart ports. These nations are harnessing cutting-edge technologies to enhance the efficiency, safety, and sustainability of their maritime and logistics sectors, thus redefining the notion of trade empowerment in the Middle East. The GCC, particularly the UAE and KSA, are witnessing the ascendancy of intelligent ports as pivotal hubs of technological innovation, integrating advancements such as Artificial Intelligence (AI), Machine Learning, the Internet of Things (IoT), and Automated and Robotic Systems, among others. This fusion of technologies is fundamentally transforming traditional port operations, rendering them more efficient, expeditious, and environmentally conscientious.

A comprehensive understanding of port resilience is thus crucial. Hence, this chapter seeks to contribute to the comprehension of resilient ports by reviewing existing literature and gathering insights into how port resilience can be implemented in the Gulf Cooperation Council (GCC) region. This endeavor involves identifying gaps in knowledge that warrant further exploration.

The remainder of this chapter is structured as follows: After the introduction, we delve into Sect. 2, which examines existing literature. Section 3 explores the effects of port disruptions on maritime supply chains, while Sect. 4 outlines ongoing initiatives aimed at enhancing port resilience. Additionally, Sect. 5 highlights efforts within the GCC region to bolster port resilience, and lastly, Sect. 6 offers concluding thoughts and suggestions for future research avenues.

2 Review of Literature

In the review of the literature, first, we examined the definitions of resilience. Next, we investigated the components of port resilience in studies and identified their contributions.

Definition of Resilience

"Resilience", as a concept, is derived from the Latin root "resilire," which means to leap back or rebound (Notteboom et al., 2022). Increasingly, the term resilience has been used across multiple domains, especially when facing the challenge of the recent epidemic and emphasizing a focus on coping with unexpected situations (Holling, 1973; Rice & Caniato, 2003). Linkov et al. (2014) define resilience as the ability of a system to resist, recover from, and adapt to adverse events/shocks. Resilience aims to maintain or even enhance performance by effectively managing changes (Christopher & Rutherford, 2004). Gaonkar and Viswanadham (2007) explain it as "the ability to maintain, resume, and restore operations after a disruption." Thus, resilience denotes a system's ability to endure, adjust to, and recover from hardship or challenging circumstances. It encompasses the capacity to rebound from tough situations, uphold a sense of stability, and operate efficiently despite encountering adversity. Notteboom et al. (2022) define resilience in three ways including engineering resilience, which focuses on the ability of a system to resist shock and return to equilibrium; ecological resilience, which is how much shock or disturbance a system can take before it is destabilized; and adaptive resilience, which is when a system can anticipate and react to reorganization of both form and function to minimize the destabilization.

Previous literature also indicates that resilience may have two dimensions: one is mitigation resilience (Naderpajouh et al., 2018), and the other is adaptive resilience (Panahi et al., 2022). Mitigation resilience refers to the capacity of a system, community, or organization to reduce the impacts of potential hazards or disasters through proactive measures (e.g. shift to renewable energy sources). In contrast, adaptive resilience refers to the ability of a system, community, or organization

to adjust and thrive in the face of change, uncertainty, or adversity (Leon-Mateos et al., 2021). The Netherlands stands out as a frontrunner in addressing rising sea levels with its Delta Works initiative, consisting of various engineering endeavors aimed at safeguarding its coastal areas (EARTH5R, 2024). These efforts involve the implementation of various protective structures like barriers, sluices, locks, dykes, and storm surge barriers. Unlike mitigation resilience, which focuses on reducing the likelihood or severity of potential hazards, adaptive resilience emphasizes the capacity to respond effectively to challenges as they arise and to learn and evolve from those experiences.

Based on these explanations, we define port resilience as the capability to withstand unforeseen impacts, ensure continuity of operations, adapt to changes, and swiftly restore original functions. Key concepts include the capacity to absorb shocks, maintain functionality, and promptly recover from disruptions. A disruption in port functions can cascade into supply chain interruptions, affecting the broader economy. Hence, emphasis is placed on absorbing impacts to sustain operations. Additionally, the ability to promptly adapt and restore original functions aligns with common resilience definitions.

Port Resilience

Ports are critical nodes in global supply chains, serving as key interfaces between maritime and land-based transportation systems. However, they face various challenges, including natural disasters, geopolitical tensions, and technological disruptions, which can disrupt operations and threaten supply chain integrity. Port resilience has emerged as a crucial concept in ensuring the continuity and reliability of port operations in the face of these challenges. Notteboom et al. (2022) look at port resilience as a system that can cope with shocks, absorb disruptions, quickly recover and restore operations to a level similar to or better baseline, and adapt to changing situations while continuing to develop.

Several researchers commonly used various mathematical models as a tool, which is quite popular at the port level to analyze and manage disruption. The advantage of this tool is that it allows us to quantify the risks as well as losses in a specific context. For instance, both Hsieh (2014) and Hsieh et al. (2014) examined the risk of port failures from the perspective of vulnerability, using internal factors such as access travel time, crane efficiency, wharf productivity, electronic data interchange (EDI) connectivity, labor productivity, and free trade zone (FTZ) business volume. These authors developed and proposed a framework to assist decision-makers in understanding the vulnerabilities and adopting appropriate strategies to minimize risks and losses. Meanwhile, John et al. (2016) introduced a modeling method utilizing Bayesian belief networks to represent a range of influential variables such as operational risk, security risk, technical risk, and natural risk in a seaport system. The suggested model can aid scientists and decision-makers in comprehending intricate operational processes, thereby facilitating the development of essential strategies aimed at enhancing system resilience within a dynamic environment. Rose et al. (2018) employed an input–output model to assess the overall economic effects and resilience when confronted with a disruption in

crude oil and refined petroleum product trade at a significant seaport. Their analysis revealed potential downturns in both regional and national economic activities amounting to billions of dollars. However, they also found that resilience measures could substantially mitigate these consequences. Similarly, Cao and Lam (2018, 2019) discussed frameworks for port risk assessment. Specifically, Cao and Lam (2018) introduced a catastrophe-induced port loss estimation framework for port stakeholders, with input parameters such as ship arrival information and quay crane utilization information, while the results consist of the number of ships arriving and the volume of containers processed. In Cao and Lam's study (2019), the input factors consist of efficiency, resilience, and robustness, while the outputs pertain to the bottlenecked systems within the port.

Lam (2012) examined the disruptions in a port, discussing the propagation effects of port disruption on the supply chain and mitigation strategies. Using semi-structured interviews conducted with the management personnel of terminal operators, shipping lines, and insurance companies, it was observed that when a port disruption happens, the most immediate impact is seen, as well as the adverse effects on terminal operations. Therefore, collaboration among the stakeholders is imperative to minimize the risks.

Meanwhile, Gharehgozli et al. (2017) introduced a conceptual framework aimed at assisting port operators in assessing their strategies concerning weather-related disruptions and ensuring port resilience. Their framework involves (1) gathering and analyzing historical data on past events, (2) acknowledging and managing stakeholders' expectations, (3) developing adaptive resilience strategies, and (4) implementing these strategies with flexibility. Similarly, Almutairi et al. (2019) devised an integrated framework for port stakeholders, which includes participant mapping and analyzing disruption scenarios based on risk preferences to evaluate the resilience of container ports against challenges such as traffic congestion, economic slowdown, high operational costs, and environmental concerns. Gonzalez-Aregall and Bergqvist (2019) examined the repercussions on hinterland logistics stemming from port conflicts, proposing the integration of intermodal transport and dry ports as potential solutions to mitigate disruptions. On a different note, Amodeo and Francis (2021) outlined a trade-off space for vessel-move sequencing decisions, suggesting a temporary shift from decentralized to centralized decision-making during disruptions. Their research demonstrated that altering prioritization rules could impact the recovery process without compromising safety protocols.

John et al. (2018) introduced a decision support system (DSS) designed to assess security risks for both port operators and seafarers. This system employs the Analytical Hierarchy Process and Evidential Reasoning to evaluate three risk parameters: threat likelihood, vulnerability, and consequence. While this tool aids stakeholders in comprehending the importance of devising robust resilience strategies, it does not propose specific strategies. Meanwhile, Verschuur et al. (2020) were the first to advocate for utilizing vessel tracking data, particularly for security purposes. They analyzed historical data on port disruptions caused by natural disasters, revealing simultaneous impacts on multiple ports, which challenges previous studies focusing solely on single port disruptions. The authors also recommended incorporating

vessel tracking data into future modeling studies to assess the extent of disruptions and the potential resilience of port and maritime networks more accurately.

Another study conducted by Zhou et al. (2021) proposed integrating the port's decision support system (DSS) with digital twinning-based resilience analysis to calculate and update port resilience. This approach, according to the authors, facilitates the incorporation of routine operational uncertainties into resilience assessments while also preparing for disruptions with known probabilities. Similarly, Dhanak et al. (2021) developed a hybrid multimodal microscopic traffic simulation model (VISSIM) to analyze port operations and offer a measurable evaluation of resilience. This modeling approach enables the visualization of vessels interacting both temporally and spatially with each other and with landside infrastructure. The study quantified local and regional resilience by examining time-dependent resilience plots, utilizing them as a performance metric.

3 Port Disruption and Its Impact on Maritime Supply Chain

The maritime sector has long been recognized as a crucial facilitator of global trade and economic prosperity. Despite its economic significance, maritime transport systems are inherently intricate. They handle over 90% of global trade, a fact widely recognized by various organizations such as the International Maritime Organization (2021), OECD (2021), and International Chamber of Shipping (2021), as well as industry publications like the Washington Post (Green, 2018), and numerous academic studies (e.g., Fratila et al., 2021). As a result, the maritime sector holds a crucial position in stimulating economic expansion worldwide.

Given its pivotal role and complex structure, any disruption in the maritime supply chain can have significant adverse effects on freight supply chains, with far-reaching consequences for global trade and economic development. A recent example is the COVID-19 pandemic, which has endured for more than 3 years and has deeply affected the global economy. Specifically, the pandemic has been estimated to have led to a 3.8% decline in global maritime trade in 2020 (UNCTAD, 2021). For instance, the closure of a container terminal in Meishan island of Ningbo-Zhoushan in China—the world's third-busiest cargo port—due to a worker contracting the Delta variant of COVID-19 resulted in significant port congestion, delays in other ports, vessel backlogs, increased shipping costs, and ultimately higher commodity prices (Leggett, 2021; Xu et al., 2021a).

Additionally, port management estimated a loss of approximately USD 19.4 billion due to an 11-day closure at 29 major US West Coast ports in September/October 2002 (OECD, 2003). More recently, the grounding of the MV Ever Given in March 2021, blocking the Suez Canal—an artery accommodating roughly 12% of global trade—resulted in a daily hold-up of about $9.6 billion in trade. This equates to $400 million and 3.3 million tons of cargo per hour, or $6.7 million per minute. Such an obstruction could incur costs to global trade ranging from $6 to $10 billion

per week and could diminish annual trade growth by 0.2–0.4% points, as estimated by the German insurer Allianz (Russon, 2021).

3.1 Disruptive Cases

Supply chain interruptions may arise from diverse origins, ranging from external elements like natural calamities to internal challenges such as inadequacies in integrating specific supply chain operations (Ponomarov & Holcomb, 2009). Disruptions may manifest as either slow-onset or sudden-onset events (Van Wassenhove, 2006). Slow-onset disasters evolve gradually over time, with epidemics being a notable example. In contrast, sudden-onset disasters result from swift and unexpected events, such as critical infrastructure failures or transport accidents (UNDRR, n.d.). Therefore, analyzing distinct disruptions, such as COVID-19 and the Suez Canal blockage-21, can offer insights into supply chain complexity and highlight the need for resilience in managing different types of disruptions.

COVID-19: The coronavirus disease (COVID-19), caused by the SARS-CoV-2 virus (WHO, n.d.), emerged in Wuhan, China, in December 2019, subsequently spreading worldwide (WHO, 2020a). On March 11, 2020, the World Health Organization (WHO) declared COVID-19 a global pandemic (WHO, 2020b). COVID-19 represents a distinctive form of slow-onset disruption that profoundly affected global supply chains. Epidemic-related disruptions are characterized by their prolonged duration, cascading effects, high levels of uncertainty, and simultaneous disruptions in supply, demand, and logistics infrastructure (Ivanov, 2020). COVID-19 has led to both immediate and enduring impacts on maritime transportation due to government regulations, resource shortages, and rapid fluctuations in supply and demand (Ivanov, 2020; Kumar & Sharma, 2021; Notteboom et al., 2021). The initial drop in demand began with lockdowns and factory closures in China, followed by Europe and North America, leading to reduced import demands from China and significant disruptions in global supply chains (Cullinane & Haralambides, 2021). While epidemic impacts have been extensively studied in humanitarian logistics, there has been relatively less research on their effects on commercial supply chains (Queiroz et al., 2022).

Suez Canal blockage-21: The Suez Canal blockage-21 was characterized as a sudden disruption with immediate and short-term repercussions on global trade (Lee & Wong, 2021). This incident, where a 400-meter container ship obstructed the busy waterway for 6 days, resulted in cascading effects and widespread delays worldwide (Lee & Wong, 2021). Even after the clearance of the canal obstruction within a few days, its impact lingered on global supply chains for weeks. During the blockage, over 300 vessels were stranded, preventing approximately 12% of the world's trade from transiting through the Suez Canal (Duerr, 2021). The backlog of ships caused significant disruptions to various commodities, resulting in an estimated hold-up of nearly $15–17 billion in trade (LeBlanc, 2021). As vessels queued up for passage

through the canal upon its reopening, availability issues arose for containers, ships, and their cargoes. The vulnerability of the canal, a critical link between Europe and Asia, became evident following this recent disruption, prompting international efforts to explore alternative maritime routes (Lee & Wong, 2021).

3.2 Impacts on Maritime Supply Chain Due to COVID-19

Sea-related activities play a pivotal role in the global economy and societal advancement. The maritime and shipping sector has faced significant challenges due to the COVID-19 pandemic. Initially, many countries suspended operations at their seaports and imposed restrictions on export and import activities as the virus spread. The implementation of border closures and restrictions to curb COVID-19 resulted in disruptions to the flow of goods, capital, and individuals, leading to delays and halts in worldwide supply chains. Consequently, numerous industries had to either halt or reduce manufacturing operations due to the inability to access global markets to distribute their goods.

Port Performance: In order to curb the spread of widespread infection, governments worldwide have implemented various preventive measures, including work stoppages and travel restrictions (Narasimha et al., 2021; Xu et al., 2021b). Consequently, the global economy suffered a significant downturn, leading to a marked decrease in international trade. The shipping industry, being the primary conduit for international trade, bore the brunt of this health crisis. With reduced demand for transportation, liner companies opted to suspend certain routes to cut costs (Xu et al., 2021b). The efficiency of cargo handling has diminished, and freight prices have surged due to decreased transport capacity, port quarantines, and staff shortages. Notwithstanding these challenges, some governments implemented supplementary actions to guarantee the uninterrupted functioning of maritime operations amid the COVID-19 pandemic. These measures include the waiver of penalty fees, initiatives to digitize processes, implementation of port safety measures, and waiving charges for vessels carrying oxygen and related cargo at key Indian ports. Additionally, during the pandemic, corporate social responsibility funds from seaports were allocated to support medical and community development initiatives, as well as the repatriation of seafarers (Narasimha et al., 2021).

Supply Chain: The COVID-19 pandemic is not the first event to significantly disrupt maritime supply chains (MSCs). Previous natural disasters, such as the 2011 mega-earthquake in Japan, the 2003 SARS outbreak in China, and the 2004 tsunami in Indonesia (Tan & Enderwick, 2006; Kraude et al., 2018), have also caused shortages of parts and products. Notably, production recovered from these disasters within a matter of weeks. However, the impacts of COVID-19 differ from those of previous events. The COVID-19 pandemic not only caused significant disruptions in local supply chains but also had a profound impact on MSC across all levels, from the initial sources of supply to the ultimate consumers. The pandemic

has revealed the interconnectedness of businesses through complex networks of MSCs, where upstream actors in the supply chain are significantly impacted by the seemingly unpredictable behavior of downstream actors, particularly large companies, experiencing disruptions and sharp fluctuations in demand (Kraude et al., 2018).

Many major automobile manufacturers are facing production shutdowns at various plants in China and other nations. The global automotive industry's output is anticipated to decline by 13% (Baker, 2020). For instance, Volkswagen suspended operations at its automotive plants in China due to travel restrictions and parts shortages. General Motors resumed production at its Chinese facilities but at significantly reduced rates due to similar constraints. Hyundai halted production at its assembly plants in South Korea primarily due to parts shortages originating from China (Reuters, 2020). Additionally, Nissan ceased production at its factories in Asia, Africa, and the Middle East (Martinez, 2020).

Food maritime supply chains, encompassing everything from seeds to staple products like rice and wheat, as well as perishable items like meat, vegetables, and fruits, face significant challenges primarily related to farming and transportation. Nearly every stage of food production, including planting, harvesting, and distribution, relies heavily on labor. For instance, India, the world's largest rice exporter, halted exports due to labor shortages and logistical disruptions. Similarly, Vietnam, the third-largest rice exporter globally, plans to reduce its quotas by 40% compared to the previous year due to similar challenges (Vu & Fernandez, 2020). Delivery of fresh food has been hindered by a shortage of truckers, canceled flights, lengthy inspections, and customs quarantines (Jadhav & Bhardwaj, 2020). Without intervention, this situation could escalate into a global famine (Food and Agriculture Organization, 2020). The significant disruptions to food supply caused by COVID-19 are anticipated to lead to a twofold increase in the number of people experiencing chronic hunger (Xu et al., 2020). According to the UNICEF Global Report on Food Crises, the number of individuals experiencing food insecurity escalated from 135 million in 2019 to 155 million in 2020, marking a rise of roughly 20 million people compared to the preceding year.

Dry Bulk Shipping

As maritime shipping accounts for roughly 90% of global trade in goods, disruptions at port facilities impede the distribution of imported food. The International Maritime Organization (IMO) has consistently emphasized the importance of maintaining maritime trade flow and implementing necessary health measures (IMO, 2020). Following the onset of the pandemic, cargo ships carrying bulk ocean freight isolated crews from mainland residents to prevent the spread of COVID-19 onboard. Consequently, as marine containers were unable to be reloaded during their return voyages to Asian countries, which are frequent importers, empty container shortages emerged (Shih, 2020). On the other hand, the COVID-19 pandemic resulted in the necessity for additional time and expenditure for new loading operations due to additional health screenings. With harbors experiencing labor shortages and delays in cargo handling, refrigerated warehouses became impractical for storing

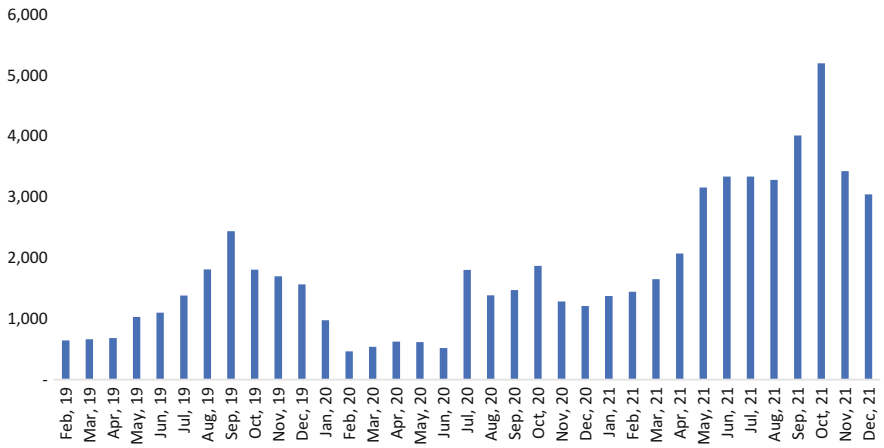

Fig. 1 Baltic dry index monthly open values. (Source: Authors' analysis (using data from https://www.investing.com/indices/baltic-dry-historical-data))

fresh food. These delays led to rapid spoilage of perishable goods, contributing to increased food waste. Additionally, the suspension of container operations during quarantine periods posed significant economic challenges to maritime trade.

As depicted in Fig. 1, the Baltic Exchange Dry Index experienced a decline starting in October 2019, reaching a decrease of over 65% by February 2020. Subsequently, some increases were noted, and by July 2020, levels comparable to those of November 2019 were nearly reached.

The COVID-19 outbreak heightened food safety concerns in Asia and the Pacific. Increased health risks led to travel restrictions, disrupting both domestic and international food supply chains and reducing food availability and accessibility (Kim et al., 2020). Apart from limitations in international transportation and logistics, disruptions in food supply chains were also caused by travel restrictions and employee illnesses during planting and harvesting seasons (Kim et al., 2020). Job losses and income reductions further exacerbated the risk of starvation and malnutrition among populations. Moreover, the global lockdown of borders and export restrictions restricted access to certain food products for import-dependent countries (Kim et al., 2020).

Tanker Shipping

During the peak of the rapid spread of COVID-19, the pandemic significantly affected both the shipping market and oil tankers. COVID-19 caused a lack of demand all over the world. Initially, it was believed that the impacts were confined to China, but over time, they spread across various populations and regions. Across maritime sectors, there was a reduction in the availability of labor, which subsequently impacted trade rates. Data from the Shipping Intelligence Network market (Clarksons, 2024) indicated a sharp decline in the demand for crude tankers in 2020 during the COVID-19 pandemic (Fig. 2).

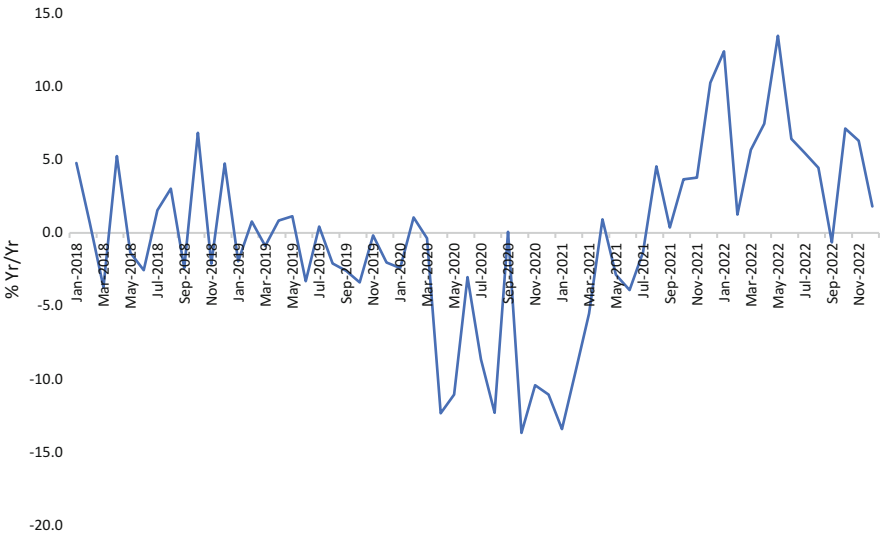

Fig. 2 Monthly global seaborne crude oil trade indicator. (Source: Authors' analysis (using data from https://www.investing.com/indices/baltic-dry-historical-data))

Figure 3 illustrates the year-to-year percentage changes over the seaborne crude oil tanker from 2018 to 2022. This implies that the percentage change in January 2018 is computed in relation to January 2017. It is clearly shown that COVID-19 had impacted the crude oil trade negatively, and it continued until March 2021. However, it rebounded to positive growth after this time.

3.3 Impacts on Maritime Supply Chain Due to Suez Canal Blockage

On March 23, 2021, at approximately 07:40 EGY (05:40 UTC), the Ever Given was traveling from Malaysia to the Netherlands (BBC News, 2021). Weather forecasts indicated strong winds reaching 40 knots (74 km/h; 46 mph) on that day (BBC News, 2021). As the Ever Given traversed the southern end of the canal, the powerful wind force caused the vessel's bow to veer off course, resulting in it becoming lodged in the southern canal (Schuttevaer, 2021).

Although the Suez Canal blockage has been resolved, its impact on the global supply chain persists. During the blockage, over 300 vessels were queued to traverse the Canal, halting approximately 12% of world trade (Duerr, 2021). The backlog of ships carried various cargoes, from livestock to crude oil, resulting in an estimated hold-up of USD $15–17 billion (Duerr, 2021). This was evident in the increase in gas prices by $0.40 on the day of the incident (LeBlanc, 2021). Despite the resumption of traffic, the backlog has led to challenges in container and

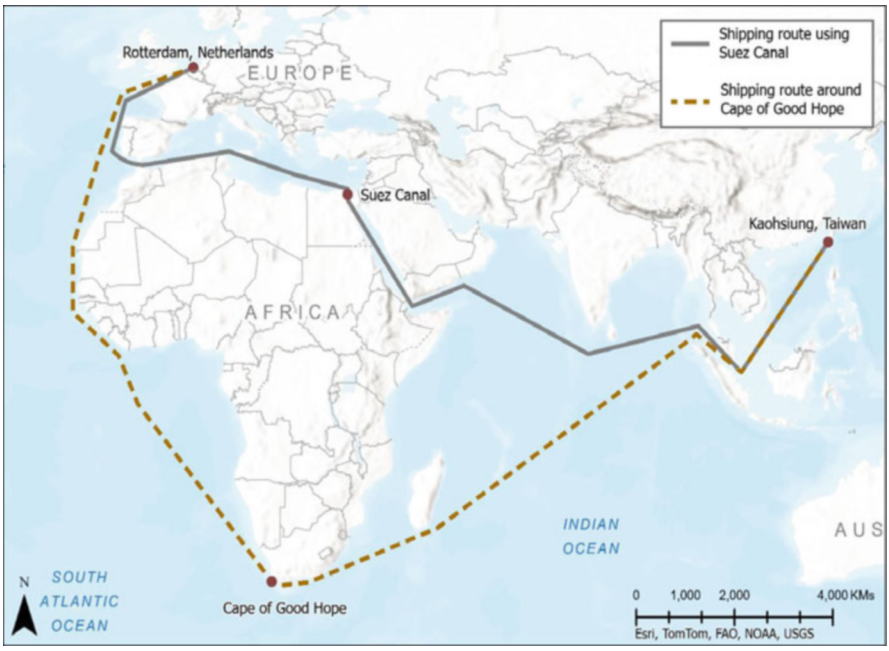

Fig. 3 Alternative routings for ship liners during Suez Canal blockage (Lee & Wong, 2021). Shipping route using Suez Canal: 10,000 nautical miles (18,520 km); 25.5 days*. Shipping route around Cape of Good Hope: 13,500 nautical miles (25,002 km); 34 days*. *Based on ship's average speed of 16.43 knots

ship availability. In contrast to European and Asian nations, the United States is anticipated to experience a milder impact, given its dependence on routes across the Pacific to the West Coast and the Panama Canal to the East Coast for transporting goods (LeBlanc, 2021).

The Suez Canal blockage has significantly impacted major development strategies such as China's "Belt and Road Initiative" (Duerr, 2021). China, as the world's second-largest economy, relies heavily on import and export trade (Gao & Lu, 2019). The Belt and Road Initiative is a vast project involving investments in 70 countries and international organizations, aiming to establish a maritime Silk Road linking South China with Central Europe and the North Sea, notably passing through the Suez Canal. The blockage of the Suez Canal has disrupted this strategy due to the traffic congestion. This incident underscores how a single ship can cause immense damage to the global economy. Consequently, there is expected to be an increase in shipping industry pricing, particularly in air freight, as some shippers have diverted shipments from sea to air due to the congested airline capacity (Kickham, 2021). Given that the Suez Canal is one of the five major checkpoints in global trade, there may be a need to reassess the most efficient methods for conducting global trade, including exploring alternative routes.

Suggestions for alternative routes to replace the Suez Canal have been proposed (Notteboom, 2012). These alternatives, such as the Cape of Good Hope route (Fig. 3), have been evaluated based on factors like distance, transit time, and generalized costs for 11 major trade lanes (Notteboom, 2012). The findings indicate that the Cape of Good Hope route holds the greatest potential as an alternative to the Suez Canal route.

4 Examples of Efforts Toward Port Resilience Globally

The Biden-Harris Administration introduced the Supply Chain Resilience Center (SCRC) in November 2023 to safeguard the US supply chain against evolving threats (DHS News, 2023). This new government initiative aims to collaborate with the private sector to enhance supply chain security, given the potential challenges posed by conflicts, political instability, and climate change in the coming years. The SCRC collaborates with private sector stakeholders to analyze vulnerabilities and conduct scenario planning, aiming to mitigate supply chain disruptions and ensure the reliable and efficient delivery of goods and services. It plays a crucial role in developing tangible, actionable solutions to counter threats to the US supply chain. The COVID-19 pandemic highlighted the need for more robust and resilient supply chains for food and essential goods relied upon by Americans. Through the SCRC, American businesses and the federal government will be better equipped to anticipate and mitigate disruptions, aligning with the Biden-Harris Administration's efforts to prevent such challenges.

The port of Singapore has emerged as a leader in sustainability and resilience, driven by several key factors. Notably, the Maritime and Ports Authority (MPA) is spearheading efforts in digitalization and sustainability. MPA is in the process of creating the Next Generation Vessel Traffic Management System to offer precise, up-to-the-minute awareness of shipping traffic, in conjunction with digitalPORT@SG™, with the goal of improving the efficiency of port operations and minimizing ship turnaround durations (MPA, 2024). Additionally, the upcoming Tuas Port is envisioned as a digital and automated facility. Equipped with versatile electrified, automated yard cranes, and automated guided vehicles (AGVs), Tuas Port aims to streamline container transport between the yard and the wharf. Automation and electrification of port equipment are expected to enhance productivity significantly. Moreover, to address the challenges posed by rising sea levels, Tuas Port will be built on an operational platform positioned 5 m above mean sea level (MSL). With initiatives like the Maritime Singapore Green Initiative complementing these efforts, Tuas Port is poised to become the resilient port of the future (WPSP, 2019).

The Port of San Francisco has launched a resilience initiative known as the "Waterfront Resilience Program" to ensure the waterfront and its critical assets, both regionally and citywide, can withstand hazards and become more accessible to all stakeholders. As a component of this endeavor, the U.S. Army Corps of Engineers (USACE), collaborating with the City of San Francisco, has introduced a Draft Plan

aimed at constructing coastal flood defenses along the Port's 7.5-mile jurisdiction from Aquatic Park to Heron's Head Park. The Draft Plan outlines the locations for building coastal flood defenses and the projected capacity to manage future sea level rise before requiring adjustments to accommodate higher water levels. The proposed solutions are estimated to require an investment of $13.5 billion (Port of San Francisco, 2024).

5 Port Resilience Efforts in the GCC

The Gulf Cooperation Council (GCC) is an intergovernmental organization made up of six countries, including Saudi Arabia (KSA), the United Arab Emirates (UAE), Oman, Bahrain, Kuwait, and Qatar. The GCC countries are located in the Arabian Peninsula between the Arabian Gulf and the Red Sea. This geographical region is endowed with a prime location along the East-West Shipping corridor, which contributed around 22% of global seaborne container traffic (UNCTAD, 2024c). Global events such as the pandemic, regional and international conflicts, and extreme weather events have affected countries all over the world, including the countries of the GCC.

With each GCC country having its own seaports, the significance of seaports to the overall economic diversification agenda of each GCC country differs. However, as a baseline, a comparison of two key performance indicators for ports will be measured for each of the six GCC countries, which include port calls and liner connectivity. These performance indicators represent two out of four indicators identified in the Review of Maritime Transport 2021 report published by the United Nations Trade and Development (UNCTAD) program. The indicators help in understanding how linked the GCC ports are globally and how disruptions of the ports can affect local markets as well as the movement of key cargo internationally. Additionally, to give more understanding of the size of the volume handled in each GCC country, container port throughput will be compared. Allowing for a basic understanding of where each country ranks with regard to the overall performance of its ports and can be informative for countries working toward improved resilience in their ports.

The first key performance indicator is the number of total port calls annually, where the number of calls from vessels to ports in respective countries is shown from 2015 to 2023, which is derived from Clarksons Research—Shipping Intelligence Network (Fig. 4). Among the six GCC countries, the UAE is ranked first with regard to port calls, having 75,476 port calls in 2023. Saudi Arabia has the second-highest number of port calls, with 46,690 calls in 2023, while Qatar is a distant third, with 18,200 calls in 2023. Oman and Kuwait fall within a similar range, with 7606 and 6090 port calls. Historically, Bahrain has always had the lowest port calls, with 2869 calls in 2023 (Fig. 4).

The second key performance indicator is the liner shipping connectivity index (LSCI), which is a quarterly index developed by UNCTAD (Fig. 5). There are

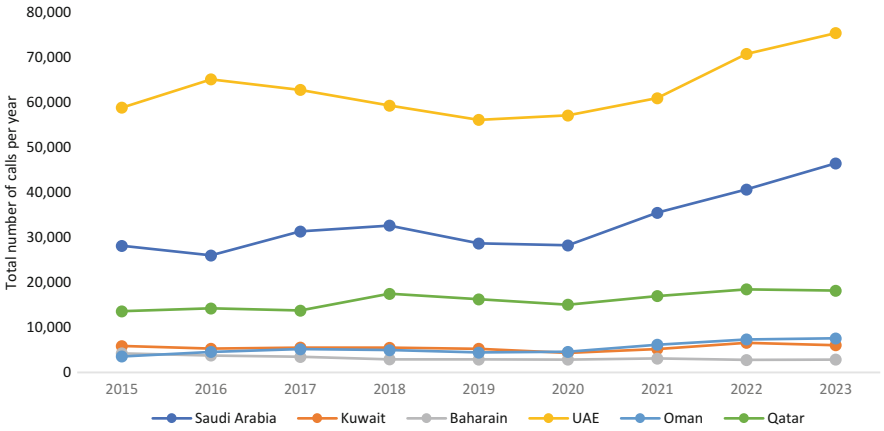

Fig. 4 Total port calls in GCC countries from 2015 to 2023. (Source: Clerksons Research—Shipping Intelligence Network (Clarksons Research, 2024))

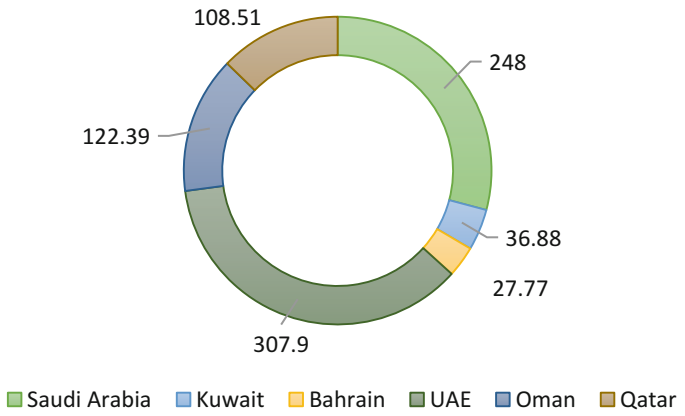

Fig. 5 Liner shipping connectivity index, Quarterly Q1 2024. (Source: UNCTAD Statistics, Liner Shipping Connectivity Index (UNCTAD, 2024a))

six key components that are accounted for in the LSCI, including the number of ship calls per week in a country; the deployed annual capacity measured in 20-foot equivalent unit (TEU); the number of regular or liner shipping services from and to a country; the number of liner shipping companies that provide services to/from a country; the TEU size of the largest vessel deployed to/from a country; and the number of countries that are connected to the country via direct liner shipping services (UNCTAD, 2024a). The higher the connectivity of a country's ports the higher the number of LSCIs. Both the UAE and Saudi Arabia perform well under the LSCI, with a score of 307.9 and 248, respectively. Oman and Qatar follow suit with scores of 122.39 and 108.51 (Fig. 5).

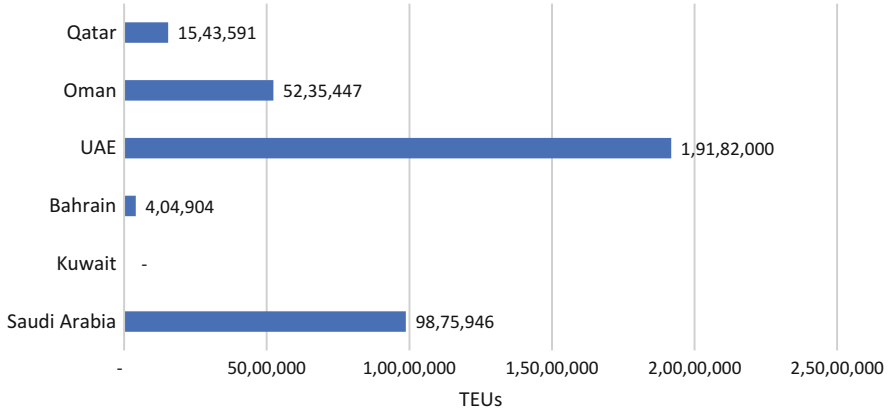

Fig. 6 Annual container port throughput in 2021. (Source: UNCTAD Statistics—Container Port Throughput, Annual (UNCTAD, 2024b))

Similarly to the other indicators, the annual container throughput for each GCC country derived from UNCTAD Statistics indicates the UAE's dominant role as a regional container hub, with 19.18 million TEUs handled in 2021, representing 53% of the total annual container port throughput handled in the GCC (Fig. 6). Saudi Arabia handles 27% of container port throughput, with 9.87 million TEUs handled in 2021. The remaining countries of Oman, Qatar, Bahrain, and Kuwait handle a smaller percent share of the total throughput in the GCC with 14%, 4%, 1%, and 0%, respectively (UNCTAD, 2024b). These indicators serve as a foundation for understanding where each GCC country is at with regard to port development, and given the significance maritime trade plays in connecting the global supply chain, highlighting the developments made by the GCC countries in terms of port resilience is imperative to understand future needs.

5.1 Saudi Arabia

Saudi Arabia is the largest of the six GCC countries in terms of density and size, with a population of around 32 million spanning its 2 million square kilometers (sq.km) land area (GaStat, 2024). Additionally, KSA is one of two GCC countries geographically situated between two seas, with the Arabian Gulf Sea located on its eastern coast and the Red Sea located on its western coastline, giving Saudi a unique positioning along key seaborne trade routes. Saudi Arabia has ten public seaports within the country, with four ports on its Red Sea coast and six ports located on the Arabian Gulf coast. These ports are operated by the Saudi Ports Authority (Mawani). The King Abdullah Port on the Red Sea Coast is the only port in Saudi Arabia that is privately owned and operated. Finally, there are several ports that

are operated by private companies, including Saudi Aramco, NEOM, and the Saudi Electricity Company (Clarksons Research, 2024).

As part of its overall direction to diversify its economy, Saudi Arabia has launched a national maritime strategy, which falls under a larger National Transport and Logistics Strategy, that focuses on six maritime sectors such as ports, shipping, marine services, shipbuilding and repair, marine tourism, fishing, and aquaculture (KSA IMO, 2024). Some projects include Port of Neom, located in the northwest of the country, which will focus on sustainability by operating a 100% zero-carbon port using wind and solar energy. Another example of projects promoting marine sectors of interest to KSA includes the development of the southwestern port of Jazan as an integrated petrochemical, mining, and transformational industries port, specifically focusing on agriculture, animal, and fish resources. Finally, KSA's efforts to enhance the presence of shipbuilding and repair sectors are manifested by the development of the King Salman Complex for Maritime Industries and Services, which aims to build, repair, and maintain Very Large Crude Carriers (KSA IMO, 2024).

In terms of Saudi Arabia's attempts to improve port resilience, the country has implemented several efforts to address port resilience. The Global Supply Chain Resilience Initiative (GSCRI) launched in 2022 aims to strengthen the resilience of the entire supply chain network, including key nodes such as ports, by supporting growth in key sectors. The aim is to attract USD $10.66 billion of investment in the first two years. Additionally, the GSCRI has a $2.67 billion USD incentive budget (Saudi Ministry of Investment, 2022).

Specific efforts in the maritime sector include providing an integrated electronic service for ports to increase security, improve efficiency, and enhance access to seaports. Additionally, KSA has worked to improve efficiency at ports, which increases resilience, by introducing 24-hour customs clearing times, automated customs processes and e-services, as well as privatizing transport and concessions contracts (Saudi Ministry of Investment, 2022). Some examples include e-services such as Naql, Logisti.sa, and Ebhar (KSA IMO, 2024).

Given these efforts, KSA is among several countries from the GCC that have ports ranked at the top of the World Bank and S&P Global Market's Container Port Performance Index (CPPI). Specifically, Saudi Arabia's King Abdullah Port topped the rankings for the year 2021, and Jeddah Islamic Port came in at the eighth spot (World Bank, 2022).

5.2 The UAE

As the second largest GCC country in terms of population, the UAE has a population of around 9 million and a land area of 83.6 thousand sq.km (World Bank, 2024). In terms of its maritime sector, the UAE currently has the most competitive seaports in the Middle East and globally. The country boasts 19 ports, 11 of which are operated by the state port authority. The remaining eight ports are mainly operated by the

national oil company ADNOC or the UAEs leading terminal operator DP World (Clarcksons Research, 2024).

In terms of port resilience, a number of local port authorities and operators highlighted the need for several elements to ensure supply chain resilience. The ownership and operation of ports in the UAE is distributed by the Emirate (State), which means that strategies for port resilience are developed on a port authority or port level. One example is the Abu Dhabi Ports, which released a white paper and conducted several webinars in 2020 to address the importance of supply chain resilience. However, there is no clear link between the suggestions made in 2020 and any direct implementation of suggestions (Abu Dhabi Ports, 2020). Another example is DP World, a leading Emirati terminal operator with a global presence, which published a report that maps climate resilience pathways for ports and terminals globally. The report examines three future scenarios across 50 ports and terminals (Kherallah & Mirza, 2023). There has not been a clear strategy or action since the publication of the white papers. It is not clear if the port operates and has adjusted its resilience preparedness.

While not solely focused on resilience, several UAE ports have conducted projects that are part of the World Ports Sustainability Program (WPSP), which aims to apply the 17 UN Sustainability Development Goals (SDGs) as key to achieving sustainable ports. There are six areas that are looked into, including digitalization, infrastructure, health safety and security, environmental care, community building, and climate and energy (WPSP, 2024). In the UAE, Abu Dhabi Ports Group has completed six projects, including Heroes of Hope, Neeshan HSE Awards, mUnity, Project Shamal, SENYAR HSE Application, and Maritime Cluster. Most of the projects focus on digitalization, health safety and security, and infrastructure. Digitalization and infrastructure projects can lead to improved port performance and increase resilience and flexibility at ports.

Overall, the UAE has been a regional leader in the maritime sector, and UAE ports have been ranked highly in the World Shipping Council's Top 50 Container Ports ranking. Specifically, the Port of Jebel Ali has ranked 11th among the top 50 container ports in 2021 (World Shipping Council, 2021). In terms of efficiency, the Khalifa Port in Abu Dhabi was ranked fourth in the 2021 World Bank and S&P Global Market Container Port Performance Index (CPPI). (World Bank, 2022).

5.3 Oman

The Sultanate of Oman has an estimated population of 5 million, spanning over a land area of about 309.5 thousand sq.km (World Bank, 2024). Similarly to KSA, Oman is geographically located along two bodies of water, which are the Gulf of Oman from the north of the country and the Arabian Sea from the east of the country. The access to the Arabian Sea situates Oman directly on the East-West Shipping corridor. Oman has seven ports, with six located in the northern part of the country along the route toward the Strait of Hormuz and one along its eastern front.

Historically, Oman is known for its rich history in seafaring dating back to the third millennium BC (Al-Lawati, 1994). Therefore, it is no surprise that the country continues to work toward the development of its seaports. Additionally, given that the country is prone to extreme weather events such as cyclones, it has been imperative for Oman to consider the resilience of all its infrastructure. Port resilience in Oman has been handled on a port level with ports. One example is the quantitative climate assessment of the port of Sohar conducted by Deltares to understand the port's preparedness in the event of a tropical cyclone (De Boer & de Jong, 2024). This assessment helps the port of Sohar develop a readiness plan in case of natural disruptions, which means an improvement of resilience to natural disasters. In terms of port performance, in 2021, the Port of Salalah was ranked second by the World Bank and S&P Global Market CPPI (World Bank, 2022).

5.4 Qatar

As one of the two smallest GCC nations in terms of land area and population, Qatar boasts a population of about 3 million and a land area of 11.5 thousand sq.km located in the Arabian Gulf (World Bank, 2024). There are seven ports in Qatar, with three ports operated by the national port authority, Mawani Qatar, including Hamad Port, Doha Port, and Al-Ruwais Port. The remaining ports were operated by different entities, including Qatar Energy, the national energy company.

In terms of port enhancements, the Hamad Port in Qatar was ranked third in the 2021 World Bank and S&P Global Market Container Port Performance Index (CPPI), signifying the constant focus on efficiency improvements in Qatar (World Bank, 2022). Several new projects are underway in Qatar, including the announcement of a new port to be constructed with a value of $7 billion USD, which will be developed over multiple phases. The aim of the port is to allow the world's largest container vessels access to the port (Royal HaskoningDHV, 2024). The new port projects will use new technologies, which will help in improving efficiency at the port and, in turn, improve response times at the port.

Overall, Qatar has focused on improving the resilience of its supply chain by increasing its self-sufficiency, specifically in several basic foodstuffs such as dairy products and poultry (Qatar Ministry of Commerce and Industry, 2022). However, in terms of port resilience strategies, there is no specific national strategy detailed for Qatar.

5.5 Kuwait

Kuwait, on the other hand, is the fourth largest GCC country in terms of population and land area, with a population of about 4.78 million and a land area of 17.8 thousand sq.km (World Bank, 2024). Kuwait is situated at the top end of the

Arabian Gulf, with five ports in the country. Three of the ports are operated by the Kuwait Ports Authority, while two ports are operated by Kuwait Petroleum. In 2022, Kuwait awarded SMEC the expansion of its Shuwaikh Port. In terms of resilience, no specific strategies have been adopted at the port level. However, the Kuwait Institute for Scientific Research (KISR) entered into an agreement with the UN Human Settlements Program (UN-Habitat) to fund a project focused on adaptation and resilience along the internal borders of Kuwait. These areas are of significant concern due to frequent sand and dust storms (KUNA, 2023).

5.6 Bahrain

Bahrain is the smallest of the six GCC countries in terms of population and land area, with a population of 1.57 million and a land area of 750 sq.km (Bahrain Information and eGovernment Authority, 2024). With its tradition of fishing and pearl diving, Bahrain has many fisherman ports; however, the country has four larger ports that conduct commercial activities. Two of these ports are operated by the Bahraini Ports Authority, while the other two ports are operated by A.P. Moller. Bahrain does not have a national strategy targeting port resilience. Additionally, there are not many projects that are taking place to enhance the ports in these countries.

6 Concluding Remarks and Future Work

The maritime industry is integral to global trade and economic progress, characterized by a complex supply chain involving numerous interconnected players, systems, and networks. Given this complexity, managing disruptions within the maritime supply chain is paramount. Any disturbance affecting one player in the chain can have far-reaching consequences for others, ultimately undermining the overall chain's performance. This chapter undertakes an extensive literature review in this crucial domain and endeavors to explore potential strategies for addressing port challenges and disruptions.

One of the key challenges to port resilience is the lack of investment to update, prepare, and enhance ports to meet the flexibility required in today's economy. For the GCC countries, there are some developments toward increased resilience. However, more can be done to ensure the resilience of regional ports to withstand all forms of extreme events, from global disruptions to extreme weather events. Countries such as Saudi Arabia, UAE, Qatar, and Oman have started to apply strategies to improve resilience at seaports. However, more efforts can be made at the collective GCC level to improve resilience and develop a standard.

The findings from this review, along with identified resilience factors, lay the groundwork for further research into the relationship between port resilience and

sustainability. Moreover, this study contributes to policy formulation by establishing a concrete measurement framework for the abstract concept of port resilience and linking it to tangible activities aimed at enhancing resilience.

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Riyadh's Urban Greenwave: Fostering City Resilience Through Large-Scale Greening

Anne Habiby and Lama Yaseen

Abstract This chapter examines the crucial role of nature-based development and urban afforestation, including parks and connected green corridors, in boosting city climate resilience and fostering green mobility. It highlights the strategic value of green spaces in protecting urban areas from climate change effects like rising temperatures and severe weather. As cities in regions with rising temperatures face climate change impacts, green areas are increasingly seen not just as recreational spaces but as vital elements of urban climate strategies. Saudi Arabia, one of the world's hottest countries, and the broader Arabian Peninsula have warmed 50% faster than other northern hemisphere land masses (Climate Futures Report, 2023, KAUST, AEON Collective, KAPSARC). Saudi Arabia is making large-scale investments in urban green infrastructure, developing Riyadh as a leading city with sustainable arid climate. Riyadh's strategies appear to be creating a Greenwave, a comprehensive, climate-positive movement through extensive citywide greening, with green corridors to support sustainable transportation. The fundamental aspects of this emerging Greenwave—urban greening and decarbonized mobility—are poised for transformative, large-scale change. A comparative spatial analysis of Riyadh suggests that new parks will extend green space across the city into nearly all residential and commercial areas, linking them via tree-lined boulevards to the newly established Riyadh Metro. This nature-based planning exemplifies Riyadh's commitment to sustainability and may represent one of the most comprehensive urban adaptations to a warming world.

Keywords Urban sustainability · Urban greening · Urban afforestation · Cities · Resiliency

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1 Introduction

Nature-based development, also known as green infrastructure, integrates natural elements like green spaces, parks, wetlands, and trees into urban areas to enhance biodiversity, air purification, water filtration, and climate regulation. This approach has been recognized as an effective countermeasure to the negative impacts of urbanization, such as air pollution and the urban heat island effect (Bowler et al., 2010). By fostering healthier ecosystems, cities can mitigate climate change impacts, reduce urban heat, and improve resident health and quality of life. The deployment of green infrastructure, including parks, green roofs, and urban forests, is vital for climate adaptation, offering cooling effects, mitigating flood risks, and promoting biodiversity (Matthews et al., 2015). These green spaces not only beautify urban settings but also improve the overall quality of life (Chen et al., 2021) and increase property values, attract businesses and tourists, and contribute to sustainable urban development, driving shifts toward green mobility and sustainable economic growth.

In the hot, hyperarid climate of Riyadh, where summer temperatures frequently exceed 40 °C, combining green infrastructures of parks, green roofs, and effective surface materials and irrigation has been shown to significantly reduce urban heat island effects and the energy use of buildings. These natural elements provide shade, absorb solar radiation, and release moisture through evapotranspiration. In recent testing in summer in Riyadh, combining these green infrastructures in tested areas resulted in lowering ambient temperatures by as much as 8 °C at night and mitigating aridity by raising humidity levels by 5–10% (Santamouris et al., 2023).

Launched in 2021, the Saudi Green Initiative (SGI) represents a revolutionary approach to environmental stewardship and climate action, with significant goals to reduce emissions and increase greening and conservation. At the core of SGI's urban strategy is the expansion of urban parks, green corridors, biodiversity, and afforestation, aiming to enhance the city's recreational, aesthetic, and ecological appeal. These initiatives play a pivotal role in providing essential ecosystem services such as air purification and urban cooling, significantly improving residents' quality of life and promoting biodiversity (Saudi and Middle East Green Initiative, 2024). Saudi Arabia also initiated the Middle East Green Initiative to spur collaboration across the Middle East to drive climate responsiveness.

This chapter explores the concept of the Greenwave and examines the role of strategic and infrastructure initiatives such as Green Riyadh, Sports Boulevard and King Salman Park in fostering a climate-positive green network in Riyadh. The introduction will discuss some of these initiatives, followed by a spatial view showing the evolution of the city's landscape with the introduction of new parks and corridors, which are expected to significantly enhance greenery for long-term urban resilience. Additionally, this chapter discusses how a connected green network might reduce car dependency by encouraging active transportation through shaded greening corridors that link with Riyadh's new Metro system. This chapter concludes by discussing some of the challenges and opportunities associated with

the full-scale implementation of an urban Greenwave, fundamental to which is water, the limiting factor to greening in Saudi Arabia and the GCC.

2 The Greening Initiatives in Riyadh

The Greenwave concept in this paper refers to a strategic and comprehensive initiative that promotes the integration and expansion of green infrastructure across a city. This approach aims to create interconnected networks of parks, green corridors, and urban forests to enhance ecological, social, and economic aspects of urban life. The primary objectives of a Greenwave strategy include improving climate resilience, supporting biodiversity, enhancing public health, fostering social cohesion, and stimulating economic benefits through increased property values and tourism.

In response to the pressing issue of urban overheating, Saudi Arabia's Vision 2030 and the Saudi Green Initiative have launched transformative programs, effectively a Greenwave in Riyadh aimed at bolstering climate resilience. This initiative intertwines various projects across the city into a climate-positive network, part of a broader vision aimed at enhancing the city's livability and positioning Riyadh as a leading global city for environmental sustainability.

Developing a citywide network of parks and boulevards, the Green Riyadh project anchors Riyadh's Greenwave. The primary goal of the Green Riyadh project is to enhance the quality of life for all residents. This is envisioned through significantly increasing green space in Riyadh—greening from 1.5% to 9% of the city, which translates to an additional 541 km^2 of green spaces across Riyadh. Planting 7.5 million trees and increasing the per capita green spaces from 1.7 to 28 m^2—a 16-fold increase—fundamentally transforms the urban environment. Green Riyadh planting is entirely supported by recycled city water.

This nature-based network is intended not only to beautify the city but also to serve functional roles in improving air quality and reducing urban temperatures. The Green Riyadh project targets a reduction in urban temperatures by 2 °C in the summer and aims to decrease the heat reflected from the earth's surface by 15 °C. Moreover, it seeks to reduce carbon dioxide levels by 6%, significantly improving air quality. This initiative also focuses on biodiversity, establishing ecological corridors to promote bird and other wildlife that are supportive of plant propagation. Economically, through its vast cooling and shading networks, Green Riyadh is expected to reduce electricity consumption by approximately 650 GWh annually by 2030, generating an estimated SAR 71 billion in savings in healthcare costs, reduced electricity usage, enhanced real estate values, and the substitution of potable water with treated wastewater for irrigation. Socially, the project enhances community well-being by developing open spaces for socializing, sports, and outdoor activities.

Figure 1 presents the current overlay of parks in Riyadh, with each dot representing smaller neighborhood parks and Wadi Hanifa, an ecological linear park, while Fig. 2 offers a prospective view of the anticipated green space expansion

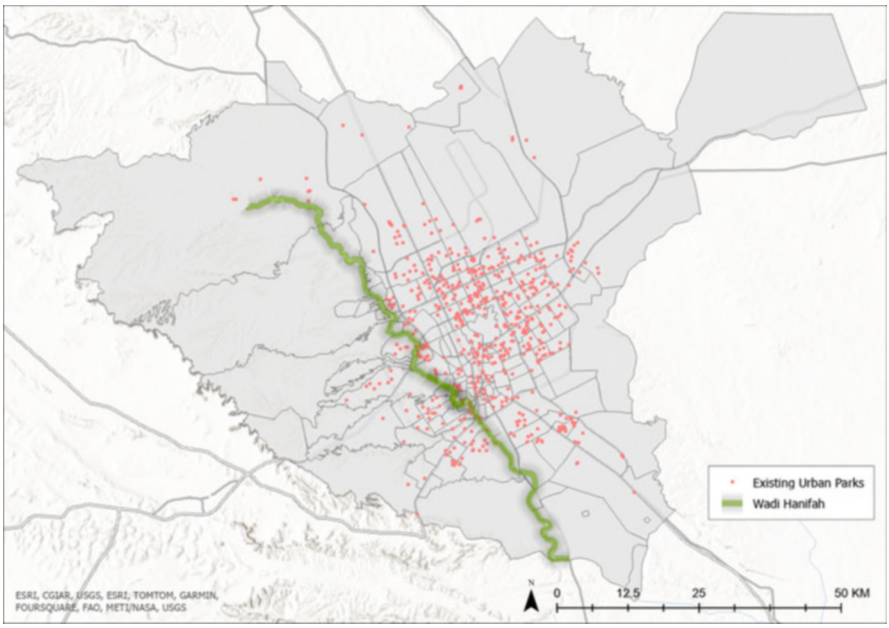

Fig. 1 Locations of existing gardens, parks, and Wadi Hanifah across Riyadh city. (Source: OpenStreetMap (2024) verified through Google search and satellite imagery in March 2024)

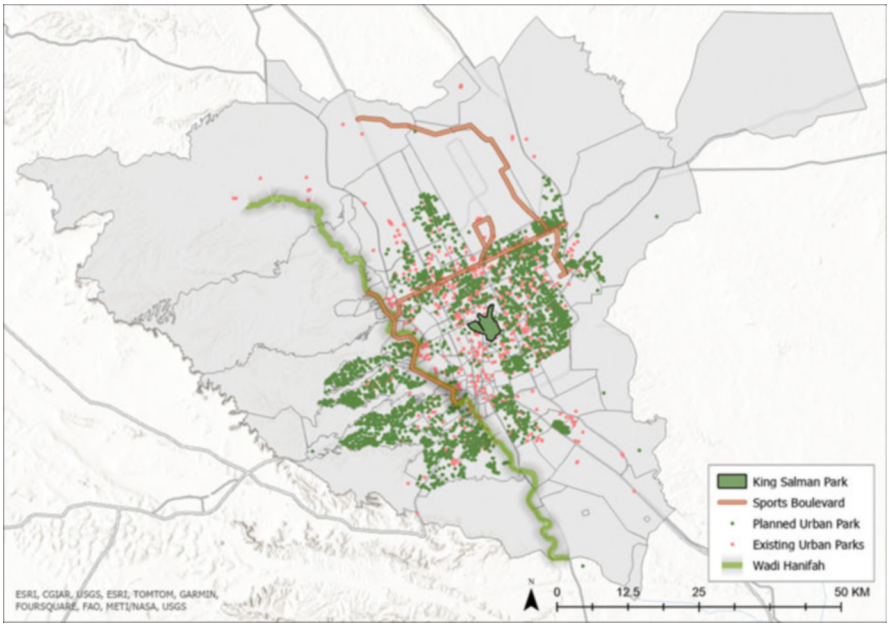

Fig. 2 Locations of current and planned 2030 gardens and parks across Riyadh city. (Source: OpenStreetMap extracted in March 2024 through the overpass and verified through Google search and satellite imagery in March 2024. RCRC (2024))

Fig. 3 Sports boulevard (Athletics District). (Source: Sports Boulevard Foundation)

and coverage upon the completion of each of the projects. These figures effectively illustrate a Greenwave of expansion of gardens and parks, highlighting both the increase in vegetation and the strategic distribution of greening areas throughout the city, including newer neighborhoods.

Complementing Green Riyadh is Sports Boulevard, a 135-km linear park that seamlessly links the city's neighborhoods, office complexes, and entertainment hubs (Fig. 3). With a focus on greenery and open spaces, the city's "green activity spine" adds 170,000 trees and aims to promote an ecosystem of sports and wellness, offering running, cycling, horse riding, and more than 40 different sports, as well as opportunities to live and work on Sports Boulevard (Sports Boulevard, 2024; Vision 2030, 2024). Riyadh's new metro and bus network runs through Sports Boulevard, promoting active mobility for recreation and commuting.

Positioned at the center of the city is King Salman Park, the "*Green Heart of Riyadh.*" King Salman Park is a dramatic example of infrastructure transformation, the world's largest conversion of a former airport, military base, or industrial area into a lush city park. Sitting in the middle of a metropolis of eight million people, it is designed as a world park and sustainability-led destination. Five times the size of New York City's Central Park and seven times that of London's Hyde Park, it contributes an unparalleled opportunity for an immersive connection to the natural environment, encompassing 800 plant species from the region and the world (Fig. 4).

Seventy percent of the former military airfield will be transformed into gardens, forests, hiking trails, playgrounds, lawns, and green spaces, acting as a sanctuary for extensive biodiversity. The remaining 30% features a wide variety of recreational amenities, including 150 attractions and 50 public venues, including museums and cultural attractions, an outdoor cinema, wellness, and sporting facilities. The park is estimated to draw 50 million visits a year and will offer nature-based living for 96,000 people, along with 2500 hotel rooms, workspace for 30,000, and a world-leading sustainable convention center (King Salman Park, 2024).

Fundamental to its mission, the park aims to create an iconic landscape that sets new standards for green spaces. Beyond its monumental size, King Salman Park

Fig. 4 Transformation of a former air base into King Salman Park into a lush green forest. (Source: King Salman Park Foundation)

emerges as a major milestone to decarbonize the built environment. The park's tree canopy and planting, comprising one million trees and 14 million shrubs, including a dense urban forest at the center of the park, act as a natural air-conditioner, mitigating the city's heat extremes. This not only enhances the park's role in providing a cool and refreshing environment for residents but also contributes to sequestering city carbon, improving air quality, and fostering an overall healthier urban atmosphere.

To foster ecological sustainability, King Salman Park is prioritizing water conservation, exclusively utilizing recycled city water and spearheading landscaping systems to reduce water needs. With extensive earthworks, the park has taken a flat site and engineered rises and valleys to maximize shading and airflow flow, including a 40-meter-high "Wadi Cascade"—a desert experiment in dynamic water movement for the whole park. These innovative land-forming designs not only enhance the aesthetics of the park but play a pivotal role in cooling the park to both reduce water needs and reflect radiation to the atmosphere.

Pillars of the Kingdom's Vision 2030 and Saudi Green Initiative, King Salman Park, Sports Boulevard and Green Riyadh, along Diriyah, the UNESCO "City of Earth," and the rejuvenation of the historic downtown, seamlessly integrate with the upcoming Riyadh Metro system, forming a city green network. Collectively, they serve as a testament to the Kingdom's steadfast dedication to investment in nature as a fundamental strategy in combating climate change.

These initiatives build upon decades of sustainable development efforts spearheaded by the Royal Commission for Riyadh City (RCRC). In the 1970s, the RCRC orchestrated the planning and construction of one of the earliest modern green cities, the Diplomatic Quarter (DQ), which accommodates all diplomatic missions to the

Kingdom. The DQ was meticulously designed with 30% green space to enhance the district's aesthetics and provide natural cooling, and it currently houses over 10,000 international and Saudi residents (Franklin, 2014). As Riyadh primarily relies on desalinated seawater for its water supply, in the 1970s, the Diplomatic Quarter took a proactive step by establishing its own greywater treatment facility. This facility recycles water from embassies to irrigate the quarter's extensive green infrastructure, showcasing an early commitment to water conservation and sustainability (Royal Commission for Riyadh City, 2024).

Furthermore, the restoration of the historic adobe capital of AlTuraif into an outdoor museum and UNESCO World Heritage site stands as a proud testament to the Kingdom's rich history of innovation and heritage in sustainable adobe architecture. In tandem with these endeavors was the preservation of Wadi Hanifa, a natural 100-km river that traverses the desert and historically served as Riyadh's liquid spine. Through extensive restoration, Wadi Hanifa was transformed into the city's ecological park, serving as a crucial natural asset for Riyadh. The Diplomatic Quarter and Wadi Hanifa, alongside other projects in Riyadh, have received prestigious recognition, such as the Aga Khan Award for Architecture, for their exemplary sustainable landscaping, architecture, and urban planning.

To grasp the scale of Riyadh's current planting initiative, one only needs to compare its tree density to that of London and New York City. Despite having similar populations of approximately 8.5 million residents, London, considered an urban forest, has 8.4 million trees in public and private spaces (Greater London Authority, 2024), equating to roughly one tree per capita, while New York City has approximately seven million trees in public and private spaces (Jalil, 2023), slightly less than one tree per capita. In contrast, Riyadh's mega projects and green urban code aim to introduce over 16 million new trees by 2030, adding nearly two additional trees per capita.

The increased tree and plant density and extensive dispersion of green spaces evident in the maps illuminate a citywide inclusive and interconnected green infrastructure of natural landscapes, crucial for reducing city temperatures while enhancing urban ecological corridors and biodiversity, and offering shaded walking and biking across the cityscape. This systematic investment in the expansion of greenery lays the groundwork for bolstering Riyadh's overall resilience in a warming world.

3 The Role of a Greenwave in Green Mobility

The interconnected green infrastructures comprising Green Riyadh, Sports Boulevard, King Salman Park, and other large projects form an emerging citywide climate-based network. Integrated seamlessly with the soon to open Riyadh's public transport system, these initiatives represent the potential for a transformative shift toward a green and active mobility, enabling improvements in health, well-being, and climate adaptation across the city.

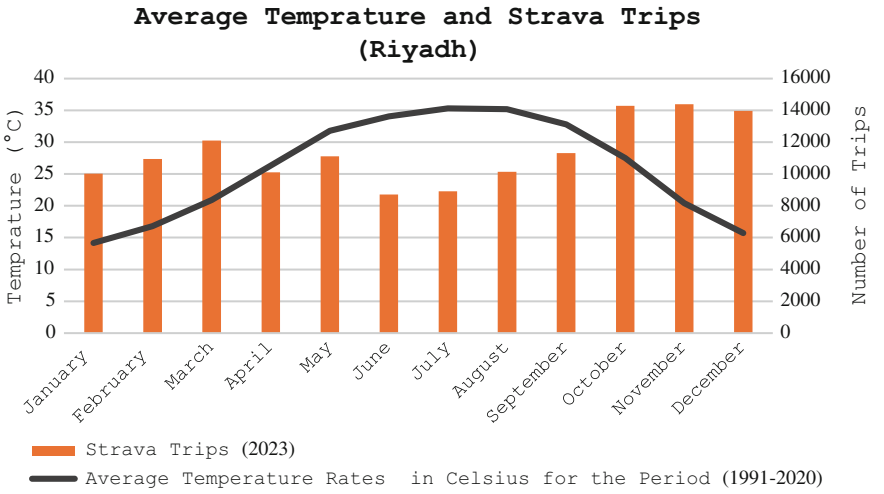

Fig. 5 Number of running/walking Strava trips per month in 2023. (Source: Strava Metro (2024) and National Center for Meteorology (2023))

However, the success of active transport in hotter climates faces steep challenges, primarily due to the discomfort caused by high temperatures, which deter outdoor activities like walking or cycling. Overcoming this barrier requires climate-adaptive urban design, such as connected shaded pathways and cycle lanes to and from stations to make public transport feasible and attractive for residents.

Riyadh data from Strava Metro (2024), a social fitness network that primarily tracks walking, cycling, and running exercises using GPS data, reveals that in 2023, a significant proportion of the app's users, about 92%, engaged with it for leisure activities, mainly running, while a smaller fraction, 8%, used it for commuting. Furthermore, the data indicates a marked seasonal variation, with usage doubling during the cooler periods at the year's end as opposed to the summer months, a trend depicted in Fig. 5.

Furthermore, as shown below in Fig. 6, the data reveals that most of these activities are concentrated around shaded parks, walkways, and regions where infrastructure is specifically designed to support and promote walking and running. Figure 6 illustrates very limited physical activity (yellow zones) in Riyadh's residential neighborhoods, and the essential role of green assets for physical activity and leisure (red zones).

These maps show heightened engagement in these areas, suggesting they serve as popular destinations for running and walking. Sports Boulevard has implemented a Design Code to recognize the demand for environmentally friendly, interconnected, and cooler areas to influence health and transportation habits. This code mandates that developers, retailers, and residential property owners looking to construct new

Fig. 6 (**a**) King Abdullah Park, (**b**) Al Nahda Park, and (**c**) Tala Park. The 2023 data shows an increase in activity by trip numbers inside and around the parks. (Source: OpenStreetMap (2024) and Strava Metro (2024))

structures or expand existing ones provide shaded pedestrian walkways. This initiative aims to promote walking and biking in Sports Boulevard area neighborhoods, providing access to the linear park as well as to Metro and bus stations (Sports Boulevard, 2024). As Green Riyadh, King Salman Park, and Sports Boulevard evolve into an integrated citywide network, the question is whether they will not only accelerate health and well-being but also function as viable commuting routes.

In the context of Riyadh, both the challenge and opportunity of scaling active transport to decarbonize the city are significant. The city has grown from a population of only 150,000 in 1950, doubling almost every decade, to eight million today. The Doxiadis 1972 Master Plan established a city grid of 2 km by 2 km superblocks to facilitate traffic corridors and an auto society and allow the city to expand endlessly (Al-Hathloul, 2017). Since the 1970s, the city's rapid growth has led to a marked increase in car dependency, and this reliance on cars has shaped the city's transport dynamics, contributing to traffic congestion and higher carbon emissions.

With roads over capacity, the Kingdom boldly decided to change course. The King Abdulaziz Public Transport Program (Riyadh Metro) was inaugurated by Royal Decree in 2012 to reshape the city's mobility. It is the largest metro construction project in the world, scheduled to open in late 2024. From the start, the Riyadh Metro (Metro and Bus) was conceived as a fundamental sustainability pathway for the city, unlocking new growth while decarbonizing transport, a key to the Kingdom's goal to achieve carbon neutrality by 2060.

The Riyadh Metro represents a significant evolution in global urban transportation enhancing the city's connectivity (Al Hosain & Alhussaini, 2021), linking over 60% of the city's employment and higher education centers. Worldwide, the majority of transport ridership is work-related, and the most competitive cities have highly concentrated employment nodes connected to public transport. However, active and public transportation as a commuting mode has yet to be tested in Riyadh.

Central to adopting public transport ridership is creating a synergistic relationship between active transport infrastructure and public transit facilities, fostering a multimodal travel ecosystem encompassing shaded and cool walking sidewalks and cycling routes to public transport. A key component of this integration is focusing on first and last-mile connectivity, ensuring that active transport options seamlessly link with public transit nodes and reducing reliance on personal vehicles for short distances. By enhancing first and last-mile connections, Riyadh's transportation network increases its functionality and accessibility, exemplifying a model for enhancing urban mobility, fostering resilience, and promoting sustainability (Yaseen et al., 2023).

Projects like King Salman Park, Sports Boulevard, and Green Riyadh, along with other mega projects and the city's transit-oriented development program, promote walkable green connectivity to and around metro stations. From a planning perspective, they represent significant potential to reduce car-based transport and build walkable "15-minute cities." Already, more than 70 transit-oriented development projects have been approved and are under construction in Riyadh (Royal Commission for Riyadh City, 2024). By leveraging densities around metro stations, connected to green corridors and public spaces, these projects lay the foundation to facilitate a shift toward more sustainable forms of transit for climate-based growth.

4 A Future Perspective of Urban Greening

Technological advancements are pivotal in the creation of cognitive cities, which integrate smart technologies and data analytics to enhance urban living. These cities utilize the Internet of Things (IoT), artificial intelligence (AI), and big data to optimize resource management, infrastructure, and public services. Smart grids, for instance, enable efficient energy use, while AI-driven traffic systems reduce congestion. Advanced sensors and data collection facilitate real-time monitoring and management of urban operations, leading to more sustainable, efficient, and responsive environments that adapt to the evolving needs of residents (Cugurullo, 2020).

A cognitive city represents an evolution beyond smart cities, where urban environments harness data-driven intelligence and cognitive computing to adapt dynamically. These cities integrate advanced technologies for proactive service delivery, data integration across sectors, and autonomous operations, all aimed at improving quality of life, ensuring sustainability, and fostering economic growth. This holistic approach to urban management emphasizes a blend of technological advancement, real-time adaptability and human-centric governance (PWC, 2023).

Looking to the future, King Salman Park, in partnership with King Abdullah University for Science and Technology (KAUST), is embarking on a visionary initiative to design the world's first "Cognitive Park." This involves installing an intricate network of sensors throughout the park to gather real-time data on all climate aspects such as temperature, airflow, soil moisture, plant growth, visitor

movement and transportation modes, and wildlife variety and activity. This endeavor involves the convergence of advanced technology, big data, and AI to investigate the detailed interactions of the park's natural world, allowing the park to adapt dynamically to environmental conditions and uncover opportunities for climate resilience.

Through this approach, the park transforms into a dynamic learning environment, continuously enhancing its understanding of itself and its evolving ecosystems. Given Riyadh's climatic similarities with other cities within the Arabian Peninsula and arid regions worldwide, it serves as a living laboratory for studies in nature-based urban resilience.

5 Conclusion

Riyadh's concerted greening initiatives are already coming out of the ground, appearing on maps as a vibrant green wave that flows over the city and enhances every facet of city life. Investments like these mark a once-in-a-century endeavor to reshape the city's urban landscape using nature-based solutions to embed future resilience. These initiatives not only bring immediate benefits such as cooling, improved air quality, health, wellness, and tourism but also promise increasing impacts over time as young trees and plants mature into thriving ecosystems.

The urban Greenwave concept, if developed to its full capacity, is a self-reinforcing strategy that can achieve the twin goals of cooling the city and reducing carbon emissions. It entails intensive and extensive citywide greening while establishing connected, shaded, and beautiful corridors to encourage low-carbon transport. The outstanding question is the extent to which residents will shift from car-centric lifestyles. As the city continues to experience rapid population growth, without transport mode changes, this would inevitably result in increased CO2 emissions. What is clear is that Riyadh's Greenwave and the soon-to-be-opened Riyadh Metro and Bus system are transforming the urban fabric, offering the best possibility to inaugurate new forms of mobility.

Should residents embrace low-carbon active mobility, the results could be exponential, creating a cooling green city reinforced by lower CO2 emissions and improved public health—a virtuous cycle of climate resilience. Further strengthening this would be advances in water conservation, as most of the Kingdom's water comes from the ocean, requiring energy to desalinate and recycle. The scale of Riyadh's Greenwave, and the Saudi Green Initiative, necessitates pioneering low-water solutions. If achieved, this would be a major third pillar in decarbonizing the city.

As Riyadh forges ahead, its ambition and innovative approach serve as a real-time laboratory for exploring what is achievable in a hyperarid, low-water context, with natural assets that grow and become more valuable with each passing decade. This investment stands as a testament to Riyadh's unwavering commitment to sustainability and may very well represent one of the most comprehensive urban energy adaptations to a warming world.

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Resilience in Practice: The Identity-Based Resilience of the Diplomatic Quarter in Riyadh

Anna Laura Petrucci

Abstract The concept of resilience is often defined in a variety of ways, depending on the specific context or field of study. For instance, in a review of resilience definitions, particularly in the context of disaster recovery, Plodinec (2009) identifies over 40 distinct definitions. Viewing cities as complex adaptive systems, and breaking them down into components and analytical elements, can facilitate the process of enhancing resilience through urban system design, planning, and management. Both physical and social processes can be seen as spatial and temporal interactions across networks, and it is the movement into, out of, and within cities that is of utmost importance for promoting beneficial operations and suppressing harmful ones. Understanding the vulnerable network components of cities, how these components enable specific interactions, and the ability to design various elements and their interactions to achieve resilience, is a complex and nuanced task.

Most of the current literature is, as a matter of fact, about post-disaster recovery, while the main goal of resilience, to be sustainable, is to plan in advance, limit or prevent disasters, not measure the time of bouncing back from it. This belief made it worth searching and analyzing case studies, making a positive impact despite the difficult conditions and making these learned lessons for future cities. Like sustainability, Resilience is an abstract and extensive concept, making it difficult to determine a specific implementation plan if it is not fully site-specific. Building a capacity for Resilience is a complex and multifaceted task, considering the myriad components, processes, and interactions within and beyond a city's boundaries. And what if the conditions of the contest are unprecedented and the most challenging due to climate, time, and management constraints? Only time can tell. That's why, after 45 years of completion, the resilience potential embedded in the planning process of the Diplomatic Quarter in Riyadh can offer assessing elements of Resilience and the potential of its applied solutions on their positive impact in the long term.

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1 Approach to the Assessment Methodology

Most accredited scholars base urban Resilience on the four pillars of resisting, recovering, adapting, and transforming, and they apply these in the five dimensions of natural, economic, social, physical, and institutional. These integrate 11 characteristics: redundancy, robustness, connectivity, independence, efficiency, resources, diversity, adaptation, innovation, inclusion, and integration (Ribeiro & Gonçalves, 2019).

The systemic complexity affecting urbanism and its resilience makes it almost impossible to develop a univocal assessment methodology and evaluation. On the other hand, it opens up wide opportunities for developing holistic studies to increase the resilience of different urban systems.

While the original concept of Resilience relates to the performances of specific materials, its adaptation to multilayered systems was first associated with ecological systems (Holling, 1973): "Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters and still persist. In this definition, Resilience is the property of the system, and persistence or probability of extinction is the result." Therefore, it can be concluded that Resilience is defined as the ability of a system to resist and/or adapt to a particular disturbance and recover its normal functioning or state of balance, which may set the initial baseline or a new situation (Ribeiro & Gonçalves, 2019).

What if the disturbance is intrinsic to the site, and the boundary conditions offer one of the worst possible scenarios? That's the story of the Diplomatic Quarter in Riyadh, built with truly extreme constraints of time, resources, and environmental qualities. The goal of Resilience is not bouncing back from a catastrophe but jumping forward in an unfavorable context.

2 Framing the Site and Time-Specific Challenge

In the early 1970s, the Kingdom of Saudi Arabia determined to relocate the international diplomatic community from Jeddah to Riyadh, destined as the kingdom's new capital. In 1975, the Foreign Ministry moved to Riyadh with a short-term project, in just 5 years, to "complete the capital function of Riyadh to provide for a functioning national administration" (Speer & Meurer, 1978). The project includes all the foreign embassies, diplomatic residences, and offices of the Saudi Ministry of Foreign Affairs and all the residential, commercial, recreational, and other support facilities that would make up a complete, self-sufficient district on the edge of Riyadh. For this purpose, a new *Bureau of the Project of the Ministry of Foreign Affairs was established, with just four employees, to trace the development strategies, manage all the administrative and legal issues, and* supervise the design and its implementation. The land allotted to the new Diplomatic Quarter was near

the urban center and detached at the same time, a plateau with an extent of 580 ha that dramatically overlooks the Wadi Hanifah with a 3-km-long cliff. The project brief targeted iconic contemporary architecture, which could also express the legacy of Saudi Arabia and its heritage values and ensure all the comforts and services required by the international diplomacy and cultural circle. The district had a master plan independent of Riyadh's, based on the Doxiadis' urban grid, developing a unique concept of landscape-based urbanism.

The project presents varying degrees of complexity in that it is a first for the Kingdom and has an extremely short design and construction time, limited human resources, and a vision as ambitious as ever: to transform a rocky heath into a paradise, livable, human-scaled, and offering a contemporary reinterpretation of traditional architecture. The challenging conditions and the ambition to undertake a project never attempted before, rather than hindering progress, become the key factors for success. They push the project's leaders to adopt a bold, unconventional vision and approach for the time. The design of the entire district is rooted in landscape and environmental solutions, entrusted to Richard Boedecker, who is given the task of transforming the barren, rocky land into a thriving oasis.

Furthermore, the human factor declined on the different scales of the project, the urban, landscape, and architectural. It was well maintained in scale and well-being despite the highly representative requirements of the institutional space.

The ecological design of the Diplomatic Quarter would win an Aga Khan Prize, along with the urban center (Al-Kindi Plaza) and the diplomatic club (Tuwaiq Palace). With lush greenery and prime examples of contextual architecture, the Diplomatic Quarter has become Saudi Arabia's most accomplished work of "green architecture" and a model for other new Islamic communities worldwide. After 45 years of completion, it is possible to evaluate—based on factual-based research—the success factors for the Diplomatic Quarter in Riyadh, assessing the level of achievements on its different scales and complexity—landscape, urban development, architecture—as well as its Resilience and value set in reference to the natural, human, and cultural environment.

3 Natural Resilience: Challenges, Approach, and Strategic Solutions

The construction of the new Saudi Diplomatic Quarter in Riyadh's arid climate was the most significant challenge for landscape, architecture, and livability. Therefore, landscape was chosen as the project's leading element and the definitive game-changer in making it livable and globally iconic.

Landscape solutions had to consider the extremely hot temperatures, often reaching 50 °C with very low humidity, just 20%, in the summer, as the usual sand storm from the desert nearby. In the 1980s, at the time of the project, water was in extremely short supply and only based on groundwater because the desalinization

plants to supply Riyadh, located 400 km away from the coast, would have been constructed later. Rain was also very rare and, in most cases, quite violent, so the storm-water drainage systems in the city were inadequate or nonexistent, and people could drown in their cars in freeway underpasses. Even the wind threatened the vegetation, drying the soil due to the high amount of sand moved. Addressing these extreme climate conditions requires a thorough understanding of ecology and adopting a holistic, systemic approach. This involved implementing multiple cooperative strategies to support plant growth while caring for it at the micro and macro scale. Key measures included shielding vegetation from intense sunlight and sandstorms by reducing their exposure, cooling the surface temperature, and minimizing evaporation. The project's initial step was to identify local plant species capable of surviving extreme drought and dryness, as well as the occasional but severe flooding conditions.

Landscape, called to lead the whole project, was embedded in the rocky nature of the site, following and controlling the airflow and relinquishing to any linearity to create the "oasis city" (Speer & Meurer, 1978). The landscaping of the entire project has been planned as a self-sustaining ecological system, minimizing the use of intensive green by preferring an extensive landscape and implementing plant materials to be found in the surrounding desert environment instead. The Aga Khan awarded it as "a realistic and imaginative understanding of the natural and spatial organization in hot and arid regions" (Aga Khan Foundation 1987–89).

Nevertheless, the first established building of the Diplomatic Quarter was the nursery, a highly symbolic gesture of a pragmatic, long term and radical approach to the project. The nursey was first established as the core and foundation of the whole district, as a complex of 50,000 sqm. It included the administrative offices for the Bureau of the Project of the Ministry of Foreign Affairs, besides the traditional cool houses and propagation beds, shaded staging, storage, and parking areas. A water treatment and water recycling plant were built next to the nursery to recycle water for the embassies to generate gray water to support the greening of the new city. The nursery is, up till now, serving the maintenance of the green of the whole district and Riyadh; during the years, several test gardens have been established, and a seed bank in 2010.

The public landscape areas for the Diplomatic Quarter consisted of three types: responding to the condition and the specific requirement of the site and the master plan and moving from the outskirt areas to the internal plots:

(a) The Earth Berm: A constructed landscape feature along the site's eastern edge provides screening from an adjacent freeway and serves as a spoils pile for huge quantities of rubble limestone excavated for site infrastructures. Since infrastructure excavation was the first work done on the site, the landscape architectural design had to be fast-tracked to stay ahead of the bulldozers and dump trucks. The final design had the berm transition from 8 to 18 m above the base, with terraces to collect rainwater. This portion of the project included limited irrigated planting along with hiking and fitness trails, steps, shaded seating alcoves, and viewpoint areas, providing facilities for outdoor

recreation that men and women could use with respect to their privacy without the traditional formal segregation. The concept has been largely expanded to the next urban landscape design, becoming a sort of Riyadh's landscape signature.

(b) Extensive Landscape Areas: Nonirrigated desert park areas along the escarpment on the western periphery of the site with views down into the valley of Wadi Hanifa. The performance specifications for the project ended up being 600 pages, covering the innovative design and taking the place of construction standards, which did not otherwise exist. Much of the detailed design, however, actually had to be developed on the fly by a full-time landscape architect on-site during construction. The result was the creation of benches, shade structures, steps, and "rock art"—all made of limestone, in an organic-appearing, flowing form. Planting was limited to a few native species that required no irrigation; these species were also generally thorny and/or poisonous to ward off grazing goats.

(c) Intensive Landscape Areas: Elegant landscape design, green roads, and elaborate roundabouts highly developed plantings in small, irrigated parks and along boulevards as a multilane, clover-leafed expressway that borders the development to the east and south is screened by intensive and concentrated landscaping. The plantation had to follow accurate nursing procedures first, as well as shading and wind protection during the first growing phase once embedded.

In response to the extreme environmental challenge of the site, further environmental strategies were part of both the urban and the architectural approach to the site.

4 Urban and Environmental Resilience: Strategies and Approaches

A complex socioeconomic evaluation was needed to get a fully integrated diplomatic community in the city, planning for its growing into a more and more functional integration by also serving the surrounding districts through new services and facilities. In only 5 years, 88 embassies and about 10,000 people had to relocate to the new district; this was the first target, while it was developed a growth plan in three phases, bringing the population from 10,000 up to 25,000 in the year 2000; of it 3/4 were planned to be diplomats or embassy related, and 1/3 private citizens. The second wave of development still left room for further implementation of functions and institutions.

The districts were meant to be walkable and encompass low-speed car mobility, flowing with the landscape. The challenge was to define a well-articulated circulation that served diplomacy through official alleys and ensured the residents' privacy. Still, the climate factor was the biggest threat to a walkable district to be solved in terms of temperature reduction and dimensional scale. The urban scale is where the

human factor gets the main importance, and the requirement of a livable outdoor built environment makes it successful. Also, the entire plan had to balance two opposite factors: early completeness due to the targeted moving of all the inhabitants within 5 years versus long-term flexibility in the urban design.

The German office of Albert Speer and Partners developed the master plan. The main strategic goals were to structure the urban settlement to gain good ventilation on both macro and microscales, implement it through a district's design synergic to the landscape, and incorporate a series of manufactured shading and protecting systems. It is well-known that green landscapes reduce the passing air temperature by 5 °C, so a strategic integration of landscape and buildings leads the whole urban project. The Wadi Hanifah also naturally delivered a great mitigation effect, and its impact extended to the residential areas through green fingers. The tools implemented were a good balance between solids and voids, the orientation of land uses according to sun and ventilation, the type and size of green, as seen above, roads and footpaths, and density. Wide roads were limited to the main spine and compensated by small green areas in the settlement zones and bylined trees and bushes to accelerate the airspeed and protect the surrounding small-scaled areas.

The housing areas are arranged in five neighborhoods, flanking the embassies zone and, at the same time, connecting easily to the core sine and its facilities, adapting to the topographic shape of the land; these clusters also get a proper characterization by the green areas. Also, urban planning is based on strong environmental criteria, and the dimensional standard is low-rise so that the buildings do not exceed the height of the palm trees. This, together with the favorable orientation to the wind, will keep an active microventilation, with an urban mass dense enough to maintain a low soil consumption while allowing wind flow to play around the buildings and the courtyards. Each typology's dimensions and proportions have been measured and balanced with the surroundings.

The urban structure of the embassy areas was kept with free land to increase their capacity in the future, while simultaneously generating a buffer of privacy and security between residential and consular scale and uses. The Embassies' plots were planned as a modular grid system along the main alleys, giving consideration to the flexibility and security requirements of the different layouts. From an architectural point of view, guidelines were delivered to merge the local Najdi style with the different international styles.

The residential areas, on the other hand, were developed in clusters following a certain abacus of possible typologies, with the intent for each district area to express its own identity and connectivity with the focal points and services in the immediate neighborhood. The road sections were low-dimensioned to host single or double-lane carriage and one- or two-sided linear parking for the townhouse areas. Clustered villas, on the other hand, were served by pocket parking, introducing the smaller scale of the urban features. In the original plan, each urban island would have its service setting, including retail, banks and offices, manufacturing and grocery shops, café, and restaurants. This part, however, was never developed, having those functions only grouped in the civic center.

5 Architecture and Environmental Challenges and Identity-Driven Solutions

The resilient potency of the buildings had to deal with the extremely hot weather, different cultural backgrounds and statements, and the status and social needs of the inhabitants. The 28 °C sun inclination in the region generates almost vertical or very limited shadow extensions, requiring special attention in managing elevations and outdoor shading systems, both to contain the heat gain and the sun's direct light radiation; the extreme temperature requires, finally, an introverted and insulated wall system, in cooperation with natural ventilating systems. The key principles for the residential areas were summarized in the report as follows: creating a social structure within the neighborhood that encourages community engagement; giving each neighborhood its own distinct identity; designing flexible stages to allow for future development and incremental growth; ensuring efficient circulation and pedestrian connections; providing bioclimatically suitable residential units with environmental controls; designing units that are easy to navigate and well-organized; and ensuring good site and climate adaptation (Speer & Meurer, 1978).

The residential areas have been developed following dimensional typology standards, including villas, attached and semi-detached houses, and wide flats.

Thus, to serve all the different levels of diplomatic staff joining the district. The master plan provides an abacus of the possible typologies of interventions, while the execution was assigned mainly to private developers, as per the financial and funding strategies. Masharabia, gardens, fountains, wide glass elements, inside-out by extended roofing, gazebos, freestanding pergolas, veranda, porches, and arcades are essential parts and not just details of the architectural solutions.

The requirements were brilliantly solved by accurate research of the *genius loci*, of the intimate character of the local environment and conditions. The wadi on one side, with its harsh canyon landscape with magic flourishing and unexpected greenery during the rainy season; and the traditional Najd architecture, its thick loadbearing mud walls, screening vertical and horizontal system, courtyards, and quasi-public passages, environmental embedded solutions in the conventional architecture by centuries of preserved knowledge by generations. While the guidelines for embassy and residential buildings required a mix of international and Najdi traditional design, the public architecture, specifically the civic center and the diplomatic cultural center, were designed as a rediscovery of the traditional architectural literature of the Najdi style. The main public building complexes surged up to the level of icons of style for decades, defining the language for two main archetypical typologies: the urban civic center and the outskirt desert settlement.

6 The Prototype of the New Najdi Civic Center: Al-Kindi Plaza, Civic Center, and Housing

The main urban complex was designed by the Saudi architecture office Bee'ha, which approached the delicate theme of creating a representative Saudi urban environment. Between three main arterial roads, access to pedestrians is granted by narrow paths, mainly shaded as gates on city walls; the perimeter of the plaza hosts café and shops. The Al-Kindi Plaza, the civic center of the district, lies between two secondary roads forming an arch and dividing the development into two roughly equal segments. The envisioned mixed-use core was successfully created

by integrating cultural, administrative, educational, commercial, and recreational facilities. This area is fully accessible from the main spine, offering maximum flexibility and adaptability for future uses. Residential blocks are organized around hallways and passageways, which provide shaded pedestrian routes that remain comfortable during the hot summer months. These pathways lead to green urban courtyards, featuring abundant vegetation and fountains. These roads are lined with contiguous buildings designed as a linear development, interrupted by courtyards, open spaces, and a median, part of the plaza, that faces the district's central mosque together with institutional buildings around a main square and a secondary system of narrower and screened linear connections, opening up on small green squares and courtyards. Tertiary roads lead to five intensive housing clusters, built as a commercial and tertiary covered corridor, and a walkway system on the upper floors to give access to duplex apartments.

The complex includes the Friday mosque, which is in a revised traditional Najd architecture, accommodating 5000 people with two minarets and a flat walkable roof from the educational facilities, in immediate proximity to the main institutional buildings. The updated Najd style by Ali Shuaibi's Be'aah shows sandy walls and modular stepbacks, achieving both the esthetical function and the environment. On the opposite side, the fortress-like administrative office of the newly established ArRiyadh Development Authority, which was in continuity with the Bureau for Ministry, its elevation with a triangular screen with several courtyards, offers lighting and natural ventilation to the building.

The quality of the intrinsic valuable connections merging public space with architecture brought a second Aga Khan Prize to the Diplomatic Quarter (prize recipient 1987–89). In the statement of the jury, the Al-Kindi Plaza has been considered "to be an ideal model for cities in Islamic and Arab societies for having attractively preserved the traditional link between the mosque and the other public services of the city" and "because the open spaces in dry and warm areas are usually reserved for the use of the evening, the design of plaza in this way is consistent with the rhythm of the local social life. A harmony is expressed by the presence of the people of Riyadh at the Al-Kindi Plaza during the day for prayer at the mosque for shopping along the arcade, and in the evening for entertainment during some special occasions attended by thousands worldwide."

7 An Archetypical Najdi Desert Architecture: The Tuwaiq Palace

Tuwaiq Palace offers an amazing counterpart to the urban fair of the civic center, with a more specific organic character as a desert building. If the Al-Kindi Plaza plays the role of the civic center, the Tuwaiq Palace responds to the majestic promontory plateau overlooking the sweeping Wadi Hanifa below and the townscape of Riyadh beyond. It has been built as the central cultural facility for the district and designed as a club, offering 24,000 sqm of recreational, social, dining, banqueting, conference, and accommodation functions. The building features an 800-m-long sinuous "Living Wall," a manufactured reef that winds on itself and wraps around a lush garden. Five huge tensile structures, recalling the desertic Bedouin tradition of tents, make room for the gathering halls and sports facilities. Sensational landscaping generates the inner gardens and outer spaces within the protective mud-like winding wall, water features, and the painted glass tent as the focal point of the inner courtyard. This unique design touches on three local archetypes: the fortress, the tent, and the oasis, and it incorporates the natural phenomenon of the *wadi*. In their combination, these elements suggested a new building typology with a special relationship to its context and a marriage of tradition and high tech. The design of this third award-winning masterpiece of the Diplomatic Quarter (Aga Khan Prize recipient 1997–98) has resulted from a successful collaboration between Omrania & Associates, Frei Otto (Germany), and Bureau Happold (UK) after qualifying in an international competition in 1981.

8 The Second Phase of Expansion

As planned, in 2005, the master plan was updated (Speer & Meurer, 1978), and the second phase of expansion started. Major urban interventions are represented by AlOud Square and, a few steps ahead, two main hotel complexes; 40 years from the first establishment of the district, the Diplomatic Quarter confirms the strength

and the consistency of the designed system already in place. The building complex of AlOud Square, the new hotel, expresses a sense of urban flair by reverberating in the existing building's colors, materials, and shape. The Marriot Hotel, also a Platinum LEED building, dares a courtyard surrounded by a weaving elevation, in a quote of the Tuwaiq Palace. All the new buildings have a contemporary taste, mainly full glass elevations, enveloped or screened by an innovative cladding system of clay linear elements. Those might be listed under a "New Najdi" architectural style (Petrucci, 2018) and have been well received by the public, becoming new urban destinations and activators of the expected integration of the district with the city of Riyadh. Also, the Al-Kindi plaza has been implemented by the extension of the office building of the Royal Commission of Riyadh City; this is keeping the original "Najdi" stone walls in an interesting reverberating of indoor/outdoor effects which generates new internal courtyard, and introducing in the Al-Kindi an innovative twist by the glass wall screened through a diagonal metal shading system.

9 An Assessment of the Four Resilience Pillars: Natural, Economic, Social, Physical, and Institutional

Forty years after the establishment of the Diplomatic Quarter in Riyadh, it is possible to observe and evaluate the principles and good practices adopted, their replicability in contemporary architecture and urban planning, and their resiliency and adaptivity to climatic, social, and economic conditions.

The success of the Diplomatic Quarter is demonstrated by two objective factors: it is still, nowadays, the most popular residential district in Riyadh, and—as already mentioned—also awarded three Aga Khan Prizes, achieving a unique record in the history of the prestigious competition. The district was built for success because resilience elements were considered from the first conception as an integration of environmental, administrative, social district was built for success because resilience elements were considered from the first conception as an integration of environmental, administrative, social, and urban factors, upholding the long-lasting success of the district. We can say that not only has the Diplomatic Quarter overcome the passing time without becoming obsolete, but in fact, it has improved its status. Moreover, it has established the two main models of the urban Najdi culture. The first is the urban settlement on a human scale, where architecture and urbanism cooperate in creating a unicum, in the form of an updated mud city, by the Al-Kindi Plaza. The second is the *wadi* dramatic scenery and majestic outdoors, as seen by the Tuwaiq Palace and its fortress-like shapes and tents typical of nomadic life. The landscape was declined in multiple nuances, flowing from an intensive, highly decorative approach to an extensive wild approach. The strength of the long-term vision and pragmatic, sustainable approach made it an iconic reference model for the Kingdom.

10 Conclusions: A Comprehensive Identity-Based Resilience

The landscaping experiments of the Diplomatic Quarter became a long-term partnership with Boedeker architects, who were taking care of the garden project for the King Abdulaziz Historic City in the form of a botanical garden and defining the greening project for the whole of Riyadh. A surprise was that the extensive landscape areas, which had been designed without irrigation, were, in some cases, being inundated by run-off from excess irrigation in the embassy compounds above, resulting in some pathways being overgrown with overly abundant vegetation. The models have been reiterated as solutions for several areas in the city of Riyadh during the last 30 years. Palms are an iconic and symbolic tree of the nation, but they are not sustainable in terms of water consumption for irrigation and the shadow they provide to the people. The nursery is still active, providing plants for the district, and a seed bank has also been developed.

The Diplomatic Quarter established the standard for the new Riyadh's architecture, insisting on the two main cultural references: the urban flair of the Arab city and the wilderness of the desert and the wadi. Like in the Renaissance tradition, the two models of the Palazzo, or the urban space, and the countryside Villa, at the border of the urban settlement, the Diplomatic Quarter established the two leading models for the future developments in Riyadh, the desertic and the urban new Najdi architecture (Petrucci, 2018). The design principles of the Diplomatic Quarter followed the same approach as the Najd tradition, with a focus on preserving and reinterpreting key historical features. This included the creation of the new

Imam Turki bin Abdullah Grand Mosque (recipient of the Aga Khan Prize in 1993–95), as well as the restoration of the Musmak Fortress and its surrounding urban landscape. The Musmak Fortress symbolizes King Abdulaziz's triumph in establishing the Saudi state. Later, the restoration of Al Murabba was undertaken—this area was King Abdulaziz's first government center outside the walls of Old Riyadh. Additionally, the King Abdulaziz Historic City was developed, which includes the National Museum, the city's first major cultural hub. Taking an interest in restoring the old traditional architecture was a direct result of the Diplomatic Quarter project, emphasizing the need to revive Najdi architectural traditions in modern building projects. Therefore, we can affirm that the Diplomatic Quarter constitutes the catalyst for a new vision of Heritage and local tradition, anchored on traditional values of *genius loci or the Spirit of the placer* (Norbert-Schultz, 1980). What began modestly in the Diplomatic Quarter with Al-Kindly Plaza and Al-Tuwaiq Palace later evolved into an architectural model for numerous government projects in central Riyadh. This vision was largely driven by King Salman, who, at the time, was the Prince of Riyadh. His influence is acknowledged in the recently established Salmani Charter for Architecture, which is now being implemented as a guide for best practices in architecture across Saudi Arabia.

Led by a small but highly motivated team, the Ministry of Foreign Affairs' Project Bureau pursued a long-term vision to establish a new standard for the Diplomatic District—and, more broadly, for all of Riyadh. Despite the complexity of the task, the Bureau successfully created an entirely new district, working with numerous stakeholders, including the city of Riyadh, the Ministry of Foreign Affairs, and representatives from over 80 embassies. They accomplished this monumental project in just five years, transforming a barren, moon-like desert plateau into a thriving "oasis garden" and fully functional district. Following this exceptional achievement, the Bureau became the foundation for the Arriyadh Development Authority, anticipating the global trend of creating dedicated governmental agencies for urban development. Over the following decades, it set the standard for best practices in the growth of New Riyadh. This successful model has since been replicated in other major Saudi cities.

Resilience requires a long-term, wide, and wise vision founded on principles of deep ecology and sound cultural knowledge of the *genius loci*. It requires visionary and pragmatic implementation through multidisciplinary teams that can consider all the socioeconomic, administrative, and environmental issues in the long term, including management and maintenance sustainability. In 1975, when the idea of moving the diplomatic enclave to Riyadh was first conceived, international architecture was still narcotized by the modernist waves and their dystopian urban visions. The concepts of architectural revival, human-centered urbanism, and nature-based solutions were not common sense. At the time, concepts like architectural revival, human-centered urbanism, and nature-based solutions were not widely recognized, nor were urban development agencies as we know them today. However, innovative visions—rooted in a deep understanding of the *genius loci* (spirit of the place)—carried the DNA of resilience. Riyadh, derived from the Arabic word *riyada* (meaning "nursery"), was named for its expansive palm gardens

along the wadis, making it an ideal place to settle in the desert. The city was founded with a "nursery" approach to its architecture and urban development, symbolizing the region's deep connection to its environment. This approach is a clear reflection of *genius loci*—the collective intelligence used to respond to the challenges posed by the site's conditions. It mirrors how ancient societies thrived, embedding resilience in their development and learning to recover and grow after crises.

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