

Review

Water, Energy and Food Supply Security in the Gulf Cooperation Council (GCC) Countries—A Risk Perspective

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Abstract: Supply systems for water, energy and food in the Gulf region are becoming highly interlinked. In the last decades, interdependence was evident in the increase of coproduction plants and the cross-sectoral resource use footprints. In light of increasing integration due to growing scarcities, the construction of mega projects for coproduction, and the use of renewables across sectors, the security notion can be revisited. This paper proposes a view of the resource supply security based on the systems' characteristics under change and their ability to deal with risks and shocks (resilience). It introduces internal and external risk factors for the water, energy and food supply systems in the Gulf region and highlights recent knowledge on such risks. Further, the paper explains the vulnerability of supply systems to planning risks like scale, integration intensity and level of service provisions together with risks related to growth, technology, market and climate. In light of such insecurities, we stress the importance of investing in risk management and resilience policies in infrastructure planning. Response measures to future risks can focus on options like storage, knowledge, diversification and, importantly, promoting regional cooperation and synergies from common infrastructure planning between countries of the Gulf Cooperation Council (GCC).

Keywords: resource security; supply infrastructure; water–energy–food nexus; Gulf Cooperation Council; critical infrastructure; supply risks

1. Water, Energy and Food Supply Infrastructure in the Gulf Cooperation Council (GCC)

Physical scarcity of land and water resources in the countries of the Gulf Cooperation Council (GCC) is largely compensated through high-energy reserves and economic abundance. With annual rainfall rarely exceeding 100 mm in most parts of the GCC region, water resources have been scant and increasingly overexploited [1]. Although GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates) do not have significant agricultural potential, agricultural water use is one of the main drivers behind overuse and depletion of water resources. Arable land is limited, averaging 4.25% of the GCC region [2]. Still, the proportion of water use for irrigation and livestock in the region is similar to the global average of 70% and is even higher in certain countries like Saudi Arabia, UAE and Oman. At the same time, the contribution of agriculture to total economic added-value or the Gross Domestic Product (GDP) is quite negligible, around 0.8% on average (see Table 1). The physical scarcity of water and land resources is contrasted with high reserves of fossil fuel. GCC countries control around 40% of global proven oil reserves and 20% of natural gas reserves [3]. While much of the oil is exported, resulting in large state revenues, most gas reserves are consumed domestically, with the exception of the State of Qatar [4]. Average energy consumption in the region significantly

surpasses the world average consumption [5]. As a result of high energy production and consumption in the region, GCC countries constitute some of the 25 countries with the highest per capita footprint of carbon dioxide [6].

Table 1. Key data on water, energy and resources in the GCC countries (data from Food and Agriculture Organization (FAO) AQUASTAT, World Bank indicators and British Petroleum [3].)

Total Renewable Water Resources Per Capita (Cubic Meter Per Capita Per Year) (2013–2017) (FAO)	Arable Land as % of Total Land (World Bank) (2014)	Water Use for Irrigation and Livestock as % of Total Water Use (FAO)	Added Value of Agriculture to GDP (2014) (%) (World Bank)	Oil Reserves per capita (Thousands Barrels in 2015) (Calculated from Data of World Bank and BP 2016)	Gas Reserves Per Capita (Million Cubic Meters in 2015) (Calculated from Data of World Bank and BP 2016)
Bahrain	84	8.5	45	0.3	0.09
Kuwait	5	1	54	0.4	26.08
Saudi Arabia	76	1.7	88	1.9	8.45
Oman	312	0.3	89	1.3	1.18
Qatar	26	1.9	59	0.1	11.50
UAE	16	3.1	83	0.7	10.68

Much of the countries' energy is used for water production. Conservative estimations of electricity consumption for desalination in the case of the GCC countries range from 4–12% of total electricity production, while higher estimates may rise to more than 20% in UAE, 13% in Qatar, 7% in Saudi Arabia or around 8% in Kuwait and Bahrain [7]. Furthermore, energy is used for surface and groundwater withdrawals. On the other hand, water is used for extraction of fossil fuels, hydropower production and cooling of power plants. However, the water use for the last two types of energy production systems is quite low in the Middle East and Northern African (MENA) region [7]. With regard to water use in fossil fuels production, some countries in the region even use valuable desalinated water for the extraction process [8] and also in the production of minerals. In general, energy and water production systems in the GCC are highly interdependent. They are also effective in terms of achieving universal coverage of water and electricity services for their populace. Desalination plants, power plants, electricity grids as well as water and energy distribution networks constitute the critical infrastructure for achieving energy and water security.

Furthermore, infrastructure projects such as solar power plants and wind farms are being increasingly deployed to promote renewable energy resources. National policy targets foresee the increase of the use of renewable energies, as a proportion of total capacity, to 15% in Kuwait by 2020, 5% in Bahrain by 2020, 20% in Qatar by 2030, 24% in the UAE by 2021, and to 54 GW in Saudi Arabia by 2040 [9]. For Saudi Arabia, this target is to be read in the context of the current installed capacity of around 80 GW [10]. There are no clear targets for the energy mix, while recent aspirational projects aim to develop around 60 GW of solar power in the next 10 years [11], and even 200 GW until 2030 according to an announcement in 2019 [12]. In addition to these renewables targets, plans to build nuclear power plants in countries such as the UAE and Saudi Arabia are underway.

On the other side, food supply security relies heavily on the imports of food products. Countries in the region are planning to counter this dependency by investing in large-scale facilities for aquaculture or aquaponics. Common to all of this infrastructure in food, energy and water is their vulnerability to the increasing number of planning, growth, technology and market related risks. This paper conceptualizes resource supply security and proposes a dynamic and future-oriented security understandings based on the supply systems' change states, threats and risks. It then summarizes literature on key categories of internal and external threats, most of which have received little attention in research and public strategies in the GCC region. Finally, it presents concrete risk scenarios out of the broad threat categories and outlines response strategies.

2. Security Conception—Review and Propositions

Resource security is a porous concept in academic literature. A wide range of issues is examined under this term including resource endowments of countries, transboundary conflicts, mercantilism and trade, competition in the international system or supply scarcity of vital services like water, energy and food. Lately, the notion of the centrality of the security debate within environmental policies has been highlighted by the emerging paradigm of ‘water, energy and food security nexus’. The ‘nexus’ paradigm places the insecurities related to resource supplies at the center of global environmental policies [13,14]. It has inspired scientists and practitioners to develop a large number of tools and models to capture interlinks between water, energy and food that can jeopardize or strengthen the functioning of the three resource systems [15]. The understanding of resource security within the nexus in terms of access and availability of water, energy and food services resembles the traditional sector-driven security understandings.

While there has been a growing number of publications on the nexus in the context of the Arab world, little attention has been paid to specific regional approaches to enhancing resource security, or the distinct context of the GCC region. For example, Al-Zu’bi and Keough [16] outlined resource-use pressures in different sectors and highlighted the need to overcome institutional fragmentation and incoherent policies. Hamdy [17] recommended some overarching remedies such as capacity building, regional cooperation, and participation. Mohtar et al. [18] criticized reactive policies aimed at addressing the nexus in the Arab region. They stressed that adaptive management can increase local resilience and thus improve regional security. In fact, these contributions converge on the importance of the nexus for the wider Arab region and the resource security dimension in light of increased complexity, interlinkages, and uncertainty. Conceptualizing and breaking down the security notion into (sub)regional contexts is thus important, and we argue that a focus on supply systems and their risks is one way to achieve this. While ‘security’ is still a highly contested topic in the water, energy and food sectors, its occurrence or absence is largely related to the ability of the supply systems to deliver needed services. For example, the understanding of energy security has been studied by [19] who reviewed 83 energy security definitions. As a result, seven themes of such security were identified: energy availability, energy prices in relation to energy affordability, societal concerns like energy poverty, environmental effects of energy use, sound governance to secure supply reliability and energy efficiency. Cherp and Jewell [20] reaffirm in their review that the approach of defining energy security in terms of the “four As” (availability, accessibility, affordability and acceptability) is quite influential. They instead argue for a security concept focusing on risks and resilience to achieve low vulnerability of vital energy systems. Måansson et al. [21] categorized methodologies to assess security according to the supply chain stages they address. They noted a lack of method of integration and a need to focus on factors with a potential to reduce the systems’ vulnerabilities. Johansson [22] distinguished between energy system as an object exposed to security threats and as a subject generating or enhancing insecurity.

Food security is also often understood in terms of the system’s ability to perform under increasing risks. Issues such as promoting productivity and increasing efficiency represent key measures to ensure global food security for growing populations [23]. In such an understanding of security, governance arrangements are positively seen as a problem-solving mechanism [24]. Similarly, the debate about water security conception has evolved into a key theme within water management. It is often defined in terms of necessary or acceptable quantity and quality of water for different water uses [25], in relation to water-related hazards, risks and vulnerability [26] or in regard to peace and harmony during reforms and among institutions in the water sector [27]. Similar to food security, necessary governance measures to achieve water security have been discussed [28].

Common to the various conception of resource security in the water, food and energy sectors is their focus on different characteristics of the resource supply system. This notion of security is not directly related to normative discussions about resource security in terms of human rights, equity and freedoms (e.g., [29]) or to (transboundary) resource conflicts and wars (e.g., [30]). In this paper, the

pragmatic focus on the supply system in resource security is motivated by solving recurrent problems rather than investigating the drivers (rights, inequalities) or the impacts (conflicts). With regard to this focus, we classify the different definitions and assessment of resource supply systems security on whether they target one of the following three dimensions (see Figure 1): (1) system control and regulation; (2) risks arising from system change; (3) system performance.

In this paper, we use the second dimension of resource security to illustrate the case in the GCC region. The choice of this dimension to analyze the supply security in the GCC is justified for three reasons. Firstly, we argue that resource-supply security in the region must be future-focused. Security needs to be about risk exploration and future threats rather than the system's ability to exploit resources and to ensure a high level of supply coverage. In this sense, this security understanding provides an important and contemporary security view, since it is dynamic when compared with the static approaches focusing on regulation/governance or performance. Secondly, addressing the growing risks associated with changes in systems has become a priority for decision makers. The stability and reliability (the other two views of security of supply systems) are lesser concerns in the context of GCC. This is due to the high performance of the systems (e.g., universal access or high water quality) and the lack of urgency assigned to analyzing social issues (e.g., rights, legislation, equity issues) in the relatively small and centralistically managed GCC countries. Other than Saudi Arabia to a small extent, there are no complex and multi-faceted water, land, and energy resource types and interlinkages. These resources have been regulated, controlled, and supplied by so-called 'rentier states' through (over)using single sources such as groundwater, desalinated seawater, or fossil fuels. In contrast, the focus on the increasing risks is a major regional concern; e.g., due to the over-reliance on the semi-closed water body of the Gulf to provide freshwater, energy and food resources.

GCC countries face common risks affecting their supply systems, which heavily rely on resources provided by ecosystems exhibiting characteristics of common-pool resources. The Gulf waters are increasingly used for marine food and water supply and energy production, while salinity, failure risks, and environmental problems are rising. As a result, a region-wide analysis based on the neglected security notion of resilience will prove valuable. The security notion of 'resilience' corresponds to the understanding of resource-supply securities as socioecological systems (e.g., [31]) vulnerable to shocks that they can deal with to achieve a state of 'resilience', which is understood as the capacity of a system to persist or develop in the face of change [32,33].

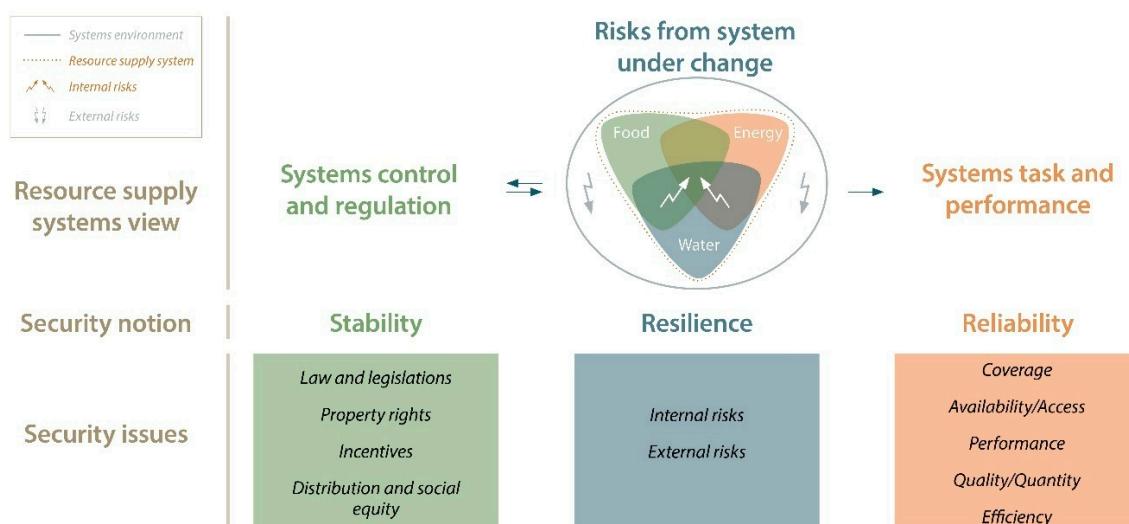


Figure 1. Resource supply security concepts.

The change of supply systems can arise from shocks that are produced from threats, which we define as categories of rising dangers entailing several risk factors. (See Section 5 for more on linking threats, to risks scenarios and resilience.) The paper looks at internal and external factors constituting sources of future risks for the supply system. These risk factors are categorized in Sections 3 and 4 in categories of threats that are inherent in the systems' configuration (internal to the supply systems), or arise from the systems' environment (risk factors for global change producing general threats). Here, this review does not seek to quantify, assess, or strategize individual risks, but rather to outline knowledge indicating the different threat categories and associated risks, while discussing overarching response strategies. The scope of this review is to map out a highly demanded research field and to encourage future studies, which might provide methodological and applied analyses as well as integrated (water–energy–food) risk assessments on a country or case basis.

3. Internal Threats

3.1. Systems Coupling

Supply infrastructure for the production of water, energy and food services in the GCC countries are increasingly coupled. The increased coupling between the water, energy, and food production systems in the GCC region brings both risks and opportunities. A greater integration of complex production systems can amplify the costs of system failure, increase the vulnerability spots, or heighten the requirements for safety. In the following section, evidence for and consequences of systems coupling between energy and water, as well as energy and food, are introduced.

The argument for the coupling between water and energy infrastructure in the MENA region has been laid out extensively by Farid et al. [34]. Accordingly, increased integration is a result of socioeconomic growth drivers, and the increased reliance on water-intensive electricity and electricity-intensive water production. In consequence, greater coordination and collaboration is needed to ensure successful operation and integrated policies. Farid et al. [34] and Lubega et al. [35] have explored opportunities for joint operation, co-optimization, and market liberalization in terms of encouraging independent producers of power, water, or both services combined.

Firstly, water use for energy production can be analyzed. Siddiqi and Anadon [7] have already noted that the energy electricity production system in the MENA region has so far been less reliant on fresh water for electricity generation than, for example, the United States where, according to Pate et al. [36], 45% of water withdrawal is used for electricity generation. However, water needs for energy usages such as cooling are increasing in the region with the advancement of district cooling and other energy-intensive cooling technologies (see [37]).

Furthermore, with regard to water use for energy, power generation using thermal or steam plants in the GCC region relies on seawater use. While freshwater use in energy production is low, there are still important environmental costs related to thermal pollution and the release of pollutants (e.g., [34,38]). There are also risks of water pollution from the burning of oil for heating, power production, and energy-intensive industries [39]. Water and energy are also coupled together in the use of thermal desalination in the GCC, in the form of Multi-Stage Flash (MSF) desalination. MSF is still by far the dominant technology in the GCC [35] and is more energy-intensive than the globally more dominant desalination technology called reverse osmosis (RO). However, MSF desalination is usually integrated in co-generation plants of both desalinated water and thermal power. The energy requirements for the RO technology are usually less than with MF. (The exact amount depends on the seawater quality.) RO use for desalination in the GCC region is expected to increase in the future.

Secondly, with regard to energy use for water production, such use is expected to be higher in the MENA region than in other regions. This is due to the increased use of desalination and groundwater for water supply. While the environmental effects of the use of fossil fuels on both freshwater and seawater need to be quantified and contained, the high power demand for water supply will continue. The 2007 total electricity demand for desalination in the MENA is expected to triple by 2030, rising

to 122 TWh [40]. In the GCC region, desalinated water comprises the largest proportion of potable water, and desalination capacity is expected to increase with increased population and economies [41]. This capacity, which accounts of around 45% of the worldwide capacity [42], is responsible for around 30% of energy consumption in Qatar and the UAE. According to Low [43], desalination, oil and water have been completely interdependent in Saudi Arabia for decades, and desalination is currently consuming around 15% of daily oil production. Besides, electricity is also used for heating water in homes and businesses.

According to Farid et al. [34], the coupling of power demand and municipal water supply takes place in processes of water treatment, membrane desalination, and water distribution. These three processes are expected to increase in the region. Furthermore, the GCC region has a large potential market for renewable energies [44]. The use of renewable energies for desalination, water reuse, or water heating and cooling is a viable option for the GCC. Depending on diesel prices, desalination using renewable energies can be competitive on a large scale or as a cost-competitive, off-grid solution for remote areas [9]. There is therefore a distinct potential along with many initiatives for renewable energies based on desalination in the MENA region at large, and the technology is expected to be widely available and competitive in around one decade [45]. In this context, Saudi Arabia is building the world's largest solar (Photovoltaic or PV) desalination plant in Khafji, with a production capacity of 60,000 cubic meters per day.

Thirdly, concerning the coupling of energy use and agriculture, renewable energies can also replace fossil fuels in agricultural production systems. Considering the high dependence on food imports in the region, local agriculture is important for achieving some level of food security. Local agriculture is highly dependent on limited freshwater resources (groundwater) and subsidized energy prices [46]. Alternative future pathways such as greenhouse agriculture, vertical farming, aquaculture hydroponics, and aquaponics are largely more energy-intensive than current traditional farming systems. Brown et al. [47] investigated how sustainable agriculture in the GCC can be enhanced using such alternatives that rely on marginal waters (reclaimed and treated wastewater or saline water). These alternative food-security options need to be understood in terms of their impact on the energy footprint of the agricultural sectors across the region.

3.2. Demographics and Growth

Population and economic growth in the last decades in the GCC countries have determined the size and capacity of the water, energy and food supply systems. Population in the GCC has increased from 1998 until 2008 by 3.4% per year and is expected to increase by the annual rate of 2.6% in the period 2009–2020, using a moderate forecast scenario [48]. In fact, we have calculated that population growth will have increased between 2009 and 2017 by 4.5% annually as a GCC average [49]. A large share of population growth until now can be attributed to the inflow of expatriate workers (non-nationals) who constitute currently around 30% of population in Saudi Arabia, 44% in Oman, 52% in Bahrain, 70% in Kuwait, 85% in Qatar and 88% in UAE. At the same time, average GDP growth rate for the GCC countries in the period 2000–2015 was 5.5% in comparison to 1.7% for G7 economies [50]. Both population and economic growth are highly vulnerable to external shocks like the recent oil price decline of 2014 and 2015 [51]. The size of the economy affects energy consumption and other policies related to sustainable development at large. Recent evidence shows that the consumption of energy and electricity goes hand in hand in both directions with economic growth in the region [52,53]. Per capita energy consumption in the region is among the highest in the world and it has been increasingly faster than economic growth in recent years, resulting in a rush to adopt renewable energies in the GCC in light of fluctuating oil prices since 2008 [53]. Similarly, water and calories consumption rates per capita are significantly higher than the world average and can be linked to changing lifestyles, e.g., [54].

In fact, one of the most urgent whole-system threats to economies of the GCC is represented by the declining oil revenues as a result of the rising domestic energy demands. This general threat can affect supply systems as declining revenues produce demographic and economic pressures, thus affecting

demands on the supply systems and their basic functioning. It is, however, difficult to accommodate this threat through sectoral policies (e.g., infrastructure or supply policies) as long as it is more urgent for some countries than others. For example, Saudi Arabia with its large population has witnessed a nine-fold increase in domestic oil production in the last 40 years, and could see domestic consumption matching oil exports by as early as 2030 [55]. Smaller countries with a comparatively lower resource base (e.g., Oman or Bahrain) might face the same challenge if the high pace of growth and consumption continues. In any case, rising domestic demands siphon off carbon revenues, and this can only be addressed in terms of changing the overall economic model. The GCC have therefore embarked on fiscal reforms and economic diversification since 2014, which has had a (temporary) effect on the growth, size, and composition of the workforce [51]. Current economic diversification policies can have an effect on the composition of production sectors, labor force, and resource footprint, although there are still many structural economic barriers to achieving such diversification [56]. Energy policy and subsidy reforms are also to be seen within this context of dwindling revenues and increasing consumption [57,58]. Moreover, diversification and interventions in the built environment can help address other overarching challenges such as the large ecological footprints and climate change [59,60].

Table 2 and Figure 2 illustrate key demographic and resource-use growth in the region in recent decades, using data from FAO AQUASTAT and World Bank indicators. In general, the risks arising from major changes in relation to the demographics of the population, economic growth models, and resource-use intensity are poorly understood. Resource-supply infrastructure is vulnerable to any increase or decrease in these factors. The sensitivity of such infrastructure and its ability to accommodate abrupt demographic and economic changes require thorough research.

Table 2. Total water withdrawal ($10^9 \text{ m}^3/\text{year}$) (data from FAO AQUASTAT).

	1975	1980	1990	1991	1992	1994	1995	2000	2002	2003	2005	2006
Bahrain			0.239							0.3574		
Kuwait						0.538			0.9132			
Oman				1.223				1.36		1.321		
Qatar	0.15					0.2849		0.2939		0.444		
Saudi Arabia					17.02							23.67
United Arab Emirates	0.9					2.108	2.904			3.998		

Total population (1000 inhab)

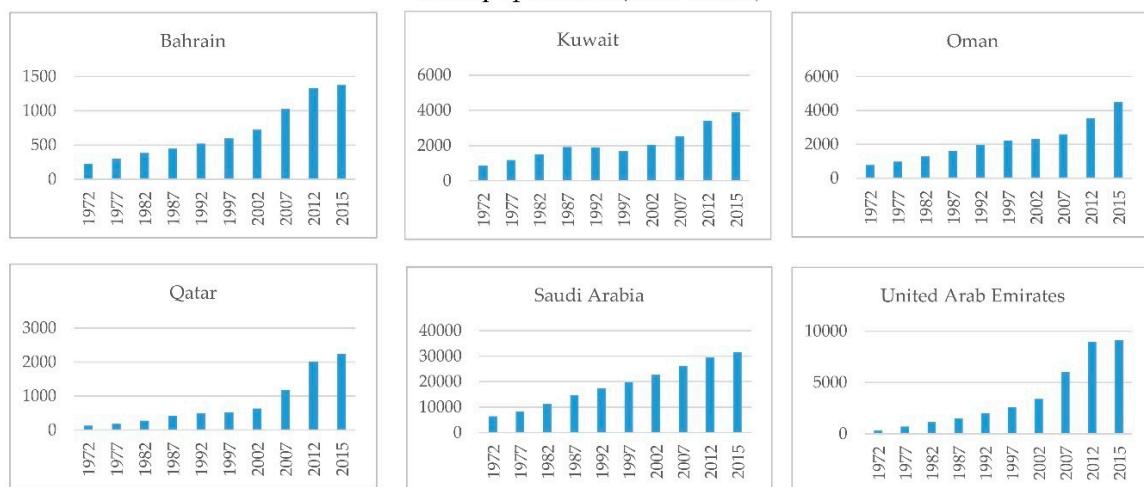


Figure 2. Cont.

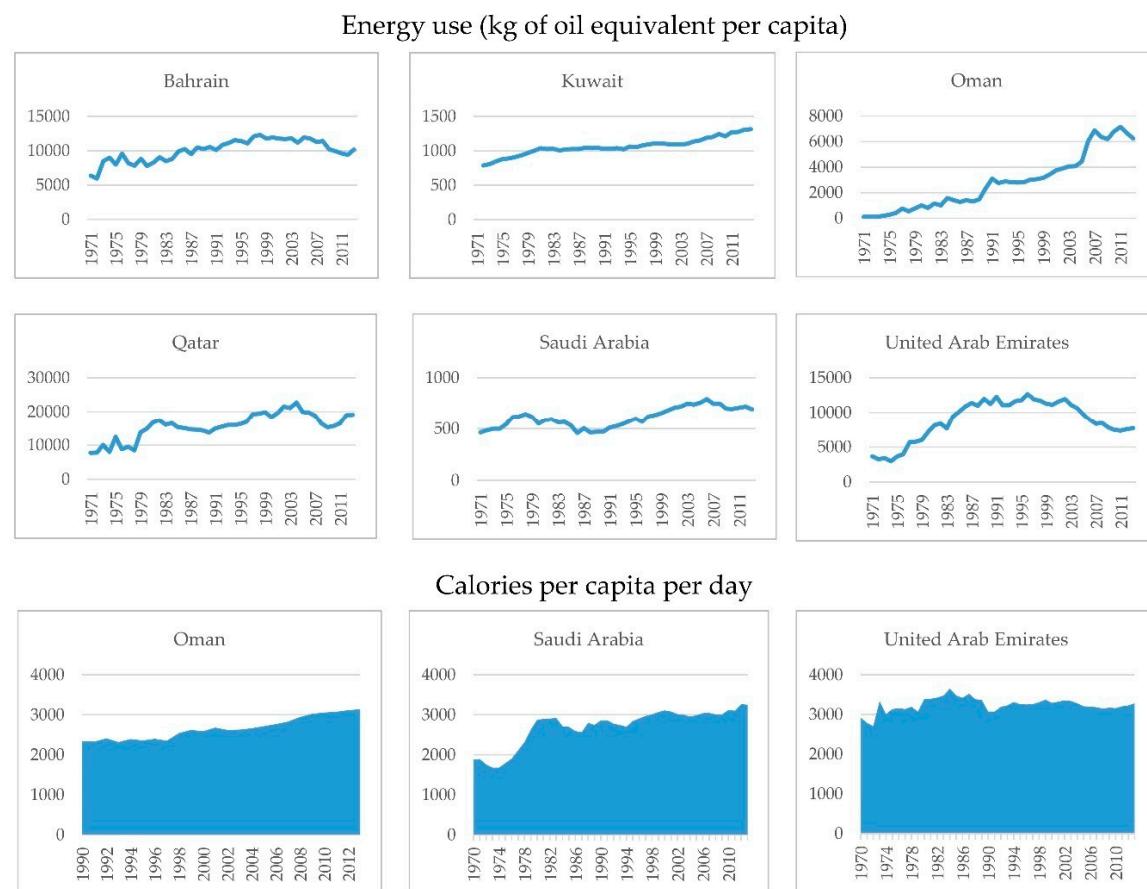


Figure 2. Demographic and resource-use growth in the GCC countries (based on data from the World Bank, FAO & FAO AQUASTAT).

3.3. Scale and Planning

Alongside the supply system's configuration (coupling between elements) and dimension (size of the boundaries), the planning scale (quantity and size of elements) constitutes an important risk factor. A supply system with few elements performing large tasks might be more vulnerable to supply interruptions and systems failures. On the other hand, a large degree of decentralization produces complexity, as it increases the number of actors, suppliers, and regulators. If not governed effectively, such decentralization can impede control, coordination, and planning. For example, decentralization of energy infrastructure might require polycentric governance and a great deal of experimentation and innovation [61]. Consequently, in the GCC, the current restructuring in the energy sector follows a centralized approach using a single-buyer methodology in order to maintain control over infrastructure and energy assets [57].

In fact, research at the optimal level with regard to power production, desalination, renewable energy provision and even farming schemes is lacking for the GCC region. Currently, generating a water supply through desalination is achieved by using hundreds of plants, most of which are small-scale. However, a small number of mega plants deliver a large share of the region's potable water and supply key major cities in the region. Table 3 shows the largest desalination and power plants in the region and their target cities to supply. In 2008, only 6 plants delivered 23% of the total desalinated water in the GCC region [62]. Such large-scale plants are still under construction like the 2014 Ras Al-Khair Power and Desalination Plant, capable of producing 2400 MW of electricity. It is also one of the biggest desalination plants worldwide, able to serve 3.5 million people in the capital city, Riyadh. Produced electricity and water deliver supplies for an alumina refinery nearby.

Other examples of large power and desalination plants are those in Ras Abu Fontas in Qatar and in Jebel Ali in the UAE. In the food sector, the Almarai dairy company in Saudi Arabia is a similar example of large-scale production infrastructure. Meanwhile, there have been a number of recent studies investigating the potential of small-scale decentralized solutions for desalination using renewable energy technologies (e.g., [63–65]) or the benefits of decentralized water and energy providers in the MENA region [34]. However, overall, participation in the supply of water, energy and food is limited in the GCC due to many reasons. The state monopoly on infrastructure, pipelines and services delivery of energy and water has deep roots in the petro-state legacy of patronage and material dependency in the region, e.g., [43]. In addition, water and energy prices remain highly subsidized, hindering market-based competition, while energy policies have created limitations to ecological modernization in the region at large [6].

Table 3. Largest desalination plants in the GCC and beneficiary cities.

Desalination Plant	Year of Operation	Total Approximate Capacity (m ³ /day)/MW	Technology	Main Beneficiary Cities
Jubail 1, 2	1982, 1983	1,150,000/2750	MSF	Riyadh, Saudi Arabia
Shoaiba 1, 2	1989, 2001	650,000/750	MSF	Mekkah, Taif & Jeddah, Saudi Arabia
Ras Alkhair	2014	1,000,000/2400	MSF & RO	Ma'aden Co. (minerals company), Riyadh, Sudair, Al-Washim, Saudi Arabia
Yanbu 1, 2, RO	1981, 1998, 1998	380,000/500	MSF, RO (Yanbu RO)	Medina, Saudi Arabia
Jeddah 3, 4	1979, 1982	300,000/850	MSF	Jeddah, Mekkah, Saudi Arabia
Jabal Ali	1976, 2013 (M station)	2,000,000/7800	MSF	Dubai, United Arab Emirates
Fujairah, F2	2004, 2011	1,000,000/2760	MSF & RO	Cities in Fujairah, Sharjah and Abu Dhabi, United Arab Emirates
Ras Abu Fontas A, A1, A2, A3	1990, 2009, 2015, 2017	640,000/1500	MSF, RO (Ras Abu Fontas A3)	Doha and other cities in Qatar
Al Ghubrah	1976	300,000/2000	MSF	Muscat, Oman
Barka 1, 2	2003, 2009	300,000/400	MSF, RO (Barka II)	Muscat, Oman
Al Hidd 1	2000	270,000/280	MSF	Most urban centers in Bahrain

4. Global Change Induced Threats

4.1. Technological and Market-Driven Change

External risks to the resource supply infrastructure represent a system's turbulences caused by changes in its exterior. There are plenty of possible external changes that can affect the resource supply system's ability to perform at a certain time. Such external drivers can be significant in the GCC region, considering the high external dependence on technology, materials for renewable energies and food-related supplies. In fact, global market competition has resulted in cost decline for major future technologies, like membranes for desalination and PV technology. This is positive for resource supply security in the region in the long-run. For example, the price of residential and commercial PV systems has been declining globally, e.g., 5–7% annually from 1998–2011 in the U.S. [66]. Such renewable energy systems hold a great potential for water, energy and food securities in the GCC region, e.g., [9,67]. Al Maamary et al. [68] studied the impact of oil price fluctuation on renewable energy policies in the GCC. Accordingly, the recent oil and gas price decline might have increased the stakes and reform motivation towards the transition to sustainable energies. This positive trend, however, results in a need to adapt to the new technologies in terms of necessary investments in grid flexibility and integration, promotion of local expertise on renewable energies and managing the vulnerability arising from import dependency of renewable energy technologies. Such issues have not been investigated yet.

The trend of technology improvement and cost reduction is similar with regard to desalination. Dawoud (2005) concluded that the sharp decline in RO technology cost for desalinating water, from 5.5 USD/m³ 1979 to around 0.55 USD/m³ in 1999, had made long-distance water transfers economically inviable in the region [41]. However, Karagiannis and Soldatos [69] reviewed studies on

desalination costs, concluding a wide variability due to the site-specific nature of such costs. Ghaffour et al. [70] reconfirmed this notion and concluded that seawater desalination cost has fallen to around 0.5–1.0 USD/m³ for large-scale osmosis plants depending on the location and conditions onsite. Cost reduction also applies to MSF technology, which is widely used in the GCC region. This technology is preferred in many GCC countries due to its high reliability and the simplicity in terms of technology and control process. On the other side, membrane-based RO technology is growing in the region and worldwide. This is due to its advantages in terms of cost, energy consumption, recovery rate and easy deployment and readjustment. However, risks associated with the increase of RO deployment in the region need to be addressed in light of the mentioned merits and the improvements in technology and costs. First, membrane-based technology requires complex configuration and skilled staff. In addition, membrane technologies are rapidly advancing, which makes continuous education and the promotion of technological knowledge a future necessity. Second, pre-treatment needs are higher, especially in the GCC region where high salinity and poor water quality are important factors. Smith et al. [71] studied the salinity outlook in the Gulf, considering seawater desalination, high evaporation rate and the semi-closed nature of this water body. Accordingly, hyper-salinity conditions can be expected in the region. There are promising technologies to address this issue. Jamaly et al. [72] reviewed RO pre-treatment technologies and found nonconventional (membrane-based) pre-treatment systems better in terms of quality but more costly than conventional methods. An emerging technology with a potential to better address high salinity is that of forward osmosis (FO). However, recent studies showed that FO or FO-RO mixed systems can be more energy-intensive than the preferred technology of RO [73,74]. Another technological risk in the context of the water quality characteristics in the GCC region is that of membrane fouling, a performance degradation due to the deposition of particles in the membrane surface. She et al. [75] provide a recent review of fouling processes, effects and control and mitigation strategies.

An important risk factor related to technology dependence is in regard to technology reliability, human errors and the overarching issue of cyber security. This issue is related to the security of so-called ‘critical infrastructure’ in general. Many studies have warned about the risks of increased interconnectedness and interdependence of important infrastructure for communications, service-based economies and also the supply of life-sustaining resources like water, energy and food. Such infrastructure is connected both physically and through modern communication technologies forming so-called “cyber-based systems” and requiring comprehensive multi-dimensional risk assessment (e.g., [76]) and integrated tools, e.g., [77,78]. Electric grid systems especially require up-to-date communication capabilities and security technologies [79]. In this context, ‘cyber security’ is an encompassing concept including issues such as information security, cyber-based attacks and data privacy. It is increasingly becoming a threat for critical infrastructure based on smart grid and broadband communication due to high technology reliance [80,81]. Research on the future implications and risk mitigation strategies for the GCC’s water, energy and food systems is highly needed.

With regard to the food supply sector, external risk arises mainly from the reliance on food imports. In fact, high food imports in the MENA correlates with the countries’ water deficits [82]. This makes many of these countries vulnerable to price volatility on global food markets and price inflation, while domestic factors like subsidies and market distortions affect the level of vulnerability [83]. For the GCC region, vulnerability to market drivers like price inflation is a common problem, e.g., [84]. The food systems in many of these countries are also vulnerable to health and control issues and do not have state-of-the-art food security plans (see Alomirah et al. for the example of the State of Kuwait [85]). For the State of Qatar, a National Food Security Plan was developed in 2013, which acknowledged the absence of a national food system as well as the high food insecurity, and suggested regulations and the development of a modern domestic market [86]. Finally, the GCC region has significant, untapped potential for the development of food security options based on fish production like aquaculture and aquaponics. However, these options have not been adequately explored nor largely promoted until now.

4.2. Climate Change

The expected effects from rising greenhouse gas emissions (GHG) due to increasing economic activities are more frequent water extremes such as droughts or low precipitation, heat waves, floods and sea level rise (SLR) [87]. The effects on resource infrastructure in the GCC and the region at large have largely not been studied. Sectors like energy, food and water in many of countries in of the Middle East and Northern African Region (MENA) are going to be negatively affected as their adaptive capacities are largely underdeveloped [88]. Reduced rainfall, greater seasonal temperature variability, SLR and loss of agricultural production are some expected consequences in the MENA region [89], in addition to even more migration pressures [90]. In the GCC region, most water and energy supply infrastructure is located in close proximity to the coast. In addition, many planned mega infrastructure and real estate development projects using renewable energies will be located in coastal areas. Literature analyzing vulnerability and risk scenarios for these infrastructure is lacking despite evidence of tangible effects of global warming. Cheng et al. [91] indicated a trend of spatially consistent warming trends in Qatar and the region. Farahat [92] studied air pollution in the GCC including greenhouse gases. Accordingly, high pollutants exist around big cities in coastal regions due to infrastructure development, consumption and city development. Studies on rainfall in the Arabian Peninsula showed evidence of greater variability, e.g., the case of Qatar [93] and Saudi Arabia [94]. In fact, countries in the region like Qatar and others are highly active in hosting and participating in climate-related international diplomacy despite having some of the highest CO₂ levels per capital in the world. Further, the effects of climate change are acknowledged by all Gulf countries in their national communications to the United Nations Framework Convention on Climate Change (UNFCCC). Some recent evidence on the efforts of the GCC countries to address this cross-sectoral challenge are presented by Al-Saidi and Elagib [15], and Al-Maamary et al. [68]. However, detailed studies on the effects of climate change on infrastructure and resource security at large and how to increase the resilience of resource supply infrastructure are still needed.

4.3. State-Based Security

Interventions to ensure state security have effects on resource supply security and vice versa. Risks for the supply infrastructure can emerge from heightened state-based security threats as an effect of specific regional or global state-power constellations, the state's foreign policy ambitions or internal tensions like security threats from nonstate actors. In the GCC context, all these sources of state security threats exist and interrelate. They also might constitute a direct risk to resource supply systems. For instance, the relationship between GCC countries and Iran, particularly Saudi Arabia and Iran, has been a leading topic for state security research. Such relationship is characterized to be a case of 'strategic rivalry' ever since the Islamic Revolution in Iran in 1979' [95]. Strategic rivals are countries that have been at war with one another but coexist under the constant threat of a confrontation or conflict [96]. In such a case, interruptions of resource supplies constitute a major risk, especially considering the direct access of both rivals to the Strait of Hormuz through which most food supplies of the GCC countries as well as the region's energy exports pass.

In addition to direct confrontations, proxy wars and the rise of nonstate actors can be considered as side effects of regional rivalry. The rise of armed nonstate actors increases risks for supply infrastructure, leading some to invoke the notion of 'infrastructure wars'. Toft et al. [97] analyzed incidents of terrorist attacks on energy infrastructure, concluding a low incidence and high concentration in a small number of countries. Accordingly, strategies to increase the stability of supply infrastructure are needed, especially for countries with unstable security contexts, but even for European countries which adopted joint legislation for energy infrastructure protection (European Council Direct 2008/114/EC). In the case of the GCC, there have been attempts in 2017 by the Iran-backed Houthi rebel group in Yemen to target power plants and energy supply transmission infrastructure in the south of Saudi Arabia using short-range missiles. In fact, threats from nonstate actors targeting energy and water supply infrastructure are increasing in the broader Middle East region as some groups even managed

to control the supply sources. For instance, the terrorist group under the name Islamic State (IS) was reported to use water as a weapon in Iraq, e.g., the closure of the gates of Nuaymiyah Dam by IS in 2014 to flood towns and villages in which government sources are located [98]. There have also been reports from Syria and Iraq of attempts to disrupt supply, cause source pollution or control production sites as a source of income like the case of IS's control of some oil and hydroelectric production sites in Syria. Finally, although not yet documented with regard to supply infrastructure, the increasing use of small unmanned aircrafts (drones) or homemade missiles by nonstate actors (e.g., IS in Mosul, Houthis in Yemen, various groups in Syria) is quite alarming for large-scale production sites in the region at large.

5. Discussion of Risks Scenarios and Response Categories

In previous sections, we reviewed knowledge on broad categories of threats to supply systems in the GCC, and indicated some risk factors based on current developments in the supply system in the region. In this place, it is useful to differentiate some terms such as threats, risks and vulnerability and outline the process of responding to these risks or improving the system's resilience. In this paper, a threat is conceived as a general category of rising dangers (e.g., supply systems integration or climate change) that entail several risk factors (e.g., the increase of the number of mega-plants or raising temperature). At the same time, the paper did not entail detailed analyses of certain risks. Risks are commonly understood as concrete events or scenarios with a certain likelihood and clear consequences [99,100]. Risk assessments represent narrow endeavors to analyze and quantify risks. In contrast, investigating the vulnerability of a system to certain risks and the overall system's resilience include the study of the relationships among risks as well as the their consequences and the reaction of the system as a whole [100,101].

Using the broad differentiation between threats and risks, we can summarize some risk scenarios based on the previously outlined categories of threats (Table 4). Here, we cannot accurately predict the likelihood as this might be site- and state-specific. Some events have occurred in the past such as oil-spills, cyber-attacks and accidents. However, past occurrence might not imply likelihood. For example, the blockage of Qatar in 2017 and the resulting food shortages of the first days are unique and rather unexpected circumstances that might not repeat again.

Table 4. Examples of risk scenarios.

Threats	Risk Scenarios
Internal threats	
Systems coupling	Power shortages in desalination plants due to increased domestic energy demand Multiple shortages in electricity and desalinated water due to failures in joint water and power plants Renewables production volatility affecting power, desalination or food production capacities Extreme peak and off-peak demands causing instabilities and failures
Demographics and growth	Supply shortages due to sudden increases in demands (e.g., due to migration influx, several mega-events, heat waves etc.) Economic declines or emigration (e.g., return of expatriate workers upon completion of mega-projects) resulting in overcapacities
Scale and planning	Failure of desalination large-scale mega-plants affecting supply of large cities Disruptions across the Gulf coast leading to cascade effect on several power and desalination plants
Global change induced threats	
Technological and market-driven change	Changes in global markets affecting local supply or prices (e.g., increase of prices membranes, production parts or food items) Current desalination technologies on the global market cannot cope with increased salinity in the Gulf Production problems due to sudden shortages of qualified staff Accidents, human errors and cyber-security problems due to increased technological sophistication Food shortages due to trade or economic wars Food health crises
Climate change	Production shortages due to extreme events such as heat waves, floods or storms affecting the coasts Raising temperature, urban pollution and heat islands affecting demands and causing supply volatility of water, energy and food State-sponsored cyber-attacks
State-based security	Terrorist attacks involving nonstate actors Oil-spillovers jeopardizing desalination capacity

The outlined risk scenarios might even occur simultaneously, amplifying the costs and constraining the system's ability to respond. Literature on the resilience of infrastructure systems often stresses the importance of integrating analysis and responses to several risks, while targeting the improvement of the overall resilience of a system. While there are many different definitions and frameworks in analyzing of resilience and vulnerability of infrastructure systems [102,103], the common approach is to highlight the independent components necessary for the resilience of an infrastructure system and propose measurement indicators (resilience measures) as well as response measures (resilience policies or responses). For example, Shin et al. [104] provided a review of resilience measurements of water infrastructure by analyzing the functional requirements and design parameters needed to analyze the four key capabilities of a system. These commonly used capabilities in resilience analyses are as follows. The *withstanding capability* is the ability to withstand disruptions and maintain normal functions. The *absorptive capability* is the ability to absorb disruptions and minimize associated damage. The *restorative capability* refers to the recovery ability while the *adaptive capability* refers to the ability to function on the long-term in an acceptable manner despite disruptions. For the supply infrastructure in the GCC region, it is necessary to address the four system's capabilities to achieve resilience to previously highlighted threats and risks. In Table 5, we summarized some general response categories. This is done by summarizing insights from Ouyang et al. [105] who provided some resilience application strategies across the earlier mentioned capabilities of infrastructure systems and Labaka et al. [106] who proposed resilience policies based different dimensions of resilience, i.e., technical, organizational, economic, organizational resilience. We joint these resilience strategies and policies in broad response categories along the four capabilities mentioned by Shin et al. [104]. Further, for the global change induced risks, we proposed additional responses since these risks represent a particular challenge for the context of the GCC region.

Table 5. Responses for strengthening resilience.

Capabilities of a Resilient System	General Response Categories	Additional Response Categories for Global Change induced Risks
Withstanding capability	Use of accident models and past-experiences; adequate monitoring and forecasting systems; emergency preparation and staff trainings; decision support systems for risk anticipation; safety and design measures; high maintenance quality	Diversification of supply; improving supply chain management; use of global and regional models for risk calculation; investments in infrastructure security and supply, including cyber-security
Absorptive capabilities	Flexible engineering and infrastructure design; design for system redundancy; inclusion of self-healing and self-adapting measures; emergency response and crisis management	Incorporation of risks analysis in regional infrastructure planning including site-selection; improving infrastructure for trade and external supply
Restorative capabilities	Efficient communication & coordination; recovery strategies and systems; external crisis budgets and equipment	Regional contingency plans; increased integration of supply networks
Adaptive capability	Adequate crisis regulation, legislation and budgets; regulations for system redundancy; public awareness and trust	Development of local technologies; investments in local expertise; development of storage capacities and alternative supply strategies

In the following, concluding section, these responses are aggregated into four broad priorities for future supply-security strategies, namely knowledge and research, storage, diversification, and regional cooperation. These priorities do not present exclusive answers to address the discussed risks, but rather common denominators of responses across different capabilities and scenarios. For example, risk scenarios related to shortages, failures, disruptions and extreme volatilities can be addressed by some common responses among the four capabilities; e.g., accident models, training, emergency and recovery strategies, or crisis management and regulations. These responses thus reiterate the importance of broader strategies such as increasing knowledge and improving storage capacities. As another example, risk scenarios related to global change (e.g., market changes, human and material supply shortages, or environmental crises), can be addressed by responses such as regional

plans, trade relations, or integrated infrastructure. Here, the strategic priorities of diversification and regional cooperation are common to these responses. In fact, more research is needed in order to address single-risk scenarios, to model relationships between risks, or to provide detailed case studies. There have been few, mostly descriptive, nexus studies detailing status, interlinkages, and challenges in some GCC countries (e.g., Qatar [107], or Saudi Arabia [108]) or the wider Arab region; e.g., [16–18,109–112]. However, analyses of supply-related risks of integrated systems are lacking for this region, while some supply-risk assessments and reviews of quantitative methods exist for other cases [77,99,101,102,113–115].

6. Conclusions: Future Risk-Oriented Security Strategies

Risks-based security conception represents a future looking, pre-emptive but also versatile view because not all risks are measurable or manageable. As the increased integration of water and energy production systems in the GCC region shows, security risks are unlikely to be addressed by standalone or sectoral planning instruments, and are often transboundary. The exercise of mapping risk sources and types is an initial and necessary step in a broader effort to redefine the understanding of resource-supply security and to address crucial uncertainties in infrastructure planning. Ultimately, national and regional policymaking is the primary arena responsible for investing in the study of future supply risks and the development of adequate risk-governance mechanisms. Understanding and addressing this vital topic of supply security through the lens of cross-sectoral (water, energy and food) and integrated (internal–external, supply–demand, technological–human) risk management is indeed a long-term endeavor. This requires experimentation and innovation with regard to estimation models, response measures, and broader security strategies.

We believe that uncertainties related to the risk scale, timing, location, and strategies can be commonly mitigated via four overarching priorities that should be incorporated in future security strategies: increasing knowledge, building storage and reservoir options, diversification, and promoting regional cooperation. These priorities represent commonalities among the response categories highlighted earlier. The first common response category relates to education, research and development, and addressing critical technologies in resource supply; e.g., desalination, use of renewables in arid contexts, alternative (urban-based) food production systems, etc. At large, knowledge and research is highly important for technology-intensive and high-risk societies. In fact, all national visions of the region's countries converge on the notion of a knowledge-based economy. Research investments are increasingly promoting hotspot technologies with a potential comparative advantage like membrane technologies, algae harvesting, soilless or saline agriculture, smart cities etc.

Secondly, priority response measures targeting storage capacities are emerging in the region. Mega projects to increase emergency water reserves through mobile storage units, the construction of underground storage sites, or the recharging of aquifers are underway in many GCC countries. Storage silos for vital grains like wheat and rice are increasing in the region while energy storage is not urgent due to wide availability of fossil sources. Third, diversification is necessary for addressing the elaborated dependence and scale related risks. The use of renewables, decentralization and the promotion of markets for independent resource suppliers are some emerging response measures to encourage such diversification. Fourth, regional cooperation in infrastructure planning, grid and pipeline integration, resource trade, technical and financial exchange in terms of experts and money, among other forms of GCC-wide cooperation, represents a promising set of responses to common risks to water, energy and food supplies. This regional response option is largely unexplored. For instance, efforts to accommodate uneven coverage and supply interruptions through water transfers and pipeline expansions are confined to new national security strategies like a recent effort in the UAE as only one example. Much can be gained from exploring this option, using optimization models to investigate optimal scales and synergies, and even enhancing GCC cooperation with neighboring regions like East Africa, Iran, Northern Arabia or North Africa.

While these broad risk-mitigation strategies can be resource and time-intensive, they do not replace the need for sector- and issue-specific risk management strategies and detailed vulnerability analyses. Vulnerability assessments as well as risk management studies represent basic investigations of the interlinked supply systems. They can provide insights into the best technological and production options in terms of adaptability, flexibility, and resilience to address specific risk scenarios. Such studies are lacking and are essential for enhancing future supply security in the GCC region. Furthermore, institutional and policy arrangements have focused on increasing the stability of the supply system and maintaining its high performance in terms of reliability and supply coverage. However, it is more evident that policymakers need to equally consider the overall resilience in order to encourage low-risk options in the design, regulations, and institutional frameworks of the supply systems. As a prerequisite for this change, the increasing complexity of integrated supply systems as well as the risks they face need to be acknowledged. At the same time, the notion of supply security needs to be re-examined and broadened. The required security safeguards are set to become multi-faceted (across disciplines), horizontally (across sectors), and vertically (e.g., different spatial units) integrated, and more coordinated (e.g., from design to recovery, or national to transboundary).

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