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Scenario-Based Assessment of the Water-Energy-Food Nexus in Kuwait: Insights for Effective Resource Management

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Abstract

The interdependency among water, food, and energy (WEF) in the GCC countries is strongly and closely interlinked, and is intensifying as demand for resources increases with population growth and changing consumption patterns, and are expected to be further compounded by the impacts of climate change. Therefore, integrated management of the three sectors is crucial to reduce trade-offs and build synergies among them. This paper presents a comprehensive framework to assess the WEF nexus in Kuwait as a representative case for the GCC countries. The framework consists of three main steps: 1) evaluating the influence of socio-economic development and climate change on water, energy, and food resources; 2) generating scenario-based projections; and 3) conducting an extensive quantitative nexus analysis. The WEF interlinkages in Kuwait are modelled quantitatively using the Q-Nexus model, and current critical interdependencies are evaluated. Then, various WEF-Nexus scenarios were conducted for the year 2035 to explore the effects of management interventions in one sector on the other two sectors. The main findings are that per capita municipal water consumption is a major influencer on the WEF-nexus due to the heavy reliance on thermal desalination in municipal water supply in Kuwait, which is attributed to its energy intensity, financial cost, GHGs emissions, and environmental impacts on the marine and air environments. To reduce WEF trade-offs, mitigate risks, and build synergies among the three sectors, it is important to shift the current policy focus on supply-side management approach to the demand-side management and efficiency approaches.

Keywords

Climate Change, Socio-Economic Development, Municipal Water

Consumption, Agricultural Water Consumption, Renewable Energy, Desalination Technology

1. Introduction

The complex interconnection between water, energy, and food security poses significant challenges for the Arab world, particularly in the Gulf Cooperation Council (GCC) countries [1]. These countries, characterized by energy-intensive practices, water scarcity, food deficiencies, and high vulnerability to climate change impacts, face growing interdependencies among these sectors. Unsustainable consumption patterns, rapid population growth, and focusing on a supply-side approach in the management of these three sectors further exacerbate and intensify these interlinkages. With limited freshwater resources and absolute water poverty, the GCC countries heavily rely on desalinated water, groundwater, the majority of which are non-renewable, and recycled wastewater, all of which require substantial energy inputs, and in the case of desalination, high associated environmental externalities. Additionally, the production of food necessitates both water and energy, creating a high dependency between the water-energy-food (WEF) sectors.

The WEF nexus concept entails exploring the interconnected relationships among water, energy, and food and their mutual impacts. Understanding the trade-offs and synergies within this nexus is crucial for informed decision-making, especially concerning climate change and socio-economic development. Meeting the demands of one sector can have repercussions on the others, underscoring the necessity of adopting a WEF nexus approach to effectively manage these sectors, mitigate risks, minimize trade-offs, and promote synergies [2].

Presently, the majority of the GCC countries, including Kuwait manage their water, energy, and food sectors independently, thereby amplifying risks [3]. The interdependency among these sectors calls for a paradigm shift towards a nexus approach in planning and management. Therefore, the objective of this research is to identify and analyze the critical interlinkages, trade-offs, risks, and potential synergies within the WEF nexus in Kuwait, serving as a representative case study for the GCC countries. By doing so, we aim to propose effective WEF nexus policies that enhance synergies and minimize trade-offs among the three sectors.

By comprehensively analyzing the connections between water, energy, and food, this study aims to discern the trade-offs and mutual benefits involved. Kuwait is examined as a representative case of the GCC countries to formulate WEF Nexus policies that foster mutual sectoral support and limit trade-offs. The study quantifies the three sectors' interconnections and evaluates their status under the impacts of climate change and socio-economic growth. The findings provide valuable insights for informed decision-making toward the sustainable management of the WEF nexus in Kuwait as well as the other GCC countries.

2. Materials and Methods

The WEF nexus approach recognizes that the management of these resources is interdependent, meaning that changes in one sector can have significant impacts on the others. This approach involves, firstly, assessing the current state of water, energy, and food systems, and identifying the challenges and opportunities for sustainable resource management in light of socio-economic development and climate change. This analysis is crucial for understanding the potential impacts of these changes on the availability and quality of WEF resources, and for developing appropriate strategies to mitigate or enhance these impacts (**Figure 1**). Secondly, the WEF nexus approach involves developing a range of scenarios for the future, which can provide insights into the potential impacts of different development pathways on the WEF nexus. Finally yet importantly, the WEF nexus approach involves synthesizing the information and insights from the previous steps to identify and assess the trade-offs and synergies among water, energy, and food systems. The goal of this step is to support informed decision-making and policymaking by providing a comprehensive and integrated view of the WEF nexus and its potential impacts on sustainable resource management. The above-mentioned WEF nexus analysis elements will be examined sequentially, as illustrated in **Figure 1**.

2.1. Impact of Socio-Economic Development on Municipal Water Demand

The impact of socio-economic development on water production and utilization is substantial and can be seen in several ways [4]: 1) an increase in population and economic growth can lead to higher water demand for household, industrial, and agricultural use; 2) improved living standards and rising incomes can increase water usage for domestic purposes, such as for washing and flushing toilets; 3) expansion of the agricultural and industrial sectors can result in higher water usage for irrigation and industrial processes; 4) changes in consumption patterns, such as an increase in meat consumption, can lead to higher demand for water-intensive food production.

This increase in demand is influenced by factors such as urbanization, industrialization, population growth, and changes in consumer behavior. Additionally, as economies grow, more people can afford to live in single-family homes with lawns, swimming pools, and other amenities that require substantial amounts of water. This heightened demand for water puts stress on the municipal water supply and requires the development of new water sources or the expansion of existing ones.

The strain on municipal water supplies as a result of increased demand is well-documented. The development of new water sources or the expansion of existing ones is often necessary to meet the growing demand [5]. In addition, improved water management practices, such as water-saving technologies, are also needed to ensure sustainable and efficient use of water resources.

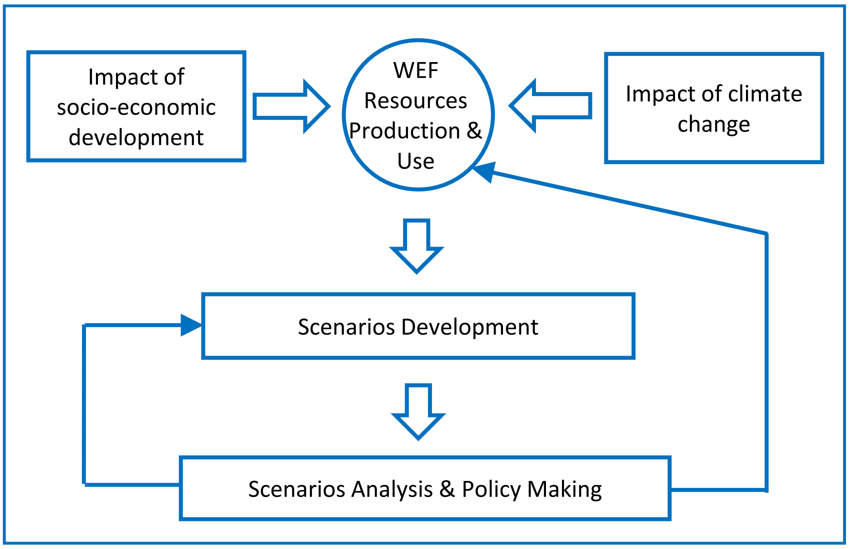

Figure 1. WEF nexus analysis framework.

In many GCC countries, the industrial sector is one of the users of the municipal water supply network. Industrialization can also has a significant impact on municipal water demand, as it requires large amounts of water for processes such as cooling, cleaning, and chemical production [6].

2.2. Impact of Socio-Economic Development on Agricultural Water Demand

The effects of socio-economic development on agriculture water demand can be diverse and multifaceted. On the positive side, a rise in income levels and advancements in technology can result in higher demand for food and agricultural products and more efficient use of water. However, increased urbanization and competition for water from other sectors, such as urban areas, industry, and energy production, can lead to land-use changes, reducing the availability of water for agriculture. It is important to note that the impact of socio-economic development on agriculture water demand will depend on the unique circumstances and the interplay of various factors, including environmental, economic, and political conditions [7] [8]. Moreover, effective water management policies and practices can help mitigate the negative impacts and enhance the positive effects of socio-economic development on agriculture water demand [9].

The increasing demand for food, driven by population growth, urbanization, dietary changes, and consumption patterns, is further exacerbating food insecurity [10]. Changes in consumer behavior, such as increased meat consumption, can also put pressure on water resources as animal agriculture (fodders) is a water-intensive industry [11]. The Food and Agriculture Organization (FAO) of the United Nations warns that food supply will be under unprecedented stress as the world's population reaches 10 billion by 2050, and food demand approaches the limits of modern agricultural development [12].

Food production is both water- and energy-intensive, with agriculture accounting for 70% of global human freshwater consumption and 23% - 48% of energy consumption in agriculture being attributed to irrigation [10]. Energy shortages and water scarcity in food production can limit food output. Moreover, the energy sector faces a supply-demand imbalance, with energy demand projected to increase by 50% in 2030 due to population and economic growth [10]. This means that energy production will not be able to keep pace with demand, leaving about 3 billion people without access to safe and reliable energy. Water scarcity also poses a significant threat to global energy security, as water withdrawal for electricity generation accounts for 88% of that from the energy sector [10].

2.3. Impact of Socio-Economic Development on Energy Demand

The relationship between socio-economic development and energy demand is complex and can vary greatly based on local and global factors. On one hand, higher income levels, economic growth, and urbanization can drive up energy demand as individuals and businesses have greater resources to invest in energy-intensive activities and technologies [13]. On the other hand, advancements in energy efficiency and the growth of renewable energy sources can reduce energy demand by limiting the need for traditional fossil fuels [14]. Additionally, shifts in social and cultural norms, such as a greater focus on sustainability, can lead to decreased energy consumption [15]. Ultimately, the specific impact of socio-economic development on energy demand will depend on the interplay of various factors, including economic, political, and technological conditions, as well as the availability of energy resources.

2.4. Impact of Climate Change on Municipal Water Demand

Warmer temperatures lead to higher water usage. These effects can lead to challenges for municipalities in meeting the water demands of their communities and protecting public health. It can also result in increased water management costs, potentially affecting the overall economy [16]. Using monthly per capita consumption, population and average temperatures for the period 1998-2017 in Kuwait, it is estimated that an increase in temperature of 1˚C, lead to an increase in per capita municipal water consumption by 5.386 l/cap/day [17].

2.5. Impact of Climate Change on the Agricultural Water Demand

The impacts of climate change on food production are becoming more severe, as predicted by the Intergovernmental Panel on Climate Change [10]. Climate change impacts on agriculture water demand can be significant, including [12]: 1) increased water demand due to higher temperatures and longer growing seasons; 2) decreased water availability due to droughts and reduced snowpack; 3) intense precipitation leading to runoff and decreased infiltration, making water less accessible for crops; 4) sea-level rise affecting water quality and availability in coastal regions; and 5) shifting precipitation patterns leading to changes in crop water requirements.

These impacts can result in challenges for agriculture, including decreased crop yields, reduced production, and increased costs for irrigation and water management. This, in turn, can impact food security and the economy. Quantitatively speaking, in arid regions, an increase of 1˚C temperature will increase crop water requirement by 2.9% [18].

2.6. Impact of Climate Change on Energy Demand

The impact of climate change on energy demand can be significant and far-reaching, with important implications for both energy production and consumption. The main effects include [19]: 1) rising demand for cooling, as temperatures rise due to climate change, there is a growing need for air conditioning and cooling systems, leading to increased energy demand; 2) boosting renewable energy, climate change has led to increased interest and investment in renewable energy sources such as solar, wind, and hydro power, as a way to reduce greenhouse gas emissions and limit global warming; 3) changes in consumption patterns, climate change is also leading to changes in patterns of energy consumption, with more use of air conditioning in the summer and heating in the winter, further driving up energy demand; and 4) shift away from fossil fuels, as awareness of the damaging impact of fossil fuels on the environment grows, there is a growing trend towards clean energy sources and away from traditional fossil fuels, further shaping energy demand. Quantitatively speaking, an increase of 2˚C in 2050 will increase the energy demand by 41.5% [20].

2.7. Scenario Development

Scenario development aims to create a set of future scenarios that consider future changes of WEF production and use technologies as well as the impacts of climate change and socio-economic development. This step should examine the relationships between the sectors, and how changes in one sector affect the others. For example, increased water availability may lead to increased energy production, but may also lead to reduced food production due to competition for water resources.

This can involve the use of scenario planning techniques to create a range of possible futures, considering expected trends in each sector, potential impacts of climate change, and potential technological advancements or policy changes. A range of future prospects to support the development of effective policies in the WEF nexus is presented in sequence.

2.7.1. Per Capita Water Reduction

Reducing per capita water consumption is an important policy option for an effective WEF nexus scenario [21]. Lowering per capita water consumption helps to ensure the sustainable use and management of water resources, which are essential for both food production and energy generation [22]. By reducing water consumption, we can also reduce the amount of energy needed to treat, transport and distribute water, leading to lower greenhouse gas emissions and improved energy efficiency [23].

There are several practical ways to reduce per capita water consumption, including: 1) promoting water conservation practices in households, such as fixing leaks, using water-efficient appliances and reducing water waste [24]; 2) encouraging the reuse and recycling of water [21]; and 3) implementing policies and regulations that promote sustainable water management and conservation [21]. Overall, reducing per capita water consumption is an important action towards a sustainable WEF nexus, where the interconnections between municipal water and energy are very strong due to the heavy reliance on desalination in providing municipal water supply in Kuwait as well as all the GCC countries.

Currently, the per capita water consumption in the municipal water sector in Kuwait is about 480 l/capita/day, which is considered relatively high. The recommended per capita municipal water consumption in Kuwait, as well as for all the GCC countries, was indicated at 250 l/capita/day. This figure represents the set target by the GCC unified Water Strategy 2035 to be gradually achieved by the year 2035 [25].

2.7.2. Switching to More Efficient Desalination Technology

Desalination is a vital source of fresh water for regions facing water scarcity, however, conventional technologies are often energy-intensive and can have significant environmental impacts [5]. To reduce the energy consumption and environmental footprint of desalination, it is important to adopt more efficient technologies, such as those powered by renewable energy sources [26]. Moreover, the use of membrane desalination technologies, which are more energy-efficient and have a smaller environmental impact compared to traditional thermal desalination technologies, can also help to increase the efficiency of the desalination process [27]. The use of Reverse Osmosis technology in combination with energy recovery systems can further improve the overall efficiency of the process [28]. In Kuwait, currently thermal technology (Multi-Stage Flash and Multi-Effect Distillation), is the primary desalination technology used which results in a relatively large energy intensity.

The shift towards more efficient desalination technologies is part of a larger effort to manage the WEF nexus sustainably. By reducing the energy consumption and the environmental impact of desalination, a sustainable supply of fresh water can be ensured while protecting the environment [5]. The adoption of more efficient desalination technologies can also contribute to improved energy security and reduced dependence on non-renewable sources of energy [26].

2.7.3. Increased Irrigation Efficiency

Increased irrigation efficiency is a crucial aspect of the WEF nexus scenario. Irrigation is the largest human use of water and is essential for food production. However, traditional irrigation methods can be wasteful and inefficient, leading to significant losses of water and energy [5].

Improving irrigation efficiency helps to reduce the amount of water and energy required for food production, leading to a more sustainable WEF nexus. There are several ways to increase irrigation efficiency, including: 1) implementing precision irrigation techniques, such as drip irrigation and sprinkler systems, which allow water to be delivered directly to the roots of plants, reducing water waste [29]; 2) using soil moisture sensors and weather-based irrigation controllers, which help to optimize irrigation schedules based on real-time weather and soil conditions [30]; 3) adopting conservation tillage practices, such as no-till farming, which help to conserve water and reduce soil erosion [31]; 4) developing water-saving crops, such as drought-resistant varieties, which require less water for growth and yield [32]; and 5) implementing policies and regulations that promote water-saving practices and encourage the adoption of more efficient irrigation technologies [33].

Currently, the irrigation efficiency in Kuwait is about 25% due to the use of traditional irrigation methods, which considered very low. The recommended irrigation efficiency for all the GCC countries was set 60%, and represents the target of the GCC unified Water Strategy 2035 to be gradually achieved by the year 2035 [25].

By improving irrigation efficiency, we can reduce water and energy use, lower greenhouse gas emissions, and improve food security.

2.7.4. Switching to More Efficient Fuel in Electrical Energy Production

Switching to more efficient fuels, such as natural gas, in electrical energy production is an import aspect of the WEF nexus scenario. Electrical energy production is a major source of water consumption and greenhouse gas emissions, and the fuel used to generate electricity has a significant impact on water resources and the environment [34].

Gas turbines are a more efficient and less water-intensive alternative to traditional energy sources, such as coal and nuclear power, for electrical energy production [35]. Gas turbines use natural gas or other gases as fuel and can achieve high levels of thermal efficiency, which means that less fuel is needed to produce the same amount of energy. Additionally, gas turbines can use recycled waste heat from the combustion process to generate additional electricity, further increasing their efficiency [35].

Switching to gas turbines for electrical energy production can help to reduce water consumption and greenhouse gas emissions compared to traditional energy sources [34]. While natural gas is a fossil fuel and still generates greenhouse gas emissions, it is considered a cleaner source of energy compared to coal and oil, and its use can help to reduce emissions in the energy sector [35].

2.7.5. Switching to Renewable Energy Production

Renewable energy sources, such as solar, wind, and hydropower, have the potential to provide a sustainable and resilient energy supply while reducing the impact of energy production on water resources and the environment [36].

One of the main benefits of renewable energy production is that it does not require water for electricity generation, unlike traditional energy sources, such as coal and natural gas, which often require large amounts of water for cooling and other processes [37]. This helps to reduce water consumption and pressure on water resources in the energy sector [36].

In addition, renewable energy sources generate electricity with zero or low emissions, helping to reduce greenhouse gas emissions and mitigate the impact of energy production on the environment [36]. This is particularly important for addressing climate change and preserving water resources for future generations.

By increasing the use of renewable energy, we can ensure a more sustainable and resilient energy supply, while also reducing the impact of energy production on water resources and the environment.

Overall, switching to renewable energy production is a crucial step towards a sustainable WEF nexus, where the interconnections between water, energy, and food are managed in a balanced and sustainable way [1]. By transitioning to a renewable energy future, we can ensure a sustainable and resilient energy supply while preserving water resources and mitigating the impact of energy production on the environment [36]. Moreover, it will help in achieving the GCC countries' commitments of reducing the countries' greenhouse gasses emissions and meeting their nationally determined commitments as well as carbon neutrality plans.

2.8. WEF Nexus Analysis

The aim of the WEF nexus analysis is to identify and prioritize opportunities to quantify and optimize the use of the water, energy and resources in a balanced and integrated manner, taking into account the trade-offs and synergies between them [2] [38]. The WEF nexus analysis consists of the following two key elements: 1) quantification, which it refers to the measurement and assessment of the availability and demand for water, energy, and food resources. This includes evaluating the resources' current and future use, and their potential for growth and expansion [22] [39]; 2) allocation, which it refers to the distribution of resources among different sectors and uses, such as agriculture, industry, households, irrigation, electricity generation, and food production. The aim is to allocate resources in a sustainable and equitable manner, taking into account the interdependence of the water, energy, and food systems [22] [40].

There are various modeling approaches to model the interconnections between water, energy, and food systems, each having strengths and weaknesses [41] [42]. There are various tools and approaches that can be utilized in WEF nexus analysis, depending on the specific context and objectives of the analysis. In this study, the Q-Nexus method [2] [22] [43] was used. The Q-Nexus method provides a comprehensive framework for simulating the WEF nexus at a systemic level and assessing the interrelationships between water, energy, and food systems. In this model, the water, energy and food sectors are categorized by a set of production technologies. It integrates a Leontief production function, which considers inter-sectoral resource utilization and final demand to determine sector outputs. By applying the Q-Nexus method, we can obtain quantitative results that directly and indirectly demonstrate the interdependence of water, energy, and food systems.

3. Case Study of Kuwait

Kuwait is a severely water-scarce country with limited freshwater resources and rapid population growth. Kuwait's water supply is heavily dependent on desalination, which accounts for more than 90% of the country's water supply [44]. The country's limited freshwater resources and high demand for water put a strain on the country's water supply [45]. Kuwait's energy sector is heavily reliant on oil and gas, which account for more than 90% of the country's total energy production [46]. The government is investing in renewable energy sources, such as solar and wind energy, to diversify its energy mix and improve energy security [47]. Kuwait's food sector is heavily dependent on imports, with most of its food being imported from abroad [48]. The country has limited agricultural land and the arid climate makes it difficult to grow crops [49]. The food sector relies on adequate water and energy supplies to grow crops and import food [50].

The water, energy and food resources in Kuwait are closely linked, with each sector relying on the others. However, in Kuwait as well as in the other GCC countries, this relationship is highly skewed towards energy due to the considerable role the energy sector plays in the water and food value chain. Desalination is an energy-intensive process, especially thermal technologies which are used in Kuwait, and can strain the country's energy supply [44]. At the same time, the food sector depends on adequate water and energy supplies to grow crops and import food.

The water, energy and food sectors in Kuwait face several challenges, including water scarcity, energy security, food security, and environmental sustainability [1]. The government is taking a number of steps to address these challenges, but more efforts are needed to ensure sustainable resource management practices.

Based on the Q-Nexus requirements, the following set of WEF production technologies are considered in this study:

1) Water sector production technologies: Groundwater; desalination MED; desalination MSF; desalination RO; tertiary treated and reused wastewater; quaternary treated and reused wastewater.

2) Energy sector production technologies: Primary energy; electricity (gas turbine); electricity (steam turbine closed-loop cooling); combine cycle turbines; electricity (PV).

3) Food sector production technologies: Vegetable (drip irrigation); tubers, roots and onions (drip irrigation); pulses (drip irrigation); field crops and green

fodders (flood irrigation); cows and buffalo Meat; sheep and goats' meat; poultry meat; eggs; fresh milk; fresh fish; fresh shrimps.

3.1. Collecting the WEF Nexus Data

Tables 1-3 illustrate the water, energy and food sector production quantities presented by production process/technology considered in this study.

Table 4 and Table 5 present the collected data of water use in food production for plants and animals, respectively. Table 6 and Table 7 present the collected data of energy use in water production and food production, respectively.

Table 1. Water sector production quantities in 2018 [51].

Process	Total production (Mm^3)
Groundwater	697
Desalination MED	172.93
Desalination MSF	500.2
Desalination RO	45.86
Tertiary treated and reused wastewater	77.98
Quaternary treated and reused wastewater	86.56

Table 2. Energy sector production quantities in 2018 [51].

Process	Total production (GWh)
Primary Energy (evaluated as secondary energy equivalent)	1,889,629
Electricity (Gas turbine)	28,108
Electricity (Steam turbine closed-loop cooling)	37,102
Combine cycle turbines	8892
Electricity (PV)	3.9

Table 3. Food sector local production quantities in 2018 [52].

Process	Total production (kiloton)
vegetable (Drip Irrigation)	301.9
Tubers, roots and onions (Drip Irrigation)	56.7
Pulses (Drip Irrigation)	3.67
Field crops and green fodders (Flood Irrigation)	396.9
Cows & Buffalo Meat	66.42
Sheep & Goats Meat	6.89
Poultry Meat	61.11
Eggs	10.11
Fresh Milk	72.261
Fresh Fish	2.250
Fresh Shrimps	0.617

Table 4. Calculated water requirements for crop types of Kuwait in 2016 (based on [53] data).

Type of crops	Total production (kiloton)	Average Water Use (Mm^3)
Green Fodder	301.9	408.9
Tubers & Bulbs	56.7	33.4
Pulses	3.674	0.7
Vegetables	396.9	52.3

Table 5. Calculated water requirements for livestock production in 2018 (based on [52] data).

Livestock types	Total production (kiloton)	Total Water use (Mm^3)
Cows & Buffalo Meat	66.42	185
Sheep & Goats Meat	6.89	7.843
Poultry Meat	61.11	47.058
Eggs	10.11	7.843
Fresh Milk	72.26	54.901
Fresh Fish	2.25	-
Fresh Shrimps	0.61	-

Table 6. Calculated energy requirements for water production in 2018 (based on [51] data).

Process	Total production (Gwh)	Total Water use (Mm^3)
Desalination MED	701.5	172.93
Desalination MSF	2046.2	500.2
Desalination RO	231.4	45.86
Tertiary treated and reused wastewater	11.8	77.98
Quaternary treated and reused wastewater	13.3	86.56

Table 7. Calculated energy requirements for food production in 2018 (based on [52] data).

Process	Total production (kiloton)	Electricity share (MWh)
vegetable (Drip Irrigation)	301.9	123.88
Tubers, roots and onions (Drip Irrigation)	56.7	23.97
Pulses (Drip Irrigation)	3.6	1.99
Field crops and green fodders (Flood Irrigation)	396.9	163.85
Cows & Buffalo Meat	66.4	27.97
Sheep & Goats Meat	6.8	3.99
Poultry Meat	61.1	23.97
Eggs	10.1	3.99
Fresh Milk	72.2	27.97
Fresh Fish	2.2	0.15
Fresh Shrimps	0.6	0.04

3.2. Scenarios Analysis

Several WEF-Nexus scenarios were conducted to explore the effects of management interventions in one sector on the other two sectors. These scenarios aimed to assess the future implications of various factors such as WEF demand projections, climate change, and the introduction of renewable energy in Kuwait.

Reference scenario: A baseline was established by creating a reference scenario for the year 2035, taking into account the projected demands of the Water-Energy-Food (WEF) sector. These demands were determined by considering the anticipated population growth and assuming the current rates of water, energy, and food consumption per person. The reference scenario also incorporated the impact of climate change on municipal water demand in 2035, considering the temperature rise under RCP 8.5 [54], and an estimation that an increase in 1˚C in temperature in Kuwait would result in an increase in per capita municipal water consumption by 5.4 liters/day [17]. Furthermore, the influence of climate change on agricultural water demand in 2035 was factored in, based on the existing agricultural water demands [53], and the research findings that a 1˚C increase in temperature would result in a 2.9% growth in crop water requirement (CWR) in arid regions [18]. In addition, based on Kuwait's national plan to have 15% of renewable energy in its energy portfolio, by 2030; this scenario includes replacing 15% of energy produced by steam turbines with renewable energy production technology (Solar Photovoltaic).

Following the establishment of the reference scenario, several management intervention scenarios were compared to it to assess their effectiveness in reducing trade-offs and building synergies among the three sectors. These scenarios focused on changes in demand and technology within the water, food, and energy sectors, as follows:

1) Reduction in per capita water consumption scenario: In the water sector, the first scenario explored a reduction in per capita water consumption, incorporating efficiency measures aligned with the targets of the GCC Unified Water Strategy 2035 [25].

2) Switching to more efficient desalination technologies scenario: The second water scenario involved transitioning to more efficient desalination technologies, specifically increasing the share of multi-effect desalination technology (MED) from 19.2% in 2018 to 42.2% in 2035 [55], while decreasing the share of MSF technology from 51.7% to 28.7%, as per the government efforts and plans to enhance the efficiency of energy use in desalination.

3) Improving irrigation efficiency scenario: The food scenarios focused on improving irrigation efficiency to reduce water demand in the agricultural sector. Similar to scenario for the reduction in per capita water consumption, the irrigation efficiency target is aligned with the targets of the GCC Unified water Strategy 2035 [25].

4) Switching to more efficient fuel for electricity production scenario: Within the energy sector, scenarios explored the adoption of more efficient technologies

and a shift from oil to gas as a fuel source for electricity production.

Each of these scenarios was analyzed individually and combined, comparing their impacts on the WEF-nexus with the reference scenario. The reference year for all scenarios was 2018, and the target year considered was 2035, aligning with the objectives of Kuwait Vision 2035.

Table 8 presents the simulation results, showcasing the percentage decrease of various factors/indicators when compared to the reference scenario. These factors/indicators include total water demand, total energy demand, desalinated water production, implementation cost, energy consumption for desalination, and desalination greenhouse gas (GHG) emissions and brine discharge.

The simulation results indicated that business-as-usual scenario (*i.e.*, reference scenario) for the management of the water, energy, and food sectors will be associated with relatively high investment costs and resources shortage risks; yet, there exists major opportunity to reduce these costs and risks, especially in the water sector, where it is found that the reduction in per capita municipal water consumption from 175 m^3/year in 2018 to 90 m^3/year by 2035 is the most effective scenario in reducing desalination cost and its associated environmental impacts by 45%. In this scenario, desalinated water can be reduced and consequently, desalination energy cost, GHGs emissions, and brine discharge to the marine environment will be also decreased.

Due to the fact that Kuwait depends essentially on imports for its food supply, the impact of the food sector scenarios on the other sectors is found to be very minor.

Finally, the combined scenario, representing the efforts in the three sectors, shows a higher saving in total energy and water demands up to 46%. Consequently, this will lead to a reduction in desalinated water. Therefore, the cost of desalination energy, GHGs emissions, and brine impact will decrease accordingly.

Table 8. Percentage decrease of various factors/indicators when compared to the reference scenario for the year 2035.

Factors/ Indicators	Scenarios				
	Reduction in per capita municipal water consumption	Switching to more efficient desalination technologies	Improving irrigation efficiency	Switching to More Efficient Fuel	All Scenarios Combined
Total water demand	40%	0%	18%	0%	56%
Total energy demand	40%	7%	18%	0%	55%
Desalinated water	45%	0%	0%	0%	46%
Implementation costs	45%	6%	0%	0%	56%
Energy consumption for desalination	45%	19%	0%	0%	46%
GHG emissions from desalination	45%	6%	0%	1%	46%
Brine discharge	45%	0%	0%	0%	46%

3.3. A Proposed Way Forward for WEF Nexus in Kuwait: Adaptation Strategies and Technologies

The WEF nexus in Kuwait highlights the importance of balancing the needs of different sectors and ensuring sustainable resource management practices. Addressing the challenges faced by the WEF nexus is crucial for ensuring the long-term sustainability of Kuwait's resources and for meeting the needs of its growing population. The country has the potential to become a leading example in sustainable resource management, but more efforts are needed to address the challenges faced in the WEF nexus and to ensure long term sustainability.

Since the per capita municipal water consumption in Kuwait is an important influencer on the WEF nexus, particularly in terms of water and energy consumption, it is important to focus on demand management as more effective approach than on supply management and efficiency approaches. In other words, it would be important to look at policies that reduce per capita water consumption in the municipal sector prior to the expansion in desalination plants. To implement demand management strategies in the municipal water sector, there are basically three policy instruments that can be used: 1) structural & operational (e.g., metering, retrofitting water saving devices, flow control, recycling); 2) socio-political (e.g., education and awareness, building codes, appliances labelling); and 3) economic (incentives and disincentives). Experience has shown that combining these policy instruments to achieve the desired consumption changes is considered to be more effective and can complement and reinforce each other. In the case of Kuwait, probably restructuring the current water tariff system, which is currently a flat rate tariff that does not encourage conservation, installing water saving devices, enacting water conservation building codes, and education campaigns are the policy instruments that would be effective in influencing per capita water consumption in the municipal sector.

It is important to revise Kuwait policies related to desalination technologies presently in use. Currently, Kuwait relies on thermal desalination technology and it is highly recommended that a shift towards membrane technology (*i.e.*, RO) is made. This will provide the advantage of less emissions compared to thermal technologies and the ability to use any source of energy such as renewable and nuclear energies.

With regard to the agriculture sector, it is recommended that the government adopts policies to encourage farmers to use modern irrigation technologies, which would lead to greater efficiency in water use. Because the agriculture sector is highly subsidized by the government, the government can enhance the irrigation efficiency by linking subsidies with implementation of water saving irrigation and agricultural systems.

Moreover, it is highly recommended that the current institutional structure in Kuwait is revised to allow for WEF coordination and collaborative planning. A WEF governance structure will need to exist in order to facilitate the interaction between the three sectors and their collaborative planning. This structure need not be a new physical structure, *i.e.*, establishing new institutes, but could be a soft structure, such as a committee that coordinates and allows collaborative planning and management of the three sectors.

4. Conclusions and Recommendations

This paper presents a framework for analyzing the interconnections between water, energy, and food in the context of climate change and socio-economic development in the State of Kuwait as a representative case for the GCC countries. Solving the challenges of the WEF nexus requires a multi-disciplinary approach that encompasses scenarios development and analysis to address climate change, supply-demand conflicts, and water scarcity. Technical advancements are crucial for power generation and water usage, especially in areas of water scarcity. Implementing water-saving and recycling technology, as well as striving for zero wastewater discharge, can reduce the competition between food and energy for water. Increasing water, energy and food security and reducing environmental impact requires not only improving water efficiency but also transitioning away from fossil fuels towards clean, safe, and efficient energy generation.

Although uncertainties are inherent in the data used for the quantitative WEF nexus assessment for Kuwait, the proposed policy options remain valid. However, high-quality and more accurate quantitative study on WEF nexus scenarios development and analysis in changing climate and socio-economic development is still needed in the future. Furthermore, future research should also consider the consumer side by analyzing population growth and economic development's impact on WEF demand.

Moreover, one of the main limitations that affected this research is the knowledge gap of the inter-sectoral use intensities between water, energy and food under Kuwait conditions. It is recommended that more research work is conducted on the WEF intensities under Kuwait circumstances and other GCC countries. Additionally, it is important to establish a dedicated database platform for the three sectors to facilitate future WEF Nexus research, and to use this study as a baseline for future studies and comparisons.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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