Provision of Sustainable Electricity & Water in the State of Kuwait

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Doctor of Philosophy

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DECLARATION

Part A: General Declaration

I, Abdulaziz Ahmad Al-Shalabi, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

☒ This thesis is a presentation of original work.

☒ This work has not previously been presented for a degree or other qualification at this University or elsewhere.

☒ All input or assistance in the creation of the academic work other than from the supervisory team (including AI) has been acknowledged in Part B below.

☒ Any text or data in the thesis that has been presented for publication (including in review) elsewhere is declared in Part B below.

Part B: Declaration of contribution from other sources

Data sources not collected by myself: n/a

Software code, instrumentation development, etc: n/a

AI: n/a

Other: n/a

Publications: n/a

[redacted]

Abdulaziz Ahmad Al-Shalabi

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ABSTRACT

Water scarcity represents a fundamental challenge to economic and social development. For coastal energy-rich countries experiencing extreme freshwater scarcity, seawater desalination technology offers an opportunity to overcome the natural freshwater constraints and meet national development aspirations. Large-scale desalination processes are either integrated with electricity generation processes or grid-connected, thus, making potable water inseparably linked to electricity.

In the oil-rich Kuwait, this electricity-water linkage raises concerns about the country's Electricity-Water System (EWS) sustainability. The use of indigenous oil and gas reserves to produce potable water, while regarded as a foregone profit opportunity in the global markets, also results in the cost of potable water becoming sensitive to the variable price of fossil fuels. Furthermore, electricity generation and water production processes are coupled, however demand for these services is not.

This research developed an extension of the TIMES (The Integrated MARKAL-EFOM System) model incorporating residential electricity and water end-uses. By incorporating end-uses, the dynamic relationship between supply and demand is enabled. The model is solved in a series of scenarios to allow estimation of the effects on Kuwait's EWS as a result of: 1) demand growth under different economic conditions; 2) influence of demand conservation measures and efficiency improvement within the residential sector; 3) decarbonisation of energy mix.

The research concludes that residential consumers dominate the electricity and water demand in Kuwait. A significant portion of the future demand comes from a demography subject to growth uncertainty. Therefore, planning Kuwait's EWS is subject to substantial influences that can lessen the planning precision. Electricity and water efficiency measures provide energy savings and improve overall system sustainability. Additionally, combining efficiency measures with current seasonal consumption patterns facilitates the penetration of renewable energy resources. Finally, a cost-effective pathway towards decarbonising Kuwait’s energy mix is viable, thus reducing potable water’s sensitivity to fossil fuels’ availability and prices.

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To my parents, Dheya and Ahmad, and my daughter, little Dheya, for their unconditional love and support.

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Impact Statement

This research methodology, the results presented, and the model extension developed have beneficial impacts both inside and outside academia. This thesis addresses a gap in energy system optimisation modelling by developing a supply-demand model focused on the electricity-water interactions in countries relying on seawater desalination technologies for their potable water needs. The novelty of this research lies in incorporating residential water end-use and efficiency technologies into TIMES (The Integrated MARKAL-EFOM System) model.

The developed model, KEWSM, is particularly applicable to other countries in the region, such as Saudi Arabia, Qatar, and the UAE (Dubai, Abu Dhabi…), since all these countries share similar electricity-water systems structure, buildings typology, demand patterns, and demographic profiles.

Furthermore, this research provides a wealth of information for researchers interested in Kuwait's electricity-water system and other fields. The information ranges from an inventory of existing stock to projections of: primary energy supplies, energy conversion technologies, conversion products and by-products, residential consumers, and electricity and water end-use. A method for projecting Kuwait's housing demand under different socioeconomic assumptions was also developed.

Outside academia, this research provides policymakers and system planners with valuable insights into electricity and water interactions. Moreover, it provides them with a tool for analysing system pathways under uncertainty, insights into the potential of efficiency improvement measures, and insights for robust decarbonisation pathways while maintaining the integrity of the potable water supply.

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ABBREVIATIONS

Bbl	Barrel of Crude Oil
CCGT	Combined Cycle Gas Turbine
EWS	Electricity and Water System
FAO	Food and Agriculture Organization of the United Nations
GCC	Gulf Cooperation Council
GH	Government House
GO	Government Owner-built House
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt-Hour
HFO	Heavy fuel oil
IA	Investment Apartment
IEA	International Energy Agency
KEPA	Kuwait Environment Public Authority
KEWSM	Kuwait Electricity-Water System Model
KISR	Kuwait Institute for Scientific Research
kW	Kilowatt
kWh	Kilowatt-hour
LNG	Liquified natural gas
M	Mega or Million
m	Metres
MED	Multi-Effect Distillation

MEW	Ministry of Electricity and Water
MSF	Multi-Stage Flash Desalination
Mtoe	Mega tonnes of oil equivalent
MW	Megawatt
MWh	Megawatt-hour
NGA	Natural Gas
OPEC	Organization of the Petroleum Exporting Countries
PAHW	Public Authority for Housing Welfare
PH	Private House
PJ	Petajoules
RHSPP	Reheat Steam Power Plant
RO	Reverse Osmosis Desalination
SPP	Steam Power Plant
Toe	Tonne of oil equivalent
TWh	Terawatt-hour
UN	United Nations
UNEP	United Nations Environment Programme
VES	Virtual Energy Storage
WB	World Bank

Chapter 1

INTRODUCTION

1.1 Background and context of study

1.1.1 Economy and demographics of Kuwait

Kuwait is a Middle Eastern Arab state located at the north-western edge of the Arabian/Persian Gulf (Figure 1-1). It is bounded by Iraq to the north and northwest, the Gulf and Iran to the east, and Saudi Arabia to the south and southwest. Kuwait has a total land area of 17,818 square kilometres including nine small islands of which only one is inhabited. The distance from the furthest eastern and western points is approximately 170 kilometres and between the northern and southern points is approximately 200 kilometres (Central Statistical Bureau, 2019).

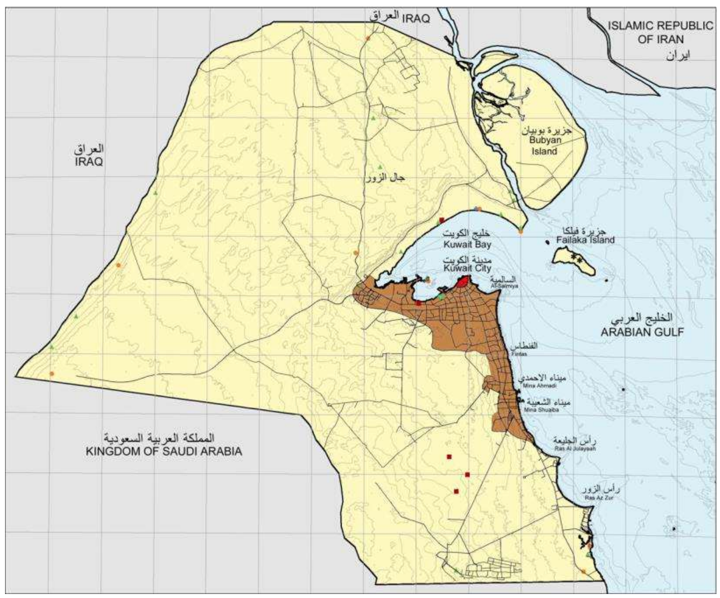

Figure 1-1 Map of Kuwait ***Source: Kuwait Municipality (2005)***

Since the nationalisation of oil assets in the early 1970s, the government has assumed the role of economic growth architect through its involvement in the public and private sectors. Indigenous oil and gas resources are exploited through the state-owned Kuwait Petroleum Corporation (KPC), which manages all upstream and downstream operations with its subsidiaries. Today, Kuwait's economy is heavily dependent on the oil industry. The State's economy is viewed as a single-sector, oil-based, narrow productive capacity economy (Eltony, 2002). Petroleum earnings account for more than half of the GDP. Nearly 94% of national exports are petroleum products, and 95% of government revenue is from petroleum sales (World Bank, 2018). Furthermore, the government employs 92% of Kuwaiti citizens in the public sector (ILO, 2018). The government spending also plays a vital role in the private sector, where it acts as a corporate partner with local businesses in profit-making activities.

Thanks to its oil endowments, Kuwait underwent rapid socioeconomic growth over the past seven decades, placing it among the fastest-growing economies in the world (EIU, 2009). The development activities associated with this economic growth and attempts into diversifying the national income resulted in an influx of migrant workers and a rapid population growth (Figure 1-2). The total population grew from 206,500 inhabitants in 1957 to nearly 5 million inhabitants in 2019, with an average annual growth rate during the 2009 – 2019 period of 4.18% (Hill, 1969, PACI, 2019, World Bank, 2020a). Today, migrant workers constitute 69.9% of the total population (PACI, 2019).

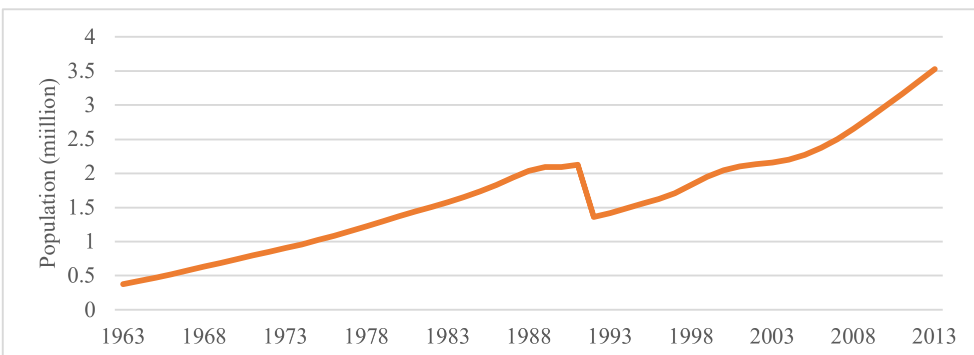

Figure 1-2 Historical population growth in Kuwait *Source:* Adapted from PACI (2019)

1.1.2 Freshwater availability

In stark contrast to the energy abundance, freshwater is extremely scarce. Kuwait is mostly a dry desert with an arid climate. It is one of the most arid regions in the world with marginal renewable freshwater resources and limited brackish groundwater resources (FAO, 2020).

The United Nations (UN) classifies countries to be undergoing absolute water scarcity when "they have less than 500 m^3 of renewable water resources available per capita per year" (UN-Water, 2012, UNESCO, 2012). Kuwait falls far below the absolute water scarcity line with 4.83 m^3 per inhabitant per year placing it high on the list of the world's most water-scarce countries (Figure 1-3).

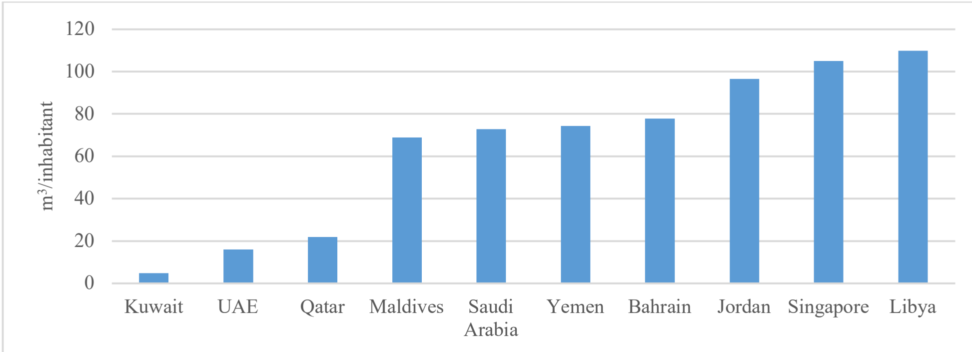

Figure 1-3 Total renewable water resources per capita ***Source:*** **Adapted from FAO (2020)**

1.1.2.1 Groundwater

Brackish groundwater exists in two aquifers with declining production (Figure 1-4). It is consumed by the agricultural sector, oil sector, construction projects, for mixing with distilled water from desalination plants to produce potable water, and for domestic uses in watering house lawns. In the year 2018, withdrawal of brackish groundwater totalled 69 million m^3, of which 5 million m^3 was used in the desalination plants for potable water production (MEW, 2019). The aquifers are naturally recharged with flows of 20 million m^3 annually from outside Kuwait's political boundaries (FAO, 2020, UN-ESCWA, 2007). Groundwater flows from shared aquifer in Saudi Arabia to the southwest of Kuwait and discharges to the northeast in Iraq and the Gulf (Al-Otaibi, 1997).

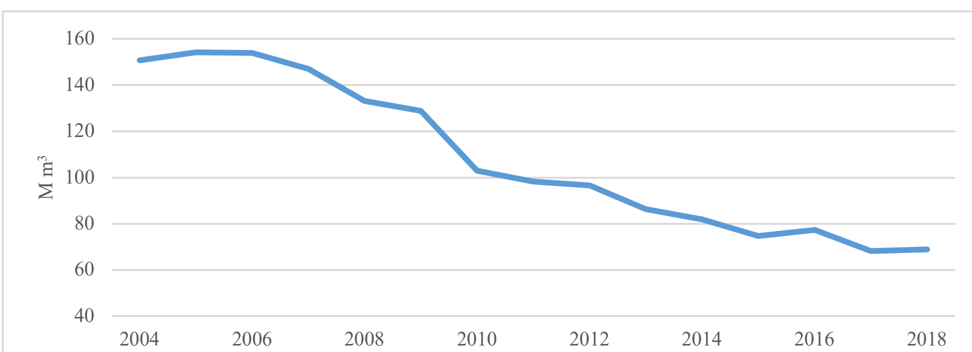

Figure 1-4 Brackish water production ***Source:*** **Adapted from MEW (2019)**

According to the United Nations Environment Programme (UNEP) report on the implications of shared water resources in the West Asia region (2012), the shared groundwater aquifers between Kuwait, Saudi Arabia, and Bahrain present high level potential for conflict between these Gulf States which are all undergoing absolute water scarcity. Such a conclusion is indeed likely given Kuwait's experience with its neighbours over shared natural resources such as oil and gas.

For instance, in the east of Kuwait, the Dorra offshore gas field is shared between Kuwait, Saudi Arabia, and Iran and has been experiencing dispute since 1963 leaving it undeveloped for production to date (Snellgrove, 1963, Upstream, 2008, Reuters, 2013). Similarly, in the north of Kuwait, production from the shared oil fields with Iraq remain at a halt even after 30 years following the Gulf War (KUNA, 2018). Finally, in the south of Kuwait, production from the onshore and offshore oil and gas fields shared between Kuwait and Saudi Arabia remain at a standstill since 2014 when Saudi Arabia ceased the 47-year-old operations (Mills, 2020). These examples highlight the geopolitical climate in the region and the potential obstacles should the country choose to rely on or further utilise its groundwater resource. Just as with oil and gas, water is a high-charged political resource.

1.1.2.2 Importing potable water

Potable water has always been scarce in Kuwait even before witnessing growth associated with the oil boom. Prior to oil discovery, the population relied entirely on brackish water occurring in shallow wells in the eastern region. Though the water of these wells was salty, the population had adapted to the flavour of their only water source (MGI, 1964).

Increasing demand in the 1920s led to the import of freshwater from Lower Tigris-Euphrates (also known as Shatt al Arab) using dhows which became the main source of freshwater for decades to come (Hill, 1969). Dhows (Figure 1-5) were fitted with tanks to carry between 30 m^3 to 45 m^3 of freshwater from Basra in Iraq to Kuwait's capital (Al-Marzook, 2006). The 200 nautical miles round trip took between 1 to 4 days depending on wind conditions. At the peak of their service in 1947, dhows were delivering nearly 320 m^3 of freshwater per day (MGI, 1964).

Figure 1-5 Dhows at Kuwaiti seaport pumping freshwater into goat-skin bags transported via donkey carriers & tanks carried over men's shoulders. *Source:* Villiers (2006)

During that period, Kuwait exported its first oil shipment and preparations for drilling in one of the world's largest oilfields "Burgan" had begun (Chisholm, 1975). New townships were being established and workers started migrating to the country to support oil operations (Hewins, 1963). The need for a reliable flow of freshwater was evident and so began the search for alternative sources of water.

In search for reliable flow of freshwater, the government of Kuwait actively engaged in negotiations with Iraq to construct a water canal from Basra that would supply freshwater from Shatt al Arab[1] to Kuwait. The canal, later refined to a pipeline (Figure 1-6), was envisaged to supply nearly 400,000 m^3 of freshwater per day for domestic and agricultural use (Gibb, 1954). The negotiations were aborted in the late 1950s, revived again in the 60s and 70s but never materialised due to political reasons (Tyler, 1963, Wilton, 1973).

[1] Over the past three decades, Shatt al Arab had experienced mismanagement and neglect leading to its pollution with filth, bacteria, algae, and plastics. The city of Basra is undergoing water crisis and some violent unrest due to its water situation (Ali, 2019).

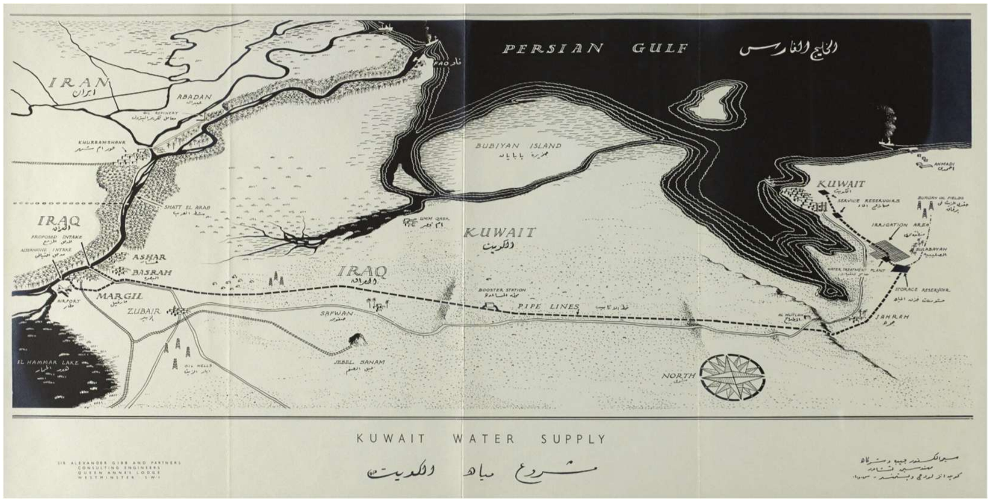

Figure 1-6 Proposed water channel between Basra and Kuwait.*Source:* Gibb (1954)

Political reasons and security concerns have hindered several other opportunities for Kuwait to import freshwater (Nazerali, 2007). In the late 1980s and early 90s, Turkey proposed a Peace Pipeline that would carry freshwater to Kuwait and other Gulf States. The pipeline would deliver to Kuwait 600,000 m^3/day of freshwater (Luelmo, 1996). Most recently, in 2001 Kuwait entered negotiations with Iran to construct 540 km long pipeline that would supply Kuwait with 200,000 m^3/day of freshwater (BBC, 2001). This project did receive technical approval from the Kuwaiti side (Independent, 2011), however due to geopolitical considerations the project is unlikely to materialise (Amery, 2012).

1.1.2.3 Seawater desalination

In 1951, the world's first large-scale seawater desalination plant was commissioned in Kuwait producing nearly 2,700 m^3/day of distilled water from the sea (MEW, 2014, MGI, 1964). Recognising the risks that water scarcity poses to the country's sustainability and development, Kuwait invested heavily on expanding seawater desalination capacities (Hewins, 1963, NCBC, 2009, Lahn et al., 2013). Seventy years after commissioning the first large-scale desalination plant, Kuwait continues to rely solely on desalination technologies producing almost 3 million m^3/day of distilled water to meet its entire freshwater needs (Figure 1-7).

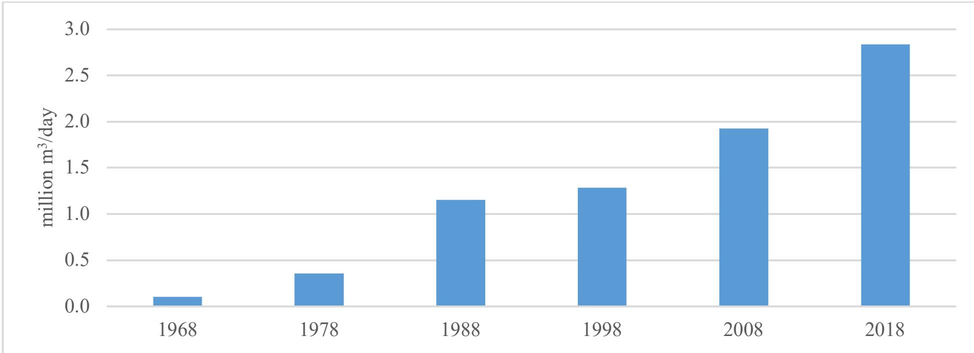

Figure 1-7 Development of desalination capacity.*Source:* Adapted from MEW (2019)

Today, water demand varies slightly between different seasons but not to the same extent as change in electricity demand and therefore it is represented by quarters (Figure 1-8). Effects of hourly fluctuation in demand do not influence production due to the use of water storage. The total water storage capacity in Kuwait amounts to 19.7 M m^3 which would last for about 10 days of supply in case of complete disruption in desalination capability.

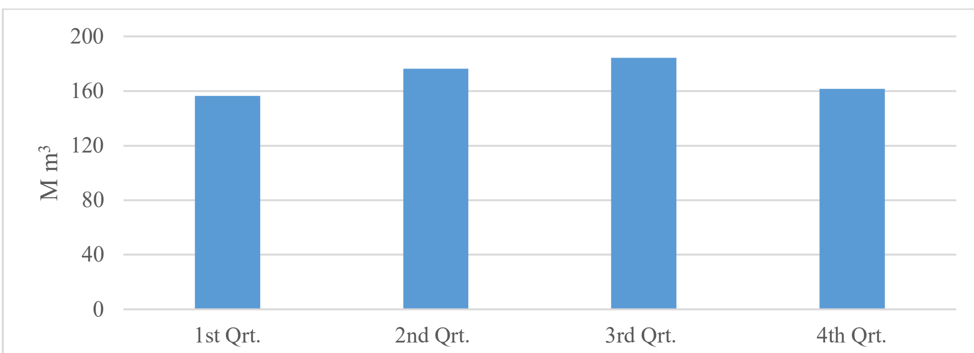

Figure 1-8 Quarterly water consumption in year 2018. *Source:* Adapted from MEW (2019)

Ensuring adequate and dependable freshwater availability continues to be a challenge that goes beyond the essential social, economic and environmental development objectives of Kuwait. Given its geographical location, freshwater availability and stability of the supply becomes part of the geopolitics and the country self-autonomy concerns. Despite the numerous failed attempts to secure a reliable freshwater flow, Kuwait met its freshwater needs by utilising seawater desalination technologies. Seawater desalination is the process of removing dissolved salts from seawater and thus producing freshwater. Seawater desalination has proven its reliability and ability to meet the ever-increasing freshwater demand over the decades. Given the experience of securing freshwater from neighbouring countries, lack of natural freshwater resources, and limited rainfall to harvest, it is envisaged that seawater desalination will continue to play a vital role in meeting potable water demand in Kuwait for many years to come.

1.1.3 Topography and climate

Kuwait's mainland is a flat desert with gradual sloping from the coastline east towards the highest point west at 300 metres above sea level. The mainland's coastline is 290 kilometres long, consisting primarily of sandy beaches with 70 kilometres long mudflats. Nearly two-thirds of the shoreline is occupied by facilities ranging from seaports, power plants, business, and private properties (Central Statistical Bureau, 2019). This highlights the land constraints that could play a role in the expansion and selection of seawater desalination technologies.

Kuwait has a subtropical desert climate that is hot, dry, and mostly sunny throughout the year. Winter temperature averages between 8.7℃ and 21.1℃ and on cold winter nights can reach -4℃ (Central Statistical Bureau, 2019).

Summer months are long, hot and dry, running from the end of March till the end of October. Temperatures vary significantly between night-time and daytime ranging from 32℃ to 51℃ during the days' peak with daily mean maximum temperatures ranging between 44.8℃ and 47.4℃ (Central Statistical Bureau, 2019). The highest temperature recorded in Kuwait was 53.9℃ in July 2016.

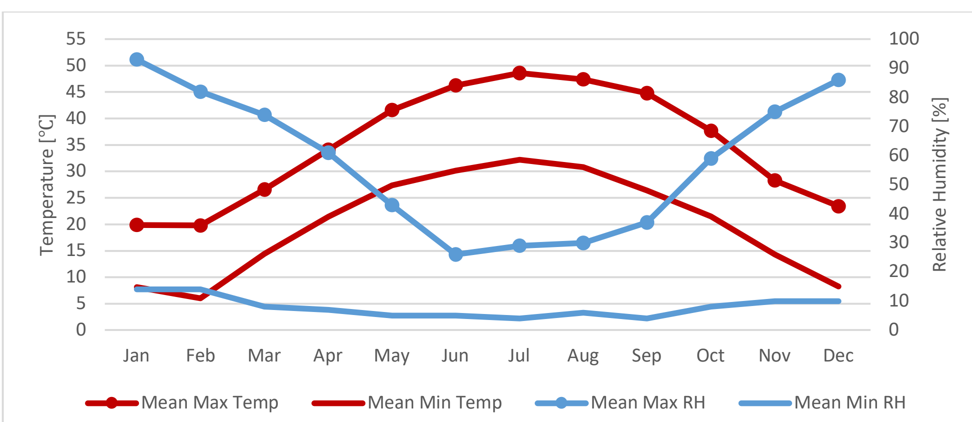

Figure 1-9 Mean maximum & minimum temperatures and relative humidity for the year 2018*Source:* Adapted from Central Statistical Bureau (2019)

As a typical arid region, rainfall is scarce and occurs sporadically between November and April. According to the Meteorological Department (2022), Kuwait receives on average 117.6 mm per year of rainfall. Rainfall totals are highly variable from year to year and can range from 34 mm to 218 mm. The limited rainfall is not sufficient for overland runoffs or ground infiltration due to the nature of Kuwait's topography and high evaporation rates (Fadlelmawla et al., 2005). Rainfall scarcity renders rainfall harvesting impractical and not viable for substantial water collection. Furthermore, drier winters typically result in dustier days the following year.

Dusty days are frequent (Figure 1-10) with an annual average number of 225.4 days a year (Al-Dousari, 2012). During June and July, approximately 87% of the days are dusty. Hot and dry wind of 9.25 m/s or more can carry sand particles in the air causing dust storms and limiting visibility to less than 200 metres (Mohammad, 1989).

Dust storms are one of the key features of summer months in Kuwait. North-western winds reaching the speed of 19 m/s carry particles of average size 2 mm in diameter causing severe dust storms (Kuwait Municipality, 2005). Severe dust storms often limit visibility, interrupt the transport system, and have numerous effects on the metropolitan area and its residents. One main effect of interest for this study is the water use following dust storms for cleaning houses and private vehicles.

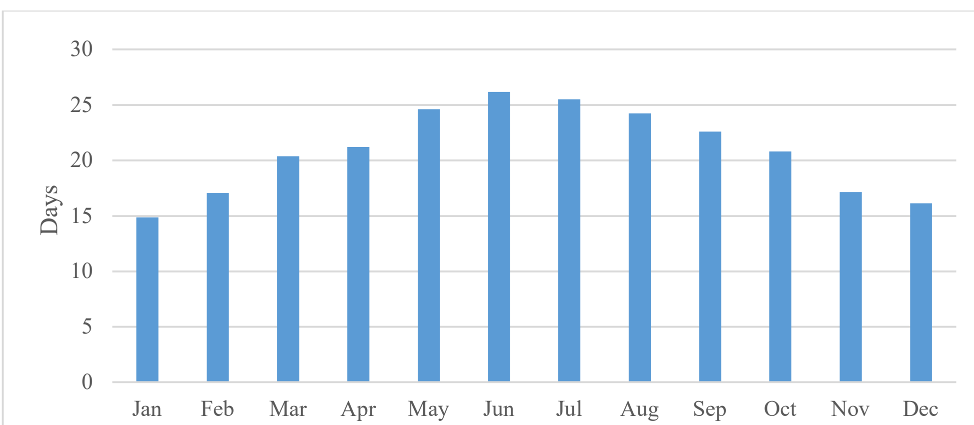

Figure 1-10 Average number of dusty days in Kuwait (period from 1962 to 1986).*Source:* Adapted from Mohammad (1989)

Recent record summer temperature peaks were associated with record electricity demand, due to the wide spread use of air conditioning. The dry desert climate where ambient temperature averages around 48°C and peaks during summer months at around 53°C (DGCA, 2010) have led to extensive use of air conditioning to overcome indoor thermal discomfort.

Demand patterns for electricity in Kuwait have shown to be sensitive to seasonal changes in temperatures and vary significantly over the year. According to Alsayegh et al. (2007), air conditioning accounts for 70% of the annual peak load and over 45% of the total annual electric power consumption. Peak loads occur during summer months when solar intensity on horizontal surfaces is at its greatest, and demand during these months vary significantly between day and night (Al-ajmi et al., 2008). Consequently, peak loads occur between June and September and particularly between 12:30hr and 16:30hr of the day where solar intensities on horizontal surfaces peak (Figure 1-11).

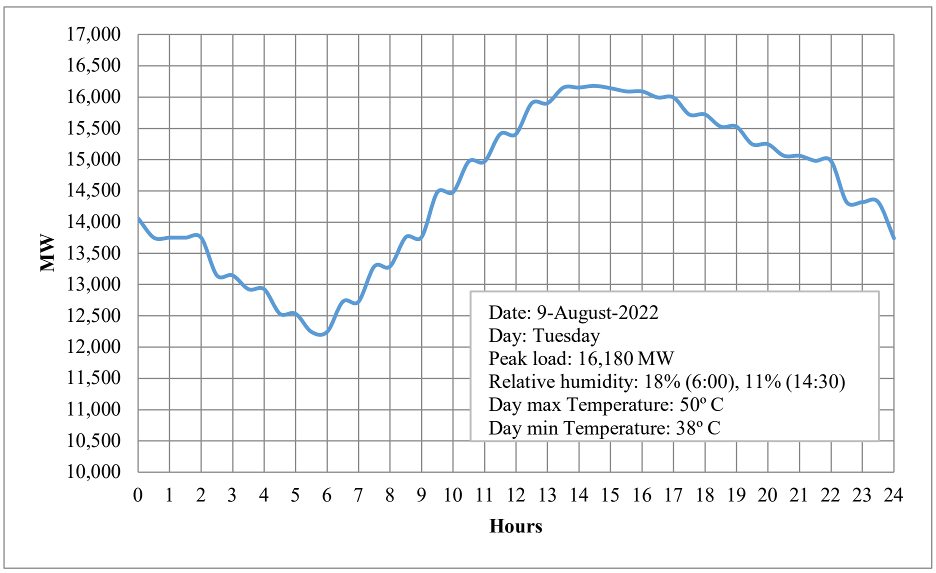

Figure 1-11 Electric power peak load behaviour for sample day from year 2022. *Source:* Adapted from MEW (2023)

Figure 1-12 illustrates the maximum and minimum power demand over year 2022 where demand curves follow the same pattern of the temperature. The figure also shows how available electric power capacity varies during the year. Largest share of electric power generation comes from oil-fired steam power plants while about 32% of total capacity is from gas-fired turbines. Some of these turbines are taken out of service during the months where demand for electricity is low.

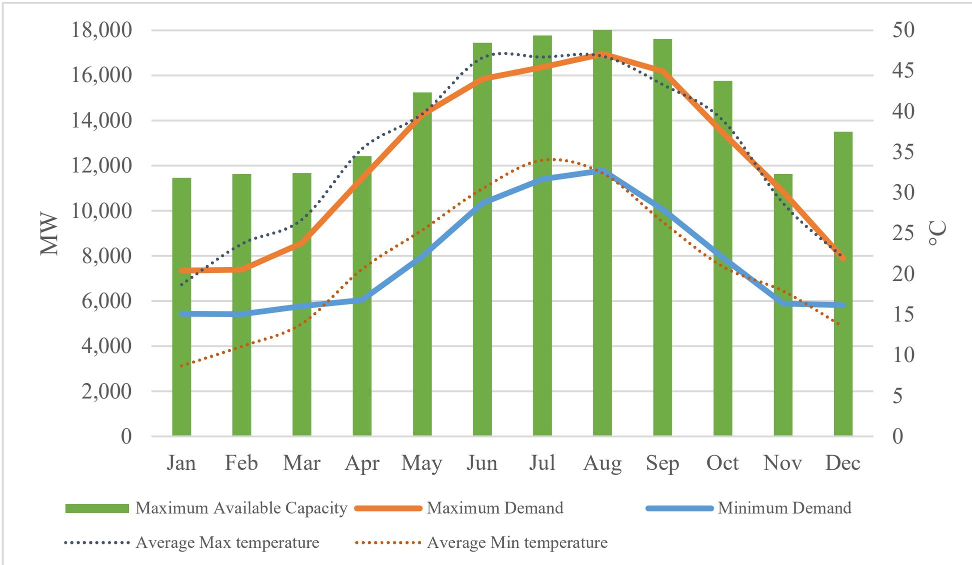

Figure 1-12 Electric power loads and available capacities for year 2022. *Source:* Adapted from MEW (2023)

1.2 Electricity and water demand

In the year 2023, the total water consumption across the country was 788 M m^3, while the overall electricity consumption reached 79.2 TWh (MEW, 2024). Figure 1-13 illustrates electricity consumption per segment of the economy. The increase in demand is being met by expanding current production capacities using conventional technologies. The MEW approach has always been increasing supplies as a response to potential crisis rather than managing the demand (Fadlelmawla, 2008).

Electricity demand is steadily increasing and so is the consumption per capita (Figure 1-14). However, this is not the case for water demand. While water demand continues to increase, the consumption per capita has reached a saturation level (Figure 1-15). This implies that any increase in water demand is coming from new customers. Even though electricity and water production are coupled, demand is not and electricity demand is rising faster than water demand.

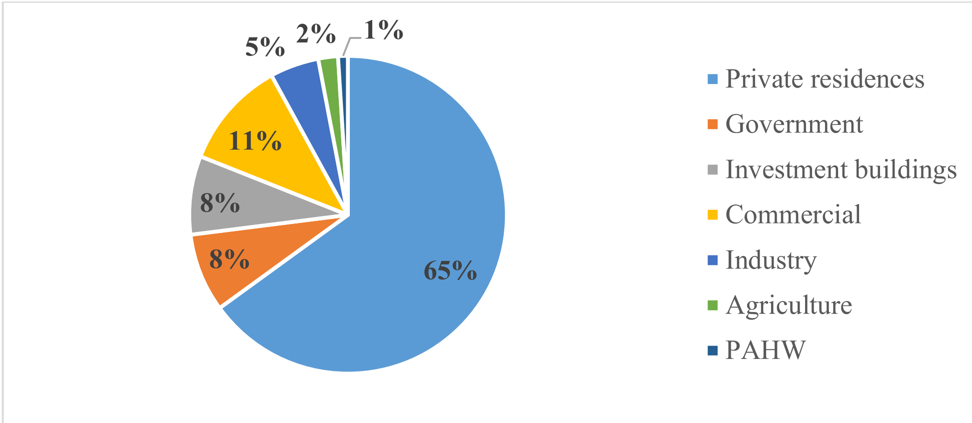

Figure 1-13 Electricity consumption per sector. ***Source:*** **Adapted from MEW (2019)**

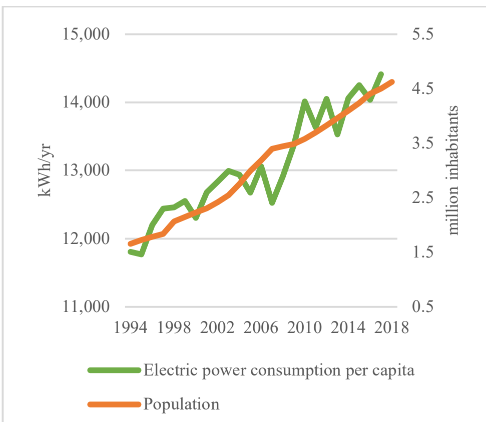

Figure 1-14 Electric power consumption per capita. ***Source:*** **Adapted from MEW (2019) and PACI (2018)**

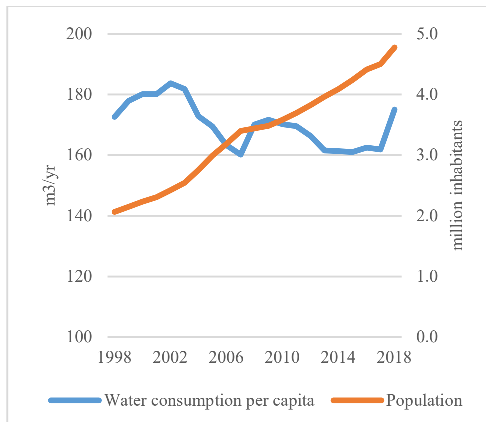

Figure 1-15 Water consumption per capita. ***Source:*** **Adapted from MEW (2019) and PACI (2018)**

The residential sector is the main driver behind Kuwait's electricity and water demand. It accounts for 60% of the total electricity and 87% of the total water demand (MEW, 2019). The basic needs for freshwater and indoor thermal comfort are the main drivers of the residential demand. Therefore, this sector will be the focus of this research. Kuwait's residential sector can be divided into three main categories:

Government housing: A government-run welfare scheme implemented by the Public Authority for Housing Welfare (PAHW). The welfare scheme began in 1956 to develop suburban areas soon after the exploitation of indigenous oil reserves. Since its launch, the scheme distributed 158,107 dwellings (PAHW, 2021). Today, this scheme serves as the main housing provider for Kuwaiti families providing three housing welfare options (Alshalfan, 2013).

The first option is a government house designed and built by the PAHW on a 400 m^2 plot of land. The second option is a 400 m^2 plot of land provided by the PAHW with an interest-free long-term construction loan provided by the government through the Credit Bank equivalent to $231,000 USD. The loan is issued once land become available. Finally, the third option is an instant $231,000 USD interest-free long-term construction loan to build or buy a house subject to proof of private land ownership. The PAHW develops the residential areas in which welfare houses are distributed. The PAHW is struggling to meet housing demand, with over 112,000 requests on its waiting list. It is anticipated that 70,000 units will be distributed over the next five years (PAHW, 2021).

Private housing: According to Kuwait Municipality (2016) building code, private residences refer to single-family dwellings in low-density areas. By law, only Kuwaitis are permitted to own private houses. Letting is permitted, however, conversion of the houses into apartments is not permitted. Nevertheless, in order to compensate for the delay in government housing distribution, private houses are often built with two apartments on the top floor to house homeowner adult children (and their families) until government housing becomes available (Al-Ghannam et al., 2012). Growth in the private houses stock is limited due to land availability and the citizens' view that the fulfilment of their housing needs is a responsibility of the government (Alshalfan, 2013).

Investment housing: As defined by Kuwait Municipality (2016), investment housing refers to multi-dwelling buildings purpose-built for renting. This housing category predominantly serves the migrant workers population, representing approximately 70% of total population (PACI, 2019). Property ownership for non-citizens is prohibited (Ministry of Justice, 1979), and investment housing is only allowed in areas categorised by Kuwait Municipality (2016). Given the limited housing options for migrant workers, the population consequently concentrated in areas within the governorates that allowed investment housing.

One of the main challenges of studying the residential sector is information and data availability. Little data is available regarding Kuwait's housing stock characteristics. The available information is limited to stock count and type of dwellings. The absence of official development plans and strategies amplifies the lack of clarity surrounding the housing sector. Furthermore, information regarding Kuwait's electricity and water end-use in the residential sector is very limited. Stock estimations of electricity and water-related equipment across the residential sector in Kuwait are non-existent. All of which are essential for building an energy system model.

In summary, Kuwait relies entirely on seawater desalination to meet its development aspirations and population's potable water requirements. Potable water availability is tied to energy resource availability and coupled with electric power generation. While electric power generation and seawater desalination processes are coupled, the demand for electricity and water is not.

The largest consumer of electricity and water is the residential sector, with the main driver of the demand being indoor thermal comfort and basic freshwater needs. The growth of the residential sector itself is tied to the rate at which the PAHW deliver new housing stock and socioeconomic conditions influencing the investment apartments renters' demography.

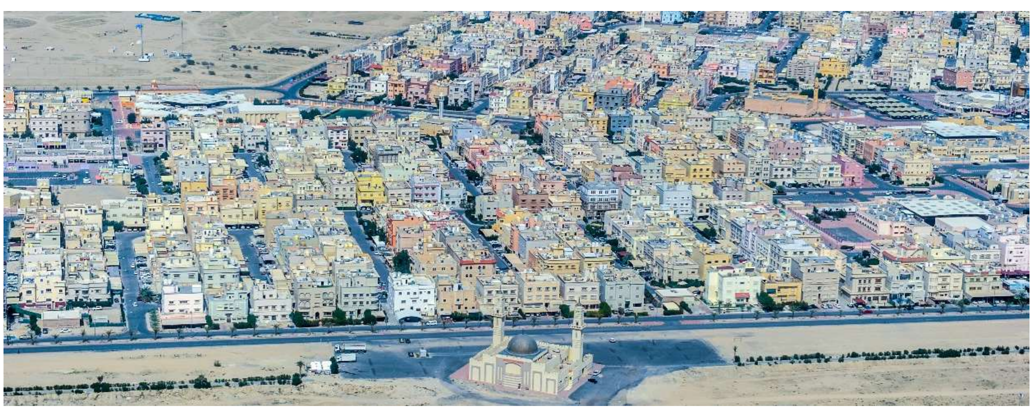

Figure 1-16 View of a typical residential block featuring common types of houses. ***Source:Abdulkhaliq (2017)***

1.3 Electricity and water production interlinkage

Despite the scarcity of natural freshwater, 100% of the population has access to potable water (UN-ESCWA, 2007), primarily from desalination. Kuwait currently has a total installed desalination capacity of 3.1 M m^3/day (Figure 1-17). There are two major groups of seawater desalination technologies. The first one is thermal desalination such as the Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED), and the second one is membrane desalination such as Reverse Osmosis (RO). Approximately 67% of Kuwait's desalination capacity consists of Multi-Stage Flash Distillation (MSF) technology, followed by Reverse Osmosis (RO) at 18%, and finally Multi-Effect Distillation (MED) at 16%. All desalination plants are coupled with electric power generation plants with a total capacity of 20.3 GW (MEW, 2024) The electric power generation mix consists of steam turbines that make 48% of the mix; open-cycle gas turbines making 40% of the generation mix; and the remainder 12% is combined-cycle gas turbines (Figure 1-18). According to the Ministry of Electricity and Water planned projects, the desalination capacity will be increased to 3.8 M m^3/day by the year 2029. The electric power generation capacities are planned to expand to 32.8 GW by 2029 (MEW, 2024).

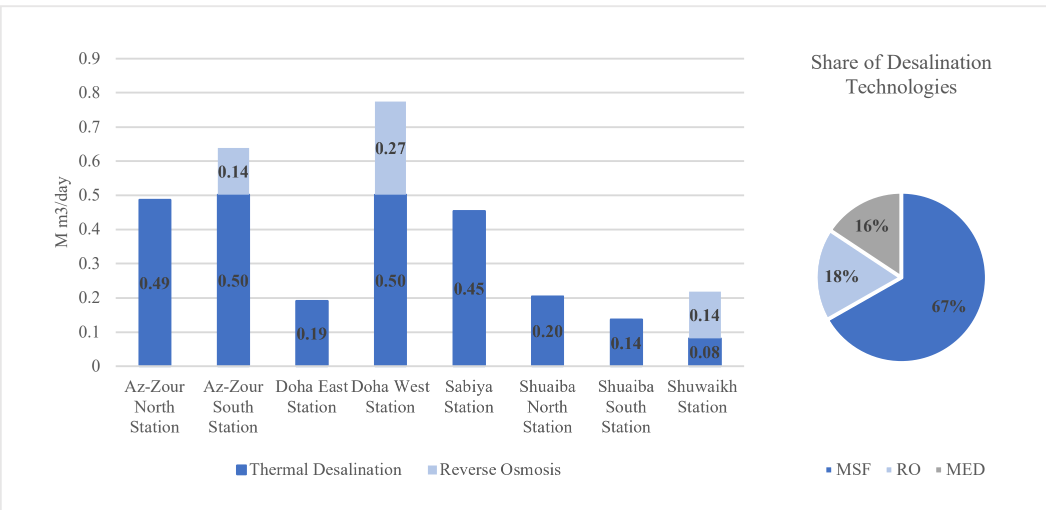

Figure 1-17 Share of desalination technologies and their production capacities.*Source:* Adapted from MEW (2024).

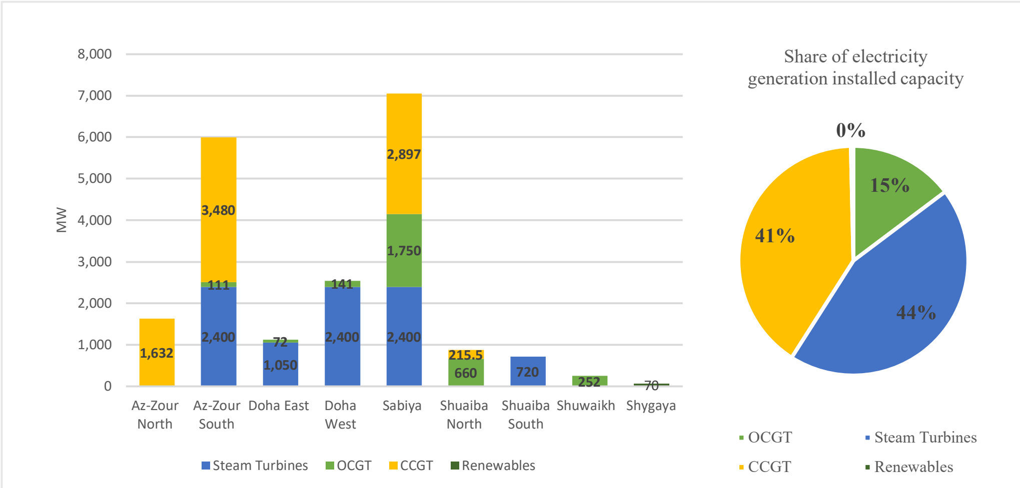

Figure 1-18 Share of electric power generation technologies and their production capacities.Source: Adapted from MEW (2024)

Seawater desalination in Kuwait is a fossil fuel-based electricity-dependent process. According to MEW (2019), the year 2018 fuel mix consisted of 81% heavy oil, followed by 11.8% crude oil, 6.8% gas oil, and the remainder was natural gas (Figure 1-19).

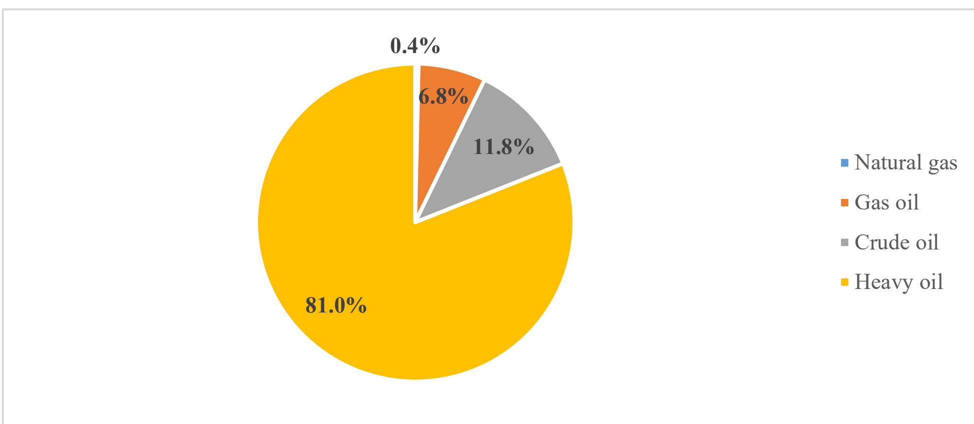

Figure 1-19 Share of fuel utilisation by electric power generation and seawater desalination plants.*Source:* Adapted from MEW (2019)

The cost of freshwater and electricity has increased substantially and is now considered uneconomic (IMF, 2013). The ministry of electricity reported that the cost of cogeneration in 2019 was in excess of 6 Bn US$ (Alqassas, 2021). Seawater desalination and electricity economics are tied directly to the cost of energy. For desalination in Kuwait, the cost of fuel account for 65% of the total cost for producing one cubic metre of freshwater (Al-Hajri et al., 1994). This makes seawater desalination sensitive to the variable cost of oil and gas in the global markets. Kuwait Institute for Scientific Research (KISR) estimated in a (2011) report that by the year 2050 the majority of Kuwait's oil revenue will be required to maintain adequate supply of freshwater. Furthermore, the locally produced oil and gas used to produce freshwater is regarded as a foregone profit opportunity in the global markets. This is a critical point particularly given the fact that Kuwait's economy is reliant on oil-income (Darwish et al., 2008, Lahn et al., 2013).

Indeed, freshwater is inseparably linked to electricity generation; both of which completely reliant on oil availability. Whether oil is used as fuel for water production processes or through the utilisation of its revenue, seawater desalination economics are tied directly to the cost of energy. Consequently, freshwater in Kuwait has become wholly dependent on energy. Without adequate energy mix, oil could continue playing important role in freshwater production long into the future. The sustainability challenge is to provide sufficient freshwater without crippling national exports of hydrocarbons that represent the majority of the government's revenue.

Below is a brief description of the different desalination technologies utilised in Kuwait:

1.3.1 Multi-Stage Flash Distillation

Multi-Stage Flash Distillation (MSF) is a thermal desalination process where distilled water is co-produced with electricity in an oil-fired power plant. The desalination process takes advantage of heat emitted from the electric power generation process. Seawater is evaporated and subsequently condensed at various stages under different pressures (Gray et al., 2011).

MSF is a proven robust technology under high level of salinity of the Gulf, and it is the prevailing technology in Kuwait with an installed capacity of 2.08 million m^3/day (MEW, 2019). It is favoured for its reliability, performance, and large production capacity (Al-Bahou et al., 2007). A large MSF plant can produce up to 800,000 m^3/day of high-quality water (CEBC, 2014).

The disadvantage of this technology is that it is an energy-intensive process consuming about 38 kWh/m^3 of thermal energy and 3.5 kWh/m^3 of electrical energy (Al-Shaikh, 2014). It lowers the efficiency of the electric power plant it is coupled with, due to high heat requirements for water distillation (Darwish et al., 2007). It is inflexible in terms of operation and cannot operate below 70% of its design capacity, causing an issue with varying seasonal demand resulting in a huge surplus of redundant electricity generation capacity in winter months when demand is low (Al-Hajri et al., 1994, Al-Shaikh, 2014). The salinity level of MSF plants effluent is about 50,000 mg/L at 5 to 15 degrees Celsius above ambient temperature (Lattemann et al., 2008) and a brine concentration between 60 to 70 g/kg (Missimer et al., 2015).

1.3.2 Multi-Effect Distillation

The Multi-Effect Distillation (MED) is a thermal desalination process that involves evaporating seawater in several stages or ‘effects’. As with the MSF, the MED takes advantage of heat emitted from the electric power generation process of the power plant it is coupled with (Gray et al., 2011). Energy-wise it is more efficient than MSF consuming 37 kWh/m^3 of thermal energy and 1.5 kWh/m^3 of electrical energy, though it shares with the MSF the same operation inflexibility and quality of effluents (Al-Shaikh, 2014). However, it cannot be economically built to the same size as MSF (CEBC, 2014). MED came into service in Kuwait in 2017 with an installed capacity of 486,000 m^3/day. The long-term reliability of large-scale production has yet to be verified (MEW, 2019).

1.3.3 Reverse Osmosis

Reverse Osmosis (RO) is a desalination process where water is pushed under pressure through a membrane that filters seawater (Gray et al., 2011). The main advantage of membrane desalination technologies like RO is that it is grid connected and not tied to power generation processes. Additionally, it is more energy-efficient than MSF and MED, consuming about 3.37 kWh/m^3 whether being operated as a stand-alone RO plant or in a Combined Cycle Gas Turbine RO plant (Altaee, 2017).

A shift towards electrification of desalination in the region opens the door to a wider range of energy resources, including renewables, nuclear, and regional electricity interconnections. This transition could reduce reliance on fossil fuels for water production and consequently lowers carbon emissions across the region. Therefore, Deluque Curiel (2021) identified RO as one of the tools that support the diversification of electricity resources and facilitate regional electricity trade.

Although electricity generation in the Gulf remains largely oil and gas based, the adoption of membrane desalination technologies like RO is increasingly seen as an opportunity to align water production with cleaner energy sources and support broader green energy transition goals in desalination-dependent countries (MOEI, 2017, SWA, 2024, Vision 2030, 2025, GCO, 2025).

Despite the various advantages that membrane desalination offers over thermal desalination, the adoption of membrane desalination in the region is not a straightforward technological succession, where RO plants naturally replace thermal ones at the end of their service life due to efficiency gains or emissions targets. In a region where potable water supply depends heavily on the reliability of desalination plants, highly strategic considerations dictate technology choice. The continued reliance on thermal desalination is driven by key factors such as operational reliability, proven dependability, and reduced vulnerability to certain feedwater quality risks. As RO technology is still relatively new in the Gulf, some utilities continue to prefer thermal desalination due to the expertise of local operators and proven reliability experience (Al-Shalabi et al., 2013).

Furthermore, environmental implications of membrane desalination technologies (the discharge of RO effluents) pose a significant concern to the marine ecosystems of the Gulf. This is due to the unique characteristics of the Gulf, which is a shallow, semi-enclosed sea with high salinity, high evaporation rates, limited freshwater input, and weak circulation (Bashitialshaaer et al., 2011, Uddin, 2014, Nesterov, 2025). Consequently, the dense, hypersaline brine does not readily disperse and tends to sink, forming concentrated plumes along the seafloor that negatively impact sensitive benthic communities and can impair the region's overall marine biodiversity (Roberts et al., 2010, Uddin et al., 2011). Brine concentration is higher than thermal plants and ranges between 65 to 85 g/kg (Missimer et al., 2015), while the salinity level of the RO effluents is approximately 70% higher than that of thermal desalination plants (Lattemann et al., 2008).

Additionally, the RO membrane is highly vulnerable to oil and fuel spillages, and its flux could deteriorate to zero in a short period of time (Hodgkiess et al., 2001). This risk is confirmed by major membrane manufacturers, who explicitly indicate that organic fouling from contaminants like oil leads to severe flux decline, increased pressure, and membrane destruction (Dupont, 2024). This is not just a technical vulnerability but a recurring operational threat, as demonstrated by multiple incidents in which oil spills have forced the catastrophic shutdown of desalination plants in the Arabian Gulf to prevent irreversible equipment damage (Paleologos et al., 2018, Liu, 2025). This could represent a high-risk factor for the stability of water production, particularly in conflict regions where aggression is likely.

Finally, the risk of supply-chain disruption or market monopoly over membrane acts as a disincentive towards high reliance on RO technologies (Ronzitti, 2013), which would effectively making national water security and geopolitical stability dependent on the commercial interests of the handful of global membrane suppliers. Despite the aforementioned challenges, Saudi Arabia offers an example of a methodological approach to mitigating the risks associated with RO in order to meet its ambitious goals of Vision 2030.

As part of its objectives to diversify its energy mix and scale up electricity generation from renewable sources for instance, Saudi Arabia is aggressively transitioning its desalination portfolio from thermal technologies to RO (SWA, 2024a). This strategy is being implemented through vertically integrated solutions that directly engage RO's vulnerabilities. It is countering supply-chain vulnerabilities by developing domestic manufacturing capabilities, such as the Toray Membrane Middle East plant in Dammam, one of the world's largest future RO membrane factories (Zawya 2022). Simultaneously, to transform the environmental liability of brine into an economic asset, the Saudi Water Authority (SWA) is engaging in brine mining initiatives. The mining initiative would help extract valuable minerals such as magnesium and sodium chloride from RO effluent, thereby reducing marine impact whilst creating new revenue streams (SWA, 2024b). This proactive strategy of localising supply chains and developing a circular economy for desalination demonstrates a viable pathway to de-risking a large-scale technological shift.

In conclusion, despite the advantages of RO desalination, there are significant disadvantages that consequently affect its utilisation rate in Kuwait. At the moment, there are only three RO plants operating in Kuwait with a total installed capacity of 0.55 million m^3/day representing only 18% of total desalination capacity.

1.4 Kuwait's climate commitments

The 2015 Paris Agreement has reshaped the landscape of global energy and climate policy. This accord led to a worldwide shift towards low-carbon development with energy transition at its core. Within the Gulf region, this momentum is reflected in the adoption of ambitious emissions reduction targets, as evident in the national strategies of neighbouring states, such as Saudi Arabia's 'Vision 2030' and the UAE's 'Energy Strategy 2050'. Joining this regional momentum, Kuwait has more recently signalled its strategic direction through the announcement of its 'National Low-Carbon Strategy 2050' (KUNA, 2022).

The National Low-Carbon Strategy 2050 marks the latest development in Kuwait's commitment to the global climate agenda. Prior steps taken by the country include ratifying the UNFCCC and Kyoto Protocol in 1994 and 2005, and signing the Paris Agreement in 2016 (KEPA, 2019). Building on these steps, Kuwait has advanced its climate ambition through successive pledges. At COP26, Kuwait adopted a Circular Carbon Economy (CCE) approach and updated its Nationally Determined Contribution (NDC), pledging to cap greenhouse gas emissions growth at 7.4% by 2035 compared to a business-as-usual scenario (KUNA, 2021; KEPA, 2021). This trajectory was further reinforced at the World Climate Action Summit during COP29 in Baku, where Kuwait announced a commitment to harmonise economic growth with low-carbon development and climate resilience by 2050, and to achieve economy-wide carbon neutrality by 2060. The commitment also included the goal of promoting clean energy initiatives, deploying new low-carbon technologies, and fostering long-term partnerships for sustainable energy investment (KUNA, 2024). The Baku announcement, which outlines Kuwait's National Low-Carbon Strategy 2050, sets Kuwait's goal of achieving carbon neutrality within the oil and gas sector by 2050 and at the national level by 2060 (Almejren, 2025). Underpinning these climate pledges are equally ambitious renewable energy targets, which have been raised to 30% of generation capacity by 2030 and 50% by 2050 (KISR, 2024; Ghanem, 2025).

However, translating these successive pledges into tangible action presents a significant challenge. This is due to the nature of Kuwait's political economy and its electricity-water system, both of which are fundamentally shaped by hydrocarbon wealth. The result is a reality where high-level national aspirations have yet to be matched by specific, actionable policies required for a genuine energy transition. This issue will be contextualised in Chapter 2 and addressed through the analysis in Chapter 7.

1.5 Research aim, questions, and objectives

Integrating the supply and demand dynamics for both electricity and water in an energy system model presents a multilayered challenge. Both resources, while intrinsically linked through their production processes, have distinct characteristics, and their demand is influenced by different sets of variables. Furthermore, by incorporating the demand side, we move beyond the economic and technical aspects and incorporate the human dimension.

This research aims to address the electricity and water interlinkage in coastal energy-rich countries experiencing extreme freshwater scarcity and relying heavily on seawater desalination technology for potable water supplies such as the GCC[2] countries. Concentrating on Kuwait, the research analyses the interlinkage between electricity and potable water under supply-demand uncertainties. This research focuses on analysing the electricity and water services demand within the residential sector and the implication of that demand on the future of the production supply mix and decarbonisation pathways. The outcomes of this research will inform system planners and policymakers about the electricity and water interaction and the supply-demand dynamics in addition to the cost-effective opportunities to achieve a low-carbon electricity-water system.

The research questions for this research are:

[2] The Gulf Cooperation Council (GCC) established in May 1981 is a regional intergovernmental political and economic union with aims of integrating, interconnecting and promote stability and economic cooperation among its member states. It consists of Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.

1. How might baseline electricity and water demands in Kuwait be affected by socioeconomic changes and government housing policy?
2. How might residential efficiency improvements affect future demands for electricity and water?
3. To what extent could these residential efficiency improvements influence the optimal electricity-water supply technology portfolio?
4. What are possible decarbonisation and emissions reduction pathways while maintaining the reliability of the potable water supply?

The objectives of this research are to:

1. Address a gap in energy system optimisation modelling by developing a supply-demand model focused on the electricity-water interactions in countries relying on seawater desalination technologies for their potable water needs.
2. Identify a robust decarbonisation pathway for the State of Kuwait while maintaining the integrity of the potable water supply.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This chapter first reviews the literature on projections of electricity and water demand in the GCC. Then, the potential impacts of residential efficiency improvement on electricity and water demands are reviewed. This is followed by the challenges facing subsidy removal. Next, the implications of efficiency improvement for the future supply of electricity and water are presented. A justification for the use of an energy system model for this study is also presented. This chapter concludes by identifying gaps in the literature.

2.2 Projected future demand for water in the GCC

The State of Kuwait is one of six Arab States in the Middle East overlooking the Arab/Persian Gulf. Kuwait, Saudi Arabia, the United Arab Emirates, Qatar, Bahrain, and Oman (which together form the Gulf Cooperation Council, herein referred to as GCC) show some common characteristics in terms of socio-economic development and water scarcity.

Water scarcity across the globe is driven by various factors such as population growth, rising per capita consumption, economic growth, water resource pollution and climate change. The GCC countries have all these factors in addition to the depletion of natural water aquifers and reduced rate of natural water resource recharge, thus raising the concerns regarding water security.

Water security is defined by the UN-Water (2013) as "the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability". Thus, the key to continuing development and growth success in the GCC will be determined by their ability to achieve water security.

As renewable water resources in the GCC decline sharply (Figure 2-1), water stress increases, reaching 1,182%. This is significant stress compared to the EU's 20% and the OECD's 22% (Figure 2-2) according to the Food and Agriculture Organization of the United Nations (2014, 2023) that demonstrates that natural water resources are insufficient to meet the GCC population's water demand. Hence, the reliance on unconventional water resources for potable water needs, such as seawater desalination, and the concern of water security.

Indeed, the water supply system in the GCC countries is experiencing a trend common among growing cities in water-scarce regions. A review of literature (Hundley Jr, 1994, Fitzhugh et al., 2004, Molle et al., 2009, Forslund et al., 2009, Richter et al., 2013) shows that the typical pattern a water-supply system undergoes in water-scarce regions begins with complete exploitation of local freshwater resources, leading to the attempts to import freshwater from external water basins, the collection and use of storm water, and ultimately turning to seawater through the utilisation of desalination technologies. For instance, this pattern was observed in California (Hundley Jr, 1994).

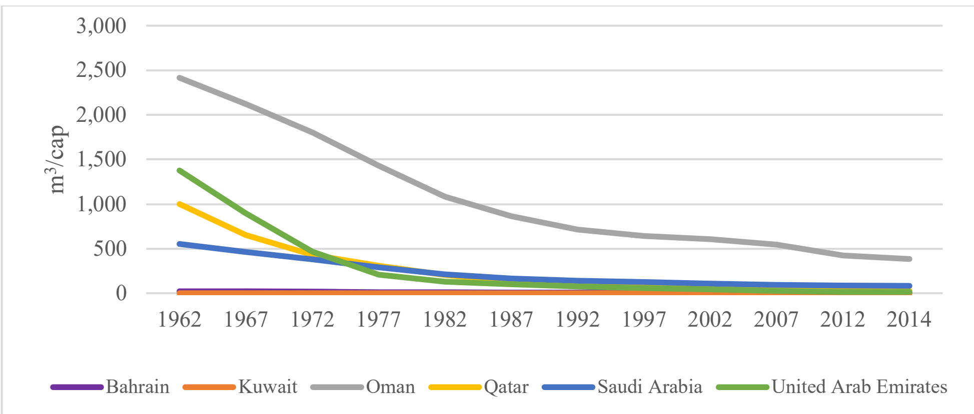

Figure 2-1 Renewable water resources per capita across GCC. *Source:* Adapted from FAO (2014)

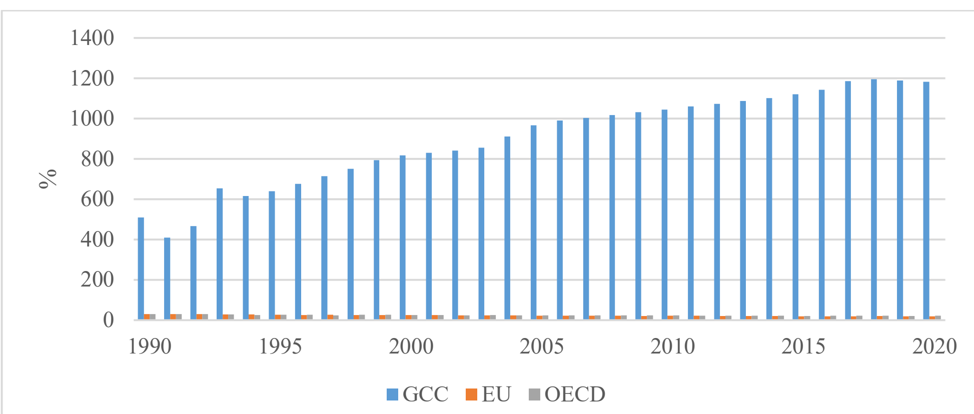

Figure 2-2 Water stress comparison between GCC, EU, and OECD. *Source:* Adapted from FAO (2023)

As GCC countries continue to meet their development aspirations, water demand is expected to continue growing. For Saudi Arabia, Ouda (2014) forecasts the gap between renewable water resources and the total water demand using population growth data, per capita water consumption information, and renewable water resources recharge information. Ouda (2014) forecasts that by the year 2030, the gap will be between 2,360 million m^3 and 9,410 million m^3. The study predicts this gap cannot be met even with natural non-renewable water supplies. However, how that gap in demand will be met was not within the scope of the study.

A similar conclusion regarding water shortages was also confirmed by Rambo et al. (2017). This study had a broader scope, looking at the water-energy nexus as a whole. The study employed a simple forecasting method based on population growth and consumption data. The study predicts that by 2038, nearly 3 million barrels per day of crude oil will be required to meet local water and electricity demand. This amount of oil would turn Saudi Arabia into a net importer of crude oil.

It is worth noting that nearly 70% of the total water demand in Saudi Arabia is met by seawater desalination, representing 18% of total global desalination output (IDA, 2022). Furthermore, the population comprises 60% citizens and 40% migrant workers. Rambo et al. (2017) forecasts that by 2040, the Saudi citizens' population could grow by 77% compared to the 2016 level, reaching 56 million inhabitants.

The influence of population composition on demand uncertainty is evident in the case of Qatar, where 99% of domestic water demand is met by seawater desalination. With migrant workers constituting 88.5% of the total population, Qatar's water demand is forecasted by Baalousha et al. (2017) based on population growth rate assumptions and current per capita water consumption. The forecasts predict that demand could evolve from 540 million m^3 in 2016 to anything between 516 and 2,718 million m3 in the year 2040, depending on various trends in population growth.

For the UAE, water demand is forecasted by Ahmed et al. (2020) using the Long Short-Term Memory (LSTM) model. This model utilises an artificial neural network that relies on previous information to forecast sequences and their dependencies. The LSTM model was "trained" using data from 2007 to 2017 to forecast water demand for ten years from 2018 to 2027. The data used in training the model consisted of temperature, rainfall, humidity, gross domestic product, consumer price index, and population growth. The forecast suggests a slight and consistent decrease in water demand, with consumption levels predicted to drop from 1,830 million m^3 in 2017 to 1,810 million m^3 in 2027. Notably, this is the only study that predicts a drop in demand contrary to trends from previous years. Additionally, it's also the only publicly available study forecasting UAE water demand.

In the case of Kuwait, a macroeconomic model was developed by Wood et al. (2012) in which electricity and water demands were forecasted up to the year 2030. The model forecasts are based on historic data of GDP, oil revenue, population, per capita electric power demand, and per capita water demand for the period between 1998 and 2009. By factoring in the economic behaviour and changes to the GDP, migrant workers population growth as well as the commercial and industrial sectors growth were forecasted to project future demand for electricity and water. The study forecasts that by 2030, water demand would reach 1,285 million m^3, 89% higher than the demand in 2018.

2.3 Projected future demand for electricity in the GCC

Almulla (2014) used the International Institute for Applied Systems Analysis (IIASA) mathematical model "MESSAGE" to develop electricity demand projections for GCC countries. The MESSAGE model, which stands for "Model for Energy Supply Strategy Alternatives and their General Environmental Impacts", is a cost optimisation tool now acquired by the International Atomic Energy Agency (IAEA). This model evaluates long-term strategies for energy mixes based on user-defined constraints on fuel availability, technology investments, environmental emissions, and more.

According to Almulla (2014) study, the electricity demand forecasts are as follows:

- Kuwait: expected to reach 134 TWh by 2030 and rise to 180 TWh by 2040;
- Saudi Arabia: demand is forecasted to reach 633 TWh by 2030 and increase to 846 TWh by 2040;
- The UAE is forecasted to reach 410 TWh by 2030 and 631 TWh by 2040;
- Qatar is predicted to reach 106 TWh by 2030 and increase to 160 TWh by 2040.

Fahmy et al. (2023) forecasted Saudi Arabia's electricity consumption using a Polynomial model that analysed past electricity consumption data. The outputs of this model were subsequently synthesised with Autoregressive Integrated Moving Average Model. The study forecasted electricity consumption for the period from 2020 to 2030. It found that consumption would increase from 341 TWh in 2020 to 575

TWh in 2030. Notably, this forecast is 10% lower than the one presented by Almulla (2014).

Soummane et al., 2022 present a projection methodology for sectoral components of the Saudi electricity demand using a Computational General Equilibrium model. The model builds on a hybrid (energy-economy) recursive-dynamic macroeconomic model developed for the Nationally Determined Contribution (NDC) for greenhouse gas mitigation study on the oil sector. The study projects electricity demand to increase from 2018 levels of 299 TWh to 365.5 TWh in 2030.

The econometric tools known as the Error Correction Model and the Autoregressive Distributed Lag Model were used in Khalifa et al. (2019) study to forecast electricity consumption in Qatar. Based on GDP growth assumptions, population growth assumptions, and past electricity consumption data, the consumption is projected between 80 TWh and 152 TWh in 2030, depending on various trends in population growth.

During the literature search, no UAE-specific study was found investigating future electricity demand. However, in 2017, the UAE's Ministry of Energy and Industry conducted a study forecasting electricity demand up to 2050, based on GDP and population change. Unfortunately, the findings from this study were not publicly available at the time this literature review was written.

In the context of the GCC, there is notable interdependency between electricity generation and water production. Interestingly, upon reviewing the available literature on this topic, it became evident that there is a significant gap in comprehensive studies that address both electricity and water demand pathways simultaneously. While several works have individually explored either water or electricity, only Wood et al. (2012) stands out as a source that examines both in tandem. In this study, Wood et al. (2012) forecasts Kuwait's peak electric load to reach 28 GW by 2030.

In all the publicly available research projecting electricity and water demand in the GCC countries, there is a consistent methodology observed. These studies predominantly base their forecasts on current/targetted per capita consumption levels, economic growth, and population growth. This methodology overlooks several fundamental factors influencing electricity and water demands. First, it doesn't account for potential technological advancements of different electricity and water end-use services or behavioural shifts stemming from socioeconomic progression that the population of these developing countries experience. More significantly, these approaches do not analyse the primary source of electricity and water demand and main consumer of it across all GCC countries: the residential sector.

Growth of the housing sector itself is influenced by various factors that were not considered in the previous studies. Growth of the housing sector and housing options are dictated by government policies, government spending, and welfare systems. A change to either of these components could redirect the housing sector into a different growth path.

The population composition also is a factor in the residential sector growth. The studies acknowledge that the migrant worker population is susceptible to national economic fluctuation and that adverse economic conditions could lead to a decline in the migrant worker population and, therefore, a decline in electricity and water demand. However, these studies often neglect the country's development trajectory.

As nations' development progresses and the pace of development stabilises, the type of migrant workers they attract undergoes a transformation. Initially, the population composition leans towards labour-intensive roles to meet the demands of infrastructure development and construction. These roles are predominantly occupied by single men who often reside in shared accommodations. Over time, there will be a shift in market needs towards attracting white-collar and skilled professionals who typically opt for independent living and bring their families with them.

2.4 Fuel price volatility influence on electricity generation and potable water production

2.4.1 How fuel mix and generation efficiency shape total energy consumption

Analysis of the annual growth in total fuel energy input for Kuwait's power and water sector (Figure 2-3) reveals a pattern that does not consistently align with the year-on-year changes in electricity production (Table 2-1). There are instances where electricity output shows minimal growth, yet total fuel consumption increases. In contrast, there are periods where significant growth in electricity generation is observed with a disproportionately smaller, or even negative, change in the total fuel energy input. This observed decoupling between the growth rates of production output and total fuel energy input can be attributed to dynamic fuel switching in generation plants, which is evident from the fuel mix data (Figure 2-3 and Table 2-2).

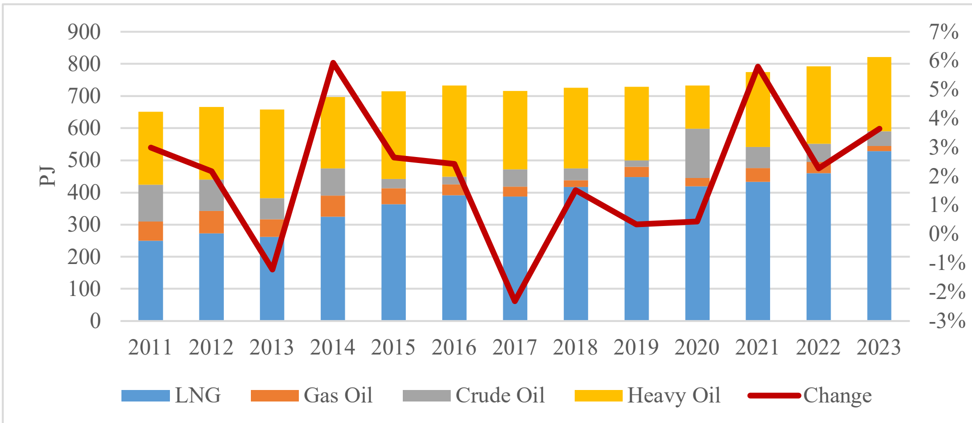

Figure 2-3 Annual fuel consumption for power and water production by type and percentage change in input fuel. *Source:* Adapted from MEW (2024).

Increased utilisation of certain fuels, often associated with higher thermal efficiency, can lead to lower aggregate fuel input per unit of electricity generated. The use of LNG in combined-cycle gas turbines, for example, represents a shift towards a more efficient generation (Rodriguez et al., 2020). An example of this is observed in MEW's fuel consumption data in Table 2-2, where the upward trend in LNG consumption is modulating the sector's overall energy intensity.

Therefore, while the underlying growth in demand for electricity and desalinated water drives the overall demand for energy, the actual trajectory of total fuel energy input on an annual basis is significantly modulated by these operational choices regarding the fuel mix. The variations in total fuel input observed in Figure 2-3, when compared against electricity production growth in Table 2-1 and the detailed fuel consumption patterns in Table 2-2, underscore the critical role that fuel selection and the varying efficiencies of Kuwait's power generation assets play in shaping the overall energy intensity of the power and water sector.

Table 2-1 Annual changes in electricity & water production and associated costs. ***Source:*** **Adapted from MEW (2024) and Alqassas (2021).**

Fiscal Year	*Elec & Water Production Costs*	*Change*	*Produced Electricity*	*Change*	*Produced Water*	*Change*
	Bn US$	**%**	**TWh**	**%**	**M m^3**	**%**
2010/2011	7.71		57.5		618.1	
2011/2012	9.88	28%	61.1	6.3%	630.8	2.1%
2012/2013	9.80	-1%	61.0	-0.2%	634.9	0.7%
2013/2014	9.80	0%	65.1	6.8%	651.0	2.5%
2014/2015	8.75	-11%	68.3	4.8%	675.0	3.7%
2015/2016	5.91	-32%	70.1	2.6%	709.3	5.1%
2016/2017	5.21	-12%	72.8	3.9%	720.9	1.6%
2017/2018	6.23	20%	74.1	1.8%	719.0	-0.3%
2018/2019	6.11	-2%	75.1	1.3%	722.6	0.5%

Table 2-2 Energy input by fuel type for electricity & water production. ***Source:*** **Adapted from MEW (2024).**

Year	*LNG*	*Gas Oil*	*Crude Oil*	*Heavy Oil*	*Total Energy*
	PJ	**PJ**	**PJ**	**PJ**	**PJ**
2010	217.0	53.3	105.3	257.3	632.9
2011	249.6	60.1	114.0	228.2	651.9
2012	273.2	69.8	97.1	226.0	666.1
2013	262.2	54.1	66.4	275.3	658.0
2014	324.7	65.4	84.5	222.5	697.0
2015	363.0	50.2	28.4	273.9	715.6
2016	391.5	33.6	23.8	284.1	733.0
2017	387.9	30.5	53.9	243.8	716.0
2018	417.3	21.2	36.6	251.8	726.9
2019	448.5	31.5	20.2	229.2	729.4
2020	419.1	26.7	152.6	134.2	732.6
2021	433.6	41.7	66.5	233.3	775.1
2022	460.2	35.0	55.8	241.7	792.7
2023	529.3	15.8	45.6	230.9	821.6

2.4.2 Energy price volatility as the main driver of production costs

While the previous discussion established that fuel switching and the utilisation of different power generation technologies can significantly influence the volume and type of fuel consumed, it is ultimately the cost of these fuels that drives MEW's overall electricity production expenditure reflected in Table 2-1.

Figure 2-4 presents the annual percentage changes in total fuel energy input, total production costs for electricity and water, and average international crude oil prices for Kuwait, covering the period from fiscal year (FY) 2011/12 to FY2018/19. The graph highlights a significant divergence in the behaviour of these metrics. Specifically, the annual percentage change in total fuel input, which fluctuates within a relatively modest range (-1.2% to +5.9% annually during this period).

In stark contrast, the annual percentage changes in both total production cost and average crude oil prices exhibited significantly greater volatility and a strong correlation. This strong coupling suggests that the rate of change in production costs is more closely tied to the rate of change in energy prices than to the marginal, and often efficiency-modulated, variations in domestic fuel consumption volume.

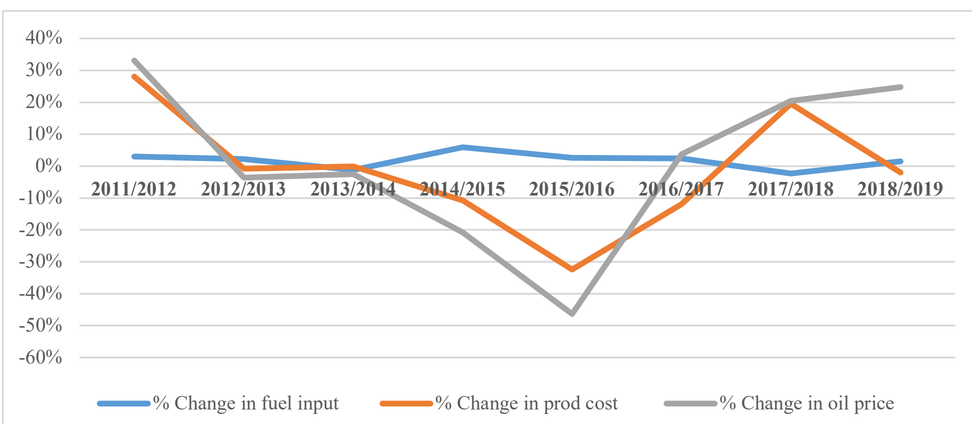

Figure 2-4 Annual percentage change in total fuel input, production cost, and average crude oil prices in Kuwait

A clear illustration of this price-driven relationship is observed in FY2015/16. During this fiscal year, average crude oil prices experienced a dramatic year-on-year decrease of approximately 46.3% (OPEC, 2018). Correspondingly, total production costs saw a sharp reduction of 32.5%. This cost decrease occurred even as the total fuel input registered a slight increase of 2.7% for the same year, reflecting both demand changes and fuel switching.

In absolute terms, which underscore the magnitude of these changes, the period FY2014/15 to FY2015/16 saw production costs fall from $8.75 billion to $5.91 billion despite fuel consumption rising from 697 PJ to 716 PJ, while average crude oil prices dropped from $82.9/barrel to $44.5/barrel. Conversely in FY2017/18, an annual increase in crude oil prices of approximately 24.7% coincided with a 19.6% rise in production costs, while fuel input saw a more minor year-on-year change. However, it is notable that in FY2018/19, production costs registered a slight decrease of approximately 1.9% from $6.23 Bn to $6.11 Bn despite a substantial increase in oil prices of 24.6% from $55.6/barrel to $69.3/barrel.

Figure 2-4 demonstrates a generally strong correlation between the annual percentage changes in crude oil prices and total production costs, minor deviations highlight the influence of other significant factors, particularly the use of LNG. Such an example is observed in FY2018/19, where despite a substantial year-on-year increase in average crude oil prices of approximately 24.6%, the total production costs for electricity and water registered a slight decrease of approximately 1.9%. This apparent anomaly can be primarily explained by two concurrent developments within Kuwait's fuel mix and the broader energy market during that period represented by a significant increase in LNG utilisation and favourable LNG price trend.

Analysis of the detailed fuel mix reveals a marked shift towards LNG consumption in FY2018/19 compared to the previous year. Specifically, the energy contribution from LNG increased its share of the total fuel feedstock from approximately 54% to 61%. This increased reliance on gas, which is often utilised in more thermally efficient combined-cycle power plants compared to liquid fuels in older steam units, tends to lower the overall fuel energy required per unit of output, partially mitigating cost pressures.

During this same period, international natural gas price benchmarks experienced a downward trend, decoupling somewhat from rising oil prices. For example, average Henry Hub spot prices (a key US benchmark indicative of broader market trends) decreased from $3.15/MMBtu in 2018 to $2.56/MMBtu in 2019 (EIA, 2025c). While Kuwait's specific LNG import contract prices may differ, this benchmark indicates a softening in global gas markets. Therefore, not only was Kuwait utilising a larger proportion of a more efficiently burned fuel (gas), but the cost of that gas was likely also lower relative to both the previous year and the rising oil prices. It is also worth noting that while the LNG contracts are long-term in their nature, MEW purchases its fuels through the Kuwait Petroleum Corporation (KPC) subsidiaries at market price.

The combined effect of utilising a larger share of more efficiently burned natural gas/LNG observed for FY2018/19, successfully counteracted the inflationary pressure from the concurrent rise in international crude oil prices for that specific year. This example brings attention to the reality of Kuwait’s EWS where while fluctuations in international energy prices, particularly crude oil, are the dominant long-term driver influencing the overall trajectory and volatility of Kuwait's electricity and water production costs, operational decisions regarding the fuel mix can lead to significant year-on-year variations and occasional deviations from the expected oil-cost trend.

In conclusion, the preceding analysis shows that even with operational flexibilities like fuel switching, Kuwait’s electricity and water production costs are still fundamentally tied to the volatility of international fuel markets. This creates a sharp fiscal paradox for Kuwait's fiscal structure. As established in Chapter 1, the government's financial health benefits from the high global oil prices that provide over 90% of its revenue. Yet, these are the same prices that drive up the domestic cost of producing essential services. In effect, Kuwait’s primary source of income is also the primary driver of its domestic expenditure. The principal mechanism employed by the government to manage this paradox and absorb the resulting financial pressure on the consumer of the essential services of electricity and water is a system of subsidies, the structure and implications of which are the focus of the next subsection.

2.5 Kuwait’s utility subsidy

2.5.1 Tariff structure

The State of Kuwait provides a subsidy system to manage the fiscal paradox created by highly volatile energy prices. This subsidy system is designed to insulate consumers from the true fluctuating costs of production. The system is represented by a fixed tariff structure for electricity and water.

The fixed tariffs (Table 2-3) are set by the Ministry of Electricity and Water and show significant variation across different consumer sectors. The structure is heavily weighted to support the residential sector, which benefits from the lowest rates for both electricity and water. All other sectors face higher, albeit still nominal, tariffs.

These fixed tariffs are a sharp contrast to the actual cost of production, which fluctuates significantly year-on-year in response to international fuel prices as demonstrated in Section 2.4. For instance, compared to the aforementioned subsidised tariffs, production cost for FY2018/2019 was approximately 0.132 US$/kWh for electricity and 5.90 US$/m^3 for potable water (Alqassas, 2021).

The substantial gap between the global energy market-driven cost of production and the state-mandated consumer price translates into a direct per-unit subsidy. For electricity (Table 2-4), the residential sector receives the most significant support. The fixed tariff of 0.007 US$/kWh covers less than 6% of the production cost, meaning the state subsidises nearly 95% of every kilowatt-hour consumed in the FY2018/19. Even the government sector, which has the highest fixed tariff, gets approximately 40% of its electricity costs covered by the subsidy. A similar pattern is observed for potable water (Table 2-5). The production cost of 5.90 US$/m^3 is heavily subsidised across all consumer sectors. The residential consumers paid just over 10% of the actual cost, reflecting a subsidy of nearly 90% in the FY2018/19.

The analysis reveals a subsidy system where most production costs are absorbed by the State rather than the consumer. Thus, shielding the consumer from energy prices volatility in global markets. This direct link to global price fluctuations renders the subsidy programme a key source of fiscal uncertainty for the Kuwaiti government.

Table 2-3 Electricity and water tariffs. ***Source:*** **MEW (2024)**

Sector	***Electricity*** [US$/kWh]	***Water*** [US$/m3]
Residential	0.007	0.6
Commercial	0.016	1.4
Government	0.08	2.9
Industrial	0.016	0.9
Agriculture	0.016	0.9
Other	0.04	1.4

Table 2-4 Per-unit of electricity subsidy analysis (FY2018/2019)

	Production Cost [US$/kWh]	***Tariff*** [US$/kWh]	***Per-Unit Subsidy*** [US$/kWh]	***Subsidy as share of production cost*** [%]
Residential	0.132	0.007	0.13	94.7%
Commercial	0.132	0.016	0.12	87.9%
Government	0.132	0.08	0.05	39.5%
Industrial	0.132	0.016	0.12	87.9%
Agriculture	0.132	0.016	0.12	87.9%
Other	0.132	0.04	0.09	69.7%

Table 2-5 Per-unit of water subsidy analysis (FY2018/2019)

	Production Cost [US$/m3]	***Tariff*** [US$/m3]	***Per-Unit Subsidy*** [US$/m3]	***Subsidy as share of production cost*** [%]
Residential	5.90	0.6	5.30	89.8%
Commercial	5.90	1.4	4.50	76.3%
Government	5.90	2.9	3.00	50.8%
Industrial	5.90	0.9	5.00	84.7%
Agriculture	5.90	0.9	5.00	84.7%
Other	5.90	1.4	4.50	76.3%

2.5.2 Quantifying the national fiscal burden of utility subsidies

The previous subsection highlighted how the size of the subsidy expands and contracts in direct response to the volatile global energy prices. This subsection assesses the implications of this dynamic relationship, using the total cost of producing electricity and water as an indicator of the national subsidy burden. As revenues from the heavily subsidised tariffs cover only a fraction of the actual cost, the total annual production cost represents the overwhelming majority of the financial commitment borne by the State.

The size of this fiscal burden is evident in the data presented in Table 2-1. During the observed period between FY2010/11 and FY2018/19, the total annual cost of producing electricity and water fluctuated significantly. The fluctuation ranged from a low of US$ 5.21 billion to a high of US$ 9.88 billion. This demonstrates that Kuwait’s subsidy expenditure can nearly double or halve in response to global energy market conditions. Consequently, this fluctuation introduces a significant unpredictability into the national budget.

For instance, in the 2018/2019 fiscal year, expenditure on electricity and water production accounted for approximately 8.7% of the government’s US$70.06 billion total budget (Ministry of Finance, 2018a). Thus, directly competing with and constraining funds for other national priorities such as healthcare, education, housing, and infrastructure development in new cities. Furthermore, this amount accounted for roughly 4.5% of Kuwait’s GDP for the same fiscal year (World Bank, 2020b), which represents a significant portion of national economic output being diverted to subsidising domestic consumption. Therefore, the substantial and fluctuating fiscal commitment of Kuwait's subsidy system has two far-reaching implications for the nation's economic management:

First, it creates a considerable opportunity cost. The billions of dollars allocated annually to these subsidies are effectively diverted from strategic investments for advancing Kuwait's National Development Plan and the objectives of "Kuwait Vision 2035". Consequently, instead of fostering the development of local industries and diversifying the economy away from its reliance on hydrocarbon resources, a considerable portion of the nation’s oil revenues is consumed to maintain existing consumption patterns.

Second, this subsidy framework fosters profound fiscal rigidity and susceptibility to economic shocks. For example, when oil prices are high, the government's revenues increase. However, because subsidy costs are tied to energy price fluctuations, the government spending on subsidies also rises dramatically. Conversely, when oil prices fall, state revenues decrease sharply while the commitment to subsidies remains high. This results in pressure on the national budget, often triggering the government to withdraw from its sovereign wealth fund to mitigate the resulting deficit (Reuters, 2021). Consequently, the volatility of global energy prices directly impacts domestic spending, deepening Kuwait’s exposure to fiscal risk.

In conclusion, while the objective of the subsidy system is to offer price stability to consumers and secure their needs for essential services such as indoor thermal comfort, refrigeration, and potable water. It inadvertently generates considerable price instability and fiscal uncertainty for the country itself.

2.6 The challenge of subsidy reform

Energy consumption levels across the GCC countries -both per capita and per unit of GDP- are the highest in the world, directly influencing their energy intensity levels (Figure 2-5). The IMF (2013) and KAPSARC (2016) conclude that government policies sharing fossil fuels resource rents have driven these high consumption levels, leading to economic inefficiencies. Across the GCC, and in Kuwait, residential consumers receive benefits from government interventions in the form of fixed tariffs and subsidies for electricity and water. The consumers are, therefore, not exposed to fuel price fluctuation or increases in service production or delivery costs and have guaranteed affordable access to electricity and water services.

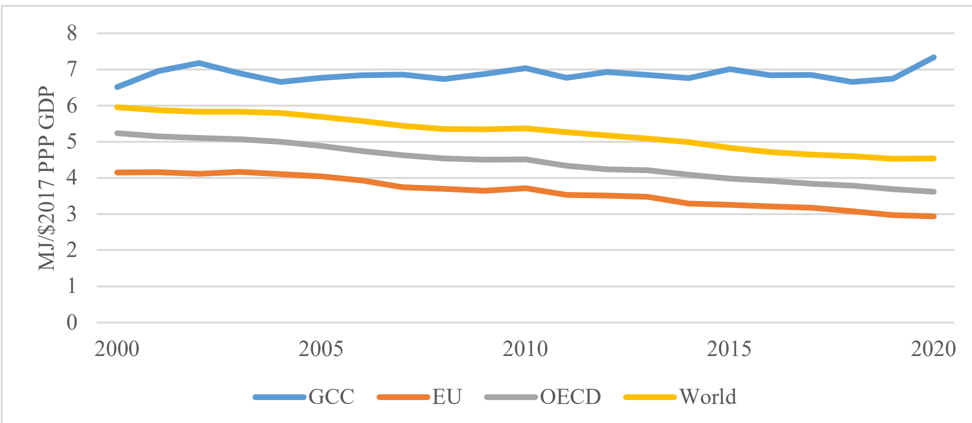

Figure 2-5 Energy intensity level. *Source:* Adapted from World Bank (2020b).

A substantial body of empirical work explores the impact of tariff and subsidy adjustments on the demand for electricity and water, generally confirming that altering prices can serve as a mechanism for demand reduction, although the extent and nature of the response vary considerably. Studies examining electricity tariffs in the GCC, including Kuwait (Ameer et al., 2016, Krane et al., 2016, Matar, 2019, Al-Saidi, 2020), and wider MENA region (Javier Arze del Granado et al., 2010, Timilsina et al., 2023), find some level of price responsiveness. Alfalah et al. (2020), for instance, examined Kuwait and determine that while income effects on electricity consumption are insignificant, demand does exhibit significant price elasticity in the long run, suggesting potential for demand moderation over time if price signals are adjusted.

Similarly, research focusing on water tariffs, often in contexts with increasing block tariff structures (Xayavong et al., 2008, Alshawaf, 2008, Dale, 2009, Monteiro et al., 2011, Srouji, 2017) indicates price sensitivity, although residential water demand is frequently found to be price inelastic overall. Studies examining both utilities (Fattouh et al., 2014, Al Ojayan, 2016, Shehabi, 2019) highlight the potential cross-sectoral impacts within integrated energy-water systems.

While this literature collectively affirms that economic responses to price signals exist, cross-country analyses conducted by the World Bank (Javier Arze del Granado et al., 2010) on fuel subsidies caution that such reforms can have significant adverse effects on household real income, necessitating careful consideration of welfare impacts. Therefore, the practical effectiveness and feasibility of achieving demand reduction through subsidy reform in a specific context like Kuwait are profoundly complicated by socio-political and behavioural barriers to subsidy reform discussed subsequently.

2.6.1 Socio-political barriers to subsidy reform

Despite the theoretical potential for demand reduction highlighted by economic studies, actual subsidy reform invariably encounters significant political and social resistance. In Kuwait and other GCC States, for instance, subsidies are deeply ingrained not merely as price-reduction/social-support tools but fundamentally as a mechanism for wealth distribution, widely perceived as a citizen's 'fair share' of state-controlled resources (Al-Shalabi et al., 2014, Hertog, 2020, Aljamal et al., 2022, Moujaes et al., 2024).

This perception of subsidies as an entitlement primarily for citizens takes on heightened significance given the demographic structure of Kuwait and other GCC states, where nationals often constitute a minority of the total population. Consequently, a common pattern observed in recent GCC subsidy reforms, particularly following the 2014 oil price decline, has been to differentiate pricing explicitly between citizens and non-national residents (Krane et al., 2016).

Reforms in the UAE, Bahrain, and initially Saudi Arabia often involved substantially larger price increases for expatriates and businesses, while partially or wholly shielding citizens, especially from initial increases in electricity and water tariffs (Fattouh et al., 2014, Krane et al., 2016). This politically pragmatic approach attempts to address fiscal pressures while mitigating direct opposition from the citizenry, reflecting the deep-seated nature of the social contract regarding resource wealth distribution.

This explicit segmentation further complicates the socio-political dynamic and aligns with insights from behavioural economics, which highlight that individuals are often motivated by concerns that include perceptions of fairness and equity. Theories of inequity aversion, such as that proposed by Fehr et al. (1999), demonstrate that individuals often resist outcomes they perceive as unfair or unequal, sometimes even at a personal cost. This suggests that resistance among citizens may stem not just from the absolute price increase, but from the alteration of a long-established distributional system of national wealth that they perceive as equitable for them.

In relation to this, models focusing on the theory of equity (Bolton et al., 2000) suggest that individuals evaluate their well-being not only in absolute terms but also based on their payoff relative to others or an average; subsidies directly influence this perceived relative standing. Furthermore, the dynamics of managing shared resources or public goods and willingness to pay for these public goods, as analysed by Kollock (1998), highlight the inherent tension between individual incentives (consuming cheap subsidised resources) and collective outcomes (fiscal unsustainability and resource depletion). Navigating this classic social dilemma, where individual rationality conflicts with collective well-being, is a core challenge for subsidy reform, further explaining potential public resistance.

Overcoming social dilemmas often requires robust norms of fairness and trust, making any reform that disrupts perceived fairness inherently contentious. Indeed, studies exploring willingness to pay for public goods sometimes suggest that factors other than disposable income, such as fairness norms or trust in the process, can be significant drivers (Ostrom, 2000, Liebe et al., 2010, Grassi, 2010).

Compounding these socio-political and behavioural hurdles are persistent technical challenges related to accurate utility metering and timely billing systems, which are two very common issues and widespread in Kuwait (Milutinovic, 2006, AlRukaibi, 2013, Aljamal et al., 2022), further complicating the implementation and public acceptance of any potential reform measures.

2.6.2 Subsidy reform and the behavioural dimension

Beyond the socio-political sensitivities and technical constraints outlined above, the relationship between subsidies and consumer behaviour presents a challenge when modelling the nation's energy consumption and exploring decarbonisation pathways.

While subsidies undoubtedly influence overall energy consumption and therefore consumption for electricity and water, their primary impact lies in shaping energy service demands.

Energy service demands are the demand for the outcomes or utility that energy enables, such as achieving a desired level of indoor thermal comfort, accessing sufficient potable water for domestic use, ensuring adequate lighting, or powering essential appliances. Consumers make their decisions based on obtaining these services, rather than direct demands for kilowatt-hours of electricity or cubic metres of water. Subsidies, by making the cost of achieving a specific service level (e.g., a very cool room) artificially low, directly impact behaviours related to service intensity (e.g., lower thermostat settings, longer appliance use) and technology choices.

Regarding technology choices specifically, highly subsidised prices significantly reduce the economic incentive for consumers to invest in more efficient end-use technologies and building designs, as the potential operational cost savings are masked. Therefore, focusing solely on aggregate electricity and water consumption overlooks the role that the efficiency of these end-use systems plays in determining the actual energy required to satisfy desired service levels.

The distinction between energy demand and energy service demand is crucial because the factors influencing these two types of demand can differ substantially. For example, while overall energy demand might be primarily driven by macroeconomic factors like economic growth and population increase, energy services demand is more complex, influenced by micro-level factors such as building design, appliance efficiency, and individual consumer preferences. Therefore, the effectiveness of subsidy reform in reshaping energy consumption patterns hinges not just on economic mechanisms but also on the understanding of consumer behaviour and the specific context in which policies are implemented.

While fiscal instruments, such as tariff adjustments, subsidy reduction and taxes, operate through established economic principles, their impact is ultimately mediated by consumer responses, shaped by factors such as income levels, cultural norms, and access to information. Non-priced measures, including public awareness campaigns and educational initiatives, aim directly at influencing these behavioural dimensions; however, they do not always result in the desired changes in behaviour. The extent to which consumer responses determine policy outcomes is fundamentally shaped by individuals' perceptions of the benefits and costs associated with the lifestyle changes these measures necessitate.

2.6.3 Mediating public acceptance and behavioural responses to subsidy reform

According to Dodds (2008), past technological transitions that successfully prompted behavioural changes were characterised by the provision of immediate and tangible benefits to consumers. Consumers may be more willing to embrace change if they perceive adequate alternatives to meet their needs, believe that the transition is necessary for future generations, and understand how specific measures contribute to the overall process. Dodds (2008) suggests that public acceptance of fiscal instruments can be strengthened through hypothecation (i.e., the practice of allocating the revenues generated from fiscal instruments for specific, identifiable purposes, thereby creating a direct and transparent link between the financial burden imposed and the societal benefits delivered). This links back to the psychological aspect of consumer behaviour, where perceived fairness and tangible benefits influence the acceptability of policy interventions.

Schuitema et al. (2008) support this notion, demonstrating that such policies are more acceptable when revenues are recycled and earmarked for sector-related improvements rather than directed to general public funds. The linkage between policy acceptance and trust is typically conditioned by consumers' perceptions of governance quality.

Evidence from societies characterised by weak governance and low levels of trust show that there is a decreased willingness to accept, for instance, higher climate taxes due to concerns about potential misappropriation of funds and corrupt practices (Steenkamp, 2021). This observation aligns with existing research on revenue earmarking in low-corruption environments (Davidovic et al., 2020, Ejelöv et al., 2022, Sivonen, 2022), which underscores the importance of transparent and accountable revenue allocation mechanisms for securing public support for fiscal policy interventions.

Applying this understanding directly to the challenges in Kuwait, such targeted reinvestment of revenues highlights a crucial insight for policymakers considering subsidy reform as part of efforts to tackle the electricity-water system stability and decarbonise the system: the perceived fairness and efficacy of fiscal instruments are significantly influenced by how the generated revenues are utilised. This perception directly impacts public acceptance and the ultimate success of the reforms. While a comprehensive econometric analysis of subsidy impacts, incorporating elasticities of demand and complex behavioural responses, is essential for fully understanding the potential implications of such policies, this level of detailed modelling is beyond the scope of this thesis.

This research recognises that in the context of Kuwait, where the electricity-water system is predominantly state-owned and operated, the success of subsidy reforms depends not only on their direct impact on consumption behaviour but on the government's ability to demonstrate a transparent and equitable reinvestment of the resulting revenue stream. Effectively, achieving sustainable reform necessitates a mechanism, such as hypothecation, where funds generated from subsidy reductions are channelled back into the sectors and thus funding improvements in electricity-water system infrastructure, enhancing efficiency, and promoting the adoption of sustainable technologies. This understanding that successful reform is essentially linked to efficient, targeted reinvestment has guided the choice of modelling approach.

2.7 Potential impacts of residential efficiency improvements on electricity and water demand

A number of studies (Allcott, 2015, Akhmouch, 2012, Brown et al., 2012, Ferraro et al., 2013, Visser et al., 2017, Datta et al., 2015, Kotwicki et al., 2011) emphasise the importance of efficiency improvement in reducing buildings consumption. The ESMAP (2020) of the World Bank identified efficiency improvement as a critical enabler for economic growth and higher living standards, particularly in developing countries experiencing rapid growing demand for electricity and water services. Improving residential efficiency can offset increased demand caused by population increase.

The technological approach for efficiency improvement of water consumption in the residential sector (Mukhopadhyay et al., 2000, Mukhopadhyay et al., 2001, Al-Otaibi et al., 2005, Al-Senafy et al., 2018, Waterwise, 2014, Abu Dhabi Urban Planning Council, 2010, Milutinovic, 2006, Kotwicki et al., 2011) can be summarised by high-efficiency fixtures and appliances (high-efficiency toilets, low flow showerheads and faucets, efficient dishwashers and washing machines), smart water metering and monitoring, leak detection systems, pressure reducing valves, pipe retrofitting, and water recycling and reuse for landscaping.

For electricity conservation, efficiency improvement measures (Balaras et al., 2000, Al-Ragom, 2003, National Action Plan for Energy Efficiency, 2008, Yun et al., 2011, UN-ESCWA, 2014, Krarti, 2015, Friess et al., 2017, Radhi, 2009, Filippín et al., 2018, Ebrahimpour et al., 2011, Maheshwari et al., 2011, Taleb et al., 2011) range from appliance upgrades to more energy efficient (light bulbs, refrigerators, freezers, etc.), to air conditioners thermostat upgrades (programmable, smart, etc.), to building retrofit (thermal insulation, double/triple glazing windows or low-emissivity coating, air infiltration, etc.).

However, the potential of efficiency improvement is not limited to the availability of technological advancement alone; it extends motivating behavioural change that would result in reducing the use of electricity and water services or the adoption of efficiency improvement measures (Dahlbom, 2009, DECC, 2012, Ucci et al., 2012, Morton, 2013, Castillo-Martinez et al., 2014, Filippín et al., 2018). Behavioural interventions, referred to as "nudges," are found to be cost-effective strategies informed by applied behavioural economics that policymakers could feasibly employ to achieve public policy objectives. Examples of behavioural nudges include social comparison, feedback mechanisms, progress tracking, and appliances labelling.

Azar et al. (2017) identified multiple obstacles facing efficiency improvement and conservation through behavioural change in buildings. First, there is limited data regarding human activity inside buildings. Studies often don’t take into account diverse factors that influence social behaviour. Behavioural drivers such as social, environmental, and economic motivators. Furthermore, data analysis methods of consumption within buildings tend to be oversimplified, overlooking the interconnected impact of behavioural drivers.

Yun et al. (2011) and Pavanello et al. (2021) examined the influence of behavioural drivers on energy consumption in buildings. They determined that behavioural drivers can have both direct and indirect effects on a building's energy consumption. The most direct impact of occupant behaviour on energy was observed in space cooling. This includes decisions regarding when air conditioners are turned on, their frequency of operation, and the desired temperature for cooling the space, etc (van den Brom et al., 2018).

This direct link between occupant behaviour and air conditioner consumption is amplified by a shifting technological landscape that is altering the underlying energy impact of those behaviours. While the average efficiency of air conditioners is projected to double by 2040 (IEA, 2018), this figure masks a risk specific to hot climates. Mandated global transitions to low-GWP refrigerants have raised concerns about performance under extreme heat (Hussain et al., 2025). Conventionally, air conditioners are tested under moderate conditions of 35 °C (ISO, 2017, AHRI, 2020). However, research shows that some new refrigerants exhibit reduced cooling capacity or higher power draw under high ambient temperatures such as those experienced in Kuwait (Payne et al., 2002, UNEP, 2010, Hussain et al., 2025). Consequently, new international testing protocols such as “T3” 46 °C (for the GCC) and the Kuwaiti-specific “T4-Kuwait” (48 °C with operability at 52 °C) have been introduced by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI, 2021). In this context, occupant decisions, such as lowering the thermostat by even one degree, can carry a greater energy consequence than with older technologies, making mindful energy use an essential companion to technical efficiency improvements.

An example of a behavioural change intervention to reduce consumption is the "descriptive norm intervention” as described by Ferraro et al. (2013) and Allcott (2011). The approach enables consumers to benchmark their consumption against their peers, which triggers consumers to improve their consumption. An example of such nudges is presented by Datta et al. (2015) study.

Datta et al. (2015) studied reducing household water consumption using the descriptive norm intervention. The study conducted an experiment which involved 5,626 individually-metered households and took place in 2014 in Costa Rica. Prior to the experiment's commencement, a focus group was conducted, yielding key insights that informed the design of the interventions. Participants expressed a broad consensus on the importance of water conservation in general but also admitted to not knowing their water consumption levels. Furthermore, residents found it difficult to evaluate the appropriateness of their water consumption levels due to the absence of a benchmark for comparison.

Two versions of the descriptive norm intervention were implemented: a "neighbourhood comparison" and a "city comparison". Additionally, a "goal-setting and planning intervention" referred to as "plan-making" was employed. The plan-making intervention drew consumer attention to their consumption levels, facilitated goal-setting for water consumption reduction, and guided households in devising strategies for water use reduction.

The findings of Datta et al. (2015) study revealed that the neighbourhood comparison intervention led to a 3.7% and 5.6% reduction in water consumption compared to the control group. The plan-making intervention resulted in a reduction of 3.4% to 5.5% of average monthly consumption for the control group. The neighbourhood comparison proved to be more effective than the city comparison, and was most effective among high-consumption households, while plan-making intervention primarily affected households with relatively low baseline consumption levels. The superior effect of the neighbourhood comparison aligns with theoretical work on 'norm-nudges' by Bicchieri et al. (2019) which argued that interventions are most powerful when the social information comes from a group that individuals perceive as similar and relevant.

The effectiveness of social comparison messages is well-documented in the literature. In a systematic review of 44 international studies on the effects of non-priced interventions, Andor et al. (2018) confirmed that social comparisons is consistently effective tool for triggering energy conservation. The review found that consumption reductions ranging from 1.2% to 30% across various studies. An example of this is a study by Ferraro et al. (2011), which experimented on 100,000 households in the USA, found that the social comparison messages have more significant influence than technical information alone. The study also found that a reduction in consumption due to social comparison had an impact equivalent to a 12% to 15% in tariff increase. Furthermore, the most effective behavioural change and consumption reduction was observed among households identified as least price sensitive.

Similarly, Visser et al. (2017) conducted their study on 400,000 households in Cape Town. The study sent billing inserts to households, showing them tariff graphs, financial gains, financial losses, social comparisons, intrinsic motivation, and tips on how to improve. The study found an immediate reduction in consumption, averaging between 2% to 3.5%. The highest reduction was observed amongst high-income households, where social recognition nudges resulted in an 8% to 9% reduction.

Bernedo et al. (2014) investigated the long-term impact of the norm intervention messaging. The study found that the influence of social messaging diminishes by 50% after the initial year. Nevertheless, this impact persists even after the messaging stopped, remaining detectable for up to five years afterwards.

2.8 Implications of efficiency improvements for the future supply of electricity and water

Efficiency improvement can have significant implications for the future supply of electricity and water. End-use efficiency improvement can result in a range of benefits on the supply side of electricity and water. According to González-Torres et al. (2022), efficiency improvements in the residential sector could reduce energy intensity, allowing for accelerated development without compromising environmental targets. The energy efficiency improvement can allow for expansion in energy services usage, thus enabling economic growth, higher living standards, and support to national development plans (ESMAP, 2020).

End-use efficiency improvement can mitigate the timing of water system expansion and the extent to which cities rely on new sources (Richter et al., 2013). Moreover, end-use efficiency improvement could achieve considerable reductions in carbon emissions in a cost-effective manner (Levine et al., 1995). According to Matar (2015), increasing the share of insulated homes in Saudi Arabia from 27 to 64% could allow the power sector to reduce its fuel use by 158,000 barrels/day of crude oil. While Sathaye et al. (2005) suggests that end-use efficiency improvement could offer a way to eliminate electricity deficit without increasing direct investment in capacity addition and reduce the burden of subsidies.

Wang et al. (2014) suggests that end-use efficiency improvement measures can result in electricity savings in the form of reduced demand, which in turn results in benefits such as fuel savings, reduced carbon emissions, and benefits for the electric power sector by slowing generation growth and reducing the need for capital investments for new generation. Furthermore, end-use efficiency improvement can decrease the energy and carbon intensity of the entire country.

2.9 The decarbonisation challenge facing Kuwait

2.9.1 Institutional and regulatory context

Kuwait's Environment Public Authority (KEPA) is the governmental body tasked with environmental protection, policy enforcement, and climate governance in the country. Established in 1995 and empowered by the Environment Protection Law No. 42 of 2014, as amended by Law No. 99 of 2015, KEPA holds jurisdiction over all environmental affairs. KEPA's jurisdiction includes setting environmental standards, regulating pollution, and overseeing environmental impact assessments (KEPA, 2015a). As the national focal point for the United Nations Framework Convention on Climate Change (UNFCCC), KEPA is responsible for preparing Kuwait's National Communications (NCs), Biennial Update Reports (BURs), and updating the country's Nationally Determined Contributions (NDCs).

However, the legal framework underpinning KEPA's authority has significant shortfalls. While the Environment Protection Law (KEPA, 2015a) provides KEPA with broad authority, there is currently no climate framework or mandate for specific emissions reduction targets or precise enforcement mechanisms. Furthermore, the Environment Protection Law and its implementing bylaws reveal significant gaps when scrutinised. For instance, Article 122 of the Law mandates energy-saving measures in the design and construction of governmental buildings only. This article fails to extend to other critical sectors such as the residential, commercial, or industrial sectors which constitute the bulk of national energy consumption. Furthermore, the law does not address water efficiency and conservation. This omission is particularly significant given Kuwait's heavy reliance on energy-intensive seawater desalination.

Additionally, the framework for implementation of the aforementioned efficiency measures is fragmented. For instance, Article 123 of the Law outlines the requirement for establishing efficiency standards and specifications for all energy-related devices. Through executive bylaw establishing the rules under Article 123 (KEPA, 2020), KEPA delegates the responsibility for specifying the efficiency technical specifications, standards, and executive procedures related to all energy devices, equipment, systems, and consumable materials to the Ministry of Electricity and Water. While the responsibility for issuing the aforementioned and publishing them in the official gazette is delegated to the Ministry of Commerce and Industry, and the enforcement of the technical specifications and standards is delegated to the Public Authority for Industry. Such delegations of responsibility hamper effective action and signals a governance gap (Wiseman, 2017, Bergsten et al., 2019, Alshadafan, 2021).

2.9.2 Climate strategies as policy instruments

Given Kuwait's fragmented governance framework and the absence of a standalone climate law, national climate policy is guided primarily by two key strategies formulated by KEPA. The first strategy is the National Adaptation Plan (KEPA, 2019b), and the second is the most recent National Low-Carbon Strategy 2050 (KEPA, 2024). These two documents function as frameworks in order to maintain coherence with the nation's international commitments by explicitly linking to Kuwait's NDCs under the Paris Agreement and broader UNFCCC obligations.

Although the government of Kuwait has set ambitious objectives for the achievement of carbon neutrality, a review of the published documents (KEPA, 2015b, KEPA, 2019a, KEPA, 2019b, KEPA, 2019c, KEPA, 2021) reveals a significant gap between the high-level aspirations and the existence of actionable implementation pathways. Such a gap is observed, for instance, with the National Low-Carbon Strategy 2050, which has been announced and reinforced at multiple Conference of the Parties (COP) summits. The strategy was first announced at COP27 with pledges to achieve carbon neutrality in the oil and gas sector by 2050 and economy-wide neutrality by 2060 (KUNA, 2022), reiterated at COP28 (KUNA, 2023), and reinforced at COP29 in Baku through commitments to harmonise economic growth with low-carbon development and climate resilience (KUNA, 2024).

Despite this sustained international affirmation, the strategy itself remains to date an announced vision rather than a published framework, with no detailed policy instruments or actionable implementation pathways available to guide national decision-makers and stakeholders across sectors. In order to address this gap, Kuwait Oil Company (the entity which bears the largest share of responsibility for achieving Kuwait's carbon neutrality target) has recently contracted a private consultant to develop the national masterplan for achieving the pledged targets (KOC, 2024b). The masterplan will include a phased deployment strategy for wind and solar power in order to achieve the pledged 2050 renewables capacities (KBR, 2024). Therefore, this indicates that the practical design of the implementation pathway for Kuwait's carbon neutrality agenda is still in its early stages

2.9.3 Overlooking the energy-water nexus

The current environmental governance framework remains narrowly focused on energy and does not explicitly address potable water resources or incorporate water-related challenges into its framework. Overlooking the critical interdependency of Kuwait's energy and water systems has multiple major consequences: First, it fails to address the stability and reliability of the nation's potable water supply by not accounting for potable water concerns. This is a significant issue in a country that is already constrained by minimal natural freshwater resources. Second, it overlooks the structural lock-in of emissions resulting from Kuwait's reliance on energy-intensive desalination. Finally, a disconnect is created between the country's climate ambitions and the identification of specific frameworks needed to decarbonise the electricity-water nexus without undermining the integrity of the potable water supply.

The most significant shortcoming of Kuwait's environmental governance framework is its failure to address the energy-water nexus as an integrated system. As established above, the regulatory focus remains narrowly on energy. At the moment, there is no explicit incorporation of potable water resources or water-related challenges into any of its energy strategies. This oversight has profound consequences that undermine the nation's stated climate ambitions of net neutrality.

By treating water demand as a given that could always be met through desalination rather than a variable to be managed, the policy framework fails to address the long-term stability and reliability of the potable water supply in a nation with minimal natural freshwater resources. This is a critical omission for national water security. More importantly, this siloed approach creates a direct and powerful barrier to decarbonisation. Without policies to manage water end-use, any increase in potable water demand must be met by expanding energy-intensive desalination capacity. This reinforces a structural lock-in, where progress on decarbonising the electricity supply is undermined by the ever-growing energy demands of an unmanaged water sector.

This approach runs contrary to the principles of integrated resource planning, which is a foundational concept in the energy policy literature. Bazilian et al. (2011) and Mansson (2015) argue that co-managing interconnected resources is essential for achieving optimal, least-cost, and sustainable system-wide outcomes in resource-constrained regions. By failing to adopt a nexus approach, Kuwait's policy architecture creates a disconnect between its high-level climate targets and the on-the-ground frameworks needed to decarbonise the electricity-water system without compromising the stability, reliability, and security of the potable water supply. To date, this linkage has been inadequately quantified in the specific context of Kuwait. The potential for integrated electricity and water demand-side management to unlock more cost-effective decarbonisation pathways has been largely overlooked.

2.10 Modelling approaches to understand the water-energy nexus

Some decisions regarding energy systems that have to be made today necessitate foresight into the future consequences over the system. Energy system models are tools based on mathematical formulas helpful in exploring how energy systems could change in the future. These models enable scenario development for the medium and long term, providing insights into different pathways toward an economical and sustainable energy system. By gaining these insights, decision-makers can make more informed decisions regarding investment and policy plans. Examples include energy efficiency plans, technology innovation assessment, subsidies, and taxation (Wei et al., 2006).

The term “model” refers to the mathematical formulae that capture the relationship between different variables in the energy system. A clearly defined scope and boundaries for the system are required for such mathematical formulas to capture the complex interconnections between different sectors of the system (Beaujean et al., 1977).

Research on residential demand-side modelling spans engineering physics, econometrics, behavioural science and systems analysis, leading to a set of complementary paradigms that have co-evolved over four decades. A range of model paradigms have been developed that are summarised in Table 2-6. Typical uses and the policy relevance of these models are summarised in Table 2-7.

A bottom-up approach, which is also referred to as engineering approach, uses disaggregated data for solving purposes. The disaggregated data are constructed through detailed analysis of existing technologies and indicators driving the technology development. Bottom-up models attempt to capture the impact of the energy usage of various devices and systems by focusing on the various demand sectors in the economy (residential, industrial, commercial, etc.). However, bottom-up models are criticised for not reflecting end-users decisions and therefore providing unrealistic system evolution (Hourcade et al., 2006). There are three main methodologies for bottom-up approaches: accounting, simulation and optimisation.

Early bottom-up engineering models focused on energy and can attribute savings to specific measures and for compliance with building codes and product standards. Examples include the UK's SAP/BREDEM lineage and whole-building simulation engines such as EnergyPlus, which provide heat and mass balance representations but historically assume standardised occupancy and behaviour (GOV.UK, 2025, BREEAM, 2025, US DOE, 2025, Crawleya et al., 2001). For water, end-use studies like REUWS established empirical baselines for fixtures and diurnal patterns that underpin conservation analysis (WRF, 2016).

A top-down approach, which is also referred to as a macroeconomic approach, uses aggregated data for solving purposes. It does not explicitly represent technologies; however, most efficient technologies are set by economic, social and demographic behaviour on demand. This modelling approach captures the interaction between energy and other economic growth components and provides a comprehensive view of the economy (Murphy et al., 2007). The strength of this approach comes from its consistency, links to historical references, economic frameworks and equilibrating prices (Helgesen, 2013). Meta-analyses consistently find residential electricity demand to be price-inelastic in the short run, with larger long-run responses, while water demand exhibits modest but policy-relevant elasticities that depend on tariff structure and climate (Espey & Espey, 2004, Zhu et al., 2018, Dalhuisen et al., 2003, Espey et al., 1997). These approaches capture aggregate responses to price and macro drivers, but poorly represent novel technologies, heterogeneity, and non-price behavioural barriers. For a system transformation as envisaged for Kuwait in this study, it is unlikely that elasticities derived for the past would be appropriate for the future in a system with substantial end-use technological change.

Stock models combine the strengths of engineering with some aspects of top-down economic approaches by embedding physics-based end uses within stock representations calibrated to survey and administrative data. The Cambridge Housing

Model and NREL's ResStock exemplify this by coupling detailed technology options and building archetypes with stochastic or probabilistic assignment of characteristics; they support robust scenario analysis for mass retrofit and electrification programmes (GOV.UK, 2015, GOV.UK, 2012, NREL, 2023, NREL, 2025b, BEIS, 2021a). Such hybrids have been extended to new contexts (such as cost-optimal retrofit packages in Jordan) demonstrating sensitivity to national prices, climate, and construction practices (Bataineh et al., 2022).

Agent-based models (ABM) explicitly represent heterogeneous households and social influence, so it can explore adoption dynamics for technologies such as rooftop PV and heat pumps, and also energy use behavioural change. Empirical ABMs such as Rai & Robinson's city-scale PV model and national tools like NREL's dGen demonstrate how peer effects and bounded rationality shape diffusion and policy effectiveness (NREL, 2016, NREL, 2025a, Rai et al., 2015). Recent Middle East work applies ABM and optimisation to urban energy performance in the UAE and to household electricity scheduling in Iran, which suggests that ABMs can also be applied to rapidly growing cities in hot climates (Mussawar, 2024, Shima et al.).

System dynamics (SD) focuses on stock–flow turnover, delays and feedbacks that generate path dependence, rebound and lock-in. In buildings, SD has been used to examine the timing of policy instruments and the long-run interplay between technology costs and uptake. FTT:Heat's diffusion formalism and the WEAP framework for integrated water planning both highlight the value of dynamic policy stress-testing under uncertainty (Knobloch et al., 2021, SEI, 2025, WEAP, 2025). In arid, energy-exporting systems, SD is well suited to analyse the energy–water nexus, where desalination and cooling loads co-evolve with demand-side efficiency (e.g. studies in Dubai/Abu Dhabi) (Rizvi et al., 2020, Younis et al., 2023). However, it can be challenging to represent technology granularity in a system dynamics model and the dynamical relationships are difficult to understand and hence represent. Pathways produced by such models are unlikely to be the optimal pathways from a national economic perspective unless a model has a high level of optimisation.

Microsimulation models operate at the household level to capture distributional and targeting effects central to fuel poverty and equity appraisal. The SIMDEUM enables bottom-up aggregation of heterogeneous savings, timing, and peak impacts. Dubai is beginning to assemble a high-resolution smart-meter dataset to populate such models with culture-specific and climate-specific profiles (CSE, 2025, Data.gov.uk, 2025, KWR, 2025, Blokker et al., 2010, Rizvi et al., 2020).

Finally, energy system optimisation models such as MARKAL, TIMES, PRIMES, and MESSAGEix provide the whole-system context to quantify how residential efficiency and electrification propagate through capacity expansion, primary energy, and emissions. They remain essential for evaluating the system value of demand reduction, resource adequacy, and carbon budgets, albeit with simplified household behaviour. Linking hybrids/ABMs/SD to system models (soft-linking or iterative coupling) yields consistent policy narratives from dwelling to grid. This whole-sequence perspective has underpinned national strategies in the UK and is increasingly mirrored in Gulf countries pursuing Vision 2030/2050 pathways (Daly et al., 2014, UCL Bartlett, 2021, IEA-ETSAP, 2022, E3Modelling, 2018, E3Modelling, 2025, IIASA, 2020, MESSAGEix.org, 2024, KAPSARC, 2025, Mehraban et al., 2024, Younis et al., 2023).

Table 2-6 Summary of model paradigms used for demand-side analyses.

Model Type	*Summary*
Bottom-Up Engineering	Physics-based end-use/device or fabric/HVAC simulation aggregated to buildings/stock. High technical detail and transparent assumptions, supports measure-level savings and interaction analysis. However, often assumes static occupancy/behaviour so overlooks rebound effects; obtaining data and calibration are challenging; and may overlook building stock heterogeneity.
Top-Down Econometric	Econometric relationships between aggregate demand and drivers (prices, income, weather, policy). Captures elasticities and macro trends; evaluates historic policies. However, little technology granularity and weak on novel conservation measures.
Stock	Integrates engineering end-use detail with behavioural/economic components and stock evolution. Balances technical realism and behaviour; supports uptake pathways and equity analysis. However, data-intensive, complex to calibrate and does not consider the wider energy system.
Agent-Based (ABM)	Represents households as heterogeneous agents with decision rules, peer effects and bounded rationality. Captures diffusion and neighbourhood effects, and can represent spatial and temporal heterogeneity. However, makes assumptions on behaviour, has validation and computation challenges, and does not consider the wider energy system.
System Dynamics	Stock–flow models with feedbacks, path dependence, rebound and delays in adoption/demand. Explores long-run dynamics, timing, lock-in and unintended consequences. However, has lower technology granularity, and structural/parameter uncertainty that require broad assumptions.
Microsimulation	Household-level simulation using survey/admin microdata and probabilistic characteristics/choices. Captures heterogeneity and equity, and links to detailed stock and socio-demographics. However, has high data/compute needs and is sensitive to micro-parameters.
Energy System Models	Whole energy system optimisation/simulation with residential measures represented as technologies/options. Considers system-wide costs, emissions and capacity impacts, and identifies long-term pathways under constraints. However, has simplified household representation, limited or no behaviour change, and previous models have not considered water as a resource.

Table 2-7 Typical uses and the policy relevance of model paradigms for demand-side analyses.

Model Type	*Typical Use*	*Policy Relevance*
Bottom-Up Engineering	Retrofit packages; building codes/standards compliance; hot-water end uses and appliance MEPS.	Evidence base for MEPS/product standards and building regulations; quantifies technical potential, bills and emissions savings.
Top-Down Econometric	Price/income elasticity estimation; tariff and policy evaluation; aggregate forecasting.	Informs tariff/carbon price design; assesses rebound and distributional effects at aggregate level.
Hybrid	Housing stock modelling; heat pump/efficiency uptake; programme design.	Tests portfolios (subsidies, standards, information) and distributional impacts under realistic savings.
Agent-Based (ABM)	Adoption/diffusion of PV, heat pumps, and conservation behaviours; targeting and nudges.	Design and targeting of incentives, social norm campaigns and local programmes.
System Dynamics	Policy stress-testing; sequencing standards vs. subsidies; housing stock turnover; water–energy planning.	Assesses long-run packages, crowding-in/out and phase-in timing for codes and incentives.
Microsimulation	National housing stock retrofits; fuel poverty and targeting; event-based water use.	Supports targeting and equity appraisal; bottom-up aggregation to local/national outcomes.
Energy System Models	Decarbonisation pathways; system value of demand reduction/electrification; carbon budget compliance.	Aligns residential measures with carbon budgets and power system needs; quantifies system benefits of efficiency.

2.10.1 Importance of the interdependency of electricity and water

Interdependency refers to the mutual reliance and interconnection of entities, processes, or systems, emphasising that these elements are not isolated but are affected by and dependent on one another (Ritchie et al., 2009). In energy systems, understanding interdependency facilitates the assessment of the vulnerability and resilience of systems to disruptions, such as infrastructure vulnerability to climate change or resource availability, or potential cascading failures where disruptions in one system segment can propagate to another (Wang et al., 2012, Buldyrev et al., 2010).

The concept of interdependency is particularly relevant when examining the water-energy nexus, as the two resources are intricately linked through various processes (Hussey et al., 2012). In Kuwait, the principal linkages are the thermal cogeneration plants and the relationships between population and demand for each commodity. This mutual dependence has significant implications for resource management, efficiency, and sustainability of the two resources (Bartos et al., 2014, van Vliet et al., 2016).

Understanding interdependencies facilitates the development of policies and regulations that promote sustainable and resilient interdependent systems by considering the effects of interdependency (Pournaras et al., 2020). It also facilitates analysis and assessment of the implications of policy decisions on one system segment on others (Coeurdacier et al., 2013). Without a comprehensive understanding of the interactions between energy, electricity, and water across multiple levels could lead to policy measures promoting aspects in one segment, unintentionally fostering negative outcomes in another, which is referred to as policy spillover (Hussey et al., 2012, Scott et al., 2011).

An example of policy spillover with energy-related nexuses was witnessed with the US biofuels policy and the implementation of the Renewable Fuel Standard (RFS) programme (Kling et al., 2017). The RFS focused attention on the energy system and the environmental gains that would be attained through carbon emissions reductions. Farrell et al. (2006) notes that an unintended policy spillover occurred, impacting corn prices in the crop market, when farmers diverted their produce into the fuel market. In addition, the impact of the US biofuels policy extended beyond just affecting the price. Research has shown that it also led to changes in land use (Liu et al., 2015), creating concerns with food availability and security (Hertel et al., 2010), and increasing pressure on water systems due to expansion of irrigated cropland biofuels market demand (Taheripour et al., 2013).

The relationship between energy and water systems is often viewed in literature as separate. In reality, however, they are interdependent and must be considered together in a water-energy nexus. This is particularly important in regions that have high water stress and are experiencing rapid changes in resource production and consumption. Policies surrounding renewable energy and decarbonisation of energy systems can have a significant impact on water supply in water-scarce regions that rely on seawater desalination for their potable water needs. For this reason, policy makers and system planners need to consider both water and energy domains as part of a closely coupled system.

2.10.2 Energy system modelling

Energy system models are differentiated by the two main analytical approaches: the top-down approach and the bottom-up approach. The selection of an appropriate modelling approach depends on data availability, temporal and spatial coverage and technological and economic aspects. The two methods significantly vary in how they identify systems, a top-down approach and a bottom-up approach (Wene, 1996). Therefore, each approach would provide different insights to policymakers (Wilson et al., 1993).

There are four main types of energy analysis models distinguished by their focus, spatial, and temporal resolutions:

- Energy system planning models, used to analyse the possible evolution pathways of energy systems. Examples of these models are MARKAL and its successor TIMES (The Integrated MARKAL-EFOM System), developed by the International Energy Agency (IEA) ETSAP Technology Collaboration Programme, and LEAP (Long-range Energy Alternatives Planning System), which is developed by the Stockholm Environment Institute.
- Energy system balancing models, used to analyse the balance between the supply and demand for energy. These models are used to calculate energy source contributions to the supply side. Examples of energy system balancing models are EnergyPLAN, developed by the department of development and planning at Aalborg University, and the Hybrid Optimisation of Multiple

Energy Resources (HOMER), which was developed by the National Renewable Energy Laboratory (NREL).

- Grid dispatch and operation models, used to examine the electricity system operation and reliability. An example of a grid model is DYMONDS (DYnamic MOtif-NoDes).
- Macroeconomic models, such as GEMINI-E3, which are used to analyse the relationship between energy systems and the rest of the economy (Bernard et al., 2008).

Energy system long-term planning and balancing analyses are most appropriate to investigate the research questions. In addition to TIMES, MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) and OSeMOSYS (Open Source Energy Modelling System) are widely-used, bottom-up energy system optimisation models.

Energy system optimisation modelling methodology looks towards a more extended timescale, exploring the evolution of energy system over decadal timescales. They can represent wide geographical coverage spanning regional to global levels. The energy system optimisation methodology models both the supply and demand sides of the energy system (Fodstad et al., 2022). Energy is delivered through a set of technologies to meet energy service demands (Fleiter et al., 2011).

Energy system optimisation models require a spatial and temporal description of the supply and demand inputs and outputs. This is achieved through the reference energy system that allocates a resource through unlimited routes to a specific end-use demand and achieves the best solution. Furthermore, they offer a high level of disaggregation and extensive technological coverage allowing for the assessment of different technology combinations and futures and aide in analysing both priced and non-priced policies (Di Leo et al., 2015).

2.10.3 Examples of energy system models

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) was developed by the International Institute for Applied Systems Analysis (IIASA). The model has since been used by the International Atomic Energy Agency (IAEA). MESSAGE is a dynamic linear programming model of energy systems at technology level. It covers the entire energy system from primary energy extraction, to conversion processes, and final energy consumption. It allows the evaluation of different technologies or processes of producing a commodity depending on the disaggregation level of the model (Messner, 1997). The objective function of MESSAGE is to minimize the total discounted systems costs including costs of emissions of the energy system as a whole (IIASA, 2020). And it can be used at global, national, and multi-regional level analysis.

OSeMOSYS (Open Source Energy Modelling System) is an open-source long-term system optimisation model for long-term system planning. It is designed to provide accessibility to energy system modelling to a wider range of users from developing countries to businesses and academia. This is achieved by requiring less significant investment in costs to license, build, and operate its models (Howells et al., 2011). The model objective function is to minimise the cost of exogenously defined demands for energy services under range of assumptions such as projections of fuel prices, technology, and primary energy resource availability. It can be used at global, regional, national, and sub-national level analysis (Taliotis et al., 2023).

TIMES (The Integrated MARKAL-EFOM System) is a techno-economic energy model generator developed in the scope of the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). It is a demand-driven partial equilibrium model that can represent, optimise and analyse energy systems over a short, medium, or long-term horizon and on local, regional and global scales (Loulou et al., 2016).

TIMES employs linear optimisation techniques that represent the energy system as a network of technology processes (such as different types of power plants) and commodities (such as energy carriers and emissions). Energy flows from resources to services demands through paths optimised by the model. The model objective function is to minimise the total energy cost or maximise the total energy surplus while ensuring that energy services demand is being met by making decisions on commodities and processes.

The model allows sectors to have different levels of disaggregation. It also offers higher number of time periods with varying lengths, facilitating the inclusion of seasonal or diurnals supply and demand dynamics.

A TIMES model database can include technologies in all sectors of the economy, namely: primary energy extraction, energy processing and conservation, energy transport, and end-use by its main sectors (residential, commercial, industry, transport). Technologies are characterised by their input output of commodities, efficiency, costs and environmental impacts. Commodities are characterised by their potential availability, demand and cost of extraction.

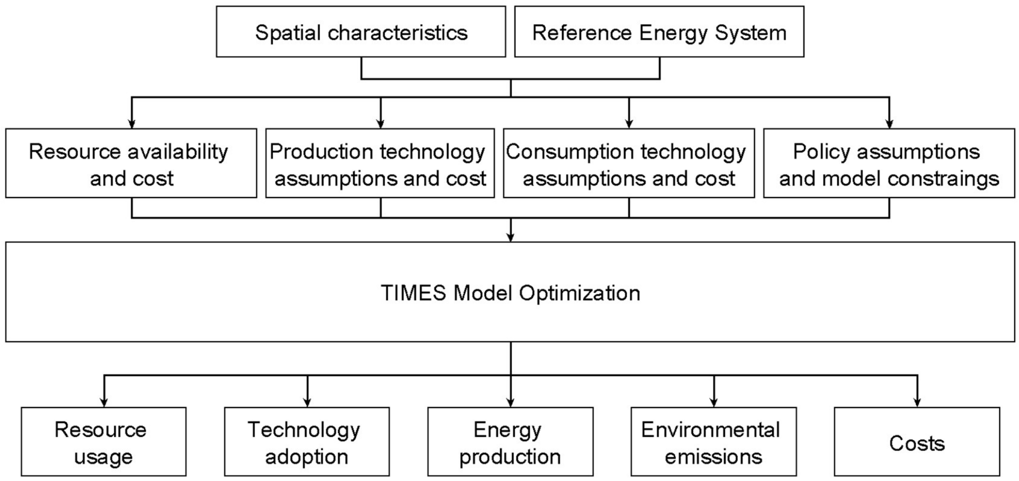

Figure 2-6 Illustration of a typical TIMES model

2.10.4 Application of energy system models for water-energy nexus

Energy system model scenarios for future energy mixes typically do not take into account the potential impact on water supply. Such studies often view water as a constant input cost for energy technologies and do not take water-energy interactions into consideration. This is particularly true with bottom-up optimisation energy systems models.

Existing water-energy models primarily focus on water usage in cooling power generation processes or energy usage in water desalination, treatment, and pumping processes rather than the interaction between electricity production processes, water production processes, and end uses of both electricity and water. For example, Bouckaert et al. (2011) presented a water module added to the global TIMES Integrated Assessment Model (TIAM-FR). Developed by the Centre for Applied Mathematics at MINES ParisTech in France. TIAM-FR is a multiregional world model that addresses 42 end-use energy demand groups across six sectors. The water module (TIAM-FR Water) adds water resources used for both upstream and downstream of the energy chain. Upstream uses include oil extraction, refining, and processing, while downstream use is electricity production (cooling of power generation processes). TIAM-FR Water projections showed that worldwide electricity generation could double by 2050, raising water consumption three times higher than its current levels. The model results demonstrate that water plays a crucial role in energy production and can serve as a tool to determine if future energy mixes are feasible considering water availability.

TIAM-FR Water was also used by Dubreuil et al. (2013) to examine water allocation issues in the Middle East. Model results have shown that electricity demand can be underestimated by nearly 40% when the additional demand for electricity caused by water needs is overlooked. Incorporating water into the energy system model enabled the estimation of the structural and technological changes necessary to meet this demand. It also enables the analyses of unconventional water resource allocation to compensate for water scarcity.

Huang et al. (2017) focused on the challenges regarding energy and water resources in China's sustainable development pathway. To address this issue, a China TIMES model was developed to integrate the country's energy system with its water resources. The main objective of the model was to project the water demand in the power sector to evaluate the impacts of China's Intended Nationally Determined Contributions (INDC) and water constraints on electric power generation.

The study revealed that the implementation of carbon dioxide mitigation targets could result in a decrease in water withdrawal from the power sector by encouraging the growth of renewable technologies which use less water. The study also found that adding a cost to the power sector water withdrawal for cooling can influence the choice of generation technology. Lastly, if carbon dioxide mitigation targets are implemented alongside water constraints, renewable technologies become prevalent.

Cullis et al. (2018) mentions SATIM-W model, which is an expanded version of South Africa's TIMES energy system model. SATIM-W accounts for regional water supply availability for different energy supply technologies. The model takes into consideration that different power technologies are situated in various parts of the country with different levels of water availability and varying infrastructure development cost and supply costs. The model also includes water supply options, such as investments in dams and water transfer projects, and incorporates the cost and quality of water. Thus, allowing the model to choose between trade-offs within the supply sector. The model is responsive to regional cost and availability of energy supply and is connected to a single national demand-side.

By including regional water supply costs, the study projects that the cumulative water consumption for the power sector is reduced by 77%, with a modest increase in system cost of 0.84%. However, including water costs also led the system to choose dry-cooling technology options for electric power generation, resulting in lower efficiency generation units and higher carbon emissions. As a result, the study concluded that there is a significant difference in the optimal future energy mix when water variability and availability are taken into consideration.

Zamanipour et al. (2023) developed a TIMES model for Iran, which aims to investigate the effects of water scarcity on the optimal expansion of Iran's power system. The study found that water costs led the model to invest in dry-cooling technology options for power generation, which increased carbon emissions. Introducing a carbon tax was found to be an effective way to increase the penetration of renewable energy in the system and reduce the switching from wet cooling to dry cooling in power generation. This helped maintain a stock of efficient power generation units and slow down the increase in carbon emissions. The study findings are consistent with the findings of Cullis et al. (2018), which used the SATIM-W model to model South Africa's regional water supply availability for different energy supply technologies.

Groppi et al. (2023) developed a model using OSeMOSYS that aimed to analyse long-term water and energy supplies for the island of Favignana in Italy. The model used an hourly resolution to simulate the energy system and considered potential synergies that could be offered by reverse osmosis (RO) desalination and the use of water storage to help store excess electricity.

The model also accounted for the indirect emissions of maritime transportation involved in delivering water and fuel for desalination to the island. The results show that the system always shifts completely to RO desalination instead of water transport.

Although the shift results in higher carbon emissions, implementing a carbon tax does not affect the shift.

Furthermore, the installation of water storage to store excess electricity was decided by the model based on a trade-off between the cost of installing storage and the cost of curtailing PV power. The model favours curtailing PV power rather than expanding energy storage since excess electricity was only achieved during summer months. Additionally, the model projects that implementing limits on emissions delays PV investment until prices get lower, leading to higher emissions down the projected horizon. Setting a carbon tax, however, is more effective in promoting PV penetration.

Ramos et al. (2022) presented a framework for representation of the Climate, Land, Energy, and Water (CLEW) systems in energy system models. The water component of the model focused on water resources, including surface water, groundwater, precipitation, and seawater; as well as conversion technologies such as water treatment and desalination plants; and transmission and distribution of supply. However, the study did not consider end-use. To incorporate cross-systems considerations in the model, a soft-linking of simple accounting methods was employed. The framework was implemented in OSeMOSYS, which enabled the representation of CLEW systems.

In conclusion, and following the thorough review of energy system models that focused on the issue of energy-water interactions, it was concluded that none of the studies reviewed delved into the end-use of water demand and water conservation measures.

2.10.5 Modelling approach in this study

A range of models could be used to explore the four research questions. Table 2-8 summarises the options.

For RQ1, economic and stock models could be used. For this study, an econometric approach was chosen and is discussed in Chapter 4.

Both system dynamics and energy system models could provide insights on the other three research questions, and agent-based models could also contribute to RQ2. A decision was made to develop an energy system model, for a number of reasons:

- A goal of the study was to understand the impact of efficiency measures on the supply side of the energy system. So, the model needed to include the whole energy system.
- The study is from the perspective of a policymaker, who would be particularly interested in the costs and benefits of efficiency measures and the implications for supply side planning. Therefore, an economic model using a social planner perspective was required.
- Primary research would be required to understand the drivers of energy and water technology adoption and efficiency take-up (e.g. government standards; efficiency labelling; subsidies removal). Such research was not available, so the focus was placed on the implications of the success of such drivers. A high level of technological detail was needed to fully understand the potential implications. Energy system models are more appropriate than system dynamics models where a high level of detail is required and where the drivers are not well understood.
- An existing energy system model of the Kuwaiti supply side was available, although the data required substantial revisions. No system dynamics model of Kuwait was available.

There were a number of challenges associated with using an energy system model. Behaviour is not solely driven by cost, so scenarios were created that assumed a range of technological and behavioural change. Even if cost were the primary driver, electricity and water are heavily subsidised in Kuwait.

The socio-political context of Kuwait, particularly the prevalence of high energy subsidies and the associated challenges of reform, presents direct implications for the modelling approach adopted in this thesis. Acknowledging that policy mechanisms like 'hypothecation' can enhance public acceptance, and thus the feasibility of subsidy reforms, shapes both the interpretation of Kuwait’s energy system model primary unsubsidised scenarios and the design of the comparative sensitivity analysis that includes subsidies.

From a modelling perspective, if public acceptance mechanisms render subsidy removal a plausible future policy trajectory, then model scenarios that explore systems without subsidies transition from purely theoretical ideal cases to representing potentially achievable pathways. This underpins the relevance of the 'no subsidy' scenarios as it can then be viewed not just as a theoretical economic optimum, but as a benchmark against which feasible, subsidy-reformed futures can be compared.

Consequently, Section 2.5 provided context on the level of subsidies in Kuwait, the difference between real production costs and the subsidized cost, and it was concluded that from a policymaker's perspective the model is best run unsubsidised. While the detailed econometric modelling of public acceptance itself, or the precise behavioural responses to specific hypothecation schemes, is beyond the scope of this techno-economic research, an awareness of these factors is crucial for framing the scenarios developed and interpreting their relevance to Kuwait's actual energy transition.

Table 2-8. Potential modelling approach for each research question.

	Research Question	*Appropriate models*
1	How might baseline electricity and water demands in Kuwait be affected by socioeconomic changes and government housing policy?	Top-down econometric; stock
2	How might residential efficiency improvements affect future demands for electricity and water?	Agent-based; system dynamics; energy system models
3	To what extent could these residential efficiency improvements influence the optimal electricity-water supply technology portfolio?	System dynamics; energy system models
4	What are possible decarbonisation and emissions reduction pathways while maintaining the reliability of the potable water supply?	System dynamics; energy system models

Unlike most parts of the world, the unique case of Kuwait and the Gulf countries the primary and most challenging energy-intensive sector coupling is between electric power and water. Thus, electricity-water nexus is viewed as a pressing challenge in these hydrocarbon-rich countries that complicates efforts towards energy transition, decarbonisation, freeing hydrocarbon resources for exports, and ensuring stability and sustainability of potable water supply. In order to maximise hydrocarbon exports, Kuwait's most significant energy policy mechanisms relate to managing domestic consumption.

Governments across the globe have widely utilised the TIMES model to carry out energy policy analysis in the development of significant legislation or climate targets. One particular country leading the way is the UK (Contestabile, 2023), where the MARKAL and TIMES models have been employed for nearly twenty years to aid the formulation of their climate change policy. The UK TIMES has been developed by the UCL and the UK Department of Business, Energy and Industrial Strategy and was recently used to inform the UK Government's Net Zero Strategy (BEIS, 2021b). Table 2-9 provides examples of TIMES models utilised by governments around the world as a tool to aid policymaking.

For this research, the IEA-ETSAP TIMES modelling framework's strength makes it stand out due to its ability to assess the economic value and optimal deployment pathways for various supply-side and demand-side technologies, while also capturing the dynamic relationship between commodity supply and demand that shapes the allocation of various technologies; a capability particularly valuable for conducting various sensitivity analyses that compare the primary model outcomes (derived without subsidies) against scenarios where such distorting market signals are introduced to assess their impact on optimal technology pathways and overall system costs.

However, it is important to acknowledge the inherent limitations of TIMES in this context. Being primarily a techno-economic model, TIMES does not endogenously model consumer behaviour, social preferences, or the direct impacts of policy instruments that influence public acceptance. The model assumes rational economic actors seeking the least-cost solutions based on the price signals they face. Therefore, while TIMES can quantify the societal cost/benefit of removing subsidies and the potential for efficiency technologies under different price regimes, it cannot directly model the consumers' responses to such policy shifts, nor the efficacy of specific revenue recycling mechanisms.

Understanding these behavioural and social dimensions requires complementary analytical approaches. Nevertheless, by outlining the techno-economic advantages of specific pathways, including the benefits of energy efficiency, TIMES provides a crucial evidence base that informs why subsidy reform might be beneficial, thereby highlighting the importance of considering politically feasible implementation strategies like hypothecation in the broader policy discussion, even if these are not directly modelled.

Table 2-9 Examples of TIMES model utilisation by governments for policymaking . ***Source:*** Adapted from Contestabile (2023).

Country	*Example of TIMES model application*
Denmark	Analysis for Danish Energy Agency renewables targets (Grohnheit et al., 2011)
Egypt	National Energy Strategy to 2035 (Rady, 2019)
Finland	Energy and Climate Roadmap 2050
Greece	National Renewable Energy Action Plan, National Energy Efficiency Action Plan, and National Energy Planning Roadmap to 2050
Ireland	Negotiations with the European Union regarding the Effort Sharing Decision for the 2030 Low Carbon Energy roadmap (Chiodi et al., 2013, Welsch et al., 2014)
Kuwait	Analysis nuclear energy potential in Kuwait for Nuclear Energy Committee; and analysis for the development of renewable energy strategy (O. Alsayegh et al., 2012)
Qatar	Intended to support policymaking at the Ministry of Environment and Climate Change and Qatar Energy (Contestabile, 2023)
South Africa	Integrated Resource Plan and the National Climate Change Response Green Paper (Cullis et al., 2018)
Sweden	Climate policy to reach net-zero by 2045 (Forsell et al., 2013)
UK	Committee on Climate Change carbon budgets
USA	Analysis for least-cost and appropriate actions to achieve statewide greenhouse gas emissions reductions

2.11 Research gap and conclusions

Energy system models are valuable tools for facilitating decision-making processes related to energy system evolution and sustainability. They can provide insights into various strategies that can be employed to satisfy future demands and environmental objectives. Furthermore, these models can shed light on the significance and worth of different technologies within the energy system, as well as pinpoint the optimal times for investments.

Energy and water systems are often treated as separate systems across the entire supply chain, from extraction to production and consumption. However, the close interdependencies between these systems in some countries require a perspective of the water-energy nexus. Despite this, few energy system models consider the water-energy interlinkage, which is crucial for sustainable development, especially in regions with high water stress and rapid changes in resource production and consumption.

In particular, the issue of water security in the Gulf Cooperation Council countries, and particularly Kuwait, is critical. Yet, limited literature is available on the future of electricity and water demands in the region and the water-energy nexus. A thorough review of the existing literature reveals that residential water end-use has not been integrated into bottom-up optimisation energy system models, highlighting a gap in energy systems optimisation modelling.

There is a pressing need for further research in this area, which could inform sustainable strategies and resource management for the GCC region and Kuwait's future. In response to this need, this research presents the first attempt to model the residential sector's electricity and water end-use, including the dynamic relationship between supply and demand, in a country experiencing extreme freshwater scarcity.

By incorporating end-uses, the dynamic relationship between supply and demand is enabled. The potential impact of residential efficiency improvement will be analysed along with its influence on the supply side. Understanding the dynamic and complex relationship between water and energy is crucial for sustainable development. This research aims to bridge the gap in energy systems optimisation modelling by incorporating residential water end-use and analysing the potential impact on the supply side. The results of this research and the model it developed could inform sustainable strategies and resource management in regions with high water stress and rapid changes in resource production and consumption, like Kuwait.

Chapter 3

MODELLING KUWAIT'S ELECTRICITY-WATER SYSTEM

3.1 Introduction

This chapter presents the rationale and methodology followed to create Kuwait's Electricity-Water System Model (KEWSM) in order to answer the research questions. Section 3.2 presents Kuwait Institute for Scientific Research (KISR) Power Water (TIMES-KPW) Model. The rationale for an electricity-water system model is presented in Section 3.3, and the KEWSM design is described in Section 3.4. Section 3.5 introduces KEWSM reference energy system. Section 3.6 introduces Kuwait's housing typology assumptions and stock estimations leading to the estimation of residential services demand. Section 3.7 introduces the physical and social drivers of Kuwait's electricity and water demand that were introduced along with the methodology developed for projecting end-use demand. Finally, an evolution of KEWSM is presented in section 3.8.

3.2 Rationale for electricity-water system model

Kuwait's potable water supply is inextricably tied to energy resource availability, primarily hinging on energy-intensive seawater desalination processes. The relationship between water and electricity stresses the need for an integrated, strategic approach towards the long-term development of solutions that address water supply and electricity demand together in a sustainable manner.

Modelling the electricity-water nexus from both the supply and demand sides would allow a multi-dimensional analysis of the nexus complexities. Such approach embeds water supply and demand issues into an energy model, providing a holistic perspective that factors water end-use and efficiency improvement possibilities. The underlying strength of this approach lies in uncovering the implications of water demand on energy consumption, thus providing an opportunity for improved analyses of electric power supply pathways.

Kuwait's residential sector is a substantial consumer of electricity and water. This sector has a significant impact on the overall electricity-water system stability and supply-demand balance. Disaggregating the electricity and water consumers into segments such as residential and non-residential enables us to gain insights into how the electricity-water system may evolve due to different socioeconomic conditions and policies.

Furthermore, the residential sector consumption characteristics are complex and intertwined. Furthermore, demographic characteristics can yield different consumption patterns. Treating the residential sector as a single unit often smoothens the difference between the different house categories. Therefore, a disaggregation of the residential sector into multiple residential segments based on archetypes can further improve the model output and results analysis.

Disaggregating the residential sector into multiple segments enables us to distinguish differences in consumer behaviour, such as the variations between residents and migrant workers. Additionally, it allows capturing the technology trends across the different residential segments. Furthermore, the disaggregation aids in assessing the impact of government policies targeting different consumer groups and house types.

This research presents the novel approach of integrating the residential water end-use into the TIMES model, particularly for nations where seawater desalination technologies constitute the primary source of potable water. It does that by significantly improving TIMES-KPW to include residential demand-side technologies for both water and electricity, house types, consumption patterns, and efficiency improvement measures.

TIMES-KPW focused on the electric power sector (the supply side). The model represented the entire country as a single aggregated consumer of electricity and water. Electricity and water demands were exogenously fed into the model and, therefore, the complex dynamics of the demand were outside the scope of the model.

Integrating water end-use into the TIMES model facilitates the assessment of techno-economic implications of various policies and technology options relating to electricity and water production and end-use. Consequently, it assists in analysing the energy transition pathways towards a sustainable electricity-water system in Kuwait and other parts of the world with similar characteristics. This also provides policymakers with a residential sector-focused energy system model.

3.3 KISR Power Water Model

KISR's Power Water model (TIMES-KPW) is an extension of a model originally developed in 2010 for Kuwait's National Nuclear Energy Commission to investigate nuclear energy prospects in Kuwait's power sector. Following the Fukushima incident, the committee was dissolved, and the study into the feasibility of nuclear energy ceased. The Kuwait Institute for Scientific Research adopted the model in 2011 and commissioned a third-party entity to expand the model and incorporate renewable energy resources.

TIMES-KPW covers only the electric power generation and seawater desalination sector. It examines the potential renewable energy resources that can be made available to meet the electricity and water production requirements up to 2030. The model was intended to evaluate the economic competitiveness of renewable energy resources as part of the electric power generation mix of Kuwait.

The reference energy system for TIMES-KPW consists of primary energy supply, conversion technologies and aggregated electricity and water demand projections. The model primary energy supply resources consist of fossil fuels, nuclear fuel and renewable energy potentials for solar and wind. Fossil fuels are crude oil, heavy fuel oil, gas oil, natural gas, and liquified natural gas (LNG). Fossil fuels availability for the electric power sector was forecasted based on existing crude oil production, processing, and export capacities, gas production, LNG import capacities, and forecasts of downstream and petrochemicals demand.

Conversion technologies built into the model consisted of existing and planned electric power generation and seawater desalination plants, new conventional electric power generation and seawater desalination technologies, nuclear power generation technology, solar energy, and one wind turbine technology. No end-use technologies were incorporated in the model.

3.3.1 Electricity and water system modelling in TIMES-KPW

Electricity and water are represented in TIMES-KPW as single, economy-wide demand commodities. Final demands for both electricity and water were estimated off-model, with no sectoral disaggregation. This top-down approach simplifies the demand-side representation to focus the optimisation on the supply-side technology mix required to meet this pre-determined demand trajectory. The aggregated demand information was projected off-model until 2030 under three oil income scenarios (low, base, and high) using methodology adapted from Wood et al. (2012). The core demand driver is population growth, with total demand established by multiplying population segments by distinct per capita load parameters. Specifically, separate, fixed per capita loads for citizens and migrant workers were calculated for both electricity (in kW/Cap) and water (in Gallons/Day/Cap), derived from the Ministry of Electricity & Water (MEW) base-year peak load data.

Electric load information is divided into 20 annual time periods. The periods consist of four seasonal (summer, winter, and two intermediate seasons) and 16 diurnals (Night, Day 1, Day 2, and peak for each of the seasons). This method allows the daily electricity demand peak to be captured in each season. Only seasonal variations are considered for water since water demand varies slightly between different seasons. Effects of hourly fluctuation in water demand do not influence production due to the use of water storage. The total water storage capacity in Kuwait amounts to 19.7 M m^3 which would last for about 10 days of supply in case of complete disruption in desalination capability.

KISR utilised the model to investigate the adequate share of renewable energy in Kuwait's energy mix. Model results reported in O. Alsayegh et al. (2012) indicated that the cost-effective share for renewables would be at 11% of electricity generation by 2030. Increasing the share to 20% would require additional costs compared to conventional power generation technologies. These results were achieved under scenarios with no constraints on carbon emissions or air pollution. Moreover, a restriction was imposed on reverse osmosis seawater desalination technology, limiting the build rate to 136,000 m^3 annually.

3.3.2 Limitations of TIMES-KPW for this study

KISR's Electric Power Sector TIMES Model considered the national demand for electricity and water as a single unit. TIMES models are proven to be capable of modelling energy demand and local policy influence on provincial and municipal scales (Comodi et al., 2012). One of the main advantages of cost optimisation models is that they allow the supply-side and demand-side to compete in their way to minimise the total system cost. The key weakness of TIMES-KPW is that it assumes sector specific electricity and water per capita consumption rates are fixed, and that the size of total demand in the future will grow based on an increase of new consumers within that sector. Therefore, TIMES-KPW doesn't have the ability to assess the evolution of energy system based on end-use technological evolution within the residential sector, changes in housing policy, and socioeconomic development that yields shifts in the migrant labour and their housing requirements.

Pina (2012) analysed the impact of Demand Side Management (DSM) strategies on the evolution of energy system. Results showed that even under higher demand growth, renewable energy resources (RES) generation capacity was achieving higher shares. This was accredited to the dynamic demand which allows for improved management of installed power generation capacities. Therefore, KEWSM aims to address this limitation by incorporating the demand-side by focusing on the largest consumer of electricity and water in Kuwait, the residential sector. Furthermore, KEWSM attempts to capture other factors that drive the demand-side growth such as housing policy and demographic changes within the housing segments.

3.4 Kuwait Electricity-Water System Model (KEWSM) design and description

The Kuwait Electricity-Water System Model (KEWSM) was developed from KISR's Electric Power Sector TIMES model (TIMES-KPW). KEWSM significantly expands TIMES-KPW in three ways. First, by redefining the demand-side from a single aggregated segment into multiple segments that reflect the diversity between population groups, each with multiple archetypes, resulting in a high-resolution representation of the residential sector. Second, by introducing electricity and water services and capturing end-use characteristics. Third, by developing electricity and water end-use demand drivers. The key changes that needed to be made to TIMES-KPW include:

1. Redefining electricity and water demand-side from a single economy-wide demands into five different segments. Four high resolution residential segments and one non-residential segment representing the remainder of the country.
2. Incorporating detailed residential electricity and water services demand, taking into consideration demographic differences of the residential segments.
3. Incorporating residential electricity and water end-use technologies.
4. Developing residential sector electricity and water services demand drivers, taking into consideration demographic differences of the residential segments.

5. Completely reviewing and updating of the supply-side characteristics and assumptions (conversion technologies and primary energy).
6. Extending the model time horizon.

In order to achieve the above, the following steps were undertaken:

1. Identification and quantification of the residential building stock;
2. Categorizing the building stock into segments according to demographic and dwelling characteristics;
3. Identification and quantification of residential segments' electricity and water end-use equipment stock;
4. Identification and quantification of the residential segments' electricity and water services demand;
5. Projecting electricity and water services demand for the residential segments under three different socioeconomic cases.

KEWSM consists of two components, a sophisticated demand model producing housing stock projections, house appliances projections, and the electricity and water end-use services demand based on input socioeconomic conditions; and the bottom-up techno-economic TIMES model projecting the evolution of the Electricity Water System (EWS) under changes in resource availability, technology advancement, operational constraints, and end-use demand scenarios. The housing stock model allows for projections to consider changes in government policy relating to housing welfare, migrant workers population, and acceptable crowding rates.

Electricity and water end-use services demands are defined in KEWSM exogenously. Documentation of the approach identifying the demand is presented in the following sections of this chapter and demand drivers in the following chapter. Other exogenous inputs include domestic primary energy supply available for electric power generation and seawater desalination, imported energy supply, energy prices, and policy constraints. The TIMES model generator then employs linear optimisation techniques to achieve an optimal configuration for the electricity-water system based on a set of detailed depictions of existing energy conversion and end-use technologies. KEWSM outputs include electricity and water production, consumption, technologies utilised, primary fuels consumed, emissions to the environment, and system costs. Figure 3-1 provides a detailed description of the KEWSM. Full diagram of the model highlighting TIMES-KPW and KEWSM is provided Figure 3-2.

The model is solved for the historic period 2008-2018 and as a projection for the period 2018-2048 in a series of scenarios to explore the potential impacts on Kuwait's Electricity-Water System as a result of: 1) demand growth under different socioeconomic conditions; 2) influence of demand conservation measures and efficiency improvement within the residential sector; 3) decarbonisation of energy mix.

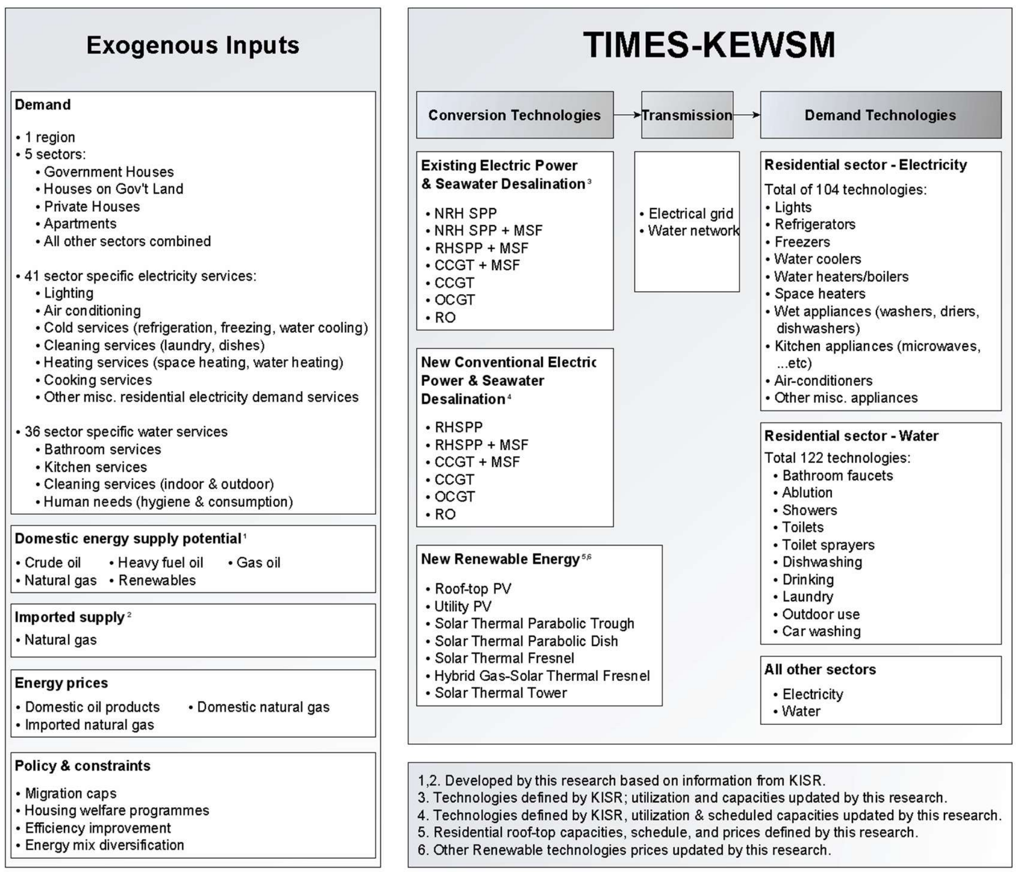

Figure 3-1 KEWSM Model Description

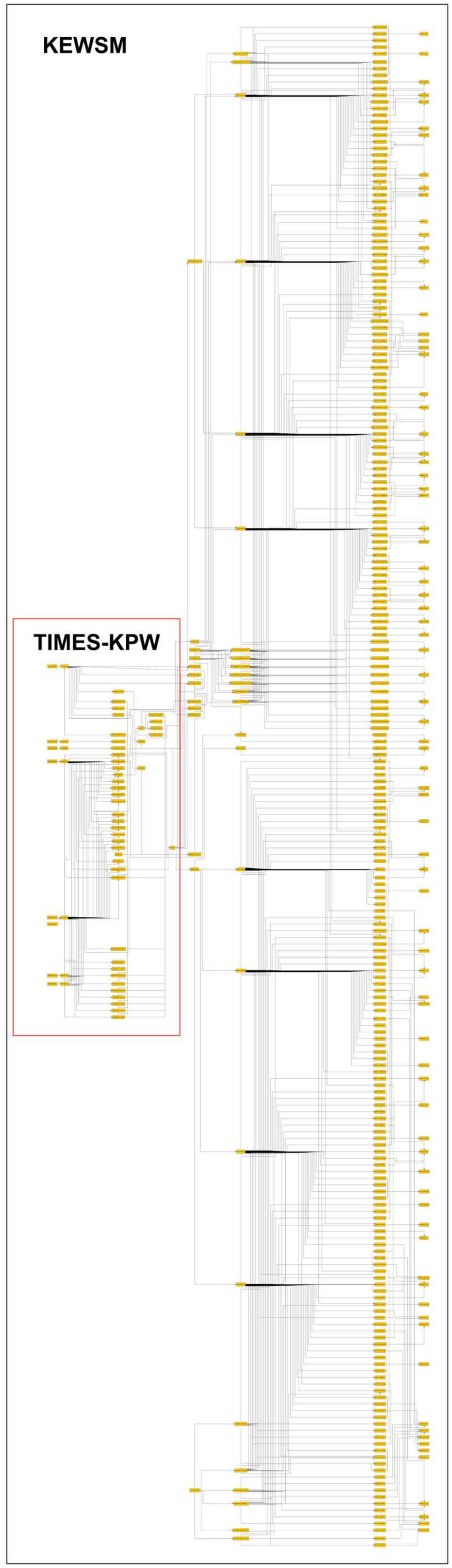

Figure 3-2 KEWSM Full Diagram

3.5 Reference energy system

The reference energy system (RES) defines potential pathways that can be followed to meet services demand. The RES consists of flows, carriers, and conversion technologies. These include energy production, transformation, and usage across a set of technologies defined within the scope of the RES. The following subsections will describe both the demand-side and supply-side of Kuwait's RES.

3.5.1 Final energy consumption

KEWSM final energy consumers are represented by two main sectors, the "combined non-residential" sector and the residential sector (Figure 3-3). The combined non-residential sector represents the commercial, industry, agriculture, and government sectors demand. Since the focus of this study is the residential sector, the combined non-residential sector consumption is treated as an aggregate whose growth is driven by the economy. The demand for this sector is treated as an exogenous input to KEWSM and is forecasted off-model. Its demand is projected to contract and expand in direct parallel with Kuwait's economy, using GDP as the primary driver for its behaviour in line with the methodology presented in Chapter 4.

The residential sector comprises four segments: Residential-GH, Residential-GO, Residential-PH, and Residential-IA. Where Residential-GH refers to houses built and distributed by the Public Authority for Housing Welfare; Residential-GO refers to houses built by their owners on lands provided by the Public Authority for Housing Welfare; Residential-PH refers to private villas built on private lands; and Residential-IA refers to investment apartments which are per definition of Kuwait's Municipality are dwelling purpose-built for renting. By segmenting the residential sector this way, the impact of different housing policies on the electricity-water system can be analysed in addition to the electricity-water policies imposed on the segments.

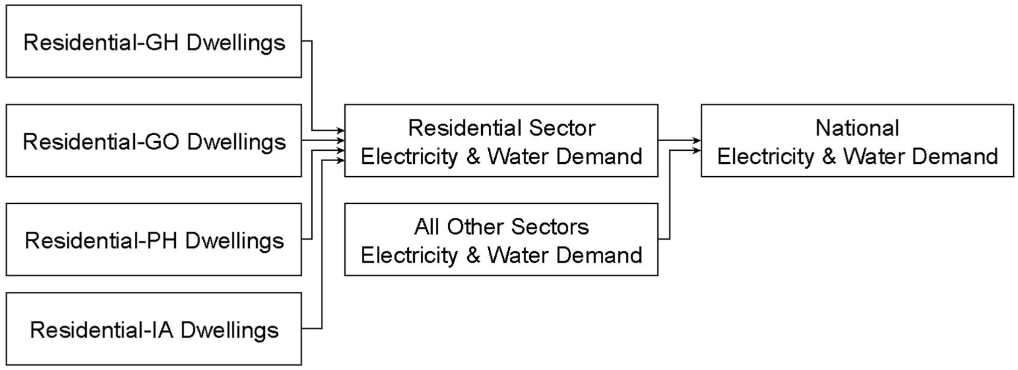

Figure 3-3 Structure of electricity-water system demand-side

The model is driven by a set of 77 segment-specific end-use demands for services within the residential sector. Electricity is represented in 41 end-use demand services and 36 for water end-use demand services. End-use technologies are modelled and calibrated for the 2008 base year demand. The electricity end-use demands consist of air conditioners, lighting, refrigerators, freezers, water coolers, water heaters, space heaters, wet appliances (washers/dryers and dishwashers), kitchen appliances, and "others" category for small miscellaneous electrical appliances. The water end-use demands consist of bathroom sink faucets, ablution faucets, showers, toilets, bathroom sprayers, kitchen filtered taps, dishwashing faucets, washers/dryers, car washing, and outdoor-use faucets.

The aforementioned end-use demands are met by an activity-specific set of technologies (Figure 3-4 for electricity end-use and Figure 3-5 for water end-use). A set of end-use technologies are defined for every residential segment individually. This approach allows the model to capture use patterns associated with each demography dominating the residential segment.

A repository consisting of 226 end-use technologies was incorporated into KEWSM, of which 104 electricity end-use technologies and 122 are water end-use technologies. The end-use technologies are modelled and calibrated for 2008 base year demand. Each technology has a service life and can be replaced by identical or improved versions or a completely new technology. After the base year, technologies compete to satisfy each end-use demand.

A complete list of the end-use assumptions and appliances demand projections are provided in appendices Section 3.6.2.

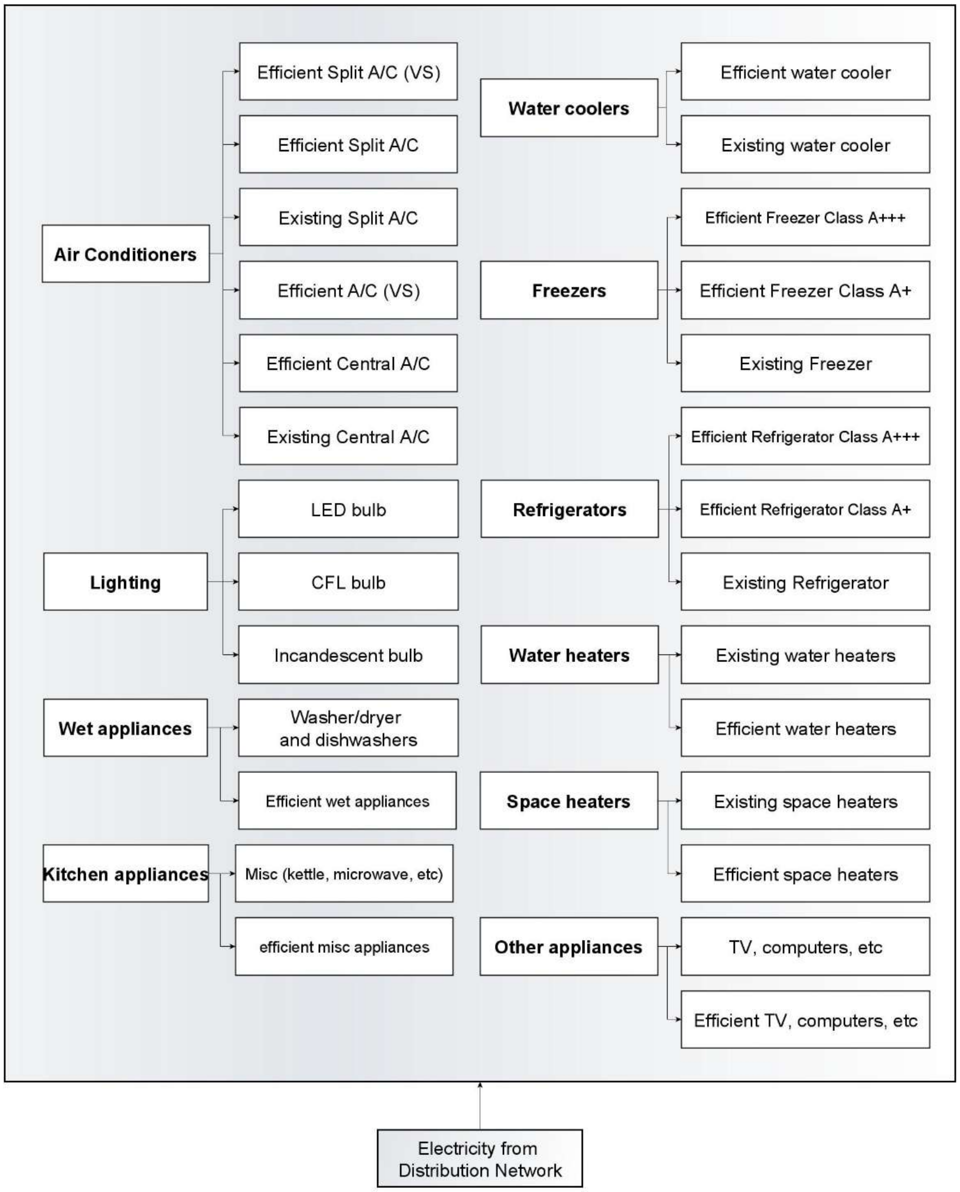

Figure 3-4 KEWSM household electricity end-use

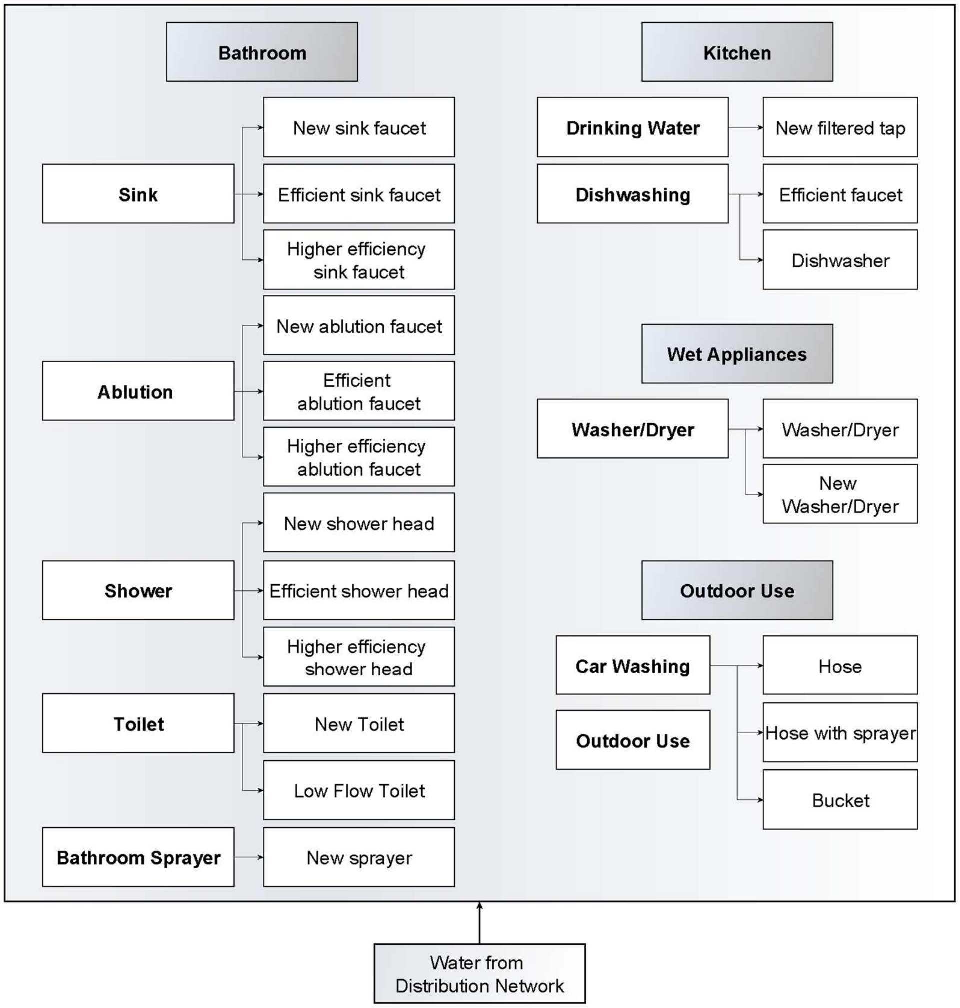

Figure 3-5 KEWSM household water end-use

3.5.2 Energy conversion

Energy conversion technologies are represented in KEWSM by electric power plants and seawater desalination plants. Figure 3-6 presents energy conversion technologies incorporated into KEWSM. The model database contains a comprehensive and detailed representation of all existing and planned electric power and seawater desalination plants. The database has been updated for KEWSM to reflect changes in the Ministry of Electricity and Water (MEW) construction, upgrade, and renovation projects pipeline. Table 3-1 lists all existing conventional electric power and seawater desalination plants. The database also includes a repository of conventional and renewable plant options for the model to choose from when replacing existing capacities or when new capacities are needed. New generic conventional options available for the model to choose from are listed in Table 3-2 and a collection of renewable options are presented in Table 3-3. The nuclear power technologies inherited from the TIMES-KPW fell outside the scope of this research and were therefore not permitted in any of the scenarios implemented.

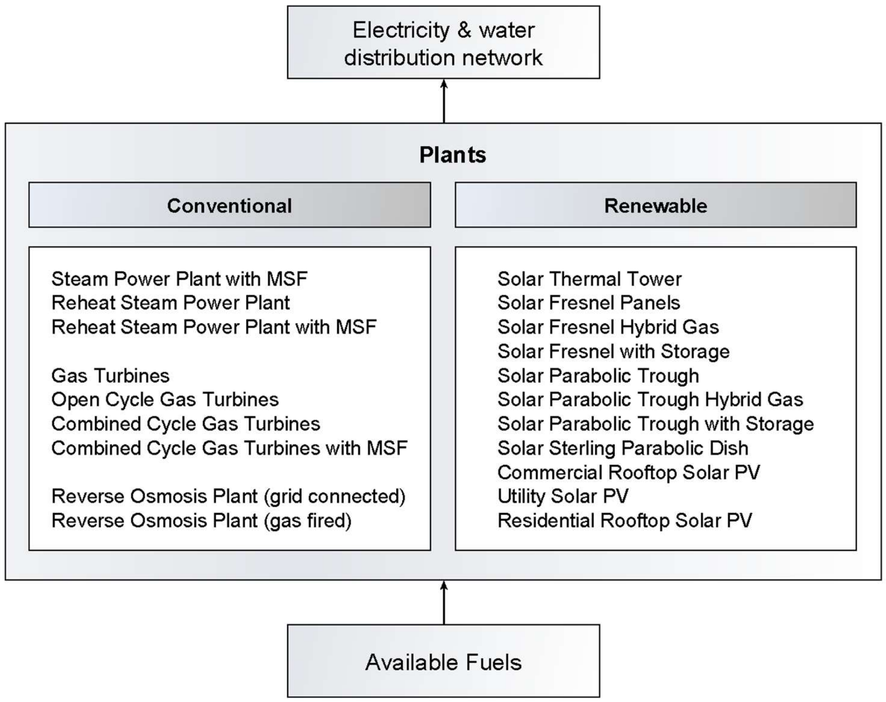

Figure 3-6 KEWSM energy conversion technologies

Table 3-1 Existing electric power and seawater desalination plants

Plant	*Technology*	*Fuel*	*Output*
Doha East Power Station	Non-reheat/MSF	Heavy Fuel Oil (HFO), Crude, Natural Gas (NGA)	Electricity & Water
	Gas Turbine	NGA, Gas Oil	Electricity
Doha West Power Station	Reheat Steam/MSF	HFO, Crude, NGA	Electricity & Water
	Gas Turbine	NGA, Gas Oil	Electricity
Subiya Power Station	OCGT	NGA, Gas Oil	Electricity
	Reheat Steam/MSF	HFO, Crude, NGA	Electricity & Water
Shuaiba South Power Station	Non-Reheat/MSF	NGA, Gas Oil	Electricity & Water
	Reheat Steam/MSF	HFO, Crude, NGA	Electricity & Water
Shuwaikh	Gas Turbine	NGA, Gas Oil	Electricity
	Multistage Flash	NGA	Water
	Reverse Osmosis	Electricity	Water
Zour North Power Station	Reheat Steam/MSF	HFO, Crude, NGA	Electricity & Water
	CCGT/MSF	NGA, Gas Oil	Electricity & Water
	Reverse Osmosis	Electricity	Water
Zour South Power Station	Reheat Steam	HFO, Crude, NGA	Electricity
	OCGT	NGA, Gas Oil	Electricity
	CCGT	NGA, Gas Oil	Electricity
	Reverse Osmosis	Electricity	Water

Table 3-2 New conventional electric power and seawater desalination plants

Technology	*Input*	*Output*
Combined Cycle Gas Turbine (CCGT)	NGA, Gas Oil	Electricity
CCGT with Multistage Flash (MSF) Desalination	NGA, Gas Oil	Electricity, water
Reheat Steam Power with MSF Plant	HFO, Crude, NGA	Electricity, water
Reheat Steam Power Plant	HFO, Crude, NGA	Electricity
Generic Reverse Osmosis Plant	Electricity	Water

Table 3-3 Renewable electric power plants

Technology	*Input*	*Output*
Solar Thermal Parabolic Trough Plant	Solar radiation, water	Electricity
Solar Thermal Parabolic Trough with storage 6.5 h Plants	Solar radiation, water	Electricity
Combined Gas-Parabolic Trough Hybrid plants	Solar radiation, NGA, water	Electricity
Solar Thermal Power Tower with thermal storage Plant	Solar radiation, water	Electricity
Solar Thermal Fresnel panels	Solar radiation, water	Electricity
Solar Thermal Hybrid gas plant with Fresnel panels	Solar radiation, NGA, water	Electricity
Solar Thermal Stirling Parabolic Dish	Solar radiation, water	Electricity
Solar PV Land Based Utility	Solar radiation	Electricity
Residential Solar PV	Solar radiation	Electricity
Commercial Solar PV	Solar radiation	Electricity

3.5.3 Primary energy supply

KEWSM primary energy resources consist of fossil fuel reserves and solar potential. The fossil fuel supply comprises of crude oil, oil products (such as heavy fuel oil and gas oil), indigenous natural gas, and imported liquified natural gas (LNG). The availability projections of primary energy for the EWS builds on and updates TIMES-KPW to reflect recent energy sector capacities expansions delivery and delays. The primary energy is defined in the model through mining processes with no redenomination applied to said processes. KEWSM developed three LNG cases that consider: complete disruption of LNG imports, LNG imports constrained by the capacity of the existing temporary floating LNG terminal at Mina Al Ahmadi, and imports constrained by capacity of Al-Zour LNG import terminal which is coming into full operation in late 2022. The latter is considered the business-as-usual LNG case. Additionally, accessibility to residential roof-top PV potential in KEWSM takes into account the residential building stock growth pathways over the modelled time horizon.

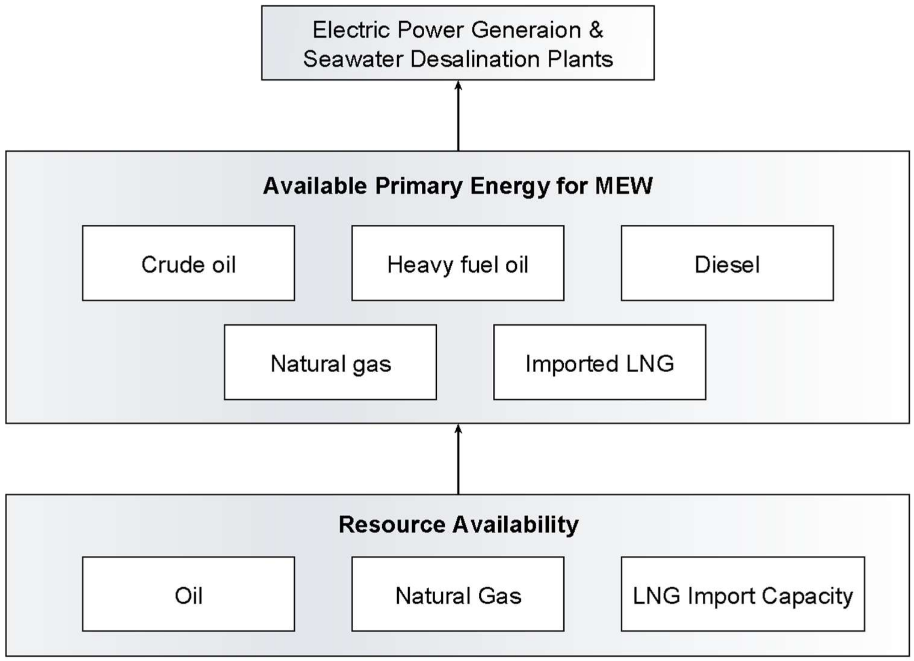

Figure 3-7 KEWSM primary energy

3.5.3.1 Fossil fuels price assumptions

Fossil fuel prices are subject to significant uncertainty and sensitive to various factors such as policy decisions, technological advancements, global economic conditions, and the political situation of exporting countries. In the case of Kuwait, since the Ministry of Electricity and Water (MEW) procures fuels from the Kuwait National Petroleum Company (KNPC) at market price (MEW, 2024), and considering that Kuwait Export Crude (KEC) is typically priced at a discount of approximately $1 to $4 per barrel relative to Brent crude (OPEC, 2024, EIA, 2025b), Brent price projections from the US Energy Information Administration Annual Energy Outlook 2025 (EIA, 2025a) serve as a suitable proxy for modelling fuel costs in Kuwait's electricity-water system under the Reference, low and high oil prices scenarios.

However, while the EIA's projections are suitable for modelling domestic crude-based fuels, identifying long-term LNG price projections relevant to Kuwait is less straightforward. As the largest importer of Liquefied Natural Gas (LNG) in the Middle East and North Africa (MENA) region (GECF, 2025), Kuwait presents a unique case compared to major hub-based markets in Europe and Asia. Kuwait's substantial LNG import volumes are driven internally by resource requirements of the electricity and water production, rather than by the market dynamics of major trading hubs whose price signals are largely shaped by consumption patterns in other regions. Consequently, long-term price forecasts prevalent in the literature, which are typically based on the dynamics of hub markets like the US Henry Hub, European TTF or the Asian JKM, are unsuitable for modelling Kuwait's procurement reality.

In light of this context, and given that Kuwait's LNG supply portfolio is dominated by long-term contracts with Qatar, African producers, and some regional spot markets rather than global trading hubs (McCracken, 2023, Hagagy, 2024, OEC, 2024), this study developed a liquified natural gas price projection using oil-indexation methodology for pricing as the most appropriate and representative methodology.

This established approach involves pricing gas via long-term contracts determined by formulae containing rolling averages of crude oil or defined oil product prices (Rogers, 2016). Despite its long history, the continued relevance of this methodology has been debated, as oil and gas have become less substitutable in end-use sectors where oil being primarily used in transport, and gas in power generation and heating (Stern, 2007). Nevertheless, oil-indexed gas pricing remains a prevalent mechanism in both Continental Europe and key Asian LNG markets (Cansado-Bravo et al., 2018, Mchich et al., 2020), and as demonstrated by the recent 27-year LNG supply agreement signed in 2022 between Qatar and China (Mills et al., 2022, Pande et al., 2023, Downs et al., 2023).

Therefore, the price of LNG is estimated using the linear equation based on Flower et al. (2012):

$$P_{LNG} = A \times P_{Crude} + B$$

Where,

- P_{LNG} is the price of LNG in US$/MMBtu
- P_{crude} is the price of crude oil in US$/Bbl. In this study the EIA (2025a) crude oil projections (Reference, High Oil Prices, and Low Oil Prices) are used.

A is the slope factor. This study adopts the value of 12.7% based on the recent long-term (27 years) LNG supply contract signed by Qatar with China (Pande et al., 2023), reflecting both pricing practices and Qatar's position as the primary LNG supplier to Kuwait.

B is a constant representing the liquefaction and regasification costs, which are set at 1 US$/MMBtu for liquefaction and 0.5 US$/MMBtu for regasification (OIES, 2025).

Based on the aforementioned approach, Table 3-4, Table 3-5, and Table 3-6 show the fossil fuels price assumptions and projections under the central, high, and low fuel price assumptions respectively.

Given the nature of Kuwait's natural gas reserves being mostly associated gas and by-product of oil production. In the absence of available Kuwaiti natural gas price projections publicly available, a simple oil-gas price ratio is used to forecast future prices using the following equation:

$$P_{gas,t} = P_{gas,t_0} \times \frac{P_{crude,t}}{P_{crude,t_0}}$$

Where,

- P_{gas} is the price of natural gas in US$/MMBtu
- P_{crude} is the price of crude oil in US$/Bbl. In this study the EIA (2025a) crude oil projections (Reference, High Oil Prices, and Low Oil Prices) are used.
- t_0 is the initial year of the available actual natural gas price.
- t is observed future year

Table 3-4 Central price assumptions for fossil fuels.

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Crude oil price	$/bbl	95	105.0	69.8	84.9	77.8	87.3	92.3	93.7	94.6
Heavy Fuel Oil	$/MMBtu	20.4	22.6	15.0	18.3	16.8	18.8	19.9	20.2	20.4
Gas Oil	$/MMBtu	30.7	34.0	22.6	27.5	25.2	28.3	29.9	30.3	30.6
Natural Gas	$/MMBtu	20.4	22.6	15.0	18.3	16.8	18.8	19.9	20.2	20.4
Imported LNG	$/MMBtu	13.7	14.9	10.5	12.4	11.5	12.7	13.3	13.5	13.6

Table 3-5 High price assumptions for fossil fuels.

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Crude oil price	$/bbl	95	105.0	69.8	84.9	129.5	143.6	151.0	152.9	154.4
Heavy Fuel Oil	$/MMBtu	20.4	22.6	15.0	18.3	27.9	30.9	32.5	32.9	33.2
Gas Oil	$/MMBtu	30.7	34.0	22.6	27.5	41.9	46.4	48.8	49.5	49.9
Natural Gas	$/MMBtu	20.4	22.6	15.0	18.3	27.9	30.9	32.5	32.9	33.2
Imported LNG	$/MMBtu	13.7	14.9	10.5	12.4	18.0	19.8	20.8	21.0	21.2

Table 3-6 Low price assumptions for fossil fuels.

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Crude oil price	$/bbl	95	105.0	69.8	84.9	46.4	46.8	46.9	47.0	47.0
Heavy Fuel Oil	$/MMBtu	20.4	22.6	15.0	18.3	10.0	10.1	10.1	10.1	10.1
Gas Oil	$/MMBtu	30.7	34.0	22.6	27.5	15.0	15.1	15.2	15.2	15.2
Natural Gas	$/MMBtu	20.4	22.6	15.0	18.3	10.0	10.1	10.1	10.1	10.1
Imported LNG	$/MMBtu	13.7	14.9	10.5	12.4	7.5	7.5	7.6	7.6	7.6

3.5.4 The rationale for unsubsidised modelling

While the fundamentals behind service demands are driven by socio-economic factors, subsidies primarily influence the perceived cost to consumers of meeting these demands, thereby shaping the means by which these services are ultimately delivered. By artificially lowering the financial cost of electricity and water consumption, subsidies reduce the economic penalty for energy wastage. Furthermore, they disincentivise the deployment of more energy-efficient technologies by consumers, especially where these technologies have a higher upfront capital cost.

Although TIMES does not directly model behavioural psychology, its least-cost optimisation reflects rational economic responses, such as where, if subsidised energy is cheap, the model will select less efficient and cheaper capital cost technologies to meet a given service demand because the lifecycle cost, including energy cost, appears lower. However, when modelling scenarios without subsidies, TIMES will demonstrate a greater uptake of efficiency technologies, as significant savings on energy consumption offset their higher capital costs. This modelling approach thus indirectly captures the impact of financial incentives or the disincentives created by subsidies on technology choices and overall energy consumption required to satisfy a given set of energy service demands.

Therefore, KEWSM scenarios were designed to exclude electricity and water subsidies. Including them would essentially force the model to replicate current market realities, where artificially low prices can perpetuate inefficient consumption and technology choices, thereby hindering the identification of the least-cost system configuration from a national economic or system planner's viewpoint. By modelling the system without these price distortions, KEWSM reveals the baseline cost-effectiveness of different supply and demand-side technologies based on their actual costs (investment, fuel, O&M).

This unsubsidised baseline provides a benchmark for strategic planning as it reflects a situation where government financial resources could be directed towards the most efficient means of meeting energy service demands through direct system investments (e.g. in generation capacities or efficiency programs) rather than being channelled into artificially lowering end-user prices via subsidies. Given that public funds are ultimately expended through subsidising consumption or direct capital investments in the energy system, modelling without subsidies allows KEWSM to identify the most fundamentally cost-effective allocation of those resources. This approach offers a clearer, undistorted perspective on the inherent potential and optimal deployment of various technologies and pathways for achieving a sustainable supply of electricity and water and decarbonising Kuwait's energy system based on economic signals and technological competitiveness.

3.6 Estimation of residential services demand

In order to overcome the scarcity of information regarding Kuwait's residential electricity and water end-use, residential electricity and water end-use demands were estimated and verified using a bottom-up approach. Figure 3-8 presents a simplified diagram of the estimation process.

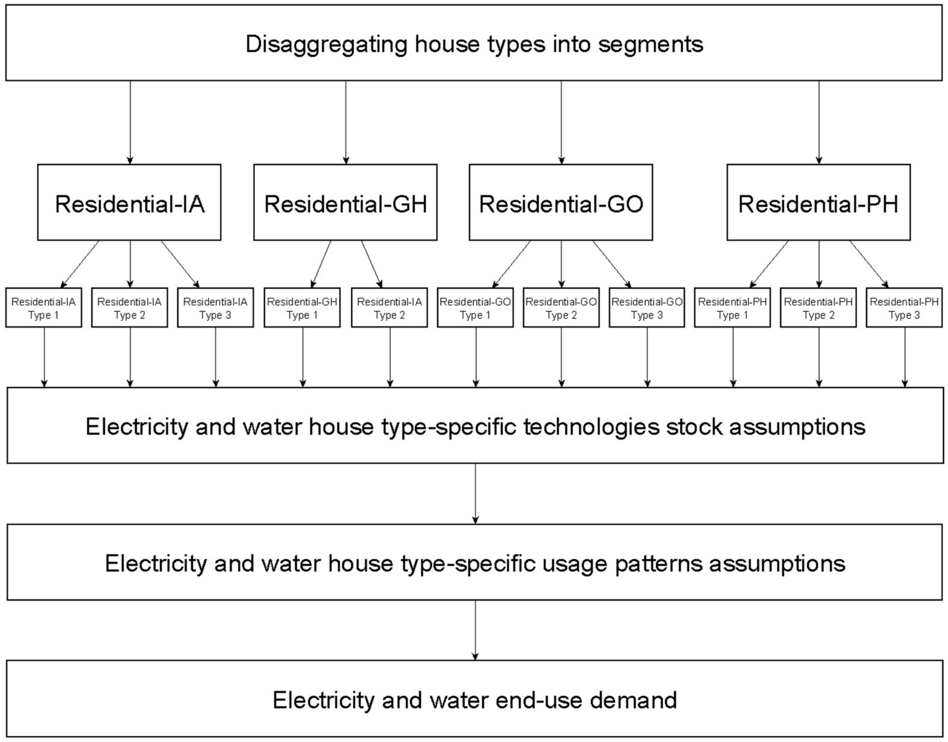

Figure 3-8 Approach for estimating electricity and water services demand

3.6.1 Appliances inventory

A stocktake for the residential sector was conducted by compiling unpublished information provided by the Public Authority for Housing Welfare (PAHW) and Public Authority for Civil Information (PACI). The total number of houses in the base year of KEWSM model is 131,406 units, disaggregated in this research into four segments. The houses built by the Public Authority for Housing Welfare (Residential-GH) represented 28% of the mix, houses built by owners on lands provided by the Public Authority for Housing Welfare (Residential-GO) represented 18%, and private villas (Residential-PH) 54%. The total number of investment apartments (Residential-IA) is 183,111 units.

Based on the information provided by the PAHW (2014) and PACI (2013a), and through expert consultation from Kuwait Municipality (2015) and Kuwait Real Estate Association (2013), dwellings stock was then categorised into segments based on size assumptions of the most prevailing archetype in each segment. Table 3-7 lists base year residential stock disaggregated by segment and size.

Houses with plot size between 400 and 560 m^2 represent the majority of Kuwait's building stock. The PAHW 400 m^2, in particular, represents a typical Kuwaiti home in terms of layout and amenities. The PAHW house model "H4" was selected as the reference house for this study and its layout serves as template for other houses categories in this study. An increase or decrease in the size of any other house type would result in a proportional increase or decrease in house amenities and electrical and plumbing fixtures relative to the H4 layouts. Table 3-8 lists the dwelling interior composition assumptions for different residential archetypes in the four residential segments.

Therefore, floor plans of multiple 400 m^2 house designs were acquired from the PAHW (2017), along with the electrical Total Connected Load (TCL) and plumbing Fixture Unit (FU) plans layouts. An inventory of electrical devices and water fixtures for each house type was estimated based on assumptions following expert consultation from the Ministry of Electricity and Water (MEW) and analysis of the TCL and FU plan layouts provided. Furthermore, the typical power rating for the lighting, extractor fans, air conditioners, water heaters, laundry, kitchen, and general-use was identified for each house type. Appendix A presents the sample house floor plan of the reference house, electrical layout plans, and plumbing layout plans.

Table 3-9 shows water fixtures assumptions for different dwellings. Table 3-10 shows the light bulbs per dwelling assumptions for base year. Assumptions for all other electrical appliances per dwelling are presented in Table 3-11.

Table 3-7 Base year residential stock disaggregated by segment and size

	Plot Size m²	*Dwellings* Units	*Share of segment*
Residential-GH			
Type 1	400	11,102	30%
Type 2	560	25,906	70%
Residential-GO			
Type 1	400	7,215	30%
Type 2	560	6,013	25%
Type 3	650	10,823	45%
Residential-PH			
Type 1	400	21,104	30%
Type 2	650	17,587	25%
Type 3	850	31,656	45%
Residential-IA			
Type 1	Studio & 1 Bed Apt	36,622	20%
Type 2	2 & 3 Bed Apt	73,244	40%
Type 3	4 Bed Apt & Penthouse	73,244	40%

Table 3-8 Dwelling interior composition assumptions

	Structure Size Increase	*Bedrooms*	*Bathrooms*	*Full Kitchen*	*Prep. Area*
Residential-GH					
Type 1	0%	6	6	1	1
Type 2	40%	8	8	1.5	1
Residential-GO					
Type 1	0%	8	6	1	1
Type 2	40%	11	9	2	1
Type 3	64%	18	8	3	1
Residential-PH					
Type 1	40%	8	6	1	1
Type 2	64%	13	9	2	1
Type 3	112.5%	17	6	2	1
Residential-IA					
Type 1	-70%	2	1	1	0
Type 2	-55%	3	3	1	0
Type 3	-45%	4	3	1	0

Table 3-9 Dwellings water fixtures assumptions

	Bathrooms	*Faucet*	*Toilet*	*Sprayer*	*Shower*	***Full Kitchen***	*Faucet*	*Water cooler*	*Dishwasher*	***Prep Area***	*Water cooler*	***Laundry***	*Faucet*	*Washer*	***Outdoor***	*Cars*
Residential-GH																
Type 1	**6**	6	6	6	6	**1**	1	1	-	**1**	1	**1**	1	1	1	2
Type 2	**8**	8	8	8	8	**1.5**	2	2	-	**1**	1	**1**	1	2	1	3
Residential-GO																
Type 1	**6**	6	6	6	6	**1**	1	1	-	**1**	1	**1**	1	1	1	2
Type 2	**9**	9	9	9	9	**2**	2	2	-	**1**	1	**1**	1	2	1	3
Type 3	**8**	8	8	8	8	**3**	3	3	-	**1**	1	**1**	1	3	1	4
Residential-PH																
Type 1	**6**	6	6	6	6	**1**	1	1	-	**1**	1	**1**	1	1	1	4
Type 2	**9**	9	9	9	9	**2**	2	2	-	**1**	1	**1**	1	2	1	5
Type 3	**6**	6	6	6	6	**2**	2	2	-	**1**	1	**1**	1	2	1	6
Residential-IA																
Type 1	**2**	2	2	2	2	**1**	1	1	-	**0**	-	**0**	-	1	0	1
Type 2	**3**	3	3	3	3	**1**	1	1	-	**0**	-	**0**	-	1	0	2
Type 3	**4**	4	4	4	4	**1**	1	1	-	**0**	-	**0**	-	1	0	3

Table 3-10 Light bulbs per dwelling assumptions. Light bulb type assumption based on UNEP (2010) country light assessment.

	Number of Lighting Fixtures	***ILB***	***HAL***	***FL***	***HID***	***CFL***	***LED***
Residential GH							
Dwelling type 1	152	78	16	26	0	30	0
Dwelling type 2	195	101	21	34	0	39	0
Residential GO							
Dwelling type 1	152	78	16	26	0	30	0
Dwelling type 2	195	101	21	34	0	39	0
Dwelling type 3	239	123	26	42	0	48	0
Residential PH							
Dwelling type 1	152	78	16	26	0	30	0
Dwelling type 2	199	103	21	35	0	40	0
Dwelling type 3	237	122	25	41	0	47	0
Residential IA							
Dwelling type 1	28	15	3	5	0	6	0
Dwelling type 2	38	20	4	7	0	8	0
Dwelling type 3	57	29	6	10	0	11	0

Table 3-11 Electrical appliances per dwelling assumptions

[Unit/Dwelling]	Refrigerators				Freezers			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	3	3	3	1	1	1	1	0
Dwelling type 2	4	4	4	1	1.5	1.5	1.5	0
Dwelling type 3	0	5	5	1	0	2	2	0.5
	Water coolers				**Space heater**			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	4	4	6	1	8	8	8	1
Dwelling type 2	6	6	6	1	10	10	10	2
Dwelling type 3	0	8	8	1		11	11	3
	Water heaters				**Water heater size [Watt]**			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	1	1	1	1	12000	12000	12000	3000
Dwelling type 2	2	2	2	2	16500	16500	16500	6000
Dwelling type 3	0	2	2	3		24000	24000	9000
	Washers				**Dryers**			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	1	1	2	1	1	1	1	1
Dwelling type 2	2	2	2	1	2	2	2	1
Dwelling type 3		2	2	1		2	2	1
	Kettles				**Microwaves**			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	2	2	2	1	2	2	2	1
Dwelling type 2	2.5	3	3	1	2.5	3	3	1
Dwelling type 3	0	4	4	1	0	4	4	1
	Package AC				**Split AC**			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	7	7	7	2	2	2	2	0
Dwelling type 2	10	10	10	2	3	3	3	1
Dwelling type 3		11	11	3		4	4	1
	TVs				**Other misc.**			
	GH	GO	PH	IA	GH	GO	PH	IA
Dwelling type 1	10	10	14	2	50	50	70	15
Dwelling type 2	14	14	17	3	70	70	86	22.5
Dwelling type 3		16	24	4		82	120	27.5

3.6.2 Appliances usage

Appliances electricity and water services demand per dwelling were estimated based on human behavioural patterns, the requirements of typical human needs, and technical specifications of water fixtures and electrical appliances. Assumptions regarding these behaviours and needs were derived from existing literature relevant to Kuwait, the region, and elsewhere in the world. However, due to information gaps pertaining to local behavioural patterns, it was necessary to incorporate assumptions based on the author's understanding and judgment.

The assumptions considered the variation between citizens' and migrant workers' consumption. The variation is mainly the result of dwelling occupancy patterns. For instance, 92% of citizens are employed by the public sector, which has shorter work hours and an earlier start in the day, whereas the private sector employs 75% of the migrant workers population (ILO, 2018). Another notable difference is the house chores schedule, as citizens' dwellings maintain occupancy during the day with approximately 40% of its occupants (Al-Mumin et al., 2003).

The behavioural and needs assumptions were used in conjunction with the appliances' technical specifications in defining conversion technologies in KEWSM. This allows capturing the effect of different conservation and efficiency improvement measures targeting different segments of the residential sector. The quality of assumptions was verified against the national electricity and water demand for the base year and calibrated.

Table 3-12 through Table 3-15 list the different behavioural assumptions for water use. Table 3-16 through Table 3-20 list the different technical assumptions for water fixtures and water use. And finally, Table 3-21 lists electrical appliances assumptions.

Table 3-12 Water use behavioural assumptions: bathroom

Behaviour assumptions		***Source***	***Notes***
Handwashing:			
Usage length [minutes]:	0.333	CDC (2019)	20 seconds recommended by the US CDC
Number of washes per day:	10	ACI (2009)	Survey findings
Total number of washing days:	358	Assumption	1 week out of country
Toilet*:*			
Number of flushes per day:	5	Worldometers (2019)	Source states average toilet use is 7 times a day. Subtract 30% workhours during day
Days of year used:	358	Assumption	1 week out of country
Sprayer:			
Usage length [min]	0.5	CDC (2019)	Assumed similar time as handwash
Number of washes per day	5	Assumption	Assumed equal number to toilet use
Number of washing days per year	358	Assumption	1 week out of country
Shower			
Citizens			Assumptions for adult population
Standard showers:			
Usage length [min]:	8.2	Kinver (2011)	
Number of showers per day:	1.75	Assumption	
Number of showers per year:	358	Assumption	Less winter showers & 1 week out of country
Quicker showers:			
Usage length [min]:	5	Kinver (2011)	
Number of showers per day:	1.75	Assumption	
Number of showers per year:	358	Assumption	Less winter showers & 1 week out of country
Migrant workers			Assumptions for adult population
Standard showers:			
Usage length [min]:	8.2	Kinver (2011)	
Number of showers per day:	0.57	SCA (2008)	Cultural differences into consideration
Number of showers per year:	345	Assumption	Assume annual leave out of country
Quicker showers:			
Usage length [min]:	5	Kinver (2011)	
Number of showers per day:	0.57	SCA (2008)	Cultural differences into consideration
Number of showers per year:	345	Assumption	Assume annual leave out of country

Table 3-13 Water use behavioural assumptions: kitchen

Behaviour			***Source***	***Notes***
Dishwashing – kitchen faucet:				
Citizens household				
Usage length	**[minutes]**	150	Assumption	
Days of washing	**[days]**	261	Assumption	Weekends excluded
Average washes per day		3	Assumption	
Migrant workers household				
Usage length	**[minutes]**	12.5	Assumption	
Days of washing	**[days]**	261	Assumption	Weekends excluded
Average washes per day		3	Assumption	
dishwashing – electric dishwasher:				
Citizens household				
Cycles per meal	**[cycles]**	4.84	Assumption	
Days of washing	**[days]**	261	Assumption	Weekends excluded
Average washes per day		3	Assumption	
Migrant workers household				
Cycles per meal	**[cycles]**	1	Assumption	
Washes per day		2	Tewes et al. (2023)	
Days of washing	**[days]**	261	Assumption	Weekends excluded
Drinking water requirements:				
Adult water need	**[litres/day]**	2.5	Shaheen et al. (2018)	
Youngsters water need	**[litres/day]**	1.25	Shaheen et al. (2018)	
Number of drinking days	**[days]**	358	Assumption	1 week out of country
Kuwaiti adults	**inhabitants**	685,158	PACI (2013b)	
Kuwaiti children	**inhabitants**	402,394	PACI (2013b)	
Expat adults	**inhabitants**	2,024,664	PACI (2013b)	
Expat children	**inhabitants**	329,597	PACI (2013b)	

Base year drinking water requirements:	**Demand per person** [million litres/day]	**Demand per person** [million litres/year]
Kuwaitis	2.22	793.29
Migrant workers	5.47	1959.57

Table 3-14 Water behavioural use assumptions: Laundry

Behaviour			***Source***	***Notes***
Resident household				
Full load cycles	[cycles]	4.81	Assumption	Assume full-load cycle per family member, use average size family.
Days of washing	[days]	261	Assumption	Weekends excluded
Migrant workers household				
Full load cycles	[cycles]	0.57	Mainali et al. (2013)	Assume weekend laundry (4 cycles per week)
Days of washing	[days]	261	Assumption	Weekends excluded

Table 3-15 Water use behavioural assumptions: Outdoor

Behaviour			***Source***	***Notes***
Carwash:				
Resident household				
Wash length	[min]	10	Assumption	
Washes per day	[washes/day]	1	Assumption	
Washes per year	[washes/year]	251	Mohammad (1989)	Based on number of dusty days
Migrant workers household				
Wash length	[min]	10	Assumption	
Washes per day	[washes/day]	0.29	Assumption	Twice a week
Washes per year	[washes/year]	104.3	Assumption	Twice a week for whole year
Outdoor wash:				
Houses only, apartments excluded				
Wash length	[min]	20	Assumption & Mukhopadhyay et al. (2001)	
Washes per year	[washes/year]	251	Mohammad (1989)	Based on number of dusty days

Irrigation:

It is assumed that garden irrigation is negligible for the following reasons:

- Low number of houses with gardens.
- Irrigation is often done with brackish water which is free and outside the scope of this study.
- Lack of data on houses with gardens.
- Lack of data on local water use for irrigation.

Table 3-16 Water technology assumptions

Technology	***Flowrate*** *[Litres/min]*	***Daily Consumption*** *[Litres/day]*	***Annual Consumption*** *[Litres/year]*
Faucets:			
Pre-1992 average	19	63.33	22,673
Standard (1998 average)	8.3	27.67	9,905
Least efficient	5.7	19.00	6,802
Maximum efficient	3	10.00	3,580
Flowrate assumptions sources: USEPA (2007), USEPA (2020)			
Shower:			
Citizens household			
Standard showering behaviour:			
Standard showerhead	13.3	191	68,326
Efficient showerhead	7.6	109	39,043
Quicker showering behaviour:			
Standard showerhead	13.3	116.375	41,662
Efficient showerhead	7.6	66.5	23,807
Migrant workers household			
Standard showers:			
Standard showerhead	13.3	62.32	21,500
Efficient showerhead	7.6	35.61	12,286
Quicker showers:			
Standard showerhead	13.3	38	13,110
Efficient showerhead	7.6	21.71	7,491
Flowrate assumptions sources: USEPA (2010), USEPA (2020)			
Toilet:			
Standard (older) flush average	13.6	67.43	24,141
Ultra-low-flow average flush	6	29.75	10,651
Flowrate assumptions sources: USEPA (2014), USEPA (2020)			
Sprayer:			
Standard	4.7	11.65	4,171
Efficient	3.8	9.42	3,373
Flowrate assumptions sources: USEPA (2020)			

Table 3-17 Water Technology assumptions: kitchen

Technology	***Flowrate*** *[Litres/min]*	***Daily Consumption*** *[Litres/day]*	***Annual Consumption*** *[Litres/year]*
Dishwashing – kitchen faucet:			
Citizens household			
Standard	9.5	1,425	371,925
Efficient	8.3	1,245	324,945
Migrant workers household			
Standard	9.5	356	92,981
Efficient	8.3	311	81,236
Flowrate assumptions sources: USEPA (2008), USEPA (2020)			
Dishwashing – standard electric dishwasher:			
Citizens household	***Water use*** *[Litres/cycle]*	***Daily Consumption*** *[Litres/day]*	***Annual Consumption*** *[Litres/year]*
	4	58	15,073
	Electricity use *[kwh/cycle]*	***Daily Consumption*** *[kwh/day]*	***Annual Consumption*** *[kwh/year]*
	1.59	23	5,992
Migrant workers household	***Water use*** *[Litres/cycle]*	***Daily Consumption*** *[Litres/day]*	***Annual Consumption*** *[Litres/year]*
	4	8	2,088
	Electricity use *[kwh/cycle]*	***Daily Consumption*** *[kwh/day]*	***Annual Consumption*** *[kwh/year]*
	1.59	3.18	830

Assumptions sources: Home Water Works (2019b)

Table 3-18 Water use technology assumptions: laundry

Technology	***Flowrate*** *[Litres/cycle]*	***Daily Consumption*** *[Litres/day]*	***Annual Consumption*** *[Litres/year]*
Resident household			
Standard	170	818.1	213,534
Efficient	113.6	546.7	142,691
Migrant workers household			
Standard	170	97.1	35,457
Efficient	113.6	64.9	23,694

Assumptions sources: Home Water Works (2019a)

Table 3-19 Water use technology and demand assumptions: carwash

Technology	***Flowrate*** *[Litres/min]*	***Consumption per car*** *[Litres/day]*	***Consumption per car*** *[Litres/year]*
Resident Household			
Standard garden hose	38	380	95,380
Garden hose with nozzle	19	190	47,690
Bucket wash	-	19	4,769
Migrant workers household			
Standard garden hose	38	108.6	11,322
Garden hose with nozzle	19	54.3	5,661
Bucket wash	-	5.4	566

Standard garden hose flowrate assumption: Joseph (2015)
Garden hose with nozzle flowrate assumption: Maryland Department of Environment (2019)
Bucket wash: 1 standard 19 litres bucket per car

Table 3-20 Water use technology and demand assumptions: outdoor wash

Technology	***Flowrate*** *[Litres/min]*	***Consumption per house*** *[Litres/year]*
Standard garden hose	38	190,760
Garden hose with nozzle	19	95,380
Bucket wash	-	4,769

Standard garden hose flowrate assumption: Joseph (2015)
Garden hose with nozzle flowrate assumption: Maryland Department of Environment (2019)
Bucket wash: 1 standard 19 litres bucket per car

Table 3-21 Electrical appliances assumptions

	Capacity [W]	*Length of use [Hours]*	*Frequency of use [Days/Week]*
Washing machine			
Single family house	2500	2	4
Extended family house	7500	2	4
Sublette house	15000	2	4
Dryer			
Single family house	2500	1.5	4
Extended family house	7500	1.5	4
Sublette house	15000	1.5	4
Space heaters			
Standard	2000	4	Winter (Wi) period
Television			
Living Room	250	15	6
Dewaniya	250	6	3
Master bedroom	250	3	6
Room 1 & 2	60	5	5
Other rooms	250	5	5
Other Appliances			
Console	180	3	7
Router	18	24	7
Printer	40	0.5	7
DVR	510	12	7
Charging phone	40	3	7
Cordless phone	6	24	7
Alarm clock	12	24	7
Coffee maker	1600	0.5	7
Microwave	1200	0.5	7
Toaster	1200	0.5	7
Vacuum	1400	2	7
Iron	1100	3	7
Hair dryer	1500	0.5	7
Lighting			
Winter		6.5	7
Rest of year		5.5	7
Air Conditioners			
Split AC (1)	900	All year round except winter period	
Split AC (2)	1440	All year round except winter period	
Package AC	3500	All year round except winter period	

3.6.3 Residential electricity and water services demand validation

Estimations of base year demand for water and electricity per end-use are presented in Table 3-22 and Table 3-23, respectively. Water consumption was estimated at 428.1 million m^3. Bathroom faucets share of the consumption 6.8%, Ablution 5.4%, Shower 26.6%, toilets 16.5%, toilet sprayers 2.4%, dishwashing (by hand) 15.4%, drinking water 0.5%, laundry 8.1%, car washing 12.5%, and outdoor use 5.9%. House gardens irrigation was not considered for multiple reasons: Most houses in Kuwait do not have lawns; there is a lack of data regarding houses with lawns; and most of the lawn watering is done with brackish water, since it is free, rather than mains water. Electricity consumption is estimated at 25,487 GWh. Air conditioning consumes 57.8%, lighting 15.2%, refrigerators 5%, freezers 4%, water coolers 0.7%, kitchen appliances 0.5%, wet appliances 1.8%, water heaters (boilers) 5%, space heating 6%, and other appliances 4%.

Water consumption for each of the services was divided into four seasons time period. The electricity consumption for each service was divided into the 20 annual time periods, four seasonal (summer, winter, intermediate 1, and intermediate 2) and 16 diurnals (Night, Day 1, Day 2, and peak for each of the seasons). For water, the total water demand was calibrated to the seasonal consumption curve. A seasonal consumption curve is sufficient since Kuwait houses are fitted with water tanks (minimum one tank with a capacity of 4,550 litres), and the water network already benefits from extensive water tower storage.

As for electricity, and given limited number of published studies and data availability, household consumption was verified and calibrated against a sample house used by the Kuwait Institute for Scientific Research, which serves as a representative model of average Kuwaiti houses. Smart meter house data recorded at 10 minutes intervals over a period of one year between January 2014 and January 2015 were provided for this research by the Energy and Building Research Center at Kuwait Institute for Scientific Research (2016). The data were recorded from a 14-years old house with characteristics representing the typical government house (and the reference house H4). The building housed seven occupants, representing the average household size in Kuwait.

Table 3-22 Base year services water demand [million m^3]

	Residential-GH	*Residential-GO*	*Residential-PH*	*Residential-IA*	*Total*	*Service Share*
Bathroom faucet	3.0	2.0	5.8	18.2	**29.0**	6.8%
Bathroom Ablution	3.5	2.3	6.6	10.6	**22.9**	5.4%
Shower	20.9	13.6	39.8	39.5	**113.8**	26.6%
Toilet	7.4	4.8	14.1	44.4	**70.7**	16.5%
Toilet sprayer	1.3	0.8	2.4	5.8	**10.4**	2.4%
Dishwashing	13.8	8.9	26.2	17.0	**65.9**	15.4%
Drinking water	0.2	0.1	0.4	1.5	**2.3**	0.5%
Laundry	7.9	5.1	15.0	6.5	**34.6**	8.1%
Outdoor wash	7.1	4.6	13.4	0.0	**25.1**	5.9%
Carwash	9.5	4.8	34.6	4.6	**53.5**	12.5%
Total	**74.6**	**47.1**	**158.2**	**148.2**	**428.1**	
Segment share	17.4%	11.0%	37.0%	34.6%		

Table 3-23 Base year services electricity demand [GWh]

	Residential-GH	*Residential-GO*	*Residential-PH*	*Residential-IA*	*Total*	*Service Share*
Air conditioning	2,400	1,691	6,366	4,267	**14,725**	57.8%
Lighting	631	445	1,675	1,123	**3,874**	15.2%
Refrigerators	208	146	551	369	**1,274**	5.0%
Freezers	166	117	441	295	**1,019**	4.0%
Water coolers	30	21	80	54	**185**	0.7%
Kitchen appliances	21	15	55	37	**127**	0.5%
Wet appliances	75	53	198	133	**459**	1.8%
Hot water	208	146	551	369	**1,274**	5.0%
Space heating	249	176	661	443	**1,529**	6.0%
Other	166	117	441	295	**1,019**	4.0%
Total	**4,154**	**2,927**	**11,019**	**7,386**	**25,487**	
Segment share	16.3%	11.5%	43.2%	29.0%		

The electricity and water services demand assumptions were validated by comparing base year estimated consumption against actual aggregated residential sector consumption data from the Ministry of Electricity and Water (2019). Table 3-24 shows water estimates and the relative error. The total estimated consumption is 0.6% higher than the actual, with summer season estimated to be 4% higher than the actual. While winter seasons is -3.2% underestimated and the 2nd intermediate period underestimated by -1.1%. Electricity consumption estimations verified in Table 3-25 against actual sector consumption show that the summer season was overestimated by 0.3%, intermediate-2 season underestimated by -0.4%. In conclusion, the model reproduces actual base-year trends with only minor discrepancies. This is a noteworthy result because it comes from the KEWSM's detailed bottom-up calibration. The close match validates that the assumptions made for end-use technology stocks and their associated service demands were realistically constructed.

Table 3-24 Water consumption verification for base year 2008

Time slice	***Winter*** **[M m^3]**	***Intermediate 1*** **[M m^3]**	***Intermediate 2*** **[M m^3]**	***Summer*** **[M m^3]**	***Total*** **[M m^3]**
National consumption based on MEW (2009) report:					
	186	46	91	223	545
Estimated consumption based on end-use assumptions for residential segments:					
Residential GH	24	6	12	32	75
Residential GO	15	4	8	20	47
Residential PH	51	13	26	68	158
Residential IA	49	12	25	62	148
All other sectors	41	10	20	49	120
Total consumption based on end-use assumptions for residential segments:					
	180	46	90	232	548
Relative error	-3.2%	0.0%	-1.1%	4.0%	0.6%

Table 3-25 Electricity consumption verification for base year 2008

Time slice	*Winter*				*Intermediate 1*				*Intermediate 2*				*Summer*				*Total*
	Night	Day1	Peak	Day 2	Night	Day 1	Peak	Day 2	Night	Day 1	Peak	Day 2	Night	Day 1	Peak	Day 2	
	[GWh]				[GWh]				[GWh]				[GWh]				[GWh]
National consumption based on MEW (2009) report:																	
	2,377	1,098	5,834	1,128	676	417	1,511	300	1,926	1,012	3,319	787	3,960	3,714	10,324	2,069	40,453
Estimated consumption based on end-use assumptions for residential segments:																	
Residential GH	244	113	599	116	69	43	155	31	197	103	339	80	409	379	1,064	213	4,154
Residential GO	172	79	422	82	49	30	109	22	139	73	239	57	288	267	750	150	2,927
Residential PH	647	299	1,589	307	184	114	412	82	522	274	900	213	1,084	1,004	2,821	565	11,019
Residential IA	434	201	1,065	206	124	76	276	55	350	184	604	143	726	673	1,891	379	7,386
All other sectors	879	406	2159	418	250	154	559	111	713	374	1228	291	1465	1374	3820	765	879
Total consumption based on end-use assumptions for residential segments:																	
	2,377	1,098	5,835	1,129	677	417	1,511	300	1,917	1,007	3,306	783	3,979	3,687	10,358	2,074	40,454
Relative error	0.0%	0.0%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	-0.5%	-0.5%	-0.4%	-0.5%	0.5%	-0.7%	0.3%	0.2%	0.0%

3.7 Demand drivers

Demand drivers for KEWSM are presented in detail in chapter 4.

3.8 KEWSM evaluation

The model is solved for the period 2008-2018 to compare the results with actual data from MEW (2019). End-use technologies could still be replaced with new options, including efficient technologies. However, higher efficiency options were disabled. New efficient appliances are considered part of the market's natural transition and, therefore, coexist with older inefficient appliances. Disabling the higher efficiency options represents the reality of the appliances market in Kuwait in the absence of product labelling and policy encouraging residential efficiency improvement.

The KEWSM base year electricity generation is 3.9% lower than the actual generation (Table 3-26). On the other hand, water production is 10% higher than the actual water production. Analysis of the KEWSM output and actual plants data show that 47 M m^3 of the water produced (nearly 86% of the increase) is produced by Az-Zour Station, which is the same plant overutilised by the model to produce electricity.

Table 3-26 Base year (2008) net electricity generated per plant. Actual vs model output.

		Shuwaikh Station	*Shuaiba Station*	*Doha East Station*	*Doha West Station*	*Az-Zour Station*	*Sabiya Station*
Electricity generation							
Actual	51,749 GWh	2.6%	7.0%	9.4%	22.7%	33.9%	24.4%
Model	49,708 GWh	2.8%	6.8%	9.1%	20.6%	36.1%	24.5%
Water production							
Actual	548 M m^3	4.40%	7.50%	9.40%	28.90%	29.20%	20.60%
Model	603 M m^3	3.90%	5.10%	11.10%	28.90%	33.90%	17.00%

A notable difference between KEWSM supply output compared to the actual data is KEWSM overproduction. The difference between KEWSM and actual production data averages around 7% for electricity generation and 6% for water production. Nevertheless, the supply curve aligns with the actual supply data, which validates the end-use assumptions. A comparison with TIMES-KPW, shows underproduction until 2012 and later overproduction until 2016. A difference between -18% and 26% is observed with TIMES-KPW electricity supply compared to actual data. And a difference between -8% and 34% is observed for the water supply. Figure 3-9 compares the model output electricity supply against the actual supply. Figure 3-10 compares the model output water supply against the actual.

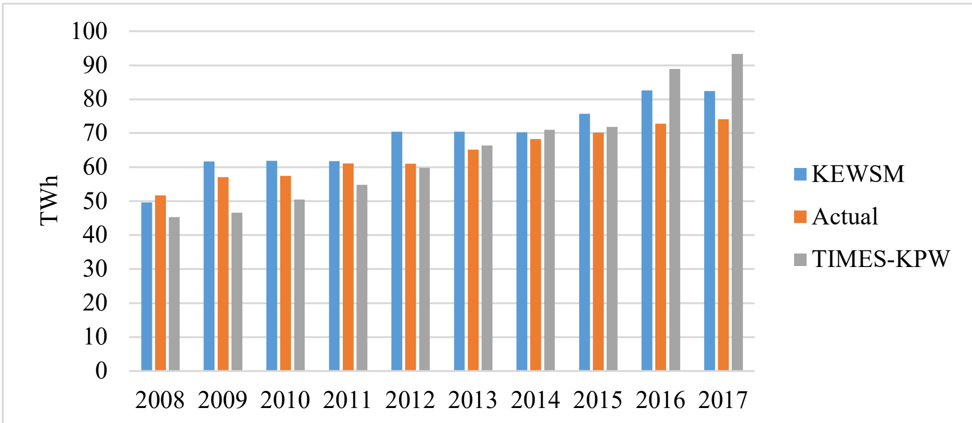

Figure 3-9 Electricity supply comparisons

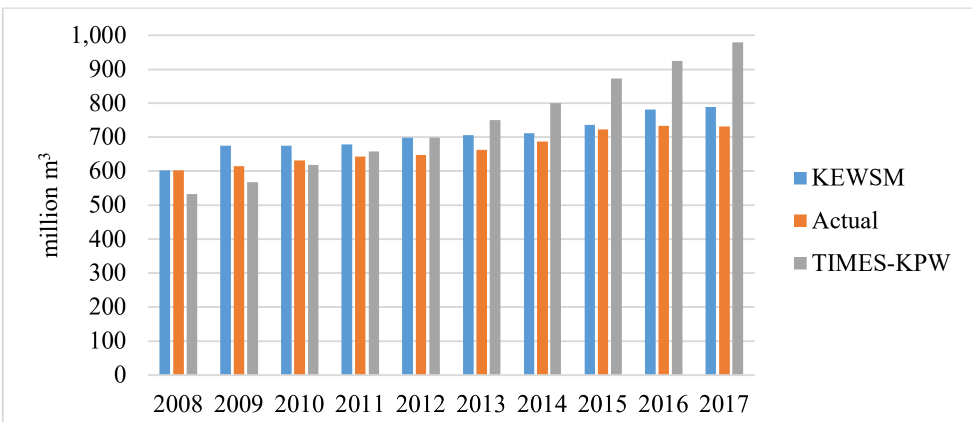

Figure 3-10 Water supply comparisons

3.9 Model limitations and uncertainties

Multiple limitations and uncertainties exist in the KEWSM approach. The model utilises ETSAP-TIMES, which is a cost optimisation demand-driven model generator. Significant uncertainties surround the assumptions driving the housing growth and, consequently, the electricity-water services demand. The uncertainty also extends to the expansive sets of technical and cost data incorporated into the model. Furthermore, given the nature of the cost optimisation model, technology selection is based on cost-effectiveness. Therefore, consumer choice is not factored into technology selection or the implementation of efficiency improvement measures.

KEWSM focuses on electricity and water consumption within the residential sector, as this sector is the largest consumer of electricity and water in Kuwait. All other consumers were treated as an aggregate demand due to data availability. Incorporating these sectors in detail would further improve KEWSM.

Moreover, no environmental constraints are imposed on electric power generation or seawater desalination. This approach aligns with the status quo regarding environmental regulations and emissions restrictions. Current regulations only focus on the quality of electricity generation stack emissions and the quality of desalination effluents. With regards to seawater desalination, the energy-efficient reverse osmosis produces higher concentration effluents compared to the less efficient thermal desalination. Therefore, expansion in the use of reverse osmosis, realistically, would be constrained by the capacity to manage the high-concentration effluents.

3.10 Summary

KEWSM is a disaggregated, activity-based, supply-demand model that helps to analyse the complex interactions between electricity, water, and energy in Kuwait. It significantly expands KISR's Electric Power Sector model (TIMES-KPW) by redefining the demand side from a single aggregated segment into multiple segments with a high-resolution representation of the residential sector. Disaggregating the electricity and water consumers into segments enables us to gain insights into how the electricity-water system may evolve due to different socioeconomic conditions. Incorporating end-use technologies into the cost-optimisation model allows the demand-side to compete with the supply-side towards minimal cost solution for the energy system.

KEWSM consists of two components: a housing demand model producing housing stock demand and appliances projections based on input socioeconomic conditions; and a bottom-up techno-economic TIMES model projecting the evolution of the EWS under changes in resource availability, technology advancement, operational constraints and end-use demand. The housing demand model allows for projections to consider changes in government policy relating to housing welfare, migrant workers population, and crowding rates.

Since the residential sector is the largest consumer of electricity and water in Kuwait, it significantly impacts the overall EWS. This sector is essential for maintaining EWS stability, supply-demand balance, and efficiency. Treating the residential sector as a single unit averages the difference between housing segments into a single archetype that is unrepresentative of any Kuwaiti residences. KEWSM tackles this issue by breaking down the residential sector into segments that differ in electricity and water use intensity. Furthermore, KEWSM considers different electricity and water end-use characteristics within residential segments (migrant workers vs citizens). Breaking down the residential sector into different segments facilitates assessing the effects of policies imposed on the residential sector, be it in terms of housing policy or demand efficiency improvement, on the overall EWS.

KEWSM is a tool to explore how Kuwait's electricity-water system could change in the future. It models the uncertainties around Kuwait's system to support optimal system planning and investments. It enables decision makers to analyse different scenarios and take more informed decisions regarding investment and policy plans (e.g. energy efficiency plans, technology innovation assessment, subsidies, taxation, etc). By doing so, it assists in reducing the risks of locking-in inefficient solutions and investments.

Chapter 4

Residential Demand Drivers and Demand Projections

4.1 Introduction

The majority of Kuwait's electricity and water demands are concentrated in the residential sector. Demographic processes such as fertility, mortality, and migration typically play a significant role in driving the electricity and water demands in the residential sector (Ali et al., 2022, O'Neill et al., 2002, Mine Şenel et al., 2013). Since the majority of Kuwait's population consists of migrant workers, studies such as (Alsayegh et al., 2012, Wood et al., 2012) suggest that the size of migrant population in Kuwait is strongly correlated with GDP. Subsequently, a large portion of the electricity and water demand is susceptible to GDP fluctuation.

In the following subsections, the GDP fluctuation under different oil prices will be projected. These projections will contribute to the estimation of the migrant workers population and the subsequent housing demand. The total housing demand is then projected across all four residential segments. The housing demand projections for each of the residential segments are then used to project electricity and water residential appliances and services demand. Figure 4-1 presents the structure of the end-use demand projections approach.

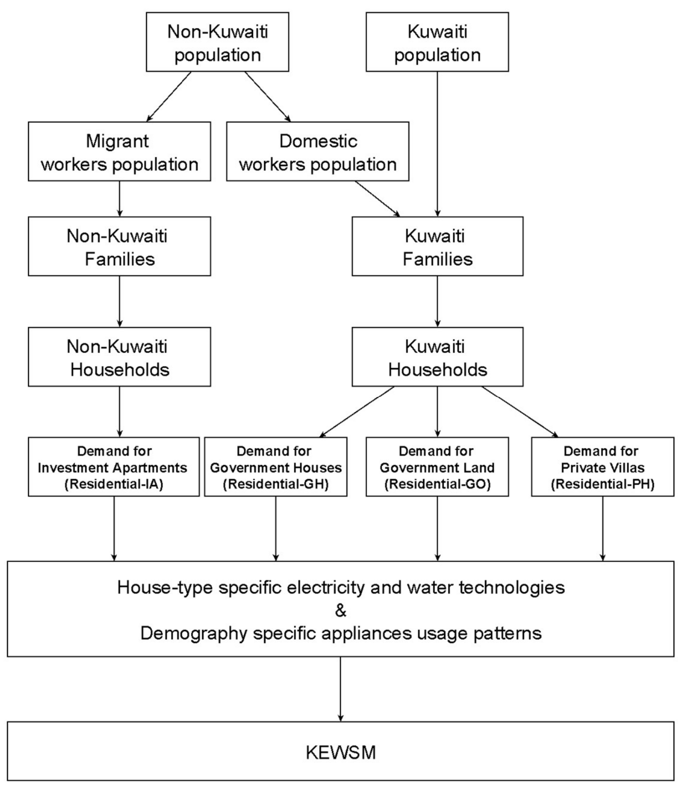

Figure 4-1 Structure of approach for projecting electricity and water services demand

4.2 Economy

Several studies (Hamdi et al., 2019, Shehabi, 2019, Charfeddine et al., 2020, Algaeed et al., 2022) have established the influence of government oil revenues on the economic growth and gross domestic product in oil-based economies. According to the IMF (2018), Kuwait's oil revenue is critical in determining the country's future and economic activity. Figure 4-2 shows the strong correlation between the government revenue and GDP for the period between 1998 and 2018 using the r-squared method. The r-squared method is a statistical approach used to measure the change of dependent variables based on independent variables. The R-square value ranges from 0% to 100%, where a number closer to 100% illustrates a close relationship between the dependent and independent variable. The r-squared value for the correlation between government revenue and GDP is 94.1%.

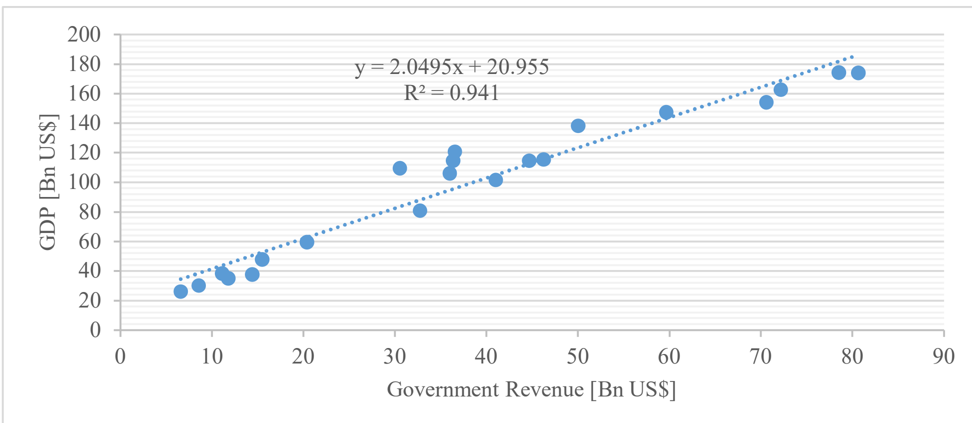

Figure 4-2 Correlation between government revenue and GDP

A simple approach for approximating Kuwait's government revenue is using equation (1):

$$GR_y = C_y P_y [1 + N_y] \quad (1)$$

Where C is the annual crude oil production capacity on the observed year as planned by Kuwait Petroleum Corporation (KPC, 2021); P is the average price of a barrel of crude oil in the observed year as projected by the EIA (2019b) for the reference, low, and high oil prices scenarios; N is the non-oil revenue as percentage share of oil revenue in the observed year as set in the MOF (2018) objectives.

The change in government revenue is used as an adjustment factor to quantify the relative change in Kuwait's economy. The behaviour of Kuwait's economy is therefore predicted using equation (2) under three oil price cases: central, low, and high:

$$GDP_y = GDP_{y_i} \times \frac{GR_y}{GR_{y_i}} \qquad (2)$$

Where GDP is the gross domestic product; GR is the government revenue; y, y_i are the observed year and initial year

The approach's validation test is conducted for the period between 1977 and 2013. The result is shown in Figure 4-3. The approach clearly does not show the effects of an oil price shock nor does it intends to forecast future GDP. However, it shows the three potential paths Kuwait's oil-based economy could follow in the absence of official reports or projections.

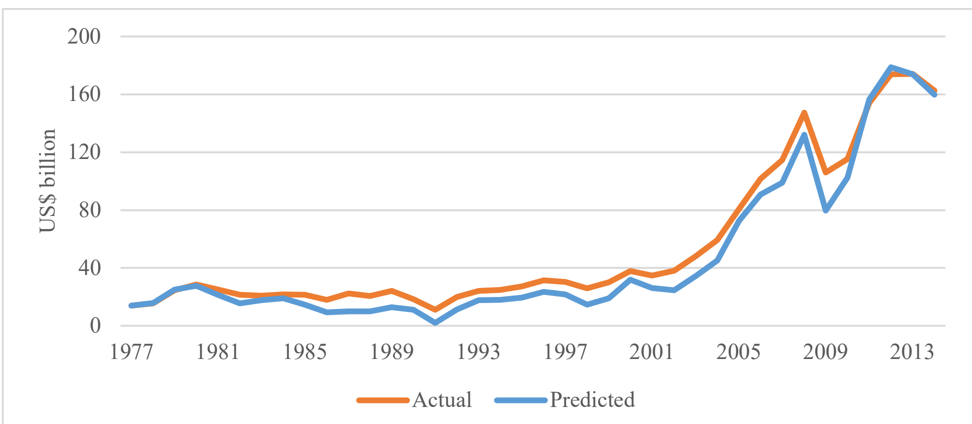

Figure 4-3 Verification of GDP behaviour prediction approach

4.2.1 Economy projections

Based on the approach above, GDP behaviour is projected to follow three different paths under three different oil price cases, as shown in Figure 4-4. Table 4-1 shows the economic assumptions for central economic growth. Table 4-2 shows economic assumptions for low economic growth. And Table 4-3 shows economic assumptions for high economic growth.

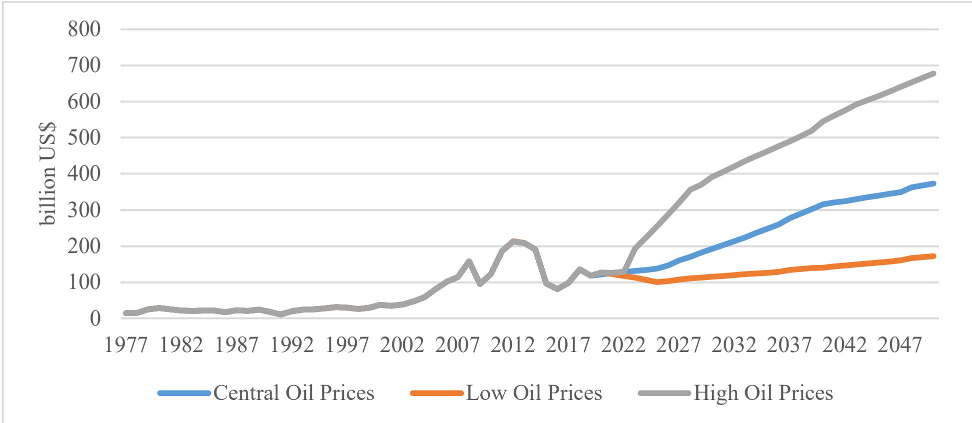

Figure 4-4 GDP behaviour projection

Table 4-1 Projected national income for central economic growth

		2008	2013	2018	2023	2028	2033	2038	2043	2048
Oil Production	M bbl/d	2.37	2.82	2.74	3.15	3.37	3.65	3.9	4.15	4.4
Oil Price	US$/bbl	95	105	69	60	69	84	99	106	107
Oil Revenue	Bn US$	52.1	88.1	39.2	45.6	57.9	76.3	96.1	109.4	117.7
Non-Oil Reve	%	6.4	6.4	8.9	8.9	11.4	11.4	13.9	13.9	16.4
Total Revenue	Bn $/A	54.8	90.9	43	49.4	62.8	81.2	102.1	115.4	124.7
GDP	Bn US$	158	208	136	132	171	225	290	330	362

Table 4-2 Projected national income for low economic growth

		2008	2013	2018	2023	2028	2033	2038	2043	2048
Oil Production	M bbl/d	2.37	2.82	2.74	3.15	3.37	3.65	3.9	4.15	4.4
Oil Price	US$/bbl	95	105	69	51	45	46	47	48	49
Oil Revenue	Bn US$	52.1	88.1	39.2	38.9	37.5	41.4	45.3	49.5	54.1
Non-Oil Rev	%	6.4	6.4	8.9	8.9	11.4	11.4	13.9	13.9	16.4
Total Revenue	Bn US$	54.8	90.9	43	42.7	42.3	46.3	51.2	55.4	61.1
GDP	Bn US$	158	208	136	112	110	122	136	149	167

Table 4-3 Projected national income for high economic growth

		2008	2013	2018	2023	2028	2033	2038	2043	2048
Oil Production	M bbl/d	2.37	2.82	2.74	3.15	3.37	3.65	3.9	4.15	4.4
Oil Price	US$/bbl	95	105	69	131	164	178	192	202	209
Oil Revenue	Bn US$	52.1	88.1	39.2	99.8	137.9	161.7	186	208.2	229
Non-Oil Rev	%	6.4	6.4	8.9	8.9	11.4	11.4	13.9	13.9	16.4
Total Revenue	Bn US$	54.8	90.9	43	103.6	142.8	166.5	191.9	214.2	236
GDP	Bn US$	158	208	136	192	356	435	507	590	652

4.3 Population

Population growth is a critical driver for electricity and water demands. In Kuwait, 69.9% of the population consists of migrant workers. A strong correlation exists between migrant workers' population and economic growth (Ffrench et al., 1971, UN, 1988, Popline, 1992, Essomba, 2014). Figure 4-5 shows the development of Kuwait's population and GDP growth. The population growth is projected to remain susceptible to economic growth (Gulseven, 2016, AlUbaydli, 2015). Therefore, migrant workers' population under three economic growth scenarios (central, low, and high government revenue) are projected using Wood et al. (2012) approach correlating the national economy with migrant workers population growth. Indeed, Figure 4-6 shows the strong correlation between migrant workers population and the GDP, with r-squared value equal to 94.4%. Therefore, the total migrant workers population is projected using the equation (3):

$$Mt_y = M_{y_i} \times \frac{GDP_y}{GDP_{y_i}} + K_y\Psi \tag{3}$$

Where Mt is the total migrant workers population; M is migrant workers population independent of citizens household; GDP is the gross domestic product; K is the citizens population; ψ is the average ratio of domestic workers to citizens estimated from PACI (2018) statistics.

Under strict naturalisation laws and complex long-term residency rules making citizens population growth more subject to fertility rate, citizens population is projected using equation (4):

$$K_y = [1 + \delta_y]K_{y_0} \tag{4}$$

Where K is the citizens population; δ is the citizens growth rate based on UN (2015) projections; y, y_0 are observed year and the previous year.

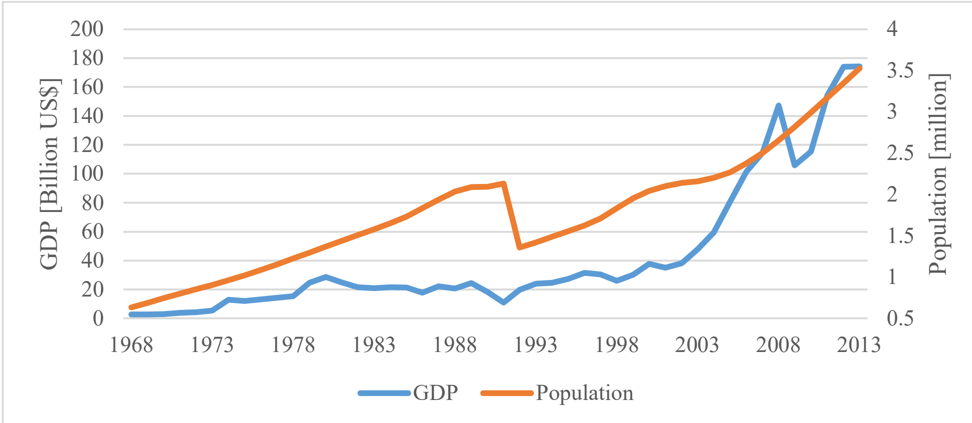

Figure 4-5 Historical GDP and population growth in Kuwait *Source:* Adapted from PACI (2019) & World Bank (2020b)

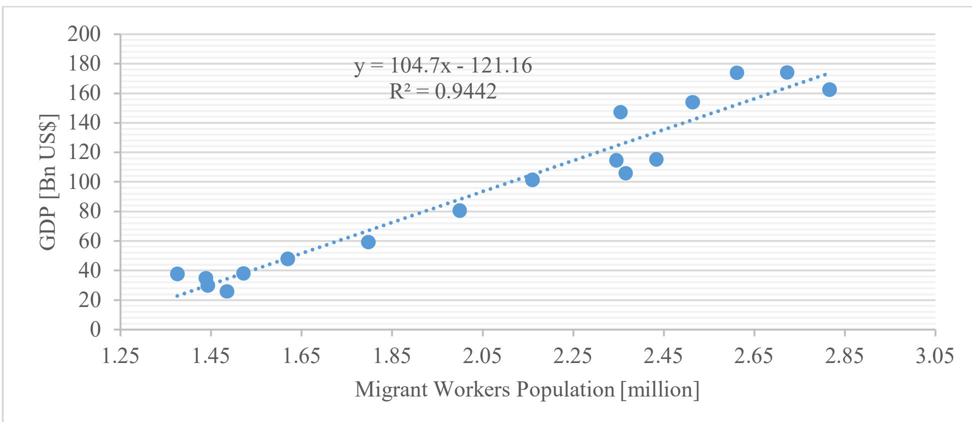

Figure 4-6 Correlation between migrant workers population and GDP

4.3.1 Population projections

Based on the stated approach, the total population was projected for three development cases: a central development case representing the status quo (Table 4-4), a low development case representing low government spending on development (Table 4-8), and a high development case representing a high government spending on development (Table 4-6).

Table 4-4 Population - central development growth case

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Kuwaiti Citizens	[million]	1.09	1.24	1.43	1.51	1.66	1.80	1.96	2.12	2.28
Domestic Workers	[million]	0.52	0.59	0.68	0.72	0.78	0.86	0.93	1.00	1.08
Migrant Workers	[million]	1.84	2.13	2.67	3.31	4.21	5.45	6.85	7.74	8.37
Total	[million]	3.44	3.97	4.78	5.54	6.65	8.11	9.74	10.87	11.73

Table 4-5 Population - low development growth case

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Kuwaiti Citizens	[million]	1.09	1.24	1.43	1.51	1.66	1.80	1.96	2.12	2.28
Domestic Workers	[million]	0.52	0.59	0.68	0.72	0.78	0.86	0.93	1.00	1.08
Migrant Workers	[million]	1.84	2.13	2.67	2.86	2.83	3.10	3.43	3.71	4.09
Total	[million]	3.44	3.97	4.78	5.09	5.27	5.76	6.31	6.83	7.46

Table 4-6 Population - high development growth case

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Kuwaiti Citizens	[million]	1.09	1.24	1.43	1.51	1.66	1.80	1.96	2.12	2.28
Domestic Workers	[million]	0.52	0.59	0.68	0.72	0.78	0.86	0.93	1.00	1.08
Migrant Workers	[million]	1.84	2.13	2.67	6.96	9.59	11.19	12.89	14.39	15.85
Total	[million]	3.44	3.97	4.78	9.18	12.03	13.85	15.78	17.51	19.22

4.4 Housing

In the absence of appropriate housing data, statistics, and projections, or even an official policy regarding migration, an approach was developed to project future housing stock within the different segments of the Kuwaiti residential sector. The approach considers the Public Authority for Housing Welfare (PAHW) delivery rate of publicly built and distributed dwellings and privately constructed dwellings on PAHW-allocated land, as well as the migrant workers' population growth behaviour.

The following subsections present the approach implemented for projecting citizens' and migrant workers' housing demands.

4.4.1 Citizens' housing demand

As indicated earlier, the residential sector in Kuwait consists of four main segments: Residential-GH (PAHW built and distributed dwellings), Residential-GO (privately built dwellings on PAHW lands), Residential-PH (private villas built on private lands), and Residential-IA (investment apartments). Kuwaiti citizens' demand concentrates within the Residential-GH, Residential-GO, and Residential-PH segments while migrant workers mainly concentrate within the Residential-IA segment. The total housing demand for Kuwait citizens is projected using equation (5):

$$HD_{K_y} = \frac{[1+\delta_y]K_{y_0}}{F_K C_{K_y}} \quad (5)$$

Where HD_K is the citizens dwelling demand; K is the Kuwaiti citizens population size as acquired from PACI (2013b); δ is the citizens growth rate based on UN (2015) projections; F_K is the average size of citizens' family assumed based on PACI (2013b) information. The family size has remained steady for the previous two decades. It is assumed that this will remain relatively steady as the government continue providing incentives for starting and maintaining families (financial allowance for newlyweds, housing welfare, social benefits, etc). This factor can be modified to test the influence of change in government policies supporting the establishment of families on housing demand; C_K is the crowding rate of Kuwaiti household in the observed year based on government policy targets laid in the 3rd National Master Plan (Kuwait Municipality, 2005) and PACI (2013b) information. It can be modified to test different government housing policies such as the shift from single family dwelling to multifamily dwelling; y, y_0 are the observed year and previous year.

The total citizens housing demand estimated in equation (5) is typically met by any of the three housing segments (Residential-GH/GO/PH). In order to distribute the demand across dwellings stock within the segments, the maximum possible number of dwellings that can be supplied by each segment is estimated using equation:

$$S_y = [1 + \alpha]S_{y_0} \quad (6)$$

Where S is the maximum possible number of dwellings that can be supplied by the observed segment in the year; α is the delivery rate of segment's dwellings. For each of Residential-GH and Residential-GO, the delivery rates are estimated based on PAHW past project delivery rate and future projects anticipated delivery dates. This factor can be adjusted to reflect change in the PAHW delivery pace or shift in housing policy between houses (Residential-GH) and plots of lands (Residential-GO). As for PH, it is assumed to have linear growth based on PACI (2013b) information; and y, y_0 are the observed year and previous year.

Therefore, the total number of dwellings that can be supplied by the three segments is estimated using equation:

$$S_{Total_y} = S_{GH_y} + S_{GO_y} + S_{PH_y} \quad (7)$$

Where S_{Total} is the total number of dwellings that can be supplied by the three housing segments combined at the observed year; S_{GH}, S_{GO}, & S_{PH} are the maximum number of dwellings that can be supplied by the corresponding segment at the observed year.

Finally, the citizens housing demand in each segment is projected using equations:

$$H_{y+1} = \frac{S_y}{S_{Total_y}} \times HD_{K_y} \tag{8}$$

Where H is the number of dwellings in the observed segment; S is the maximum number of dwellings that can be supplied by the observed segment estimated in equation (6); S_{Total} is the total number of dwellings that can be supplied by the three housing segments combined estimated in equation (7); HD_K is citizens total housing demand estimated in equation (5); and y is the observed year.

Using the above equations will provide projections of citizens housing demand in each residential segment. Different housing policies can be modelled in KEWSM using these equations by modifying factors relevant to the policy, such as the shift in housing welfare direction from dwelling distribution to only land distribution, or steering the population towards multifamily housing.

4.4.2 Migrant workers housing demand

As indicated in subsection 4.3, the migrant workers' population is sensitive to local economic changes. The correlation between migrant workers population and investment apartments stock growth is verified using the r-squared method (Figure 4-7) and the r-squared value is found to be 88.3%. A review of PACI (2013a) building occupancy stats indicates that, on average, approximately 30% of Residential-IA units were vacant between 2008 and 2013 despite the increase in total number of apartments. Therefore, it is assumed that this segment is adaptive to the increase in demand and capable of fulfilling it.

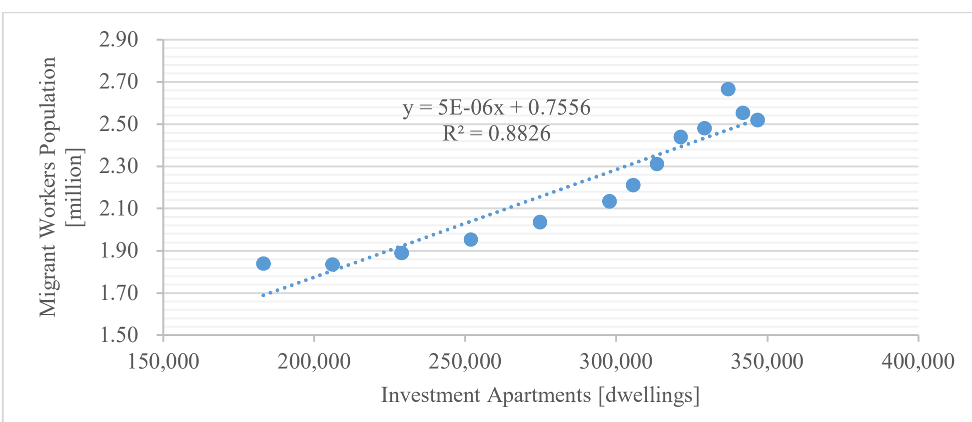

Figure 4-7 Correlation between migrant workers population and investment apartments stock

The migrant workers' Residential-IA housing demand is projected using equation:

$$H_{M_y} = \frac{M_{y_i} \times \frac{GDP_y}{GDP_{y_i}}}{F_M C_{M_y}} \quad (9)$$

Where H_M is the total number of migrant workers dwellings in the observed year; M is migrant workers population at initial year acquired from PACI (2013b); F_M is the average size of migrant workers' household estimated from PACI (2013b) information; C_M is the crowding rate of migrant workers household at observed year based on government policy targets laid in the 3rd National Master Plan (Kuwait Municipality, 2005) and PACI (2013b) information; GDP is the gross domestic product; and y, y_i are the observed year and initial year. Average household size and crowding factors facilitate the representation of demographic changes among migrant workers on housing demand. A demographic change can occur should the economy evolve or if the country's development progresses. For example, a shift in migrant workers' demographics from predominantly single individuals, unskilled labourers, and construction workers to families and skilled employees can yield different dwelling demand and electricity and water end-use patterns.

Residential-IA dwellings are segmented by size based on Kuwait's Real Estate Association reports. For this research, the Real Estate Association (2013) annual report's share distribution is used.

4.4.3 Housing projections

Demand for citizens' housing and migrant workers' housing is projected using the above approach. Table 4-7 shows the citizens housing demand projection under the status quo housing policy. Table 4-8 shows the housing requirement for migrant workers under the three socioeconomic cases (central, low, and high development). And finally, Table 4-9 shows the building stock projections for all residential segments. This breakdown of the building stock is used for electricity and water appliances stock and end-use projections.

Table 4-7 Citizen's housing demand projections

Year	*Families* [Million]	*Family Size* [Persons]	*Crowding Factor*	*GH* [Units]	*GO* [Units]	*PH* [Units]	*Dwellings Required* [Units]
2008	0.23	4.81	1.72	37,008	24,051	70,347	131,406
2013	0.26	4.82	1.82	40,515	29,048	71,818	141,381
2018	0.3	4.81	1.62	62,674	51,614	72,661	183,573
2023	0.31	4.81	1.31	80,857	90,483	69,418	240,757
2028	0.34	4.81	1.29	87,653	109,459	69,301	266,412
2033	0.38	4.81	1.27	94,946	132,312	69,131	296,390
2038	0.41	4.81	1.22	103,397	160,794	69,332	333,523
2043	0.44	4.81	1.17	112,444	195,135	69,435	377,015
2048	0.48	4.81	1.11	122,564	237,355	69,699	429,618

Table 4-8 Migrant workers housing demand projections under different socioeconomic development cases

Year	*Family Size*	*Crowding Factor*	*Central Development*		*Low Development*		*High Development*	
			Families	*Dwellings*	*Families*	*Dwellings*	*Families*	*Dwellings*
	[Persons]		[Million]	[Units]	[Million]	[Units]	[Million]	[Units]
2008	5.22	1.93	0.350	183,111	0.353	183,111	0.353	183,111
2013	4.77	1.50	0.450	297,617	0.447	297,617	0.447	297,617
2018	5.5	1.44	0.480	336,940	0.485	336,940	0.485	336,940
2023	7	1.45	0.790	544,826	0.521	280,943	1.283	681,313
2028	7	1.45	0.950	653,524	0.503	278,447	1.761	939,290
2033	7	1.45	1.150	796,206	0.553	304,677	2.058	1,095,566
2038	7	1.45	1.390	955,997	0.601	336,762	2.363	1,262,750
2043	7	1.45	1.550	1,066,756	0.654	364,686	2.641	1,408,953
2048	7	1.45	1.670	1,151,913	0.712	402,136	2.901	1,552,560

Table 4-9 Housing stock projections (in 1,000 units)

	2008	*~*	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Residential GH										
Type 1	11.1		12.2	18.8	24.6	26.7	28.9	31.5	34.2	37.3
Type 2	25.9		28.4	43.9	57.4	62.2	67.4	73.4	79.9	87.0
Residential GO										
Type 1	7.2		8.7	15.5	27.5	33.3	40.3	48.9	59.4	72.2
Type 2	6.0		7.3	12.9	22.9	27.8	33.6	40.8	49.5	60.2
Type 3	10.8		13.1	23.2	41.3	50.0	60.4	73.4	89.1	108.4
Residential PH										
Type 1	35.2		30.8	24.7	17.6	10.4	7.5	7.6	7.7	7.8
Type 2	21.1		24.1	27.6	31.6	35.7	35.3	32.0	30.8	31.1
Type 3	14.1		16.9	20.3	24.3	28.3	32.3	36.5	38.5	38.9
Residential IA Central development										
Type 1	36.6		59.5	67.4	108.8	129.8	158.9	190.0	212.7	229.0
Type 2	73.2		148.8	168.5	272.1	324.4	397.2	475.0	531.9	572.4
Type 3	73.2		89.3	101.1	163.3	194.6	238.3	285.0	319.1	343.5
Residential IA Low development										
Type 1	36.6		59.5	67.4	55.4	54.1	59.8	65.4	71.5	78.1
Type 2	73.2		148.8	168.5	138.6	135.2	149.6	163.5	178.8	195.3
Type 3	73.2		89.3	101.1	83.1	81.1	89.8	98.1	107.3	117.2
Residential IA High development										
Type 1	36.6		59.5	67.4	135.4	186.1	217.9	250.4	280.2	308.0
Type 2	73.2		148.8	168.5	338.6	465.3	544.7	626.1	700.5	770.0
Type 3	73.2		89.3	101.1	203.2	279.2	326.8	375.6	420.3	462.0

4.5 Electricity and water services demand projections

Electricity and water services demand for all segments of the residential sector are projected based on the appliances inventory estimation in Section 3.6.1 and housing projections in Section 4.4. Detailed water services demand projections for the Residential-GH, Residential GO, and Residential-PH dwellings are presented in Table 4-10. Water services demand projections for the Residential-IA dwellings are presented in Table 4-11 for different dwellings demand scenarios. While detailed electricity services demand projections are presented in Table 4-12 for the Residential-GH, Residential-GO, and Residential-PH dwellings, and Table 4-13 for the Residential-IA under different dwellings demand scenarios.

These projections serve as electricity and water services drivers in KEWSM for all different scenarios in the following chapters.

Table 4-10 Water services end-use projection for Residential GH, GO, and PH

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Residential GH										
Hand washing	[M Washes]	1,097	1,275	1,750	1,844	1,977	2,099	2,206	2,296	2,367
Ablution	[M Washes]	411	478	656	692	742	787	827	861	888
Shower	[M Washes]	192	223	306	323	346	367	386	402	414
Toilet flushing	[M Flushes]	544	632	868	915	980	1,041	1,094	1,138	1,174
Bathroom sprayer	[M Washes]	544	632	868	915	980	1,041	1,094	1,138	1,174
Dishwashing - faucet	[M Washes]	29	32	49	64	70	75	82	89	97
Dishwashing - dishwasher	[M Washes]	140	153	236	309	335	363	395	430	469
Drinking water	[M m3]	223	260	356	376	403	428	450	468	482
Clothes washer	[M Washes]	47	51	79	103	112	121	132	143	156
Outdoor washes	[M Washes]	9	10	16	21	22	24	26	29	31
Carwash	[M Washes]	19	20	31	41	45	48	53	57	62
Residential GO										
Hand washing	[M Washes]	713	914	1,441	2,064	2,469	2,925	3,430	3,984	4,584
Ablution	[M Washes]	267	343	541	774	926	1,097	1,286	1,494	1,719
Shower	[M Washes]	125	160	252	361	432	512	600	697	802
Toilet flushing	[M Flushes]	353	453	715	1,023	1,224	1,450	1,701	1,976	2,273
Bathroom sprayer	[M Washes]	353	453	715	1,023	1,224	1,450	1,701	1,976	2,273
Dishwashing - faucet	[M Washes]	19	23	40	72	87	105	128	155	189
Dishwashing - dishwasher	[M Washes]	91	110	195	346	419	506	615	746	907
Drinking water	[M m3]	145	186	294	421	503	596	699	812	934
Clothes washing	[M Washes]	30	37	65	115	140	169	205	249	303
Outdoor washes	[M Washes]	6	7	13	23	28	34	41	50	60
Carwash	[M Washes]	12	15	26	46	56	67	82	99	121
Residential PH										
Hand washing	[M Washes]	2,084	2,260	2,029	1,584	1,563	1,528	1,479	1,418	1,346
Ablution	[M Washes]	782	847	761	594	586	573	555	532	505
Shower	[M Washes]	365	395	355	277	274	267	259	248	236
Toilet flushing	[M Flushes]	1,034	1,120	1,006	785	775	758	733	703	667
Bathroom sprayer	[M Washes]	1,034	1,120	1,006	785	775	758	733	703	667
Dishwashing - faucet	[M Washes]	55	56	57	55	55	55	55	55	55
Dishwashing - dishwasher	[M Washes]	265	271	274	265	265	264	265	265	267
Drinking water	[M m3]	425	461	413	323	319	311	301	289	274
Clothes washing	[M Washes]	88	90	91	89	88	88	88	89	89
Outdoor washes	[M Washes]	18	18	18	18	18	18	18	18	18
Carwash	[M Washes]	71	72	73	71	71	70	71	71	71

Table 4-11 Water services end-use projection for Residential IA under different dwellings demand cases

		2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Residential IA - Central Demand										
Hand washing	[M Washes]	6,584	7,640	11,914	19,774	23,575	28,865	34,521	38,653	41,600
Ablution	[M Washes]	1,251	1,452	2,264	3,757	4,479	5,484	6,559	7,344	7,904
Shower	[M Washes]	363	421	656	1,089	1,298	1,590	1,901	2,129	2,291
Toilet flushing	[M Flushes]	3,264	3,788	5,907	9,805	11,689	14,312	17,117	19,165	20,627
Bathroom sprayer	[M Washes]	2,481	2,879	4,490	7,452	8,884	10,877	13,009	14,566	15,676
Dishwashing - faucet	[M Washes]	143	233	264	426	508	622	744	833	896
Dishwashing - dishwasher	[M Washes]	96	155	176	284	339	415	496	555	598
Drinking water	[M m3]	1,531	1,776	2,770	4,597	5,481	6,711	8,026	8,987	9,672
Clothes washing	[M Washes]	38	62	70	114	135	166	198	222	239
Outdoor washes	[M Washes]	5	9	10	16	19	24	28	32	34
Residential IA - Low Demand										
Hand washing	[M Washes]	6,584	7,640	11,914	10,071	9,823	10,872	11,880	12,991	14,193
Ablution	[M Washes]	1,251	1,452	2,264	1,914	1,866	2,066	2,257	2,468	2,697
Shower	[M Washes]	363	421	656	555	541	599	654	715	782
Toilet flushing	[M Flushes]	3,264	3,788	5,907	4,994	4,871	5,391	5,890	6,441	7,037
Bathroom sprayer	[M Washes]	2,481	2,879	4,490	3,795	3,702	4,097	4,477	4,895	5,348
Dishwashing - faucet	[M Washes]	143	233	264	217	212	234	256	280	306
Dishwashing - dishwasher	[M Washes]	96	155	176	145	141	156	171	187	204
Drinking water	[M m3]	1,531	1,776	2,770	2,342	2,284	2,528	2,762	3,020	3,300
Clothes washing	[M Washes]	38	62	70	58	56	62	68	75	82
Outdoor washes	[M Washes]	5	9	10	8	8	9	10	11	12
Residential IA - High Demand										
Hand washing	[M Washes]	6,584	7,640	11,914	24,607	33,816	39,588	45,500	50,905	55,962
Ablution	[M Washes]	1,251	1,452	2,264	4,675	6,425	7,522	8,645	9,672	10,633
Shower	[M Washes]	363	421	656	1,355	1,862	2,180	2,506	2,803	3,082
Toilet flushing	[M Flushes]	3,264	3,788	5,907	12,201	16,767	19,629	22,560	25,241	27,748
Bathroom sprayer	[M Washes]	2,481	2,879	4,490	9,273	12,743	14,918	17,146	19,183	21,088
Dishwashing - faucet	[M Washes]	143	233	264	530	729	853	980	1,097	1,206
Dishwashing - dishwasher	[M Washes]	96	155	176	354	486	569	654	731	804
Drinking water	[M m3]	1,531	1,776	2,770	5,721	7,862	9,204	10,579	11,835	13,011
Clothes washing	[M Washes]	38	62	70	141	194	227	261	292	321
Outdoor washes	[M Washes]	5	9	10	20	28	32	37	42	46

Table 4-12 Residential electricity end-use services demand projection (in 1,000 units)

[k Units]	*Lighting*	*Fridges*	*Freezers*	*Water Coolers*	*Water Heaters*	*Space Heaters*	*Wet Appliances*	*Kitchen Appliances*	*Central AC*	*Split AC*
					Residential-GH					
2008	6,734	137	50	200	62,914	348	126	174	337	100
2013	7,372	150	55	219	68,876	381	138	190	369	109
2018	11,404	232	85	338	106,546	589	213	295	570	169
2023	14,926	304	111	443	139,453	771	279	386	746	221
2028	16,180	329	120	480	151,173	836	302	418	809	240
2033	17,526	356	130	520	163,752	905	328	453	877	260
2038	19,086	388	142	566	178,328	986	357	493	955	283
2043	20,756	422	154	616	193,931	1,072	388	536	1,038	308
2048	22,624	460	168	671	211,384	1,169	423	584	1,132	336
					Residential-GO					
2008	4,847	100	38	152	40,887	237	82	152	230	76
2013	5,854	121	46	183	49,382	286	99	183	277	92
2018	10,401	214	81	325	87,743	508	175	325	493	163
2023	18,499	381	145	578	156,055	904	312	578	877	289
2028	22,379	461	175	700	188,782	1,094	378	700	1,061	350
2033	27,051	557	211	846	228,198	1,322	456	846	1,282	423
2038	32,875	677	257	1,028	277,320	1,607	555	1,028	1,558	514
2043	39,896	822	312	1,247	336,547	1,950	673	1,247	1,891	624
2048	48,528	999	379	1,517	409,363	2,372	819	1,517	2,300	759
					Residential-PH					
2008	14,188	292	111	485	119,590	693	260	443	672	222
2013	14,485	298	113	496	122,091	707	266	452	686	226
2018	14,655	302	114	501	123,524	716	269	458	694	229
2023	14,204	292	111	486	119,724	694	261	444	673	222
2028	14,180	292	111	485	119,523	693	260	443	671	221
2033	14,145	291	110	484	119,230	691	260	442	670	221
2038	14,186	292	111	485	119,575	693	260	443	672	222
2043	14,207	292	111	486	119,754	694	261	444	673	222
2048	14,261	293	111	488	120,210	697	262	445	675	223

Table 4-13 Residential IA electricity end-use services demand projection under different dwelling demand projections (in 1,000 units).

[k Units]	*Lighting*	*Fridges*	*Freezers*	*Water Coolers*	*Water Heaters*	*Space Heaters*	*Wet Appliances*	*Kitchen Appliances*	*Central AC*	*Split AC*
	Central Demand									
2008	7,976	183	37	183	403	403	366	366	439	146
2013	12,399	298	45	298	625	625	595	595	685	238
2018	14,038	337	51	337	708	708	674	674	775	270
2023	22,672	544	82	544	1,143	1,143	1,088	1,088	1,252	435
2028	27,030	649	97	649	1,362	1,362	1,298	1,298	1,492	519
2033	33,095	794	119	794	1,668	1,668	1,589	1,589	1,827	635
2038	39,580	950	143	950	1,995	1,995	1,900	1,900	2,185	760
2043	44,318	1,064	160	1,064	2,234	2,234	2,127	2,127	2,447	851
2048	47,697	1,145	172	1,145	2,404	2,404	2,290	2,290	2,633	916
	Low Demand									
2008	7,976	183	37	183	403	403	366	366	439	146
2013	12,399	298	45	298	625	625	595	595	685	238
2018	14,038	337	51	337	708	708	674	674	775	270
2023	11,547	277	42	277	582	582	554	554	637	222
2028	11,262	270	41	270	568	568	541	541	622	216
2033	12,466	299	45	299	628	628	598	598	688	239
2038	13,621	327	49	327	687	687	654	654	752	262
2043	14,895	358	54	358	751	751	715	715	822	286
2048	16,273	391	59	391	820	820	781	781	898	312
	High Demand									
2008	7,976	183	37	183	403	403	366	366	439	146
2013	12,399	298	45	298	625	625	595	595	685	238
2018	14,038	337	51	337	708	708	674	674	775	270
2023	28,214	677	102	677	1,422	1,422	1,354	1,354	1,558	542
2028	38,772	931	140	931	1,954	1,954	1,861	1,861	2,140	745
2033	45,389	1,089	163	1,089	2,288	2,288	2,179	2,179	2,506	872
2038	52,168	1,252	188	1,252	2,630	2,630	2,504	2,504	2,880	1,002
2043	58,366	1,401	210	1,401	2,942	2,942	2,802	2,802	3,222	1,121
2048	64,163	1,540	231	1,540	3,234	3,234	3,080	3,080	3,542	1,232

4.6 Summary

The residential sector is the largest consumer of electricity and water in Kuwait. Electricity and water demands are subject to a high level of uncertainty due to the nature of the population composition and the drivers behind the composition growth. A large portion of the electricity and water demand is susceptible to GDP fluctuation, and citizens housing depends mostly on government policy and spending.

A sophisticated housing demand model for projecting Kuwait's housing demand that accounts for changes in the demographic structure was developed and verified. The methodology allows for projections to consider changes in government policy relating to housing welfare, population composition, and crowding rates. Housing demand projections are used to project electricity and water end-use appliances stock and water services demand. The electricity and water end-use services demands are then defined in KEWSM exogenously.

Chapter 5

PATHWAYS FOR KUWAIT'S ELECTRICITY & WATER DEMAND

5.1 Introduction

Multiple factors influence the demand for electricity and water. The main factors that generally influence demand can be summarised by: changes in the number and type of consumers, adjustments in efficiency (i.e. commodity used per unit of activity), variations in buildings quantity and floor area, and changes in appliance ownership. These factors interact with each other and their influences are unique to the context of the Gulf region.

Strategies for meeting future demand are shaped by broader socioeconomic variables that must be considered in long-term planning strategy. These variables include population growth, resource availability, and future national plans for economic development. Planners and policymakers in Kuwait deal with additional complexity layers such as the population growth uncertainty, the coupling of electricity and water production and the complete reliance on energy availability for potable water. The nature of population growth and its intertwining with economic performance and government spending presents planners and policymakers with a unique challenge in anticipating electricity-water system evolution pathways, especially in the absence of an official strategy or plan regarding the population and economic direction.

This chapter addresses research question number one: What are the potential demand pathways for electricity and water in Kuwait? The question will be answered through KEWSM under different socioeconomic trends based on the approach presented in Chapter 4.

Section 5.2 presents the characteristics of the scenarios developed to explore the potential demand pathways for electricity and water in Kuwait. Sections 5.3 and 5.4 present the results under different development pathways, followed by the discussion in Section 5.5, and finally the chapter summary in Section 5.6.

5.2 Methods

In order to assess the potential demand pathways for electricity and water, three socioeconomic trends representing different economic and development conditions are selected for this chapter. These trends represent the central national development demand case, high national development demand case, and low national development demand case. For this chapter, the three cases are modelled in KEWSM for the period between 2008 and 2048 using three scenarios. All three scenarios were designed under business-as-usual assumption with absence of policies, legislations, and regulations related to the diversification of the energy mix for electricity and water production, carbon emissions reductions, or efficiency improvement in electricity and water consumption. End-use technologies could still be replaced with new options, including efficient technologies. However, higher efficiency options were disabled. New efficient appliances are considered part of the market's natural transition and, therefore, coexist with older inefficient appliances. Disabling the higher efficiency options represents the reality of the appliances market in Kuwait in the absence of product labelling and policy encouraging residential efficiency improvement.

5.2.1 Reference scenario

The reference (REF) scenario examines the long-term development of Kuwait's electricity-water system under central socioeconomic growth. Central economic growth conditions (Table 4-1) are assumed in this scenario for the socioeconomic parameters and the electricity and water services demand projections. This scenario serves as a baseline case for comparison with all cases that include alternative assumptions.

For this scenario, the GDP growth is projected to experience an upward trend, with growth change averaging 2.7% annually from 2008 to 2048, as shown in Table 5-1. The population is also projected to experience an upward trend, with growth averaging 3.3% annually for the same period growing from 3.4 million inhabitants in 2008 to 11.7 million inhabitants in 2048. The GDP per Capita, however, is projected to slow and, on occasion, experience a decline during the period up to 2033. The GDP per Capita is projected to return to its 2018 level by 2038 before a modest annual increase continues.

Housing policy is assumed to remain the same, and PAHW would continue providing housing welfare for the residents. There are no changes to the private housing strategy, and lands are assumed to be released at the same current rate. Investment apartments are assumed to maintain growth parallel to the migrant workers' demand for housing. The total number of households is projected to grow from 528,000 in 2018 to 1.47

million in 2048. All socioeconomic parameters were projected using equations presented in Section 4.2.1.

Table 5-1 Key socioeconomic parameters for REF scenario.

		2008	*2018*	*2028*	*2038*	*2048*	*Avg. change p.a.*
GDP	Bn US$	158	136	171	290	362	2.7%
Population	M	3.4	4.8	6.6	9.7	11.7	3.3%
Households	k	315	524	792	1188	1473	4.3%
Dwelling area	M m^2	116	173	249	345	431	3.6%

5.2.2 High development scenario

The high development scenario examines the long-term development of Kuwait's electricity-water system if there is high economic growth. High economic growth conditions (Table 4-3) are assumed in this scenario for the socioeconomic parameters and the electricity and water services demand projections. The scenario assumes high socioeconomic growth based on an assumption of an increase in government revenue due to a significant rise in exported oil prices and higher diversification of the economy (with diversification of the economy following the formulation of equation (1) in Section 4.2.1).

Table 5-2 presents key socioeconomic parameters for the high-development scenario from 2008 to 2048. The GDP is projected to increase significantly at an average annual change of 5.2% annually. The population is also expected to grow significantly over the projection period, from 3.4 million in 2008 to 19.1 million in 2048, representing an average annual change of 5.2%. The high-development scenario population projection is significantly higher compared to the REF scenario. It is projected that the year 2048 population to be 63% higher than that of the REF scenario for the same year.

The number of households and the dwelling area are also projected to increase significantly over the projection period. The number of households is expected to grow from 0.31 million in 2008 to 2.4 million in 2048, representing an average annual change of 6.4%. Similarly, the dwelling area is expected to increase from 116 million square metres in 2008 to 599 million square metres in 2048, representing an average annual change of 4.8%.

Table 5-2 Key socioeconomic parameters for high-development scenario.

		2008	*2018*	*2028*	*2038*	*2048*	*Avg. change p.a.*
GDP	Bn US$	158	136	406	561	705	5.2%
Population	M	3.4	4.8	12.0	15.7	19.1	5.2%
Households	k	315	524	1461	1940	2405	6.4%
Dwelling area	M m^2	116	173	370	480	599	4.8%

5.2.3 Low demand scenario

In contrast to the high-development scenario, the low-development scenario depicts the impact of slow socioeconomic growth. The low-development scenario presents a decelerated demographic growth linked to slower economic growth conditions (Table 4-2) resulting from a decline in exported oil prices and a reduction in government with a continuation of the status quo regarding economic diversification.

Table 5-3 highlights the key socioeconomic parameters for the low-development scenario. The GDP in the low-development scenario projects a downward trend, bottoming in the year 2028 at $110 billion before undergoing a slow growth trend. The average annual change in GDP for this scenario is 0.5%. Similarly, the population undergoes a slow average annual change of 2% reaching 7.4 million in 2048.

The deceleration in population growth leads to lower demand for housing in the investment apartments segment. This reduced demand in the housing sector is reflected in the number of households and dwelling area growth rate. The number of households experiences an annual change at an average of 3%. Starting at 315,000 in 2008 and increasing to 524,000 in 2018 before reaching 941,000 in 2048, representing 36% less than the projected for the same year in the reference scenario. Similarly, the dwelling area increased from 116 million square metres in 2008 to 173 million square metres in 2018 before reaching 336 million square metres in 2048, with an average annual change of 2.9%.

Table 5-3 Key socioeconomic parameters for low demand scenario.

		2008	*2018*	*2028*	*2038*	*2048*	*Avg. change p.a.*
GDP	Bn US$	158	136	110	136	167	0.5%
Population	M	3.4	4.8	5.3	6.3	7.4	2.0%
Households	k	315	524	621	762	941	3.0%
Dwelling area	M m^2	116	173	219	268	336	2.9%

5.3 The Reference scenario pathways

5.3.1 Electricity and water demand

In the central demand reference (REF) scenario, both electricity and water consumption are projected to grow substantially. KEWSM output for the electricity demand project that consumption could grow from 53 TWh in 2013 to 134 TWh in 2043 (Figure 5-1). Similarly, potable water demand is projected to increase from 664 million m^3 in 2013 to 1,788 million m^3 in 2043 (Figure 5-2). For both commodities, this growth is a direct consequence of the REF scenario underlying demographic and economic drivers introduced in Chapter 4, which were translated into housing demand and subsequently, into demand for electrical appliances, water fixtures, and other end-use electricity and water services. Therefore, the projected growth in electricity and water is a direct output of TIMES bottom-up methodology, which models technology adoption and allocation to meet services demand across different housing segment.

KEWSM outputs were compared to TIMES-KPW reference scenario projections. The electricity demand projection for TIMES-KPW between 2008 and 2028 is 49% higher than the KEWSM model projection, with the gap widening further into the future (Figure 5-1). Similarly, the water demand projected for TIMES-KPW between 2008 and 2028 is around 29% higher than the KEWSM projection (Figure 5-2).

This increasing divergence between the model projections reflects differing methodological approaches to estimating demand drivers. TIMES-KPW projections were based on base-year electricity and water per capita consumption estimates. The consumption per capita was then used to project future demand based on fertility rate for citizens and economic growth for migrant workers. In contrast, electricity and water demand projections presented above are calculated by KEWSM based on the electricity and water end-use services demand. The end-use services demand is met through a range of technologies that compete to meet the demand in the most cost-effective way. These technologies also take into consideration the behavioural variations between migrant workers and citizens in terms of cultural considerations and lifestyle (as presented in subsection 3.6.2).

Comparing KEWSM reference scenario with TIMES-KPW reference scenario projections highlights the advantage of incorporating end-use services demand into the model. It allows for capturing the influence of appliances market trends and technology development on the consumption. Incorporating end-use services demand into the model facilitates the analysis of residential demand dynamics, thus allowing us to capture subtle variations in consumption across different residential segments. This approach provides an advantage over TIMES-KPW, which relies on the per capita consumption projections. Hence, KEWSM electricity and water demand projections show closer alignment with real-world data, thereby highlighting its methodological strength.

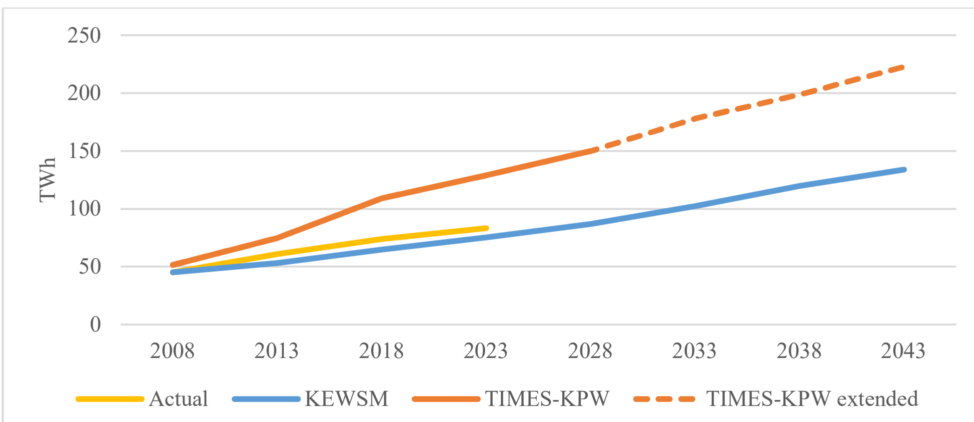

Figure 5-1 Electricity demand projection comparison

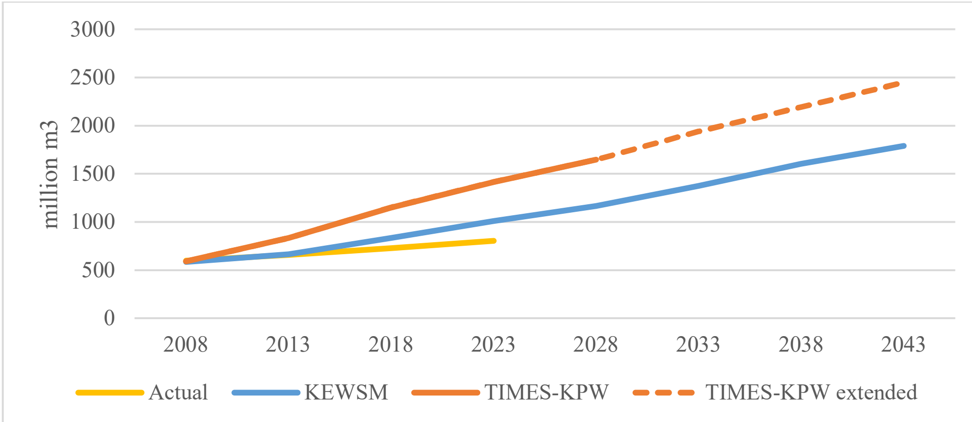

Figure 5-2 Water demand projection comparison

5.3.2 Residential electricity and water consumption

KEWSM projects the residential sector to continue dominating the electricity and water consumption throughout the modelled horizon (Figure 5-3 and Figure 5-4). Under the Reference (REF) scenario, the total residential sector electricity consumption is projected to grow from 28 TWh in 2013 to 79 TWh in 2043 with its share of final electricity consumption projected to grow from 53% in 2013 to 59% in 2043. Similarly, KEWSM projects the residential sector to maintain its dominance in water consumption. Residential water consumption is projected to rise from 490 million m^3 in 2013 to 1,460 million m^3 in 2043, with the consumption share increasing from 74% in 2013 to 82% in 2043.

The residential sector is projected to undergo a significant reshaping in the relative shares of its housing segments (Figure 5-5 and Figure 5-6). This transformation is shaped by the housing policy and demographic assumptions that drive the model based on various socioeconomic assumptions discussed in Chapter 4. These factors are examined in detail in the following subsections.

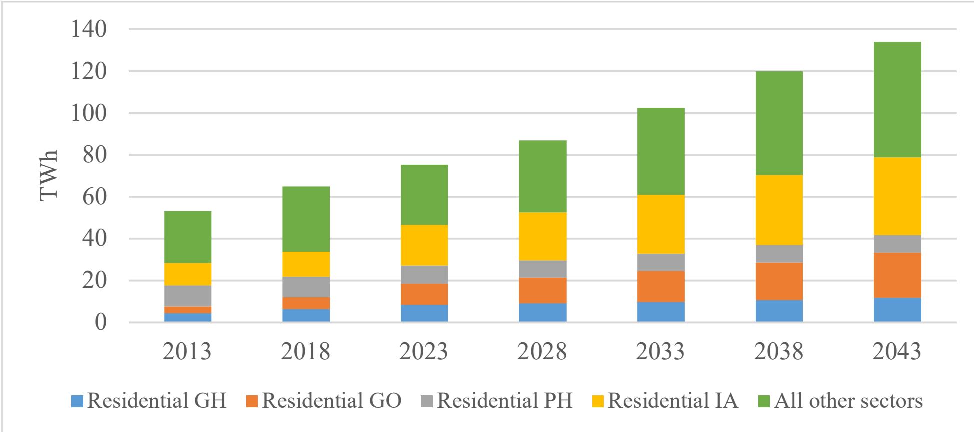

Figure 5-3 KEWSM final electricity consumption (REF scenario)

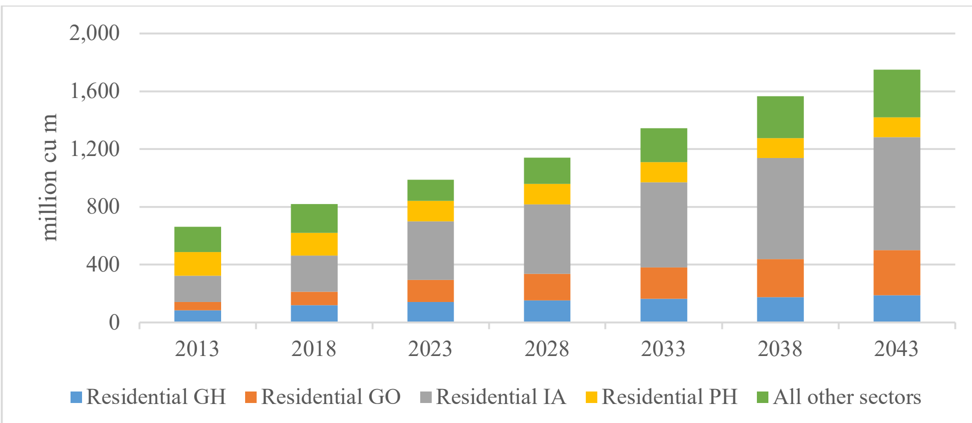

Figure 5-4 KEWSM water consumption (REF scenario)

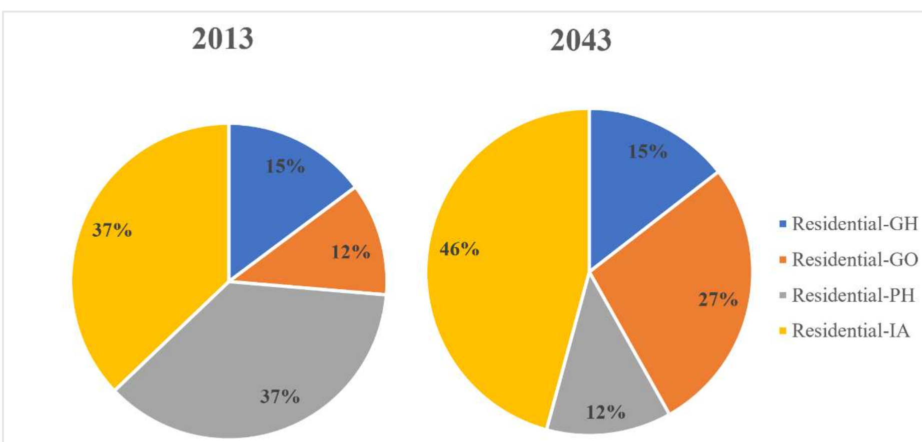

Figure 5-5 Residential electricity consumption under KEWSM REF scenario

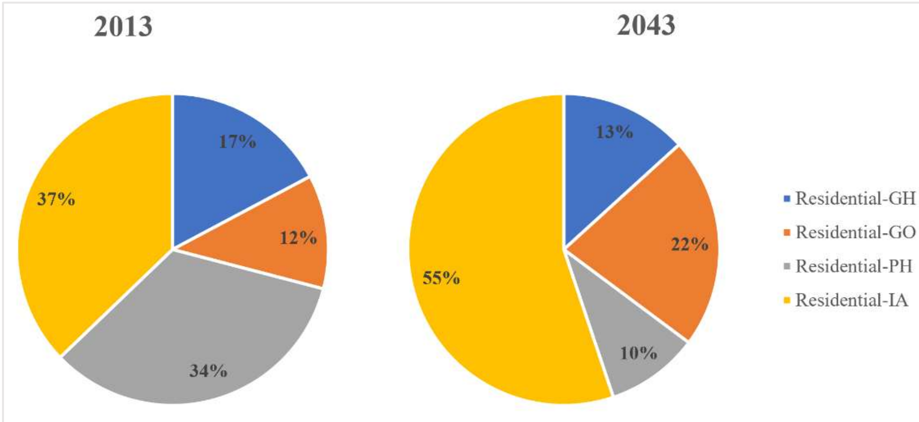

Figure 5-6 Residential water consumption under KEWSM REF scenario

5.3.3 Impact of constrained private housing

Although initially the private housing sector represents the largest sector in electricity and water consumption, it has only a modest linear growth (as defined in the housing demand drivers in Section 4.4). As a result, the private housing segment is the only segment projecting a stagnant trend with an average annual growth rate of negative 0.8% remaining relatively unchanged from 10.1 TWh in 2013 to 8.2 TWh in 2043 for electricity. A similar decline in share is observed with water as it shrinks from 36% to 10% for the same period bringing the consumption down from 165 million m^3 in 2013 to 137 million m^3 in 2043.

Due to the limited stock of private houses (Residential-PH), the Public Authority for Housing Welfare (PAHW) currently serves as the main supplier for citizens' housing (as explained in Section 1.2). Therefore, based on the scheduled development plans for new cities, privately built houses on PAHW distributed lands (Residential-GO) are projected to be the fastest growing consumption segment. The average electricity consumption is projected to experience a growth rate of 7.1% for the period between 2013 and 2043. During this period, electricity consumption for this segment is projected to rise from 3 TWh in 2013, to 22 TWh in 2043, with the segment's share of the residential consumption rising from 12% to 28%. Meanwhile, water consumption experiences an average annual growth rate of 6.5%, from 58 million m^3 in 2013 to 315 million m^3 in 2043, raising the Residential-GO water share from 12% in 2013 to 28% in 2043.

The dwellings built and distributed by the PAHW (Residential-GH) are projected to experience the slowest growth, at an average annual growth rate of 3.8% for electricity consumption, increasing from 4 TWh in 2013 to 12 TWh in 2043. Water consumption is projected to grow at an annual rate of 3%, rising from 84 million m^3 in 2013 to 190 million m^3 in 2043. As a result, the overall share of electricity consumption for all housing supplied by the PAHW (both Residential-GO and Residential-GH) is projected to increase from 29% to 35%, while the share for water consumption is projected to grow from 27% to 42% between 2013 and 2043.

5.3.4 The rise of investment apartments as major consumers

The investment apartments segment (Residential-IA), which primarily serves the rental market for the growing expatriate population, is projected to experience significant growth. During the period from 2013 to 2043, the segment's average growth rate is projected at 5.4% for electricity and 5.7% for water. Despite the slower growth rate compared to the privately built houses on PAHW distributed lands (Residential-GO), projections indicate that the investment apartment segment will dominate demand for both electricity and water by 2043.

The share of electricity consumption from the investment apartments segment is projected to grow from 37.4% in 2013 to 47% by 2043. Its share of the residential water consumption is projected to grow from 37% to 56%. This growth is attributed to the increasing demand for dwellings, with the number of households in the investment apartments segment projected to more than triple, from 0.45 million in 2013 to 1.51 million in 2043 under the central development scenario and status quo conditions of this study. That projection is based on the market's core demographics, the expatriate population, whose housing needs are served by this segment. The size of this population group is highly sensitive to local economic change, as established in subsection 4.3. Therefore, to ensure a robust forecast, housing demand was projected using the methodology presented in subsection 4.4. This approach incorporates key government policy and demographic variables such as government regulation on crowding rates and shifts in the average household size.

The above approach assumes that investment apartment stock will consistently meet the housing demand of the migrant workforce. This allows KEWSM to project future electricity and water consumption based on these housing requirements. That assumption is indeed based on the real-world dynamics of Kuwait's rental market and the demographic trends that support it.

Analysis of the occupancy rates of investment apartments, along with dwelling stock statistics from the Public Authority for Civil Information (PACI, 2013a), reveals that, on average, about 30% of the investment apartments were vacant between 2008 and 2013. This situation occurred despite an overall increase in the total number of apartments. This trend is also validated by the construction trends and occupancy rates published by the Kuwaiti Real Estate Association (2017). The report confirms the trend of continued expansion in the apartments stock, along with a declining occupancy rate, despite a steady increase in expatriate population. It is concluded that the decline in occupancy rate is not an indicator of market weakness, but rather a sign of a construction boom that demonstrates the real estate sector's capacity and financial incentive to deliver new apartment units at the required scale. Therefore, the current oversupply in investment apartments, in conjunction with construction trends, demonstrates the market's capacity to accommodate demographic growth in the migrant workforce population. Thus, the substantial growth in electricity and water demand projected by KEWSM, resulting from migrant workforce housing demand for investment apartments, is plausible given the elasticity of the housing supply.

5.3.5 Electricity and water consumption of the non-residential sector

Given that the focus of KEWSM is the residential sector, the electricity and water consumption of all other sectors were aggregated into a single entity referred to as the 'Combined Non-Residential Sector'. The demand for this sector is treated as an exogenous input and is forecasted off-model. In line with the methodology presented in Chapter 4, this demand is projected to contract and expand in direct parallel with Kuwait's economy, using GDP as the primary driver for its behaviour.

Under this methodology, electricity consumption of the combined non-residential sector is projected to grow from 25 TWh in 2013 to 55 TWh in 2043, reflecting an average annual growth rate of 2.8%. Similarly, water consumption for this sector is projected to increase from 174 million m^3 in 2013 to 328 million m^3 in 2043, at an average annual growth rate of 2.6%. These growth rates are substantially lower than those projected for the residential sector. KEWSM projections show that under the reference scenario, by 2043 the residential sector will account for 59% and 82% of the total electricity and water consumption respectively. Therefore, this disparity highlights that the residential sector is the dominant consumer and the primary driver of future demand growth, and its internal dynamics can overwhelmingly shape the demand trajectory.

Nevertheless, the active pursuit by Gulf States of establishing regional data centre hubs (Chmouri et al., 2025, Reuters, 2025, Tsuji, 2025) and the push towards transport electrification (Shannak et al., 2022), are set to become major new demand drivers in the region (IEA, 2025). Therefore, the impact of emerging large-scale electricity consumers could be examined in a future study.

5.3.6 The decoupling of the per capita consumption

KEWSM projections indicate a similar "peak-and-decline" trajectory for both per capita electricity and water consumption (Figure 5-7 and Figure 5-8). However, comparing model projections for the two resources, as well as cross-comparison with actual per capita data from 2008 to 2023, reveals two distinct narratives for electricity and water. These narratives highlight the unique challenges and opportunities associated with these interconnected and tied resources.

For electricity, KEWSM projects a long-term decline in per capita electricity and water consumption, despite the substantial growth in the total national demand. In 2008, electricity consumption was 13,144 kWh/capita. KEWSM projects consumption to peak in 2018, followed by a small long-term decline to 12,375 kWh/capita by 2043. While this projected decline appears to contradict the overall growth direction of national consumption, it is a direct consequence of KEWSM's extensive list of end-use technologies replacing existing technologies and competing to meet demand for electricity and water services in the most cost-effective way. The per capita consumption marginally levels off after 2038, with slight increase implying that efficiency gains slow down over time as a result of the steady increase in the exogenous demand of the 'Combined Non-Residential Sector'. Commercial and government offices form part of the non-residential sector building and it is possible that energy efficiency savings could be achieved for them as well. This could be examined in a future study.

In reality, data from the Ministry of Electricity and Water shows that a peak did not occur in 2018. Per capita consumption reached 16,302 kWh/cap in 2023 (MEW, 2024), an increase of 15% in the per capita consumption from 2018, while KEWSM projected a decline of 8% for the same time period. This divergence can be viewed as an efficiency gap between a cost-optimised pathway and the current actual consumption trajectory, reflecting the lack of effective building codes, as well as, policies and regulatory measures to accelerate consumer adoption of efficient technologies.

KEWSM per capita water consumption projections are higher than reality in the period to 2023. The KEWSM projection reveals a different set of underlying dynamics related to its long-term stabilisation and the magnitude of the efficiency gap when compared to electricity. Like electricity, consumption has an increasing trend up to 2018, followed by a decline. However, unlike electricity, the per capita water consumption stabilises in 2038 and remains at 165 m^3/cap. This stabilisation and difference in behaviour is attributed to the nature of Kuwait's water consumption discussed in Section 1.2. Actual water consumption was already at saturation level, which implied growth in demand was attributed primarily to new customers rather than higher consumption per capita. This stands in contrast to electricity where both population and per capita demand continue to rise. This shows that there is decoupling between electricity and water demand, which raises questions for their coupled production on the supply side of the economy.

This projected downward trend is also challenged by recent Ministry of Electricity data (MEW, 2024). While KEWSM projected a 4% decline in per capita water consumption between 2018 and 2023, MEW figures show an increase of 3% over the same period. This again points to KEWSM cost-optimisation and efficient technologies deployment against slower consumer adoption of efficient technologies under current policies and regulatory conditions. Nevertheless, the magnitude of this divergence is less acute than the 15% actual increase observed for electricity between 2018 and 2023.

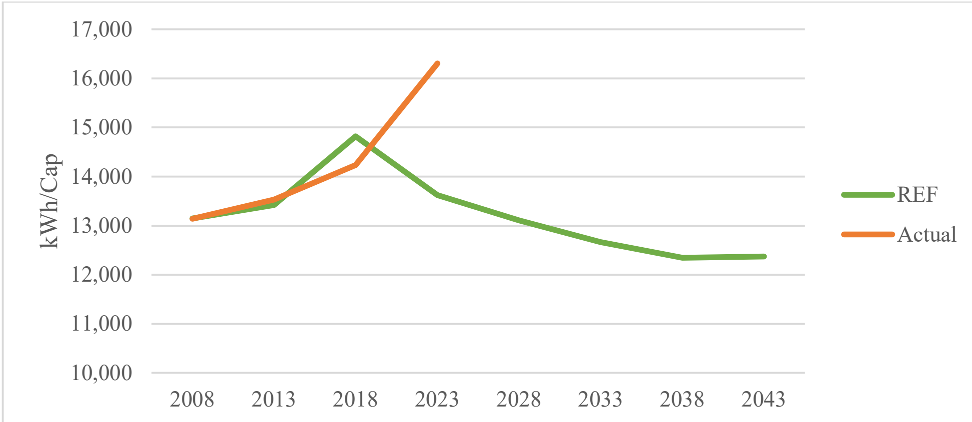

Figure 5-7 KEWSM electricity consumption per capita (REF scenario) against actual consumption

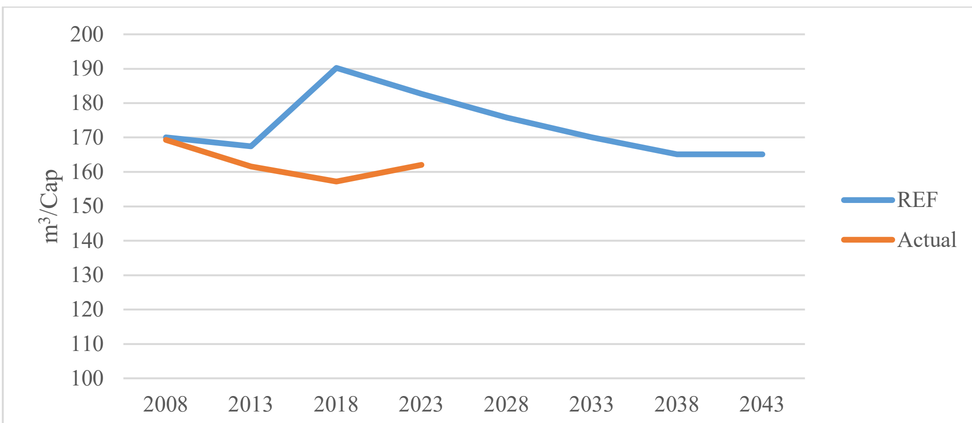

Figure 5-8 KEWSM water consumption per capita (REF scenario) against actual consumption

5.4 Low and high demand scenario pathways

5.4.1 Electricity consumption

Demand sensitivity to changes in socioeconomic conditions of Kuwait is clearly demonstrated by the wide divergence between the low and high development scenarios. While the REF scenario projects final electricity consumption in 2043 to reach 134 TWh, the model shows a plausible demand range from 93 TWh under the low-development scenario to 190 TWh under the high-development scenario (Figure 5-9).

This divergence in potential demand is caused primarily by the residential sector, whose share dominates the consumption under all three scenarios. In the low-development scenario, the residential sector share of the electricity consumption averages around 56% compared to the REF scenario which averages at 60%. While under the high-development scenario, the residential sector's share of the electricity consumption drops to 48% (Figure 5-9). The single residential segment that acts as the primary driver of the size of the residential share of the national consumption is the investment apartments segment (Residential-IA) (Figure 5-10). This variation in this segment's demand is the result of migrant workers' population fluctuation and demand for dwellings in the investment apartments segment (as discussed and illustrated in chapter 4).

Projections show that in a low-development scenario, in which the migrant population growth slows, investment apartment electricity consumption would grow only from 11 TWh in 2013 to 13 TWh in 2043, which is an average annual growth rate of 1.7%. In contrast, under high-development scenario with a flourishing migrant population, this segment is projected to grow to 49 TWh in 2043, an average annual growth rate of 6.5%. This difference in consumption is the dominant driver of future uncertainty. This means that the expatriate population and the housing market that serves them are critical in shaping long-term electricity demand. Furthermore, this outcome suggests that the concentration of uncertainty within the non-energy sector highlights a key cross-sectoral dependency unique to Kuwait. Therefore, policies governing national economic growth, migrant labour, and housing development are integral components of any effective long-term energy policy.

The other principal driver of demand variations is the non-residential sector consumption, for which demand is forecast off-model. In line with the methodology presented in Chapter 4, this demand is projected to contract and expand in direct parallel with Kuwait's economy, using GDP as the primary driver for its behaviour.

The low-development scenario is projected to have an average annual growth rate of 2.1%, meaning it consumes 29% less than the REF scenario in 2043. The high-development scenario has a projected average annual growth rate of 5.4%, consuming 81% more electricity compared to the REF scenario in 2043.

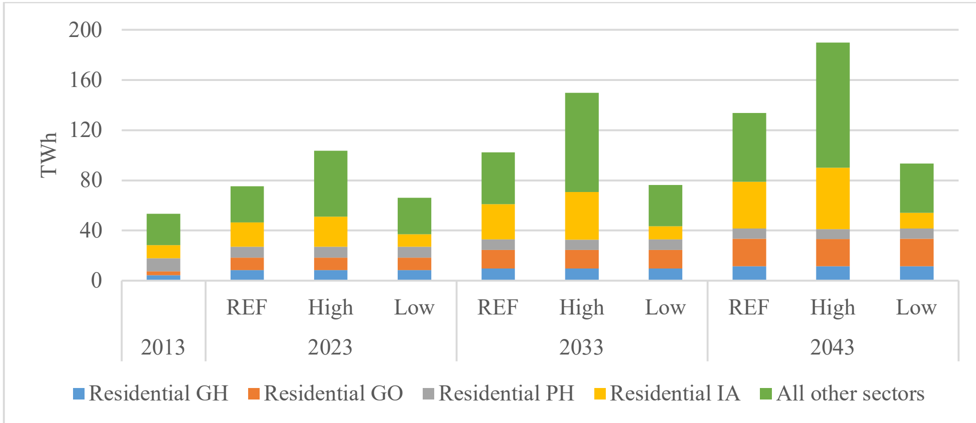

Figure 5-9 Final electricity consumption (REF, Low, and High development scenarios)

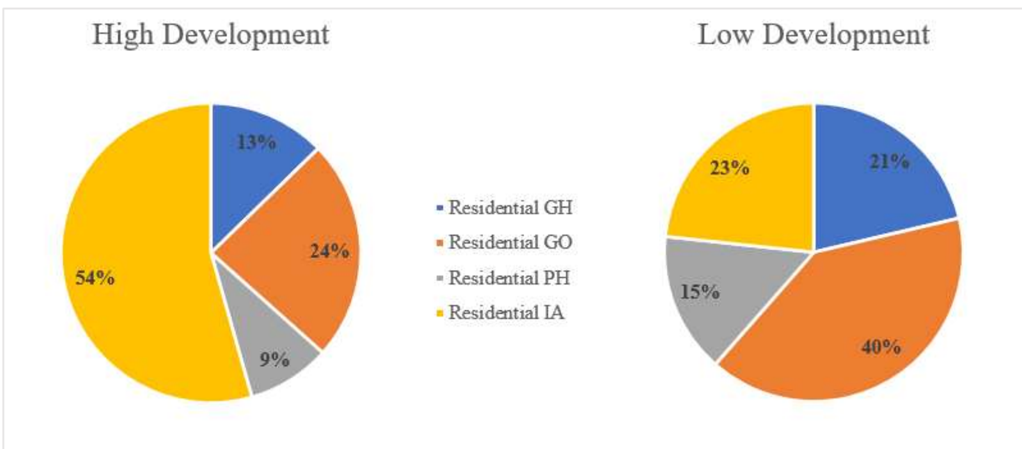

Figure 5-10 Share of residential segments of the electricity consumption, 2043 projection

5.4.2 Water consumption

Similar to electricity, future water demand is also highly sensitive to the different development pathways. Figure 5-11 shows that water consumption in 2043 is projected to range from 1.08 billion m^3 under the low-development scenario (39% lower than the REF scenario) to 2.29 billion m^3 under the high-development scenario (29% higher than REF).

Analysis of the consumption breakdown (Figure 5-11) shows that water demand is more sensitive to the residential sector changes than electricity demand. Electricity demand from the residential share is around 50% of the total under the high-development scenario. In contrast, in 2043, water share is projected to account for 85% of total demand in the low-development scenario and 75% under the high-development scenario. The size of these shares indicates that while electricity demand is significantly influenced by both residential and non-residential (economic) growth, the water consumption trajectory is almost entirely dependent on the residential demand.

As with electricity, the investment apartment segment (Residential-IA) is the main driver of residential demand. This segment's water consumption shows elasticity to the expatriate population housing demand projections (Figure 5-12). Under the low-development scenario, investment apartments consumption is projected to experience an average annual growth rate of 2%, leading to consumption being 65% lower than in the REF scenario consumption in 2043. In contrast, under the high-development scenario, the segment is projected to experience an average annual growth rate of 6.9%, with consumption projected to be 31% higher than the REF scenario in 2043. The profound influence of a single demographic variable on the water projections reinforces the conclusion established earlier for electricity with regards to policies governing national economic growth, migrant labour, and housing development as integral components of any effective long-term energy policy.

As for electricity, non-residential water consumption is projected to be driven by changes in GDP. Under the low-development scenario, an average annual growth rate of 0.4% is projected. For the high-development scenario, an average annual growth of 4.2% is projected.

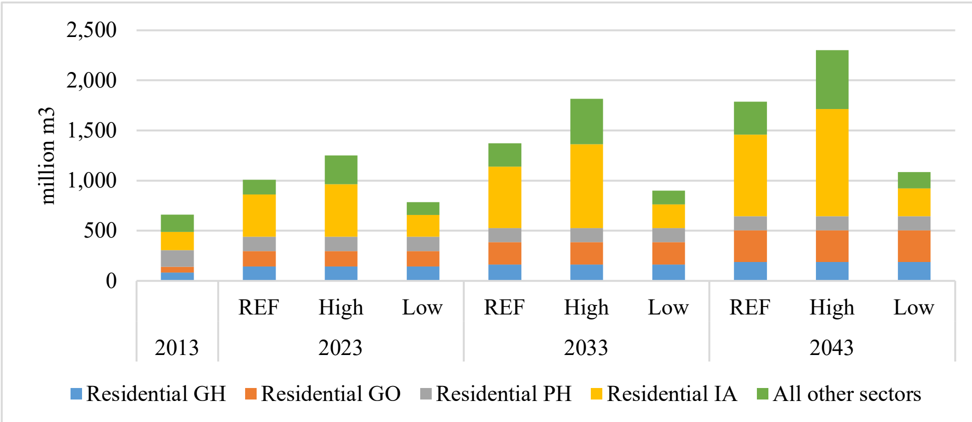

Figure 5-11 Water consumption (REF, High, and Low development scenarios)

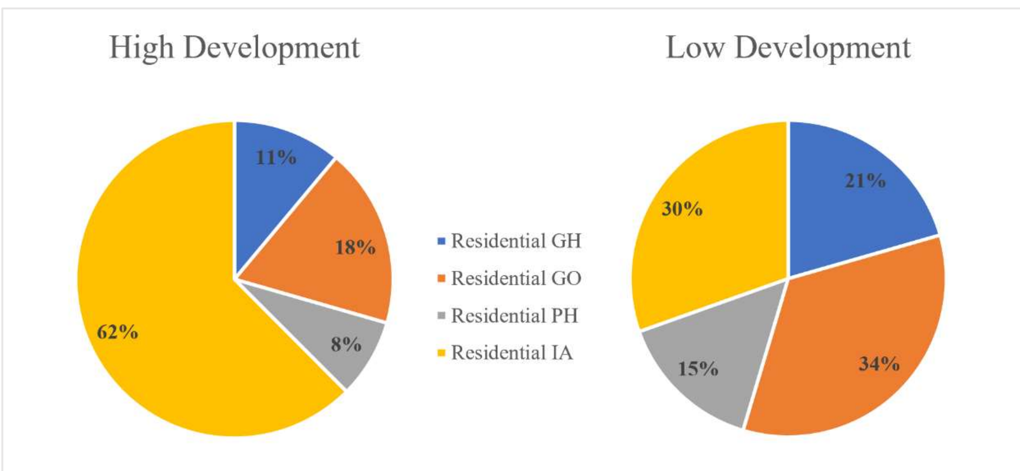

Figure 5-12 Share of residential segments of the water consumption, 2043 projection

5.4.3 Per capita consumption

While economic growth has historically been accompanied by higher electricity consumption per capita, this relationship weakens as economies mature and efficiency gains take hold (Perillo et al., 2022, IEA, 2023, Laghari et al., 2023). Therefore, prosperity and efficiency are not inherently linked on a per capita basis as the link evolves with structural and policy changes. Therefore, to comprehensively analyse the effects of end-use efficiency measures in the later chapters, the per capita consumption is estimated for the three development scenarios.

KEWSM projections for the three development scenarios under the status quo policy assume that per capita electricity and water consumption correlate with macro-economic growth.

Per capita electricity consumption (Figure 5-13) under the low-development scenario is projected to decline steadily before levelling off after the year 2033, and averaging around 8,720 kWh/cap for the following years. The high-development consumption peaks in the year 2028 at 19,719 kWh before it declines again and levels off following the year 2038 and averages around 17,895 kWh for the remainder of the projected horizon.

Water consumption (Figure 5-14) has similar trends to electricity consumption. Under the low-development scenario, water consumption per capita is projected to reach 100 m^3/cap by 2043, a 39% reduction compared to the REF scenario. This consumption doubles to approximately 208 m^3/cap under the high-development scenario.

The differences in per capita consumption across the three development scenarios highlight that per capita consumption is not an indicator of consumer behaviour associated with high development conditions (i.e. consumer becoming wasteful in prosperous times), nor is it an indicator of the system's overall efficiency. Rather, it is an indicator whose behaviour can only be understood through decomposition. Since the changes in this metric observed under the three development scenarios are less driven by efficiency and more by changes in the composition of Kuwait's economy and society, its value as it currently stands reflects the shifting demographic weight of distinct population group and the resource profile of the housing segment they predominantly occupy.

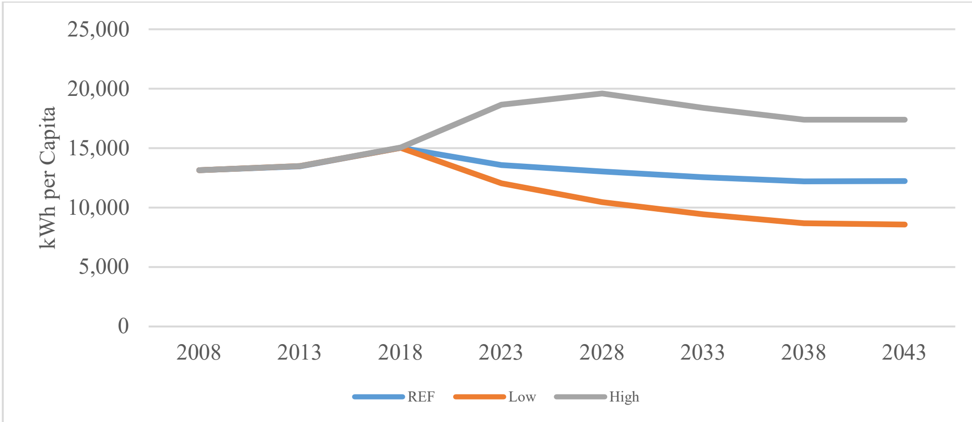

Figure 5-13 Per capita electricity consumption (REF, Low, and High development scenarios)

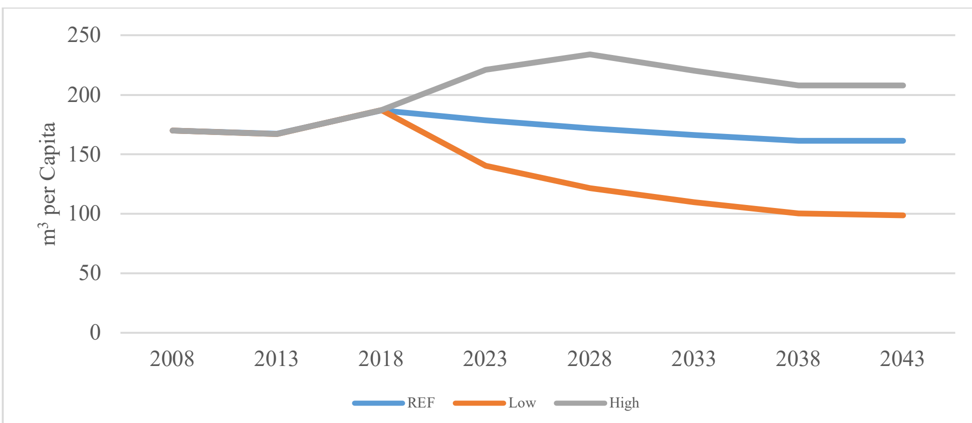

Figure 5-14 Per capita water consumption (REF, Low, and High development scenarios)

5.4.4 Primary energy consumption

Figure 5-15 projects Kuwait's EWS primary energy consumption for the three scenarios across the full economy. Projections show that under the REF scenario, there is steady growth in energy consumption at an average annual rate of 2.4%. The primary energy consumption is projected to grow from 19.4 Mtoe in 2013 to 33 Mtoe in 2043. This projection is particularly significant given that Kuwait's domestic primary energy mix is mostly entirely dependent on fossil fuels, with a negligible contribution from renewables pilot projects.

Under the high-development scenario, a sharp increase in primary energy consumption is projected as demand for housing increase and the economy grows. Consumption is projected to reach 36 Mtoe by 2028, a 66% increase since 2018 and higher than REF scenario consumption in 2043. This trend is projected to continue at an average annual growth rate of 3.8%, reaching 50 Mtoe in 2043. Given that Kuwait's primary energy mix consists almost entirely of hydrocarbons, this projection has significant economic implications as hydrocarbon exports would reduce substantially to meet escalating domestic demand if the energy system were not decarbonised.

In contrast, the low-development scenario projects consumption to peak in 2023 at 21 Mtoe before it begins a declining trend. Energy consumption stabilizes from 2028 and continues this stability until 2043. The average annual growth rate across the modelled time horizon is projected to be 0.8%. Under the low-development scenario, the 2043 primary energy consumption is projected to be 19.1 Mtoe, 1.7% lower than the 2013 consumption. This peak and decline suggest a threshold where the slower growth in end-use demand becomes insufficient to outpace the autonomous efficiency improvement in power generation and seawater desalination, thus leading to a net reduction in the primary energy required to deliver energy services.

The primary energy required to meet the electricity and water demand in the year 2023 represents 21% of Kuwait’s existing oil production capacity (Figure 5-16). Under the REF scenario, this share is projected to increase steadily, consuming the equivalent of 30% of current oil production by 2043. This domestic burden escalates further under the high-development scenario, where it is projected to increase to 44% of current production capacity by 2043. In contrast, the low-development scenario is the only scenario where this share remains relatively stable, marginally fluctuating throughout the projected time horizon, then holding at 21% in 2043. These figures highlight that without significant intervention in managing domestic demand, Kuwait’s own growth trajectory poses long-term risk to its status as a major energy exporter.

Finally, primary energy consumption has direct consequences for Kuwait’s carbon footprint. KEWSM projects carbon emissions to increase from 54 $MtCO_2$ in 2023 to 96 $MtCO_2$ in 2043 for the REF scenario, 126 $MtCO_2$ for the high-development scenario, and 52 $MtCO_2$ for the low-development scenario. Hence there is strong coupling between socioeconomic development, primary energy consumption, and emissions.

This coupling is a systematic feature of an undiversified energy system. In a system where the primary energy supply is almost exclusively derived from hydrocarbons, carbon emissions are less of a variable to be managed and more of an inherent characteristic of the primary energy demand itself. Chapter 7 will examine the role of diversifying the energy mix and the potential of decoupling the growth of carbon emissions from socioeconomic development.

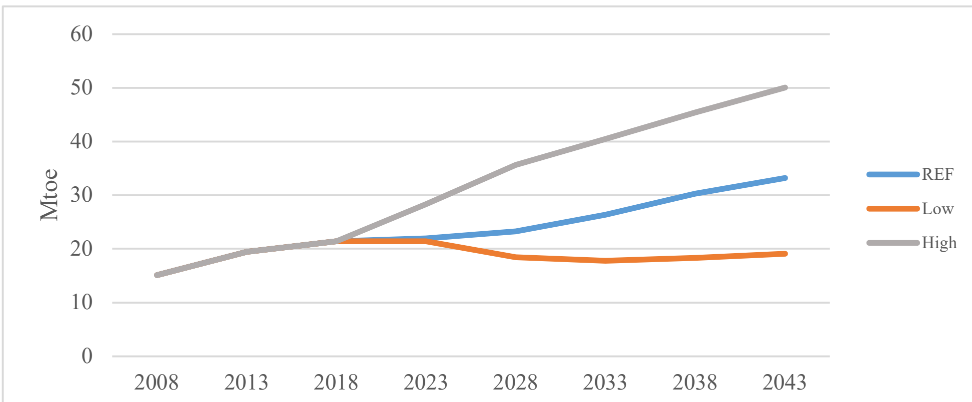

Figure 5-15 EWS primary energy consumption under different projections

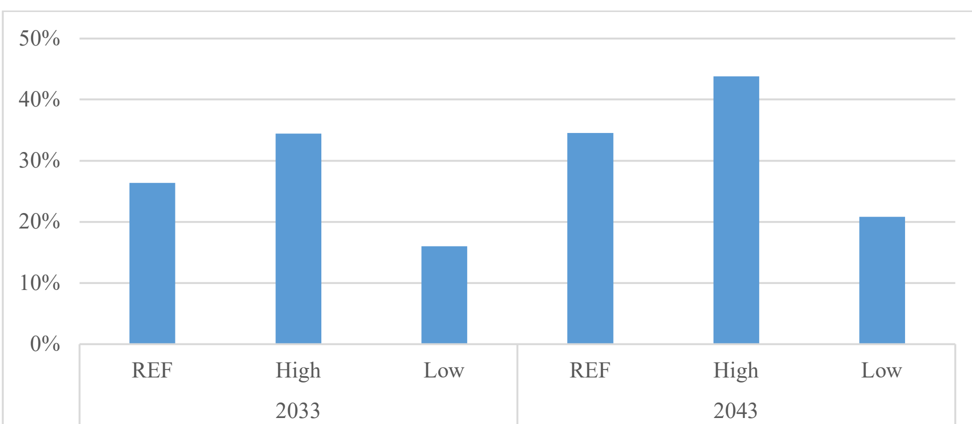

Figure 5-16 Energy required by the EWS as a share of existing oil production capacity

5.5 Discussion

KEWSM projections of both electricity and water from 2008 are close to real-world demand, as a result of the calibration process, with minimal error observed up to the year 2020. This accuracy underscores the KEWSM's effectiveness in capturing the essence of Kuwait's energy demand and its underlying drivers. Given Kuwait's relatively small energy system, which reflects the country's size and economic structure, electricity and water demand is concentrated within the residential sector. Consequently, the decision to focus on the housing sector as the primary driver for electricity and water demand is a practical approach. This approach ensured that KEWSM focuses on the principal areas of consumption, significantly enhancing the model's accuracy by minimising the risk of overlooking essential demand drivers within the analysis.

The consistency of KEWSM assumptions with the real-world data utilised in the calibration process is essential to ensure good projections of future demands. As calibration was based on identifying drivers of change, the precision and dependability observed in these projections' trajectories provide evidence that the assumptions made about future trends are based on adequate empirical evidence and analytical judgment.

KEWSM demand projections are significantly better than for TIMES-KPW. A key improvement is KEWSM's detailed examination of the residential sector, the largest electricity and water consumer in Kuwait. Unlike TIMES-KPW, which viewed the residential sector as a single consumer with future demands extrapolated solely from per capita growth aligned with population trends, KEWSM adopts a more detailed approach. By redefining demand drivers, incorporating electricity and water services, and capturing the human interaction with the services, KEWSM provides refined demand projections. By incorporating a broader range of variables, the quality of model outputs is enhanced, and the depth of analysis increases, making KEWSM a substantial improvement over its predecessor.

5.5.1 Scenario definition

Kuwait's position as a price taker in the global oil market significantly influences its production decisions. Consequently, rather than independently adjusting its output in direct response to short-term price fluctuations, Kuwait's oil production levels are principally governed by production quotas established within the Organisation of the Petroleum Exporting Countries (OPEC), of which Kuwait is a founding and active member. Therefore, Kuwait works to keep its oil output consistent with the decisions taken by OPEC as a whole. In turn, OPEC tries to steer the global oil supply to maintain stable prices, often with an eye on what is advantageous for its member producers. Although dramatic short-term price changes heavily sway OPEC's decisions on how much oil to produce globally and how to set quotas, Kuwait's output is still largely constrained by its specific OPEC target and within the limits of its production capacity.

While Kuwait's compliance with OPEC quotas moderates its short-term production responses to price, the country has maintained a long-term strategy of expanding its crude oil production capacity. OPEC (2024) shows that production allocations for Kuwait have, over the years, been situated near the country's maximum oil production capacity. The data also show that the gradual expansion in Kuwait's production capacity has been accompanied by an upward trend in its OPEC-assigned production quotas. This parallel increase in production capacity and quota allocations provides a backdrop for understanding current and future production outlooks. The relationship between Kuwait's production capacity alongside its average OPEC allocations and average annual oil prices is illustrated in Figure 5-17.

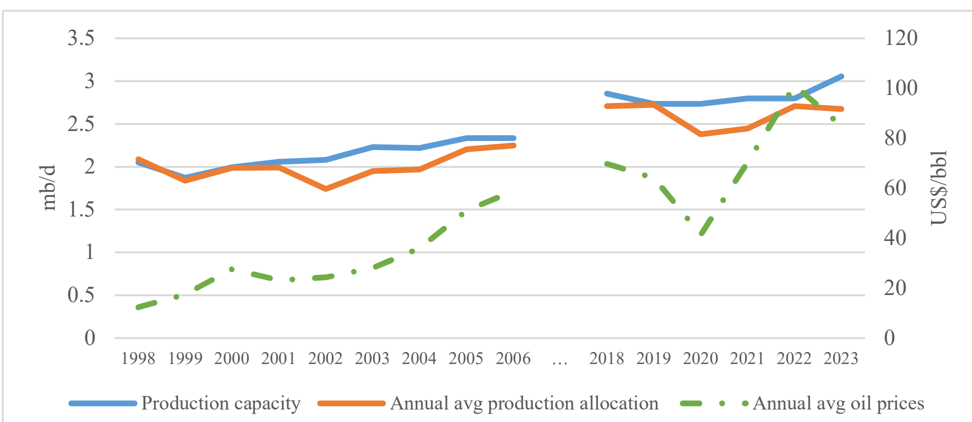

Figure 5-17 Historical trends[3] in Kuwait's crude oil Production capacity, average OPEC production allocations for Kuwait, and the annual average international

[3] OPEC did not publish production data for the period between 2006 and 2018.

oil prices. *Adapted from:* (OPEC, 2007, OPEC, 2024, IMF, 2019, EIA, 2019a, EIA, 2023)

Furthermore, the internal mechanism by which OPEC allocates production quotas among its members is not publicly disclosed. Gault et al. (1999) and Alhajji et al. (2000) indicate that there is no explicit or consistently applied formula governing these decisions. This ambiguity and the ad-hoc nature subject to complex negotiations rather than a transparent, rule-based process of allocations make it challenging to incorporate a potential OPEC production quota pathway for Kuwait within KEWSM. Therefore, relying on officially and publicly declared capacity expansion plans provides a more empirically grounded basis for Kuwait's future oil output.

Accordingly, and while the national development scenarios in KEWSM are based on different international oil price outlooks impacting Kuwait's economy and government income, the oil production capacity in the model is aligned with established capacity expansion plans publicly declared by Kuwait Petroleum Corporation (KPC, 2021, KPC, 2024) and of Kuwait Oil Company (KOC, 2024a). Therefore, the capacity expansion projection remains constant across all three economic development scenarios in KEWSM.

This modelling approach reflects an understanding that decisions regarding upstream oil capacity and overarching production targets are typically long-term strategic investments. Such commitments are less susceptible to immediate revisions based on fluctuating price forecasts for any given year, especially when the primary national drivers of these commitments are ensuring domestic energy security and maintaining sustained government income through oil exports. The varying economic consequences of different international oil prices are thus captured within the model through their effects on broader macroeconomic parameters within each scenario, rather than adjustments to crude oil production capacity projections.

The differing international oil price outlooks that frame each development scenario (Low, Central/Reference, and High) are reflected through the model by significantly shaping these macroeconomic parameters (as illustrated in Chapter 4). Varying oil prices thus directly shape GDP growth and influence projections of government spending capacity on national development projects. These macroeconomic effects are then translated into differentiated demographic outlooks, particularly in the size of the migrant worker population and growth of the housing sector, which in turn drives the varying levels of demand for electricity and water services across the three development scenarios.

Therefore, while Kuwait's hydrocarbons production is treated as an exogenous input determined by officially declared long-term strategic plans, the economic repercussions of fluctuating international oil prices are reflected in KEWSM through their impact on the scale of national development and its resulting electricity and water service demands that KEWSM must satisfy under each future pathway.

5.5.2 Role of socioeconomic development on Kuwait's energy future

Analysis of model results establishes several fundamental dynamics of Kuwait's electricity-water system. First, consumption levels correlate closely with socioeconomic development of the country. Second, electricity demand is significantly more sensitive to socioeconomic development shifts than water consumption. And third, these shifts in consumption are not uniform changes across sectors, but rather focused within the residential sector.

The finding that electricity demand is more elastic to socioeconomic shifts than water demand aligns with body of literature that recognizes their fundamentally different end-use characteristics. Electricity sensitivity to socioeconomic shifts is linked to the usage patterns and human behaviour defined within KEWSM end-use services. Water consumption primarily caters to direct human requirements such as drinking, washing, showering, laundry, etc. Such needs exhibit relatively consistent usage across population demographics and are tied to the house occupant's direct interaction with the service. This is consistent with studies, such as Abu-Bakar et al. (2023), that characterises water demand as being driven by a series of occupant-dependent events that make the overall pattern relatively predictable based on who is in the household and what they're doing.

In contrast, electricity consumption is closely intertwined with lifestyle and economic influence, such as the number of appliances and the size of space to be lit or cooled, etc. Additionally, electricity end-use, such as air conditioning among other appliances, continues to service the dwelling regardless of occupancy and are largely influenced by the dwelling type and size. This is consistent with literature, such as Jones et al. (2023), which suggest that occupant-independent demand is particularly strong in its prevalence in hot climate where space cooling is not a luxury but an essential adaptation measure. Consequently, the behavioural elasticity of electricity differs from water, as while water consumption can scale up and down depending on the number of dwelling occupants interacting with the water service (water fixture, appliance, etc), electricity demand is more influenced by the dwelling type and size rather than occupant's direct interaction (space cooling, lighting, cold services, etc). This dynamic makes electrical services demand linked to socioeconomic conditions, thus amplifying its responsiveness to lifestyle and dwelling characteristics rather than direct user interaction and aligns with literature such as (Durisic et al., 2020).

The electricity and water consumption levels projected by KEWSM under the high and low development scenarios significantly deviate from those under the REF scenario. The projections indicate a strong correlation between Kuwait's socioeconomic development and the electricity and water consumption levels. This correlation is primarily a result of the housing sector occupancy being dependent on portion of the population susceptible to government spending on national development. Nevertheless, even with a slowdown in the dwellings growth rate under the low-development scenario, the residential sector is projected to maintain its dominant role over the electricity and water consumption.

Under all three socioeconomic scenarios, the annual average consumption growth rate is projected to remain high for both electricity and water. The annual average electricity consumption growth rate is projected to be 2.2%, 3.3%, and 4.7% under the low-development, REF, and high-development scenarios, respectively. These rates are high compared to other countries. For instance, the EIA (2022) projected the US annual average electricity demand growth rate in the Reference Case to be less than 1%, and McKinsey (2010) projected EU annual average electricity demand growth rate to be 1.1% under a deep decarbonisation case. Daly et al. (2022) projected the UK's electricity demand annual average to grow by 2%. It is noteworthy that, in contrast to other countries, dwellings in Kuwait rely exclusively on electricity for thermal comfort and other services such as water heaters that cause high consumption.

The demand for these services in other countries is typically met by natural gas rather than electricity at present.

5.5.3 Residential consumption

Analysis of the residential sector reveals that future demand is not characterised by uniform growth, but rather by a significant shift in the sector's composition, and this composition is highly dependent on Kuwait's socioeconomic pathway. As each housing segment reflects unique occupancy patterns and dwelling characteristics, this compositional rebalancing directly translates into varying demand trajectories for electricity and water. Specifically, forecasts developed for this study (which drive KEWSM model) show that the housing sector is experiencing a structural shift away from the historically dominant private villas (which have been the primary focus of energy studies in Kuwait) towards two distinct centres of consumption.

The first is the state-led citizens' welfare system. Land constraints on private villas mean that the Public Authority for Housing Welfare (PAHW) becomes the primary supplier for new citizen housing. Consequently, the electricity and water demand projections showed privately built houses on PAHW distributed lands, together with houses built and distributed by the PAHW, hold a significant and steadily increasing share of the consumption. This government-managed housing stream is distinct from all other consumer segments in that it represents a centralised, predictable pipeline with clear targets and expansion plans, as well as an identifiable, stable, and predictable customer base. Therefore, the PAHW could effectively become one of Kuwait's most significant energy policymakers and a partner in efforts to decarbonise Kuwait's energy system. By controlling the design, location, and building standards of a fast-growing segment of the housing stock, its decisions on mandated efficiency measures will have a direct and large-scale impact on future national demand.

The second, parallel driver is the investment apartments segment. Model projections show that the investment apartments segment is not only the largest future consumer but also the primary source of all systemic uncertainty in electricity and water demand, with consumption fluctuating significantly between scenarios. This segment is not governed by state welfare but by private developers, landlords, and market demand for the expatriate workforce (which are the main tenants of this segment). Therefore, managing demand in this sector requires entirely different policy instruments. Unlike the direct mandates possible with PAHW, influencing the investment apartments segment will depend on market-based mechanisms, such as targeted building codes and efficiency standards for rental properties.

Such findings offer planners and decision-makers valuable insights when formulating energy policies. The segmentation of housing categories in KEWSM allows us to test different efficiency improvement scenarios targeting specific houses. For instance, targeting investment apartments, where the private sector may be more accommodating due to the improvements cost being passed on to the consumers. Alternatively, the focus could shift to the Public Authority for Housing Welfare (PAHW), which can rapidly enact code changes in their new builds to implement efficiency improvement measures. Moreover, they could potentially include new clauses in their contracts with welfare recipients choosing the land option, further enforcing the implementation of efficiency improvement measures. Chapter 6 further analyses how PAHW housing can be leveraged to drive large-scale efficiency improvements.

5.5.4 The efficiency gap

KEWSM projects that the per capita consumption for both electricity and water will peak and stabilise early in the modelled horizon under all scenarios. However, this projection contrasts with recent data from the Ministry of Electricity and Water (2024) showing that actual per capita consumption continues on upward trend. Because KEWSM is a cost-optimisation model, the divergence between its projected stable pathway and the rising real-world consumption is the "efficiency gap". This gap quantifies the considerable potential for resource savings that are not being utilised under current market conditions and behavioural patterns. Indeed, the lowest per capita consumption is projected in the low-development scenario at an average of 8,700 kWh, which is higher than that of the UK at 4,135 kWh (World Bank, 2025) and the EU at 5,300 kWh (Eurostat, 2022).

This illustrates the importance of end-use technologies in the optimisation model, where the electricity and water services needs are being met with the most cost-effective technologies, and thus highlighting inefficiencies in Kuwait's current electricity-water system. The new appliances and equipment specifications (both standard and efficient) used in the construction of KEWSM were based on information available in the US, UK, and EU markets. The behaviour observed in the model output compared to actual consumption highlights the absence of electrical appliances standards, ratings, and labelling in Kuwait. Such absence enables environmental dumping practices to continue in the local market, bringing low-efficiency appliances and equipment, and increasing overall consumption of electricity and water. Therefore, the efficiency gap identified by KEWSM can be interpreted as a direct cost of a policy and regulatory void.

5.5.5 Primary energy and the domestic burden

Since electricity and water depend on each other and are co-generated, examining the primary energy consumed by the supply-side of the electricity-water system can provide a balanced basis for comparing different system evolution pathways as a result of socioeconomic changes. Seawater desalination is an electricity-dependent process, and electricity generation in Kuwait is hydrocarbon based. Therefore, change in electricity and water demand levels directly influence the government revenue from hydrocarbon exports.

The scenario analysis quantifies the trade-offs. Projections showed that primary energy consumption could range from 19 Mtoe to 50 Mtoe by 2043. This demonstrates Kuwait's supply-side system profound sensitivity to government policy chosen economic path. The peak-and-decline trajectory in the low-development scenario establishes that decoupling primary energy growth from GDP is feasible within technological and efficiency improvement framework. This outcome reveals a threshold where the benefits of underlying supply-side efficiency gains (in electric power generation and seawater desalination) can to some extent outpace the pressure of end-use demand if demand growth is managed.

Consequently, the results frame the challenge not as a simple choice between growth and conservation, but as a race between them in order to reconcile economic expansion with resource sustainability. For instance, in the high-development scenario, the demand for primary energy within the electricity-water system could consume the equivalent of 44% of Kuwait's current oil production. This illustrates a future where the pressures to meet national development ambitions could directly compromise Kuwait's external position as a major energy exporter. This strong coupling of development and consumption highlights the vulnerability under current hydrocarbon-dependent system. It also shows that Kuwait's economic development trajectory is tightly coupled with its emission pathway. Therefore, the following chapters will assess potential pathways for decoupling domestic development from hydrocarbon consumption.

Externalities surrounding the electric power generation and seawater desalination extend beyond carbon emissions. The externalities include air pollution, effluents from desalination plants discharge into the sea, and land use. While these externalities may not traditionally bear monetary costs, their cumulative impact on the environment, human health, and quality of life could be significant. The damage costs from these externalities are not considered in KEWSM.

5.6 Summary

Planners and policymakers deal with multiple layers of complexity and uncertainty when planning electricity and water infrastructure. The complexity is amplified in the case of Kuwait, where the availability of electricity and water resources is co-dependent on one another, and both rely on fossil fuels. The high level of uncertainty often causes models to create projections with inaccuracies and a level of false precision. However, the primary function of models is not to produce a precise projection; instead, they are designed to carry out iterative system analysis. Such analysis enables decision makers to evaluate different scenarios and take more informed decisions regarding investment and policy plans.

This chapter presented and discussed the potential demand pathways for the electricity and water in Kuwait under three different socioeconomic scenarios. The demand is projected to deviate significantly under the low and high development scenarios from the reference scenario. Across all three scenarios, the residential consumers dominate the demand for electricity and water.

A significant portion of the projected demand comes from the investment apartments segment. This residential segment serves a population demography with high growth uncertainty. The second largest consumer, but with more clear growth path, is the housing program by the Public Authority for Housing Welfare.

Projections of the electricity and water per capita consumption indicate wasteful consumption and potential for efficiency improvement. Reducing wasteful consumption and improving efficiency could also reduce the fuel consumption, carbon emissions, and other externalities associated with the electric power generation.

Chapter 6

INFLUENCE OF RESIDENTIAL END-USE EFFICIENCY IMPROVEMENT ON ELECTRICITY & WATER SYSTEM

6.1 Introduction

The residential sector plays a vital role in shaping the electricity-water system in Kuwait, due to the sector's substantial demand for electricity and water. The demand was projected to continue rising under different socioeconomic conditions, outpacing growth rates in other developing countries.

The previous chapter highlighted residential segments demonstrating steady consumer growth projections with the exception of the investment apartments segment, which fluctuated and influenced by socioeconomic conditions. It also highlighted high consumption rates and the potential for end-use efficiency improvement. These insights prompt a more detailed analysis of how residential efficiency improvement measures enhancing the electricity and water end-use might impact the entire electricity-water system.

This chapter examines the potential impacts of new electricity and water end-use efficiency improvement measures in the residential sector on Kuwait's EWS. It examines both technical and behavioural efficiency improvements to address the second and third research questions of the thesis, which are:

- What influence could residential efficiency improvements have on demand for electricity and water?
- To what extent could end-use efficiency improvements influence the electricity-water supply mix?

6.2 Methods

In order to assess the influence of residential end-use efficiency improvement measures on electricity-water supply and demand, five distinct scenarios have been developed targeting different aspects of the residential sector. These scenarios were designed to cover a broad spectrum of interventions that mirror potential real-world applications relevant to Kuwait, ranging from policy-driven initiatives to regulatory mechanisms. The essence of this diverse scenario design is to offer a holistic view of how energy and water efficiency can be enhanced across different dimensions of the residential sector.

The first scenario, Moderate Behavioural Measures Scenario, is dedicated solely to the human dimension of electricity and water usage within the residential sector. This scenario underscores the pivotal role of consumer behaviour in achieving end-use efficiency, highlighting the potential of modest behavioural adjustments to facilitate improvements in the residential sector's electricity and water consumption. Beyond human behaviour, two sets of scenarios were designed.

The first set of scenarios tackles two residential segments: the Government Housing Measures Scenario and the Investment Apartments Measures Scenario. These two scenarios focus only on technical measures within these residential segments. In real-life situations, the government welfare housing segment presents a unique opportunity for implementing technical efficiency improvements via contractual reforms with housing beneficiaries, offering a fast-track path for building efficiency improvement without the complexities associated with national buildings' efficiency policy reform. The second scenario in this set tackles the investment apartments segment, a segment that primarily serves the migrant workers population.

The final set of scenarios addresses the entire residential sector. This set consists of the Moderate National Measures and High National Measures. In the Moderate National Measures Scenario, it is assumed that the market is mature and capable of supplying high-efficiency appliances. Additionally, building codes and efficiency regulations are implemented on new residential builds. Finally, the High National Measures Scenario is the most ambitious of all scenarios, where high and higher efficiency appliances are available, inefficient technologies undergo a phased-out process, building codes and efficiency regulations are implemented, and some level of retrofits are implemented.

For this chapter, the five scenarios are modelled between 2008 and 2048 under central socioeconomic development and fuel prices assumptions. The results in this chapter and henceforward will focus on the period between 2013 and 2043. The global discount rate is set to 7.8% as adopted by the government's long-term plan. All scenarios were designed under business-as-usual supply-side assumptions with no policies, legislations, or regulations related to the energy mix diversification or carbon emissions reductions. All efficiency improvement scenarios are assumed available for deployment from the year 2020. A detailed list of measures in each scenario is presented in Table 6-1.

Efficiency improvement measures in the KEWSM scenarios are implemented through three main instruments: regulatory interventions, retrofit programmes, and behavioural change initiatives. Depending on the scenario examined, each scenario includes a specific combination of these instruments, with a scope that can range from covering all residential segments to targeting only select groups (government housing, private villas, and investment apartments).

Table 6-2 presents these interventions and distinguishes between two primary deployment approaches. Interventions whose uptake is optimised by KEWSM (e.g., electrical appliances and water fixtures), and those that are exogenously defined. The deployment approach is driven by the nature of the intervention itself.

For instance, improvements in building envelope specifications and behavioural change are defined exogenously. This reflects the assumption that their adoption is primarily driven by policy mandates or programme-specific targets rather than spontaneous market-based decisions. Therefore, the uptake for these measures is estimated using consumer acceptance rates derived from the literature, while this research's housing stock projections determines the eligible households in each residential segment over time. Energy savings from these measures are observed through performance improvements in the end-use technologies. Instead of reducing the service demand itself off-model, these exogenous measures enhance the efficiency of the relevant model processes, with the specific savings quantified in Table 6-3.

6.2.1 Moderate behavioural measures scenario

The Moderate Behavioural Conservation Measures (MB-CM) scenario investigates the impact of implementing behavioural change to reduce electricity and water demand on the consumption and the supply-side. A set of behavioural measures were built into KEWSM to cover electricity and water end-use. The electricity behavioural measures include: setting the air-conditioner thermostat to 2 degrees warmer temperature and switching off lights in unoccupied rooms. The water behavioural measures include quicker or fewer showers, quicker or less car washing, and quicker or less outdoor washing.

End-use technologies could still be replaced with new options, including efficient technologies. However, higher efficiency options were assumed to be unavailable. New efficient appliances are considered part of the market's natural transition and coexist with older inefficient appliances. Disabling the higher efficiency options represents the reality of the appliances market in Kuwait in the absence of product labelling and policy towards residential efficiency improvement.

6.2.2 Government housing measures scenario

The government welfare housing conservation measure scenario (GHGO-CM) investigates the impact of implementing efficiency enhancement and demand reduction measures specific to the Public Authority for Housing Welfare (PAHW) houses. This scenario represents a case where the PAHW would improve the build specifications for new houses in the absence of national improvement to buildings and appliances codes and standards being implemented.

Technical measures implemented in this scenario target only new dwellings in the Residential-GH and Residential-GO segments. They consist of measures relating to the construction of the building, such as improved thermal insulation for the roof and building envelope, the use of double-glazed windows, and air-conditioning systems use of adaptive thermostats. Measures covering the entire Residential-GH and Residential-GO segments include reducing the number of lights per house and switching towards LED lightbulbs. These two measures represent a previous campaign that distributed CFL lightbulbs to promote their use over incandescent light bulbs. Higher-efficiency refrigerators and freezers are available for this segment. Moreover, a range of higher-efficiency water appliances and equipment to compete with existing standard-efficiency and high-efficiency measures are enabled in this scenario for Residential-GH and Residential-GO segments only.

6.2.3 Investment apartments measures scenario

The Investment Apartments Conservation Measures (IA-CM) scenario only implements efficiency improvement measures in the investment apartments segment.

Technical measures relating to the construction of the building, such as improved thermal insulation for the roof and building envelope and the use of double-glazed windows, are implemented on new dwellings only.

Existing dwellings replace inefficient lightbulbs with LEDs, reduce the number of ceiling lights, and benefit from a thermostat retrofit programme. The thermostat retrofit programme gradually replaces existing thermostats with programmable thermostats.

A range of higher-efficiency water appliances and equipment to compete with existing standard-efficiency and high-efficiency measures are enabled in this scenario for this segment only.

6.2.4 Moderate national measures scenario

The Moderate National Conservation Measures (MN-CM) scenario implements various efficiency improvement and conservation measures across the entire residential sector. It represents a case where national improvements to building codes and standards. These improvements set higher standards for building envelope thermal insulation, require double-glazed windows and implement a phaseout of incandescent light bulbs. Higher-efficiency appliances are enabled for all residential segments and compete with existing standard-efficiency and high-efficiency appliances.

6.2.5 High national measures scenario

The High National Conservation Measures (HN-CM) scenario is a more ambitious scenario in which a range of efficiency improvements are available. These include an expansive set of behavioural measures targeting electricity and water consumption. This scenario implements "easy" retrofits for existing dwellings, such as the installation of programmable or adaptive thermostats (with the selection dependent on dwelling size) and improved roof insulation for houses. It deploys improved roof and building envelope thermal insulation, and the use of double-glazed windows for all dwellings.

Table 6-1 End-use efficiency improvement scenarios overview

Case Name	*Case Description*	
MB-CM	**Moderate Behavioural Conservation Measures** ***Scenario Characteristics*** Electricity measures: • Set thermostat 2 degrees warmer • Switch off lights in unoccupied rooms	 Water measures: • Quicker shower • Less frequent car washing • Less frequent outdoor washing
GHGO-CM	**Housing Welfare Conservation Measures** ***Scenario Characteristics*** Electricity measures across **all** GH & GO dwellings: • Fewer celling lights • Use LED bulbs • Availability of higher efficiency refrigerators and freezers Water measures **all** GH & GO dwellings: • Efficient water technologies available, including dishwashers	 Electricity measures for **new** GH & GO dwellings: • Adaptive thermostats • Improved window glazing • Improved roof insulation • Improved wall insulation
IA-CM	**Investment Apartments Conservation Measures** ***Scenario Characteristics*** Electricity measures across **all** IA dwellings: • Fewer celling lights • Use LED bulbs • Availability of higher efficiency refrigerators and freezers • Thermostat retrofit – programmable thermostat Water measures across **all** IA dwellings: • Efficient water fixtures available. • Dishwashers replacing handwashing dishes	 Electricity measures for **new** IA dwellings: • Improved window glazing • Improved roof insulation • Improved wall insulation

Table 6-1 continued:

Case Name	**Case Description**
MN-CM	**Moderate National Conservation Measures** ***Scenario Characteristics*** Electricity measures: • Discontinuation of inefficient lightbulbs • Availability of higher efficiency refrigerators and freezers • Availability of programmable thermostat for Res-PH and Res-IA dwellings • Availability of adaptive thermostats for Res-GH and Res-GO dwellings. Water measures: • Efficient water fixtures available for all dwellings • Availability of dishwashers Electricity measures for **new** dwellings: • Improved window glazing • Improved roof insulation • Improved wall insulation
HN-CM	**High National Conservation Measures** ***Scenario Characteristics*** Electricity measures: • Set thermostat 2 degrees warmer • Switch off lights in unoccupied rooms • Discontinuation of inefficient lightbulbs • Phaseout of inefficient refrigerators and freezers • Retrofitting Res-GH and Res-GO with adaptive thermostats • Retrofitting Res-PH and Res-IA with programmable thermostats • Retrofitting roof insulation Electricity measures for new dwellings: • Improved window glazing • Improved roof insulation • Improved wall insulation Water measures: • Quicker showers • Quicker and less frequent car washes • Quicker and less frequent outdoor washes • Use of dishwashers • Efficient and higher efficiency water fixtures available for all dwellings

Category/Instrument	*Instrument detail*	*Affected stock*	*Deployment mechanism*	*Deployment assumptions*
Regulation interventions	Improved roof insulation; Improved wall insulation; Window glazing; Programmable thermostat; Adaptive thermostat.	New dwellings	Exogenous assumption	Reduction in space cooling energy based on literature (see Section 2.7); Deployment rate is the same as relevant residential segments' new building stocks' availability rate (see subsection 4.4.3).
	All electrical appliances.	All dwellings	Optimised by KEWSM	Efficient and higher efficiency appliances are enabled and disabled depending on scenario.
	All water fixtures.	All dwellings	Optimised by KEWSM	Efficient and higher efficiency appliances are enabled and disabled depending on scenario.
Retrofit programmes	Improved roof insulation; Improved wall insulation; Window glazing; Programmable thermostat; Adaptive thermostat.	Existing dwellings	Exogenous assumption	Reduction in space cooling energy based on literature (see Section 2.7); Deployment assumes incremental deployment based on new dwelling stock availability with maximum acceptance rate of 70% (Sachs et al., 2012); achieving satisfaction target within 10 years in line with Kuwait Vision 2030 (Ministry of Finance, 2018b).
Behaviour changes	Raising thermostat temperature by 2°C; Switching off lights in unoccupied rooms; Fewer lights.	All dwellings	Exogenous assumption	For each scenario, it is assumed that the full dwelling stock within each relevant residential segment adopts the corresponding measure commencing from the year of scenario implementation.
	Quicker showers; Less car washing; Less frequent outdoor water use.	All dwellings	Exogenous assumption	Assumed acceptance rate of 70% (Sachs et al., 2012) for human/car/front-yard population within the relevant housing segment adopts the measure starting from the scenario implementation year.

Table 6-2 Intervention deployment mechanisms assumptions

Table 6-3 Exogenous intervention assumptions

Efficiency improvement measure	*Assumption*	*Source*
Improved roof thermal insulation	2%	Based on Al-Ragom (2003), Al-Khawaja (2004), Radhi (2009), and Friess et al. (2017).
Improved wall thermal insulation	1%	Based on Al-Ragom (2003), Al-Khawaja (2004), Radhi (2009), and Friess et al. (2017).
Window glazing	Double clear glazing, resulting in 3.7% reduction in cooling energy compared to single-pane non-glazed windows.	Bojić et al. (2007) and Ebrahimpour et al. (2011)
Programmable thermostat	11%	Sachs et al. (2012) and Wang et al. (2020)
Adaptive thermostat	14%	Sachs et al. (2012) and Wang et al. (2020)
Raising thermostat temperature by 2°C	6% cooling energy saved	Brown et al. (2012) and Cluett (2014)
Switching off lights in unoccupied rooms	3% of lighting energy saved	Assumption based on Al-Mumin et al. (2003)
Fewer lights	A reduction in number of ceiling lights compared to the PAHW H4 design.	Assumption

6.3 Results

6.3.1 Reference scenario electricity and water end-use consumption

The residential electricity end-use consumption is projected to grow steadily from 28 TWh in 2013 to 79 TWh in 2043, which is an average annual growth of 3.48%. This growth trajectory is dictated by air conditioning.

Figure 6-1 shows that projected air conditioning consumption rises from 18 TWh in 2013 to 52 TWh in 2043. Cold white goods (refrigerators, freezers, and water coolers) and heating services also grow substantially. This observed difference in the scale of growth between air conditioners consumption and other end-uses is the result of scaling properties associated with the addition of new households, and is further influenced by the type and size of dwellings, which disproportionately increase cooling loads.

The distribution of consumption across different end-use services remains relatively stable throughout the modelled horizon, as shown in Figure 6-2. The only significant observations are seen with the air conditioning (increase from 62% to 66% of total consumption) and lighting (decrease from 9% to 4% due to autonomous efficiency gains as lightbulbs get replaced with more efficient options supplied by the market without any targeted policy).

Unlike for electricity, the relative shares of water end-uses remain stable. Residential water end-use consumption projected in Figure 6-3 grows faster than that of electricity, with an average annual growth rate of 3.9%. The stability in the shares of total production of each use indicates that the drivers of water consumption growth are more uniformly distributed across its end-uses, which aligns with the findings in Chapter 5 that water consumption is tied to consumer direct interaction with the service, unlike electricity, which is more associated to the dwelling type and size. Figure 6-4 shows share evolution of water consumption by end-use services.

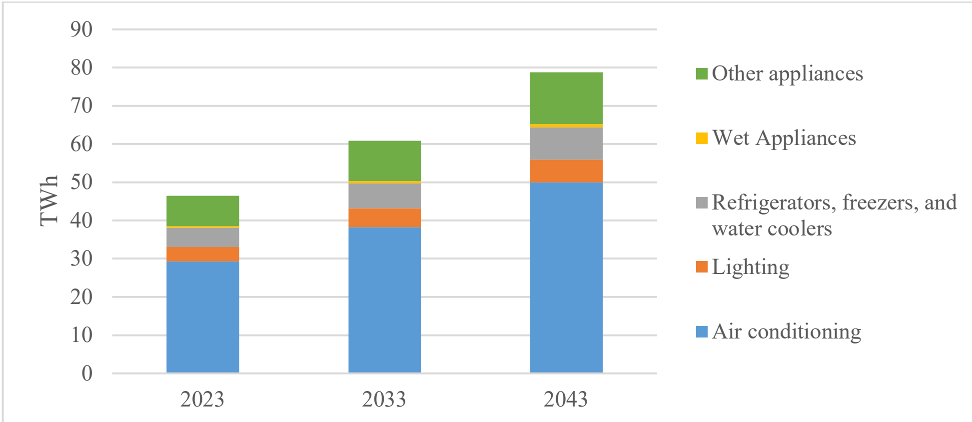

Figure 6-1 REF scenario end-use electricity consumption in the residential sector

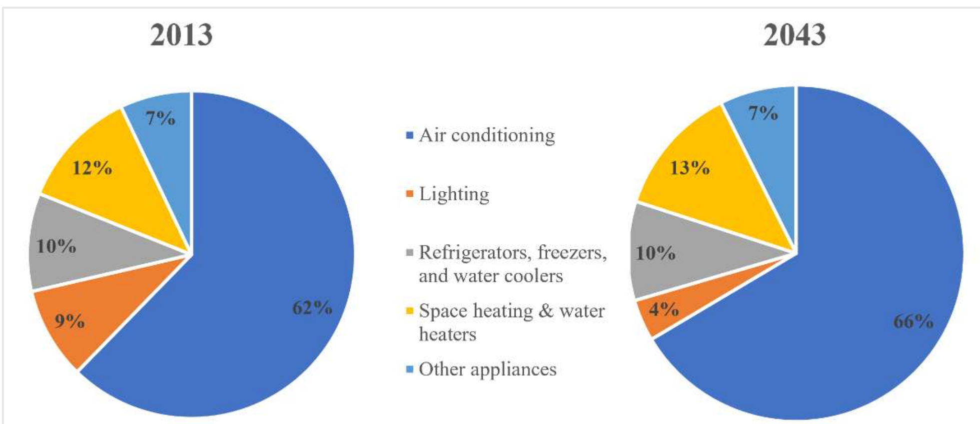

Figure 6-2 Share of residential electricity end-use services (REF scenario)

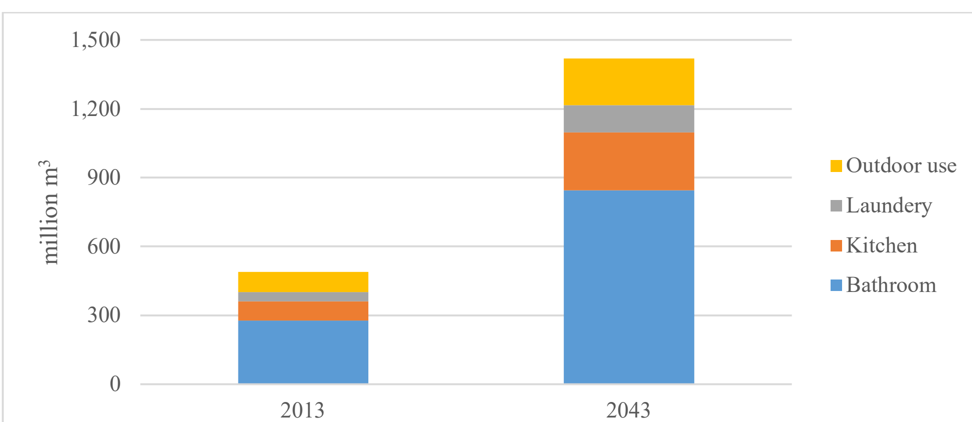

Figure 6-3 REF scenario end-use water consumption in the residential sector

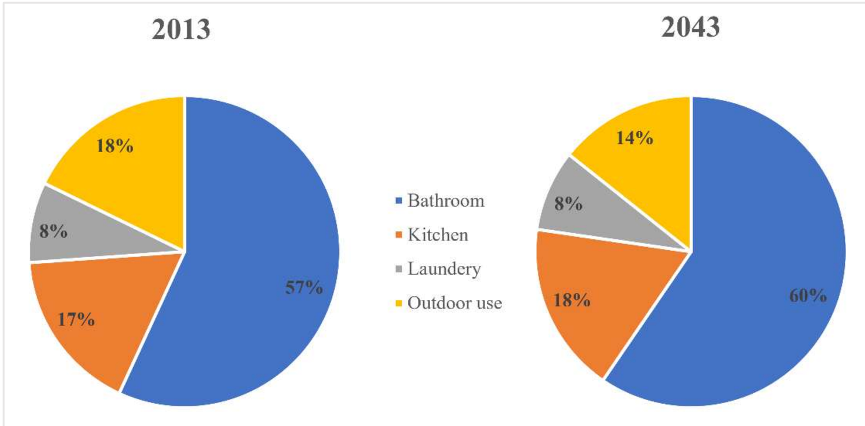

Figure 6-4 Share of residential water end-use services (REF scenario)

6.3.2 Dynamics of end-use efficiency

Conservation and efficiency improvement measures implemented in the residential sector under all efficiency improvement scenarios significantly reduce overall electricity and water consumption. All scenarios result in a higher reduction in overall water consumption compared to electricity consumption. However, an examination of these reductions provides insights into the relative effectiveness of different policy options and the saving potential for each energy service.

The results clearly establish air conditioning as the dominant end-use governing the effectiveness of residential demand reduction strategies. Across all scenarios and time periods, the vast majority of all electricity saved came from this single end-use. For instance, in the highly effective HN-CM scenario, the savings achieved in 2043 are almost entirely accounted for by the reduction in AC consumption. This demonstrates that policies targeting thermal comfort are a principal and indispensable lever for managing residential electricity demand.

The data also reveal a fundamental difference in the timing of savings between behavioural and technological interventions. The Moderate Behavioural Measures (MB-CM) scenario provides its impact immediately, delivering its entire 4% savings upfront in 2023 with no subsequent growth. However, this saving is the result of scenario definition influenced by the literature-based consumer acceptance rate. Since consumer choice cannot be modelled in TIMES, the behavioural savings remain constant over time. In contrast, the technologically-driven scenarios show incremental and accelerating savings. For example, the Government Housing Measures (GHGO-CM) scenario projects a marginal 0.6% savings in 2023 but this grows to 8.1% by 2043. This is driven by improvements such as building codes and efficient appliances in new dwellings and through more efficient replacement appliances. Therefore, the aggregate impact of these measures grows as new housing stock is built and existing electrical appliances and water fixtures are gradually replaced.

Furthermore, projected differences in how efficiency measures perform across housing segments highlight the structural trade-offs arising from the physical and demographic composition of the residential sector. For instance, targeted appliance efficiency improvements show varying savings across segments. The savings from cold services (refrigerators, freezers, and water coolers) in the government housing scenario bring down consumption from 8 TWh to 6 TWh. This is a significantly larger saving than that achieved by the investment apartments scenario. This disparity suggests that the specific dwelling characteristics and appliance stock of government housing create a greater potential for savings from such targeted interventions. These trade-offs demonstrate that a disaggregated, systems-level approach is useful to understand how the unique socio-technical characteristics of different residential segments mediate the effectiveness of a policy.

6.3.3 National measures vs targeted interventions

For electricity, comparing the effectiveness of different technical intervention pathways shows that savings are generally higher under a comprehensive national approach. However, the impact of targeted interventions within the state-managed housing programme is disproportionately large relative to its scale, indicating that concentrated measures can have a substantial potential to yield results comparable to broader national reforms.

The Moderate National Conservation Measures (MN-CM) and the High National Conservation Measures (HN-CM) scenarios outperform the targeted, segment-specific interventions. While the investment apartments and government housing (IA-CM and GHGO-CM) scenarios deliver meaningful electricity savings, they only manage to reduce the 2043 total demand by 5% and 8% respectively. In contrast, the moderate and ambitious national measures scenarios are projected to achieve a much larger reductions of 14% and 22%, respectively. This suggests that to achieve the largest scale of savings, policy must be comprehensive, applying standards and retrofits across the entire residential building stock.

However, an interesting and more actionable finding comes from deconstructing how these savings are achieved. An analysis of the targeted scenarios shows that the government housing intervention (GHGO-CM) is disproportionately effective. By 2043, it delivers an 8% savings compared to the reference scenario. This is nearly double the 5% savings achieved by the investment apartments intervention. A decomposition of the end-uses (shown in Table 6-4) reveals why the government housing intervention achieved such a reduction. For instance, the 2043 cold services consumption is reduced by 2.5 TWh under the government housing interventions compared to the reference scenario. This is more than double the savings achieved for the same end-use in the investment apartments intervention scenario.

This finding has several policy implications. It demonstrates that while air conditioning represents the largest potential for absolute savings, there is an effective pathway to mitigate overall consumption. Moreover, the pathway for mitigating overall consumption lies in other major electrical end-uses, such as refrigeration, within the citizen housing supplied by PAHW. Furthermore, this highlights that a targeted and rapidly implemented programme within this centrally-governed housing segment can yield total savings of 8%. This figure delivered by targeted measures on the government housing segment represents more than half the savings of the more complex and much larger Moderate National Conservation Programme (MN-CM), which achieved 14% savings compared to the reference scenario. Thus, a focused intervention by the Public Authority for Housing Welfare could be a highly effective initial step for policymakers.

6.3.4 Water efficiency improvements

As with electricity projections, water efficiency improvements are also most effective when implemented through national-level measures (Table 6-5). However, a comparative analysis reveals a different and more complex savings profile, differing primarily in the scale of the reduction potential.

While the High National Conservation Measures (HN-CM) scenario achieves a 22% reduction in electricity demand by 2043, water savings under this scenario are significantly larger, at 55%. This suggests the residential water sector is far more responsive to a combination of technological and behavioural interventions. Furthermore, the relative effectiveness of the targeted scenarios is inverted compared to electricity. For electricity, the government housing conservation measures (GHGO-CM) scenario had the highest potential interventions. For water, the investment apartments conservation measures scenario delivers a greater total savings (25% in 2043 compared to 22% in the GHGO-CM).

A detailed examination of end-uses reveals the dynamics behind this reversal. The investment apartments scenario achieves large savings in bathroom water consumption, projecting a drop of 219 million m^3 compared to the reference scenario. The government housing measures achieve a saving of only 118 million m^3 compared to the reference scenario. The savings projected in the bathroom category of investment apartments are so large that they outweigh the investment apartments' scenario relative underperformance in water savings elsewhere.

These trends primarily reflect the lower population concentration within government housing relative to investment apartments, which translates into fewer daily uses of water fixtures within each dwelling. Conversely, government housing shows larger savings within the kitchen and outdoor uses categories. This effectiveness is because the new efficiency measures are replacing highly inefficient end-use technologies and practices. These inefficient technologies and measures were modelled to reflect observed Kuwaiti household behaviours. The baseline conditions are characterised by high water intensity arising from cultural practices and norms. For instance, dishwashing is predominantly done by hand, which is a method culturally perceived as more hygienic than electric dishwashers. Additionally, outdoor cleaning is often performed with open hoses, both of which result in significantly higher water consumption.

Finally, the results show that water savings are accessible from a much more diverse set of drivers than electricity. Unlike electricity, where savings are almost exclusively from air conditioners (whether directly from the units and their thermostats or indirectly through walls and roofs' thermal insulation, and window glazing), significant water savings come from multiple, independent sources. For example, the behavioural scenario (MB-CM) alone delivers a 16% reduction in 2043, with its impact concentrated in bathrooms and outdoor use (areas directly influenced by user habits). This level of savings from behaviour alone is far greater than seen in electricity. Therefore, this analysis demonstrates that while an effective electricity strategy primarily focuses on thermal comfort, an effective water conservation strategy can employ a diversified portfolio, which balances behavioural nudges and targeted technological interventions across bathrooms, kitchens, and outdoor uses.

Appendix C and E provide detailed model output projections of water and electricity consumption per end-use for each housing segment under all scenarios. Appendix D provides aggregated residential end-use water projections under all scenarios.

Table 6-4 Electricity consumption of different end-use services under different conservation and efficiency improvement measures

TWh	2013	2023						2033						2043					
	REF	REF	MB-CM	IA-CM	GHGO-CM	MN-CM	HN-CM	REF	MB-CM	IA-CM	GHGO-CM	MN-CM	HN-CM	REF	MB-CM	IA-CM	GHGO-CM	MN-CM	HN-CM
Air conditioning	17.7	29.3	27.5	28.9	29.1	29.1	26.4	38.3	36.0	36.3	36.8	35.1	30.8	50.0	47.0	46.3	45.9	41.2	35.3
Lighting	2.3	3.8	3.7	3.8	3.8	3.8	3.4	4.9	4.8	5.0	5.0	5.0	4.3	6.0	5.9	6.1	6.1	6.1	5.2
Refrigerators, freezers, & water coolers	2.9	5.0	5.0	4.8	4.8	4.5	4.7	6.5	6.5	5.8	5.0	5.0	5.2	8.4	8.4	7.3	5.9	5.9	5.9
Space heating & water heaters*	0.5	0.5	0.5	0.9	0.5	0.5	1.0	0.7	0.7	1.3	0.7	0.7	1.4	0.9	0.9	1.8	1.0	0.9	1.9
Other appliances*	5.0	8.0	8.0	8.0	8.0	8.0	8.0	10.5	10.5	10.5	10.5	10.5	10.5	13.6	13.6	13.6	13.6	13.6	13.6
Total	28.3	46.5	44.6	46.3	46.2	45.8	43.5	60.9	58.5	58.8	58.0	56.2	52.1	78.8	75.8	75.1	72.4	67.6	61.9
Reduction			4.0%	0.3%	0.6%	1.4%	6.4%		3.9%	3.3%	4.7%	7.7%	14.3%		3.9%	4.8%	8.1%	14.3%	21.5%

*No measures were implemented for the space heating, water heaters, and other appliances; no additional appliance options were included aside from the standard.

Table 6-5 Water consumption of different end-use services under different conservation and efficiency improvement measures

M m3	2013	2023						2033						2043					
	REF	REF	MB-CM	IA-CM	GHGO-CM	MN-CM	HN-CM	REF	MB-CM	IA-CM	GHGO-CM	MN-CM	HN-CM	REF	MB-CM	IA-CM	GHGO-CM	MN-CM	HN-CM
Bathroom	280.6	510.7	423.5	396	439.8	343.8	338	691.3	574.9	526.4	597.7	443.1	377.9	886	738.1	667.1	767.6	569.1	469.9
Kitchen	82.94	147.2	147.2	105.1	86.14	129.3	19.34	193.7	193.7	132.4	112.8	170.3	26.78	251.7	251.7	169.5	142.2	221.3	35.22
Laundry*	40.74	71.45	71.45	71.45	71.45	71.45	71.45	92.37	92.37	92.37	92.37	92.37	92.37	119.4	119.4	119.4	119.4	119.4	119.4
Outdoor use	85.92	134.3	74.89	90.42	73.84	67.13	23.8	163.3	91.21	110.3	88.34	81.65	29.2	203.1	113.7	138	108.3	101.5	36.91
Total	490.2	863.6	717	663	671.3	611.7	452.6	1141	952.2	861.5	891.2	787.4	526.2	1460	1223	1094	1137	1011	661.4
Reduction			17.0%	23.2%	22.3%	29.2%	47.6%		16.5%	24.5%	21.9%	31.0%	53.9%		16.3%	25.1%	22.1%	30.7%	54.7%

*No measures were implemented for the laundry; no additional appliance options were included aside from the standard.

6.3.5 Electricity and water use intensity

The Electricity Use Intensity (EUI) and Water Use Intensity (WUI) metrics provide comparable savings criteria in both houses and apartments (Liddiard, 2021, UN-ESCWA, 2007). They do that by normalising buildings' consumption by floor area to reveal insights into the underlying efficiency of the building stock. Intensity projections (Table 6-6) demonstrate that houses and apartments follow different efficiency trajectories, exposing the unique case of each dwelling type.

Table 6-6 Influence of conservation and efficiency improvement measures on dwellings EUI and WUI

	2023	***2033***	***2043***	***2023***	***2033***	***2043***
	Electricity Use Intensity kWh/m^2 per year			**Water Use Intensity** m^3/m^2 per year		
Houses						
REF	193	192	193	3.13	3.09	2.99
MB-CM	185	184	186	2.46	2.44	2.37
GHGO-CM	191	178	169	1.93	1.84	1.71
MN-CM	190	176	164	2.09	2.07	2.02
HN-CM	178	160	152	1.36	1.28	1.22
Apartments						
REF	259	229	214	5.68	5.01	4.70
MB-CM	248	221	206	4.97	4.37	4.10
IA-CM	257	213	192	3.48	3.08	2.89
MN-CM	256	214	186	4.26	3.54	3.32
HN-CM	247	203	168	3.51	2.52	2.30

6.3.5.1 EUI

Under the reference scenario, houses experience stagnation in their EUI, which remains unchanged at approximately 193 kWh/m^2 from 2023 to 2043. Despite end-use technologies being replaced with newer, slightly efficient appliances in the absence of high-efficiency technologies, the autonomous efficiency gains from these appliances are cancelled out by the addition of new inefficient housing stock. This implies locking in of inefficiencies, where the total consumption from houses grows almost in proportion to the expansion of floor area. This trend is reinforced by the limited housing options available to citizens, which effectively positions the Public Authority for Housing Welfare (PAHW) as the standard-setter for new housing. With

PAHW typical developments consisting of large 400 m^2 plots with a high building-to-plot ratio (210%), these housing programmes not only add significant baseline demand but also serve as a benchmark that reinforces a cultural expectation for large, resource-intensive dwellings.

The behavioural changes (MB-CM) scenario show that behavioural measures alone are insufficient to alter the long-term trend. Projections show a slight dip in intensity but ultimately fail to create a sustained downward path, with the EUI returning to 186 kWh/m^2 by 2043. In contrast, technical measures of all other scenarios (GHGO-CM, MN-CM, HN-CM) show continuous, long-term decline in the EUI of houses. These measures progressively decouple consumption from floor area, reducing the 2043 EUI to 169, 164, and a low of 152 kWh/m^2, respectively. This demonstrates that for the long-term improvement in houses energy intensity cannot be achieved through behavioural nudges alone; it is dependent on direct technological and regulatory interventions in the building stock itself.

In contrast, apartments appear to have higher EUI compared to houses. Though apartments do exhibit a declining trend even under the reference scenario. Under the reference scenario, apartments' EUI drop from 259 kWh/m^2 in 2023 to 214 kWh/m^2 by 2043. However, it remains significantly more intensive than houses. This elevated intensity per square metre is explained by a combination of two factors. The higher EUI is justified by the air conditioning technologies typically found in Kuwait's apartments. While houses in Kuwait typically use packaged air conditioners and ducted split systems, apartments use less efficient window and mini-split air conditioners.

The justification for the investment apartments declining trend is different. The trend appears to be declining because this segment is characterised by a higher deployment rate. This results in the influence of inefficient apartments being diluted by the newer ones at a higher rate than houses. Furthermore, under the technical efficiency measures scenarios, new apartment buildings show a downward trend, with the MN-CM scenario bringing the final EUI down to 186 kWh/m^2 and the HN-CM scenario driving the final EUI close to houses at 168 kWh/m^2. This demonstrates that while apartments begin as the more intensive dwelling per square metre, they are also far more responsive to policy intervention, eventually reaching an intensity level comparable to technically improved houses.

6.3.5.2 WUI

The Water Use Intensity (WUI) projections (Table 6-4) show a different and more dynamic narrative than that of electricity. Projection data reveal that there is greater potential for efficiency improvements and higher responsiveness to policy interventions. The fundamental difference between EUI and WUI is apparent for houses. Unlike the EUI of the reference scenario, houses' WUI shows a clear downward trend, declining from 3.1 m^3/m^2 to 3.0 m^3/m^2 by 2043. This indicates that the autonomous replacement of water fixtures with more efficient standard options available in the market has a consistent impact. The impact of these replacements is significant enough to allow the housing stock to naturally improve its water efficiency over time. The intervention scenarios then act as powerful accelerators of this trend. The technical measures in the government housing sector (GHGO-CM), moderate national conservation measures (MN-CM), and the high national conservation measures (HN-CM) scenarios are exceptionally effective. Each of these scenarios reduces the 2043 WUI by 43%, 32%, and 59% respectively, compared to the reference scenario. This confirms that the housing stock is highly responsive to water efficiency upgrades.

Apartments show a similar behaviour of high responsiveness, though they have a high WUI in the reference scenario. The reference scenario's WUI for apartments in 2023 is 6.0 m^3/m^2, nearly 81% higher than for houses. This elevated value is a direct reflection of higher occupant density, which leads to a greater concentration of water activities within a smaller floor area (see Chapter 4 for information on crowding rates within investment apartments). Nevertheless, this high density is matched by a high potential for water savings. The implementation of ambitious national measures (HN-CM) scenario projects to reduce the 2043 WUI by 51% from 4.7 m^3/m^2 to 2.3 m^3/m^2. This reduction is far more pronounced than the relative savings achieved in electricity use.

In summary, the comparative analysis of WUI and EUI reveals two main insights. First, the underlying water efficiency of the building stock is improving for both dwelling types, whereas the EUI for houses is locked in a state of inefficiency. Second, the potential for policy-driven savings is proportionally far greater for water than for electricity across all scenarios and dwelling types. This suggests that while improving electricity intensity requires overcoming complicated technological and regulatory constraints, improving water intensity is a more attainable objective of accelerating an already favourable trend.

6.3.6 Supply-side consequences of demand reduction

The reductions in residential electricity and water consumption detailed in the previous sections have direct and significant consequences for the supply-side of the electricity-water system. Every kilowatt-hour of electricity and cubic metre of water saved on the demand-side represents a unit of production that is no longer required from the system's power plants and seawater desalination plants. This, in turn, reduces the need to build, fuel, and operate power plants and seawater desalination plants. The following sections quantify these supply-side benefits.

6.3.6.1 Capacities

The most significant supply-side benefit of residential efficiency improvements is their ability to defer significant capital-intensive investments across the entire electricity-water system. By curbing end-use demand, all efficiency scenarios reduce the required new power and desalination plants. Though the magnitude of this effect varies significantly depending on the policy pathway of the scenario. Figure 6-5 projects the changes in installed electric power generation capacity under different end-use efficiency, while Figure 6-6 projects the corresponding effects on seawater desalination capacity.

In the Reference (REF) scenario, the system requires 38 GW of power capacity and 5.1 million m^3/day of desalination capacity by 2043. However, under the Moderate National Conservation Measures (MN-CM) scenario this is lower, at 34 GW for power and just 3.8 million m^3/day for desalination. The most ambitious High National Conservation Measures (HN-CM) scenario is even more impactful, avoiding the need for 8 GW of power plants and 2.3 million m^3/day of desalination capacity, which halves the required expansion of the water system compared to the REF scenario.

The technical interventions in both the Government Housing (GHGO-CM) and Investment Apartment (IA-CM) segments deliver comparable and meaningful reductions in required capacity for both power and water. Furthermore, even the purely Moderate Behavioural Measures (MB-CM) scenario is shown to have a capital deferral effect, particularly on the water system, reducing the required 2043 desalination capacity from 5.1 to 4.4 million m^3/day. This projection demonstrates that even low-cost, non-technical interventions can yield savings by deferring the construction of capital-intensive desalination plants and avoiding their environmental burden.

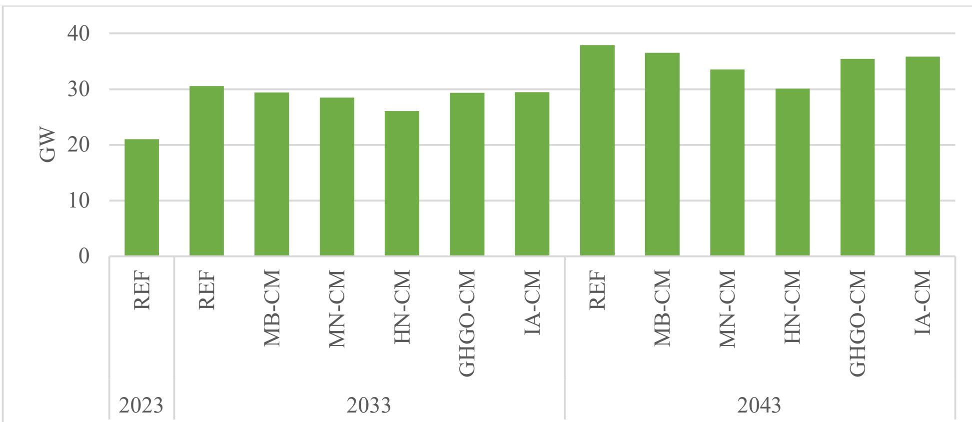

Figure 6-5 Electric power generation installed capacity for different end-use efficiency improvement measures compared to REF scenario

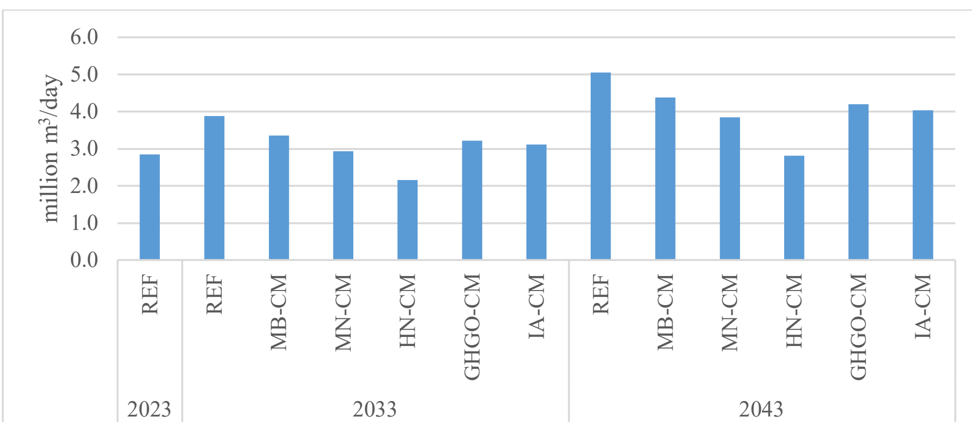

Figure 6-6 Seawater desalination installed capacity for different end-use efficiency improvement scenarios compared to REF scenario

6.3.6.2 Deferral of new capacities

Residential efficiency improvements also provide the supply-side with additional benefit by altering the timing of when capital-intensive investments in new capacities are required (Figure 6-7). The delay in investment is triggered as soon as end-use efficiency improvement scenarios are implemented. Analysis of when these deferrals occur highlights a key contrast between the immediate savings (front-loaded) and the cumulative (back-loaded) impacts of the medium and high technological improvement scenarios.

The High National Conservation Measures (HN-CM) scenario quantifies the maximum potential impact, demonstrating that a comprehensive technical and behavioural strategy can nearly halve the need for new power plant construction. This ambitious pathway reduces the required capacity additions by a 46% in the first decade (2023-2033) and maintains a similar 46.5% reduction in the second decade (2033-2043), effectively deferring the need for approximately 8 GW of new capacity by 2043.

An interesting observation in the results comes from contrasting the temporal profiles of the Moderate Behavioural Conservation Measures (MB-CM) and Moderate National Conservation Measures (MN-CM) scenarios. The behavioural measures illustrate a front-loaded behaviour where it delivers a 12% reduction in required capacity for the initial decade. However, the effectiveness of these behavioural measures reduce to just 4% in the long term, a result of the behaviour measures' savings explained in the previous section. In direct opposition, the MN-CM scenario shows a back-loaded behaviour and compounding. It begins with a 22% reduction and increases to a 31% reduction in the second decade. This dynamic occurs because building codes and appliance standards apply to the continuous flow of new construction and stock turnover, meaning their aggregate impact compound over time.

Finally, the targeted technical scenarios (GHGO-CM and IA-CM) validate this pattern of compounding technological benefits. They both begin with an impact similar to the behavioural measures (of 11% to 12% reduction). However, their effectiveness grows over the long term. Each of these scenarios achieves 14% to 17% reduction in the 2033–2043 period.

Based on the above, it can be concluded that while behavioural nudges can provide valuable early wins, only structural, technology-forcing policies can deliver the deep, compounding deferral of capital investment needed for a long-term transition.

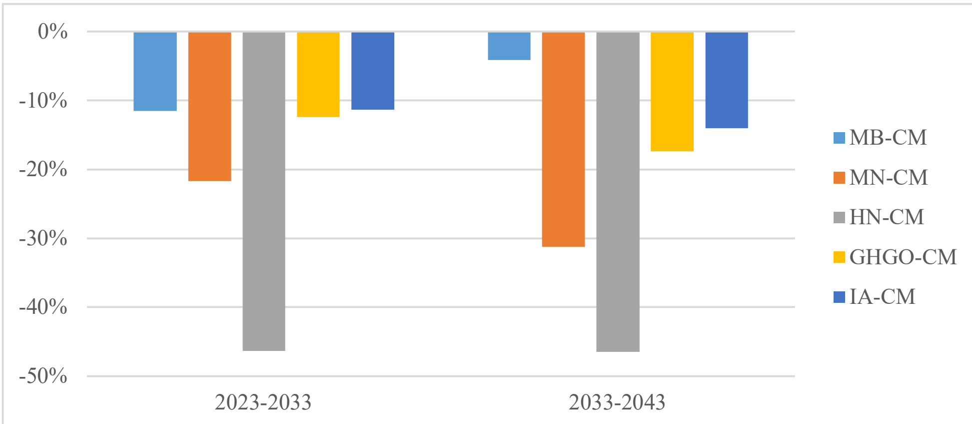

Figure 6-7 Delay in investments for new capacities as result of end-use efficiency improvement scenarios compared to REF scenario

6.3.6.3 Reduction in fuel consumption

The most direct benefit of residential efficiency improvements is the substantial reduction in the primary energy required for power generation and seawater desalination. Under the Reference (REF) scenario, total primary energy consumption for the EWS is projected to rise steadily to 34 Mtoe by 2043. All efficiency improvement scenarios successfully curb this growth, with their effectiveness directly reflecting the scale of the technical measures and the scope of their application across the residential sector.

Figure 6-8 projects the primary energy consumption required for the power generation and seawater desalination under different efficiency improvement scenarios. The impact ranges from modest reductions in the behavioural (MB-CM) and targeted technical scenarios (GHGO-CM, IA-CM) to a deep reduction under the comprehensive national measures (MN-CM, HN-CM). The comprehensive national measures reduce primary energy consumption in 2043 to 29 Mtoe and 25 Mtoe, respectively. Figure 6-9 projects the scale of primary energy savings compared to the reference scenario of the corresponding year.

A closer examination of the fuel mix reveals a similar behaviour across all efficiency improvement scenarios. All projected energy savings are achieved from a reduction in the consumption of crude oil and oil products. The consumption of both domestic natural gas and imported LNG remains maximised to its available limits. Thus, crude oil in particular is treated by the model as marginal fuel used to meet any residual demand. Consequently, every unit of electricity and water saved translates directly into a saving of exportable hydrocarbons, which eliminates both their domestic consumption and their associated emissions, while increasing Kuwaiti economic output.

Treatment of crude oil as marginal fuel is viewed as prioritisation of energy-efficient generation options. Another layer of this benefit is driven by the decoupling of electricity and water demand. As established, water efficiency measures have a proportionally greater impact on consumption than electricity measures. By substantially reducing the need for desalinated water, KEWSM lessen the EWS's rigid dependency on thermal cogeneration plants. This decoupling effect introduces flexibility into the system. It liberates a larger portion of the total electricity demand to be met by the most efficient generation technologies (which is in these status quo scenarios its gas-fired options). Therefore, water efficiency does not just save the energy needed for desalination, but also it provides the benefit of enabling a more economically and environmentally optimal dispatch of the entire power generation fleet. The subsequent chapter will examine in detail how these efficiency measures and the decoupling of electricity from water production can influence renewable energy generation and the decarbonisation pathway.

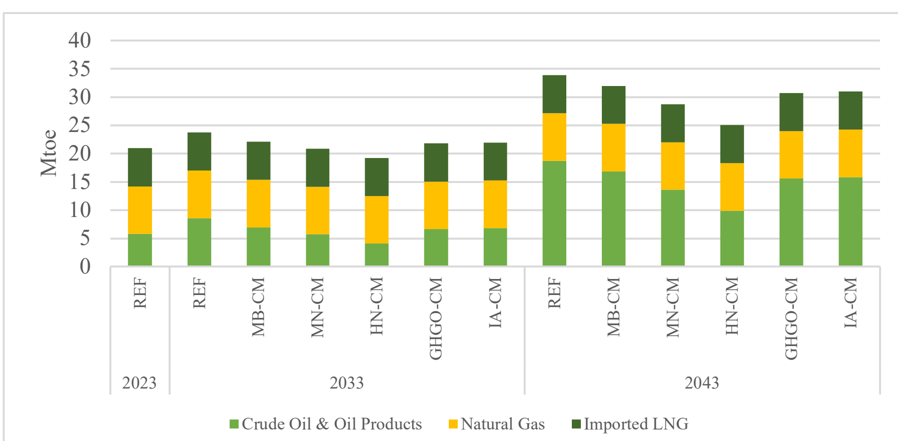

Figure 6-8 Plants primary energy consumption under different scenarios

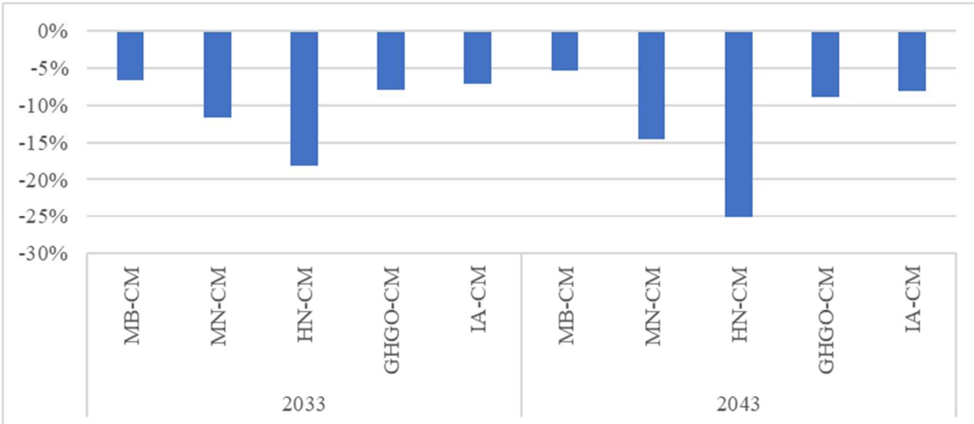

Figure 6-9 Plants fuel consumption reduction under different scenarios compared to REF scenario

6.3.6.4 Avoided production and capital cost

The immediate benefit anticipated from efficiency improvement scenarios is a reduction in the supply-side operational and investment costs. These savings were quantified by calculating the avoided costs resulting from the implementation of efficiency improvement measures under different scenarios compared to the Reference Scenario. Figure 6-10 illustrates projected total supply-side savings across three key metrics: operation and maintenance costs, fuel consumption, and cost of investments in electricity and water capacities. Figure 6-11 illustrates the projected avoided costs under the different efficiency improvement scenarios compared to the Reference (REF) scenario.

The deferment in capacities and reduction in fuel consumption as a result of residential efficiency improvements directly translate into substantial avoided costs for the electricity-water system. As shown in Figure 6-10, under the REF scenario, the total annual production cost is projected to rise from 12 billion in 2023 to 28 billion by 2043. Fuel costs alone constitute approximately 88% of total production costs in 2023.

Under the residential efficiency improvement, all scenarios successfully mitigate this cost increase. A close examination of the savings across all scenarios shows that they are overwhelmingly driven by avoided fuel costs followed by the avoided investment costs. The share of fuel costs in total expenditure is projected to drop from 88% in 2023 to a range of 71% - 73% by 2043 across the different scenarios. These savings are most evident in the High National Conservation Measures (HN-CM) scenario, where the total 2043 production cost is reduced by $7.5 Bn, resulting in a saving of 27% compared to the reference case. As stated, the savings primarily came from fuel costs, which are projected to be reduced by US$5.9 billion (from US$20.4 Bn to US$14.5 Bn), and from investment costs in new capacities, which are cut by US$1.6 Bn (from US$6.5 Bn to US$4.9 Bn).

A similar trend occurs for all of the other intervention scenarios, where the magnitude of both fuel costs and new capacities investment savings scales in direct proportion to their overall effectiveness. By 2043, the Moderate National Conservation Measures (MN-CM) scenario is projected to reduce total costs by 16%. At the same time, the targeted interventions (GHGO-CM and IA-CM) are projected to achieve cost reductions of 9% to 10%. Even the purely behavioural scenario (MB-CM) provides a cost saving of around 6%.

Figure 6-12 projects in detail the percentage of the supply-side savings gained under different efficiency improvements compared to the REF scenario. The impact of these efficiency measures is consistently and disproportionately greater for water capacities investments than for electricity capacities investments across all scenarios. While even modest interventions like the behavioural (MB-CM) or targeted (IA-CM) scenarios reduce required 2043 electricity capacity investments by 4%–9%, their impact on desalination is greater, reducing required water capacity investments by 14%–20% compared to the reference case. The ambitious (HN-CM) scenario reduces the required 2043 electricity capacity investment by 21%, with the impact on desalination more than double, bringing down the required 2043 water capacity investment by a massive 45% compared to the reference case.

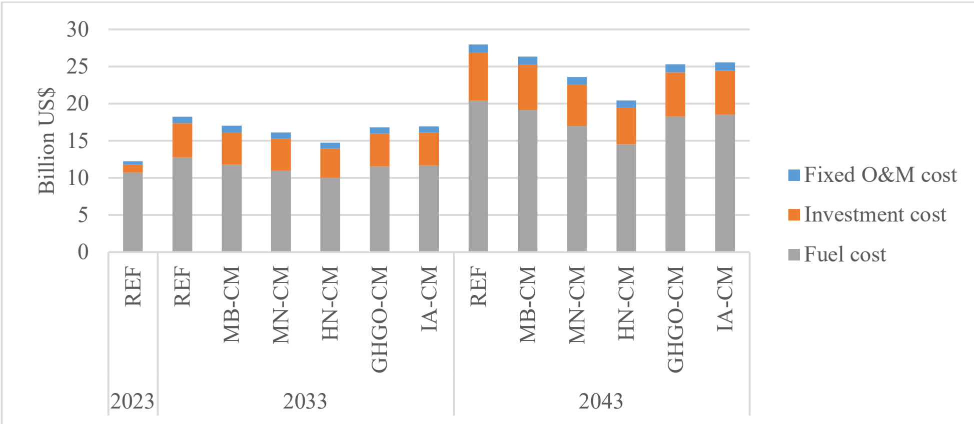

Figure 6-10 Production cost projections under different scenarios

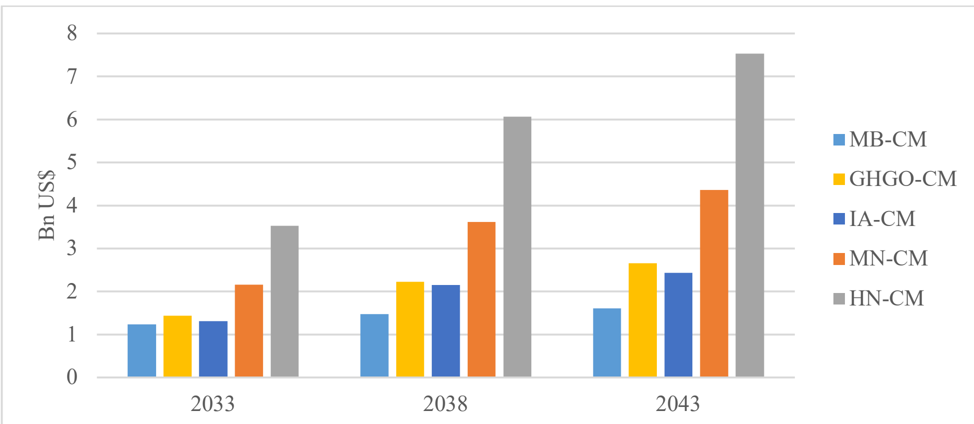

Figure 6-11 Avoided costs projections under different scenarios

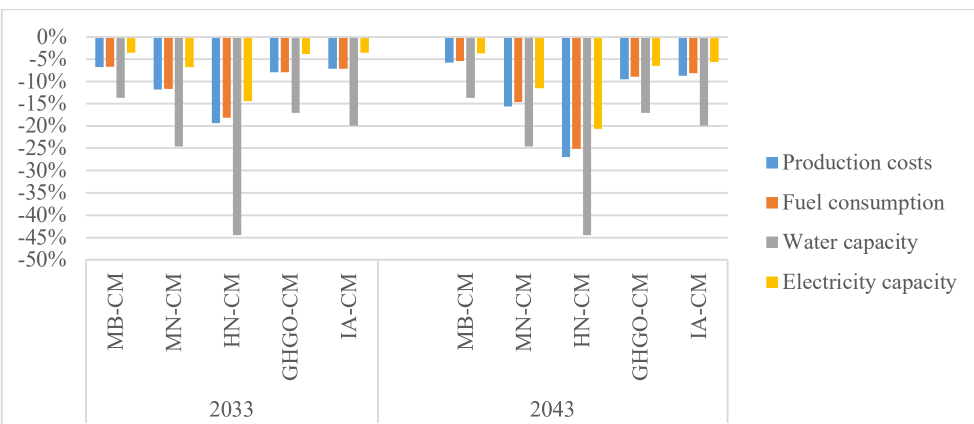

Figure 6-12 Supply-side savings gained under different efficiency improvement compared to the REF scenario

6.3.7 Sensitivity to low and high overall demand

To investigate how future demand uncertainty affects the effectiveness of a moderate national efficiency policy, a sensitivity analysis was conducted, as detailed in Table 6-7. This analysis quantifies the impact of the Moderate National Conservation Measures (MN-CM) scenario when applied to contrasting low and high development scenarios. These development scenarios are based on the socioeconomic trajectories outlined in Chapter 4 and modelled in Chapter 5. The MN-CM scenario was selected for this sensitivity analysis because it covers the entire residential sector and represents a relatively moderate approach to implementing efficiency measures, as detailed in Table 6-1. By comparing key outputs for the year 2048, this analysis helps to understand how the benefits of a comprehensive and broad policy package vary with different levels of underlying demand growth.

The results show that the absolute demand reductions achieved by the MN-CM policy are greatest under the high-demand scenario, saving 16.2 TWh of electricity and 512 million m^3 of water. However, the relative impact of these measures is highest in the low-demand scenario. The electricity demand reduction is 9% in the low-demand case, compared to 8% reduction in the high-demand case. A similar, more pronounced pattern is observed for water, with a 34% reduction in the low-demand scenario versus 28% reduction under high-demand.

These demand reductions result in lower electricity and water production capacities. However, the reduction in fuel consumption highlights a saturation point. While absolute fuel savings are lowest in the low-demand case (2 Mtoe), they are identical for both the central and high-demand scenarios (5 Mtoe). Despite higher electricity and water output in the high-demand future, MN-CM delivers similar absolute fuel savings because the model re-optimises towards more efficient electric power generation (CCGTs) and grid-connected RO desalination, thus lowering the fuel intensity of the electricity and potable water produced.

Finally, the analysis of production costs shows the most significant effect. The largest absolute cost savings of US$4.1 Bn is achieved in the central demand scenario. However, in the high-demand scenario, the absolute savings fall to US$2.4 Bn, representing a relative cost reduction of only 4%, which is much lower than the 10%

decrease of the central case. This relatively minimal cost saving is the result of the expenditure structure. The operational expenditure under the high-demand scenario increases as the system relies more heavily on crude oil to fuel its thermal cogeneration plants to meet the system demand, thus partially offsetting the efficiency gains from greater utilisation of CCGT units and grid-connected RO desalination.

Table 6-7 MN-CM Scenario sensitivity analysis for the year 2048

Observed year: 2043	***Central Demand***	***High Demand***	***Low Demand***
Demand reduction:			
Electricity [TWh]	13.0 *-9.6%*	16.2 *-7.9%*	8.5 *-9.0%*
Water [million m^3]	441 *-31.4%*	512 *-27.6%*	287 *-34.4%*
Avoided capacities:			
Electricity [GW]	4.4 *-13.0%*	5.0 *-14.7%*	3.8 *-16.3%*
Water [m^3/day]	1.2 *-23.9%*	1.4 *-21.6%*	0.8 *-25.6%*
Reduction in fuel consumption [Mtoe]	5.1 *-17.1%*	5.1 *-12.9%*	2.3 *-12.0%*
Reduction in production costs [Bn US$]	4.1 *-10.4%*	2.4 *-3.5%*	0.3 *-1.6%*

6.3.8 Cost-effectiveness

This section employs analytical framework of Benefit-Cost Ratio (BCR) for cost-effectiveness analysis in order to evaluate the energy efficiency improvement scenarios. The BCR analysis evaluates saving achieved for each unit of cost invested in the efficiency measures. This methodology is based on the National Action Plan for Energy Efficiency (2008) and it is a dimensionless metric expressing the magnitude of benefits relative to costs. The ratio is derived using Equation (10) which divides the total net present value of all cost savings over the net present value of the incremental investment of the efficiency improvements scenario. Therefore, a ratio greater than "1" signifies that the long-term benefits outweigh the upfront investment, and the higher the ratio indicates a more efficient deployment of capital.

$$BCR = \frac{\sum_{t=0}^{n} \frac{SC_{t,Ref\ Scen}}{(1+r)^t} - \sum_{t=0}^{n} \frac{SC_{t,New\ Scen}}{(1+r)^t}}{\sum_{t=0}^{n} \frac{MC_{t,New\ Scen}}{(1+r)^t}} \tag{10}$$

Where:

- t = Time period (in years), from 0 to n.
- n = Modelled horizon in years.
- r = The annual discount rate (7.8%)
- $SC_{t,Ref\ Scen}$ = Supply-side cost in year t for the Reference scenario in [$]
- $SC_{t,New\ Scen}$ = Supply-side cost in year t for the observed scenario [$]
- $MC_{t,New\ Scen}$ = Incremental cost of the measure in year t for the observed scenario [$]

The BCR test results presented in Table 6-8 demonstrate that the all of the residential efficiency pathways are highly cost-effective. All five scenarios yield a BCR higher than 1, confirming that the economic benefits of the energy savings outweigh the costs of achieving them. The analysis reveals a clear ranking of cost-effectiveness. The most impactful scenario for every dollar spent is the Moderate Behavioural Conservation Measures (MB-CM) scenario. With a BCR of 6.6, that scenario yields a system benefits of US$6.6 for every dollar invested in the programme. This is followed by the High National Conservation Measures (HN-CM), with a BCR of 6.1. Though the measures under these two scenarios yield almost the same benefit per dollar spent, their total costs and aggregate benefits differ significantly. All of the other scenarios have a BCR of 5.1 or higher.

Table 6-8 Benefit-Cost Ratio test

Scenario	*Benefit-Cost Ratio*
MB-CM	6.6
GHGO-CM	5.1
IA-CM	5.7
MN-CM	5.9
HN-CM	6.1

6.4 Discussion

6.4.1 Reference scenario end-use

Structural drivers shape residential electricity and water demand growth in Kuwait. A decomposition of electricity and water consumption shows that growth is not uniform. For electricity, the analysis confirms that the demand trajectory is overwhelmingly driven by thermal comfort. Projections show that air conditioning (AC) alone accounts for the vast majority of all projected growth. This confirms AC's role as the central determinant of residential electricity demand. The results show that this is not a matter of high baseline consumption, but a reinforcing facet of AC demand where the growing number of dwellings and their larger average size combine to scale up AC consumption. This, along with the lower efficiency [in extremely hot climates] of new low global warming potential (GWP) refrigerants, makes air conditioners a powerful driver of future consumption. The primary implication for this is that a residential energy strategy that does not focus on thermal comfort is destined to have only a marginal impact. Furthermore, the autonomous decline of lighting's consumption share due to market turnover provides a key insight and that is when highly efficient technologies (like LEDs) become market-dominant, they can successfully decouple service demand from energy consumption.

For water, there is a different and more stable structural dependency. Projections showed a stability in the composition of end-uses water demand over the modelled horizon, even as the total consumption triples. This reinforces the conclusion from Chapter 5 that water consumption is more tightly coupled to direct, predictable human needs than to the socioeconomic factors governing electricity use. For policymakers, this suggests a different strategic approach. While electricity demand is heavily influenced by the built environment, water demand is more stable. This stability implies that interventions in the water sector can be designed with a higher degree of certainty, by focusing on improving the technical efficiency of a known and stable set of end-use services such as water fixtures, rather than contending with the more complex and lifestyle-driven consumption patterns seen in electricity.

6.4.2 Residential efficiency improvements

Analysis of the different policy intervention scenarios results demonstrates that the rate at which the influence of different efficiency improvement measures takes effect differs substantially depending on the targeted segment and type of measure. This is due to the rate at which new house stock for that particular segment becomes available and the service life of the technology being replaced. Such differences allow some scenarios, despite the differences in their scales, to accomplish equal reduction at some identical timeframes.

Additionally, projections show that behavioural savings are immediate while technological savings are cumulative. Though immediate, the behavioural low-cost early savings eventually slow down and dilute compared to the technical measures. The technical measures, on the other hand, experience cumulative savings. This dynamic suggests that an impactful efficiency improvement strategy would layer these interventions together. This dynamic is reinforced by the intensity analysis, which shows that behavioural nudges alone are insufficient to reverse the locked-in inefficiency in the housing stock's Electricity Use Intensity (EUI). Only the technical approaches are able to progressively decouple consumption from floor area.

Additionally, results show that interventions must be disaggregated and targeted. Government housing intervention is disproportionately effective when it comes to electricity, due to the characteristics of the dwelling stock. The EUI analysis confirmed that the efficiency of existing and new PAHW houses creates an opportunity for high-impact technical upgrades. On the other hand, water projections show an inverted pattern of effectiveness, with investment apartment intervention delivering greater savings than government housing intervention. The Water Use Intensity (WUI) analysis explains this reversal as apartments start with a WUI some 81% higher than houses, primarily due to higher occupant density. This extremely high baseline intensity makes them exceptionally responsive to fixture upgrades, especially in bathrooms, allowing them to yield the largest proportional water savings.

Occupant density and household size in apartments influence the EUI as well. Should the country achieve its development ambitions and experience an economic transition, the occupant density of apartments will likely decline and demand for independent living increase (Salama et al., 2017).

The results position the Public Authority for Housing Welfare (PAHW) as a potential champion for energy efficiency, offering a feasible pathway for near-term savings through direct mandates. At the same time, the results identify the more fragmented market-driven investment apartment sector as a key leverage point for a high-potential water conservation strategy. Such a strategy would require a different set of tools that extend to the landlord-tenant regulations and plumbing codes to capture its savings potential.

6.4.3 Supply-side

Analysis of KEWSM projections shows that residential end-use efficiency improvement measures can reduce the need for generation plants' capacity expansion. Delaying new capacity investments has a significant advantage for Kuwait. For instance, due to the demand uncertainty discussed in Chapter 4, delaying new capacity investments could aid in more effective electricity-water system planning. A delay in investment allows demand trends to form, preventing potential overinvestment in generation capacities.

Moreover, delaying investment decisions provides a valuable temporal advantage. Such advantage enables investment decisions alignment with the ongoing development of national environmental policy and sustainability goals. It also provides an opportunity to benefit from technological advancements that decrease the cost of renewable energy technologies or enhance production efficiencies.

All efficiency improvement measures reduced fuel requirements and, consequently, the fuel component of the production cost. The fuel consumption analysis reveals precisely how these savings are achieved. The analysis shows a dynamic of strategic value. The KEWSM's results demonstrate that all scenarios, regardless of their ambition, exclusively displace crude oil and oil products. The consumption of supply-constrained natural gas remains unchanged. This marginal fuel displacement effect means that even the most modest efficiency interventions deliver a disproportionately high strategic benefit. As each unit of energy saved directly frees up a unit of high-value hydrocarbon for export.

Yet, fuel remains the most significant component of the production cost. An inherent issue arising from this cost distribution, affecting the sustainability of the electricity-water system, is exposing the electricity and water to the volatility of fuel prices in international markets. Despite Kuwait's status as a major oil-producing and exporting country, the Ministry of Electricity and Water (MEW) procures fuels from the Kuwait National Petroleum Company (KNPC) at market price. The uncertainty surrounding the large portion of the electricity-water production cost poses itself as a challenge for planners and decision-makers.

Addressing this issue is possible through multiple pathways, such as opening the system for electricity trade and adopting renewable energy options. Both can help shift portions of the cost from fuel to capacities. Planning for investments in installations and capacities encounters less uncertainty in terms of costs when compared to fuel price volatility. Nevertheless, efficiency improvement measures could play a role in improving the system's sustainability.

6.4.4 Sensitivity analysis

The moderate national conservation measures show their effectiveness under all different socioeconomic conditions. Examining the relative reductions indicates a pattern in which efficiency savings scale with demand; however, they do experience a saturation effect. Once the technical improvements reach their maximum impact, additional demand does not yield proportionally greater savings. Thus, in the high-demand scenario, total consumption grows faster than efficiency gains can offset, leading to smaller relative reductions. Conversely, when demand is lower, the efficiency measures remain effective.

This apparent weakening of end-use efficiency under accelerated demand can be attributed to two factors. First, once the existing stock of inefficient appliances and fixtures has been replaced, the savings potential of that measure becomes exhausted. This saturation occurs regardless of demand growth and addition of new dwellings. Second, the technical potential of an efficiency measure is tied to the size and composition of the replaceable equipment stock, rather than scaling proportionally with macroeconomic growth that drives overall energy demand.

Finally, with regard to electricity demand, growth behaves differently from water, especially once efficiency measures become available for the model. Once efficiency measures take effect and reduce the demand in the initial years of the measures deployment, the model re-optimises the mix of seawater desalination technologies to meet potable water requirements in the most cost-effective manner. Under all high-demand scenarios, the model shifts towards grid-connected reverse osmosis (RO) for desalination, which accounts for up to 83% of the mix in the High Demand MN-CM scenario. Concurrently, it redirects natural gas resources towards dedicated combined-cycle gas turbines (CCGTs) for electricity generation. Thus, in high-demand scenarios, potable water production becomes a net electricity consumer driving up electricity demand, in contrast to all other business-as-usual supply-side scenarios where desalination is coupled with electric power generation. These findings highlight the value of using a cost-optimisation, bottom-up, techno-economic model such as TIMES to avoid the overly optimistic, linear assumptions often made about the long-term potential of efficiency measures.

6.5 Summary

Given the nature of consumption in Kuwait's residential sector, significant reductions are projected in electricity and water consumption across all efficiency improvement scenarios. However, the influence of these measures varies between electricity and water. Efficiency improvement measures show higher influence on water compared to electricity.

The analysis show that targeted interventions can lead to significant reductions in both electricity and water consumption. However, the effectiveness of these measures is highly context-dependent with their influence varying by the type of intervention (technical vs behavioural), the target housing segment, and the specific commodity being addressed (electricity vs water).

For electricity savings, interventions targeting government housing are disproportionately effective due to the large dwelling sizes and high baseline EUI.

This is mainly due to the use of air conditioning. With regards to water savings, measures in the investment apartments segment deliver the greatest reductions. This high reduction is due to this segment's high occupant density which results in an extremely high baseline WUI that is very responsive to fixture upgrades.

The time it takes for different efficiency improvement measures to come into effect differs substantially depending on the targeted segment and type of measure. This is due to the rate at which new house stock for that particular segment becomes available and the service life of the technology being replaced. Such insights allow for a coordinated multi-direction approach to achieve higher consumption reductions.

The divergence between KEWSM's projected stable per capita consumption pathway and the rising real-world consumption is the "efficiency gap". This gap can be interpreted as a direct cost of a policy and regulatory void. Given the policy and regulatory void, these research findings position the Public Authority for Housing Welfare (PAHW) as a potential champion for energy efficiency. The investment apartment sector is also a key leverage point for a high-potential water conservation strategy. Such a strategy would require a different set of tools that extend to the landlord-tenant regulations and plumbing codes to capture its savings potential.

Residential end-use efficiency improvement measures can slow down and reduce generation plants' capacity expansion. The efficiency improvement measures also highlighted the influence of water demand on the choice of electricity generation options. Furthermore, the importance of diversifying the energy mix with renewable resources is underscored following the utilisation of crude oil as a marginal fuel and exhausting all gas supplies available from the planned domestic natural gas production and the LNG import capacity.

Chapter 7

DECARBONISATION & EMISSIONS REDUCTION PATHWAYS

7.1 Introduction

The previous chapter demonstrated that residential efficiency improvements can substantially curb the growth of electricity and water demand in Kuwait. Demand-side measures presented examples of cost-effective first steps in alleviating pressure on Kuwait's electricity and water system. However, while essential for managing consumption, efficiency gains alone do not address the underlying carbon intensity of the energy system. To achieve a deeper system-wide transformation in line with national ambitions and global climate action, a shift on the supply-side is imperative.

Chapter 6 analysis revealed that demand-side efficiency can act as a key enabler of supply-side transformation. Efficiency measures facilitate the decoupling of electricity growth from water by delivering disproportionately large reductions in water demand. This is an outcome that lessens the system's rigid dependency on thermal cogeneration plants and introduces flexibility. Such flexibility enables an expanded role for electric desalination technologies (such as Reverse Osmosis) and facilitates the integration of intermittent renewable energy resources such as solar and wind.

Furthermore, Chapter 6 also revealed Kuwait's EWS key economic and environmental pressure point, which establishes an incentive for the deployment of renewable energy resources. The analysis demonstrated that due to gas supply constraints, crude oil acts as a marginal fuel for the EWS. This high-cost and carbon-intensive fuel would enhance the competitiveness of renewables.

Therefore, this chapter shifts the analytical focus from managing the demand growth to supply-side carbon reduction by investigating pathways for integrating renewable energy technologies and identifying the potential and barriers to a low-carbon transition. It examines the implications of introducing renewable energy generation options to the supply mix in the future. It addresses the fourth research question: What are possible decarbonisation and emissions reduction pathways while maintaining the integrity of the potable water supply?

7.2 Methods

The previous chapter focused on the influence of the residential end-use efficiency improvement on the business-as-usual fossil-based only supply side. The scenarios for this chapter are solved under central socioeconomic development case presented in Section 4.2.1. Renewable technologies become available for investment starting the year 2025. The renewable technologies and batteries parameters are provided in Appendix B.

7.2.1 Reference RE case

The Reference RE scenario is designed under central development conditions with business-as-usual efficiency improvement case. End-use technologies could still be replaced with new options, including efficient technologies. However, higher efficiency options were disabled. New efficient appliances are considered part of the market's natural transition and, therefore, coexist with older inefficient appliances. Disabling the higher efficiency options represents the reality of the appliances market in Kuwait in the absence of product labelling and policy towards residential efficiency improvement.

7.2.2 RE + Efficiency case

The second scenario for renewable resources is also under central development conditions but incorporates end-use efficiency improvement measures. This scenario will be referred to as the RE+EFF scenario. In this scenario, all end-use efficiency improvement measures are enabled without any behavioural measures or imposed technical measures. Thus, under this scenario, model optimisation determines the deployment of all end-use efficiency improvements from the complete list of available technical options.

7.2.3 Land constraint

Although nearly two-thirds of Kuwait's land remains a vast desert, Table 7-1 shows that only 31% of Kuwait's total land area is available for future development. Therefore, the potential of renewables deployment is limited by land availability. To reflect this limitation within KEWSM, a conservative land availability constraint of

20% of the estimated available land has been imposed across all renewable energy scenarios.

Table 7-1 Estimated Land Use and Availability in Kuwait

	Area [km^2]	Share of total land [%]
Kuwait total land area	17,818	
Oil fields and facilities	6,682	38%
Urban area	773	4%
Agricultural area	1,532	9%
Natural Reserves:	3,283	18%
Total area utilised:	12,270	69%
Total free area	5,548	31%

7.2.4 Electricity storage

KEWSM includes a portfolio of electricity storage options available for the grid to utilise. These options comprise of three electro-chemical battery technologies. The options were selected to represent different levels of technology maturity, cost, and performance characteristics as discussed in the wider literature (IRENA, 2017, EASE, 2018, IRENA, 2020, EASE, 2022). The technologies enabled in KEWSM are:

Lithium-ion (Li-ion): As the dominant technology in the global market, Li-ion is included as the modern, high-performance default. It is characterised by its declining costs, high round-trip efficiency of over 90%, and operational flexibility.

Lead-acid: This represents a mature and low-cost technology. It serves as a benchmark for a reliable option. Though less advanced, it benefits from having a lower upfront capital cost and well-known limitations in cycle life and depth of discharge.

Sodium-sulfur (NaS): This is included as a representative high-temperature battery technology specifically suited for grid-scale applications. Its high energy density and suitability for daily deep cycling make it a distinct alternative to the other two chemistries.

7.2.5 Sensitivity tests

A sensitivity analysis is conducted for the RE+EFF scenario under different energy prices (low and high) based on assumptions in Section 3.5.3. In the context of Kuwait, these external price scenarios have a direct impact on the socioeconomic drivers of demand. Therefore, as established in Chapter 5, and based on projections in Section 4.5, the low and high energy prices sensitivity tests will also employ the corresponding demand pathways for low development and high development. The objective of this analysis was to identify solar technologies that can be cost-competitive with conventional generation technologies.

The second and third sensitivity analyses were conducted for the RE+EFF scenario to assess the impact of the land and batteries availability assumption on the deployment of renewables. For these tests, land constraint is removed and batteries disabled in order to allow KEWSM to select renewable technologies based on their economic competitiveness and technical potential.

7.3 Results

7.3.1 Reference RE (RE Scenario)

Compared to the REF scenario that solely utilised fossil-based electric power generation and seawater desalination technologies, Reference RE scenario projections demonstrate that introducing competition from solar technology options has several impacts on Kuwait's electric power generation and seawater desalination sector. Figure 7-1 shows that there is a decrease in investment in heavy fuel generation capacities as solar generation contributes to peak loads and fulfils high summer demands. By 2048, heavy fuel generation capacities under the Reference RE scenario are expected to be almost half of those under the REF scenario in the same year. This ties back to the finding from Chapter 6 that crude oil is the system's marginal fuel. Therefore, the introduction of renewable technologies results in the gradual displacement of fossil generation.

Under the Reference RE scenario, the total installed capacity is projected to grow from 31 GW in 2026 to 45 GW by 2048, of which 51% is renewables. In addition to the shift away from thermal plants towards renewables, a switch from Steam Power coupled with Multi-Stage Flash Desalination (SPP/MSF) plants towards the more energy-efficient Combined Cycle Gas Turbines coupled with Multi-Stage Flash Desalination (CCGT/MSF) plants is projected. This switching allows the system to maintain steady potable water supply as well as baseload reliability at the lowest cost in a system increasingly dominated by intermittent renewables.

The capacity of SPP/MSF plants is projected to decline by over 60%, from 11 GW in 2026 down to just 4 GW by 2043. The model replaces the retiring capacity and meets new demand by investing in energy-efficient CCGT/MSF plants, which expands from 2 GW to 5 GW in the same period. Parallel to this switching, grid-connected Reverse Osmosis (RO) desalination capacities expand to 2.6 million m^3/day in 2048, representing 47% of that years' total desalination capacity. This shift towards RO is a direct consequence of renewable energy integration into the grid. It stands in stark contrast to the REF scenario, in which the RO share in 2048 remains limited to just 6%. Figure 7-2 projects seawater desalination capacities under the Reference RE scenario.

7.3.1.1 Renewables

Under this scenario, the initial deployment of renewable energy is diversified across several technologies. The model first deploys in 2026 a portfolio comprising 61 MW of residential rooftop PV, 167 MW of wind turbines, 786 MW of parabolic trough with thermal storage, and a substantial 7.7 GW of utility-scale, fixed-axis solar PV.

Following this initial build, the model deploys concentrated solar power (CSP) technologies to address evening demand. The first deployment of CSP technology is linear Fresnel with thermal storage and is projected for 2031 with a modest capacity of 41 MW. This technology capacity then expands rapidly to 2.6 GW by 2034. At this point, the model shifts its investment to linear Fresnel hybrid gas plants, deploying 2.8 GW in 2034 and scaling this up to 4.0 GW by 2035, after which the total linear Fresnel capacity remains static for the remainder of the horizon as the model determines there is no economic benefit from further expanding this technology.

In contrast to other CSP technologies, solar power tower technology sees only a negligible deployment throughout the entire period (1 kW to 3 kW between 2031 and 2034). Thus, indicating that solar power tower technology is not a cost-optimal choice within this scenario given its performance parameters. Similar behaviour is projected for wind turbines. After their initial deployment in 2026, the model scales up its deployment to 653 MW by 2028. This capacity also remains constant for the remainder of the modelled time horizon, indicating that the model exhausted the cost-effective capacity for wind turbines.

By 2048, the total generation capacity is projected at 45 GW, consisting of 23 GW solar capacity (representing 51%). The utility-scale PV technology is projected to become the dominant technology in the generation mix, accounting for 26% of the entire 2048 generation mix. This utility-scale PV capacity itself is diversified, comprising 8.7 GW of fixed-axis PV, 2.4 GW of dual-axis PV, and 1 GW of single-axis PV. This diversification in utility-scale PV portfolio indicates that the model is making sophisticated trade-offs between lower capital cost and higher capacity factor to maximise output from a land constrained system.

The aggressive deployment of utility-scale PV technology is justified by multiple factors influencing the model decision, such as the nature of the electricity demand that peaks during summer months to meet air conditioning requirements. The deployment of CSP options is justified by the advantage this technology has over other solar technologies. Compared to other solar technologies, CSP is relatively mature and has already been widely implemented worldwide. Its efficiency/thermal performance, initial investment cost, and operating & maintenance (O&M) costs reflect this maturity. This results in the technology being competitive, allowing it to gain a head start from the beginning of the deployment of the renewable energy scenario, leading to a higher share in the generation mix.

The rationale behind these deployments becomes clear upon closer examination of the electricity supply. Projections (Figure 7-3) show that as the model shifts away from fossil-based generation, it utilises renewable technologies to meet different load profiles. PV technologies are deployed to serve morning and daytime loads, while CSP technologies with thermal storage are initially deployed to meet evening loads. Electricity generation from these technologies commence with significant contribution to the supply, competing with gas turbines. By 2027, gas turbines production is projected at 17 TWh, which is 17% of supplied electricity. While CSP produces 10

TWh (11% of supplied electricity) and utility-scale PVs produce 24 TWh (26% of supplied electricity).

In the subsequent years, the model expands CSP capacities with thermal storage and deploys hybrid gas CSP (Figure 7-3). This expansion is projected in parallel to expansions in utility scale PV, as the model reallocates the constrained natural gas supplies. It shifts gas away from standalone gas-fired electric power generation (CCGT and OCGT) and prioritises its use in cogeneration CCGT/MSF, while simultaneously retiring the oil-fired SPP/MSF. By 2048, the share of electricity generated from standalone gas turbines drops to 18% of the total supply, compared to the 30% in the REF scenario. The projected contribution of each technology to the final supply mix under the Reference RE scenario is shown in Figure 7-4.

In conclusion, the Reference RE scenario shows a significant reconfiguration of Kuwait's electricity-water nexus. Even as renewables decarbonise a large portion of the power supply, KEWSM's decision to reallocate gas towards cogeneration units highlights the ongoing constraint. The growing demand for desalinated water continues to tie a significant portion of the energy system to thermal production. This suggests that while supply-side changes are significant, the system's overall decarbonisation potential remains limited by the scale of the water demand it must meet. This raises the question of whether reducing the underlying demand for water through end-use efficiency could unlock the flexibility needed to more fully decarbonise the electricity–water system. The following section addresses this by analysing the integrated renewables plus end-use efficiency measures (RE+EFF) scenario to determine if managing end-uses can unlock a more optimal decarbonisation pathway.

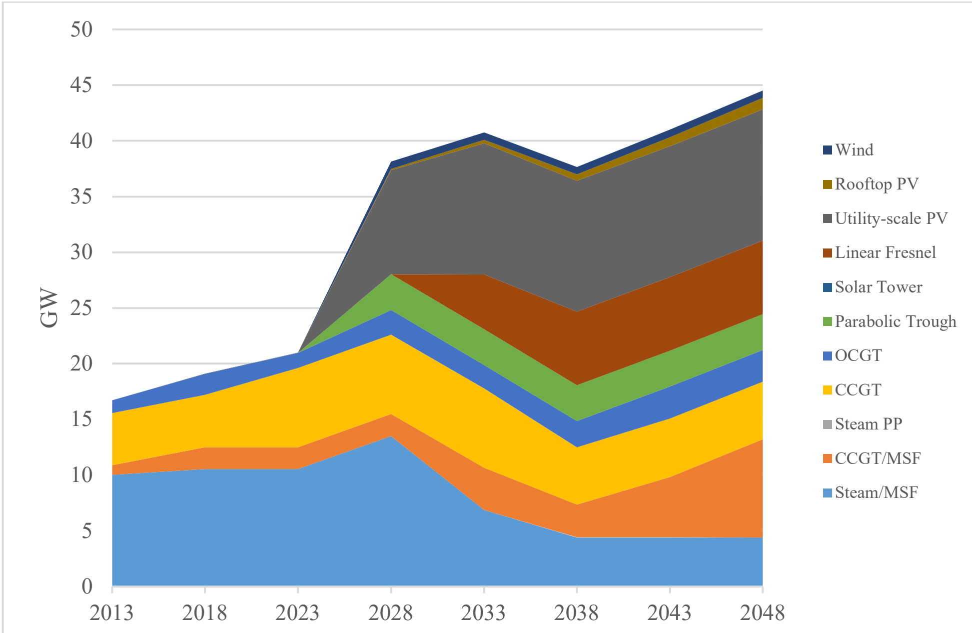

Figure 7-1 Projection of electric power generation installed capacity – Reference RE scenario

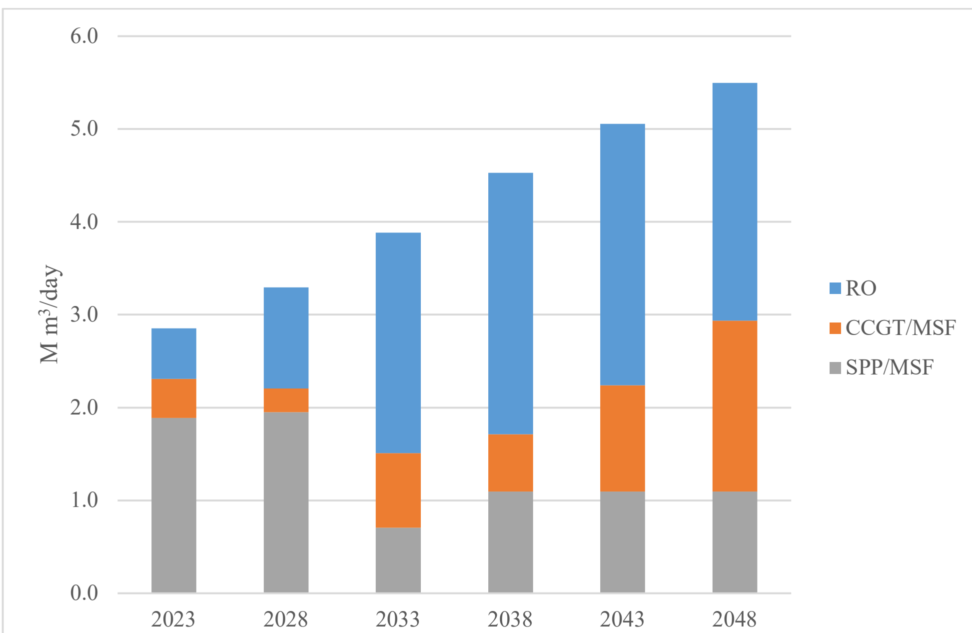

Figure 7-2 Projection of seawater desalination installed capacity – Reference RE scenario

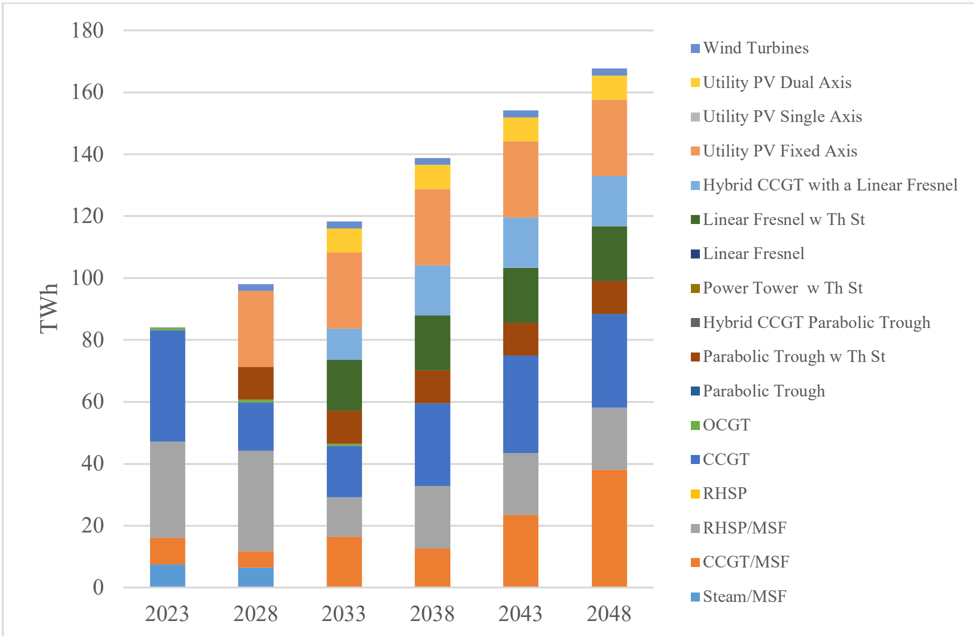

Figure 7-3 Electricity supply by source of generation - Reference RE scenario

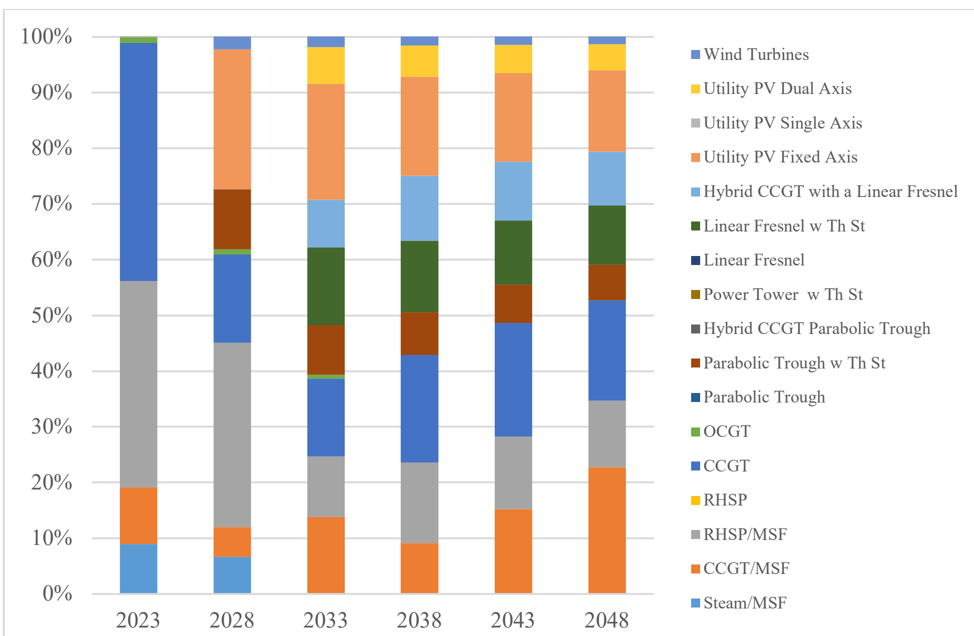

Figure 7-4 Generation technology contribution to the electricity supply - Reference RE scenario

7.3.2 Renewables + Efficiency (RE+EFF Scenario)

Incorporating end-use efficiency improvement measures in the KEWSM model scenario RE+EFF plays a significant role in redefining the optimal mix of renewable energy technologies and reducing the role of conventional electric power generation technologies. Figure 7-5 shows that KEWSM projects a further a decrease in fossil-based generation technologies and an increase in solar capacities. Enabling end-use efficiency improvement options leads to a deceleration in investments made in fossil-based capacities compared to the Reference RE scenario. By 2048, fossil-based capacities drop to 16 GW, 24% lower than Reference RE scenario.

The model's projected investments in renewable capacities occur at a faster pace and a larger scale under the RE+EFF scenario compared to the Reference RE. This acceleration is particularly evident in the first decade of the modelled time horizon. KEWSM deploys 30% more renewables in the RE+EFF scenario compared to the Reference RE scenario, bringing the 2035 renewable capacities to 29 GW. This reveals a powerful synergy by reducing overall demand, demand-side efficiency measures create the economic and operational flexibility for the model to invest more heavily in capital-intensive but zero-fuel-cost renewables. Thus, demand-side efficiency improvements act as an enabler for renewable energy penetration and supply-side transition.

By 2048, KEWSM projects that the total installed capacity will reach 49 GW, of which 67% is renewables. Within this mix, utility-scale PV expands its share to 48% of the total installed capacity. The role of land constraint becomes visible under this scenario as the model switches the deployment towards dual-axis utility PVs. The capacity of this technology increases by 400% compared to the Reference RE scenario. Thus, as land becomes the binding constraint, the model prioritises technologies that can maximise the energy output per square metre, even at a higher capital cost.

This shift toward PVs is accompanied by a reduction in investment for other technologies. The model cuts the share of linear Fresnel with thermal storage in half compared to the Reference RE scenario, while retaining only the hybrid-gas option for its dispatchable capabilities. The explanation for this trade-off is that with a lower overall demand curve due to efficiency, the system's need for expensive, longduration storage from standalone CSP is reduced. Furthermore, the massive deployment of solar generation displaces a significant amount of fossil-based generation capacities. The standalone gas-fired generation is reduced by 18%, while the more efficient CCGT/MSF capacity doubles to provide baseload and desalination services.

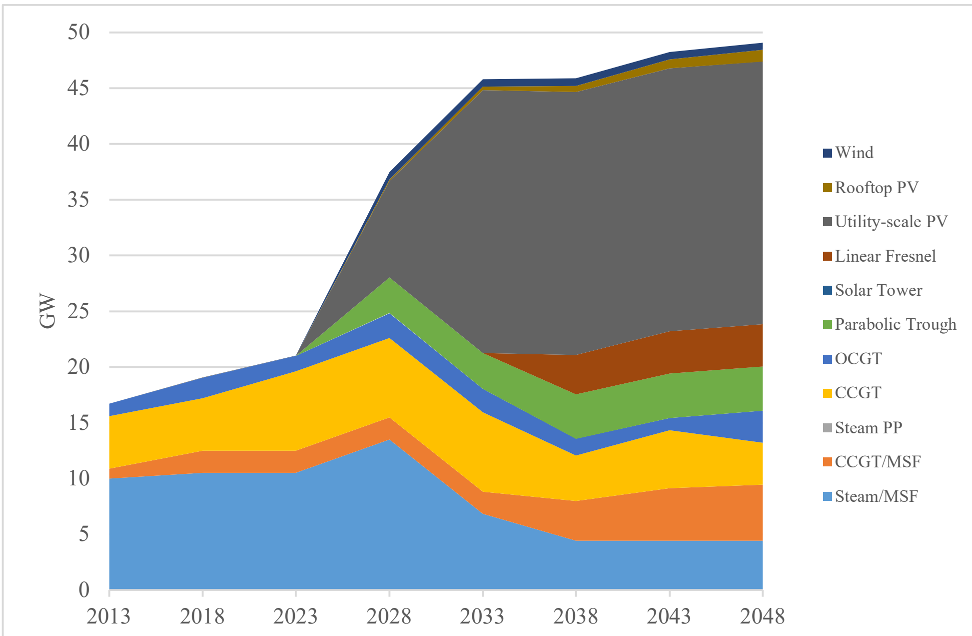

Figure 7-5 Electric power generation capacity- RE+EFF scenario

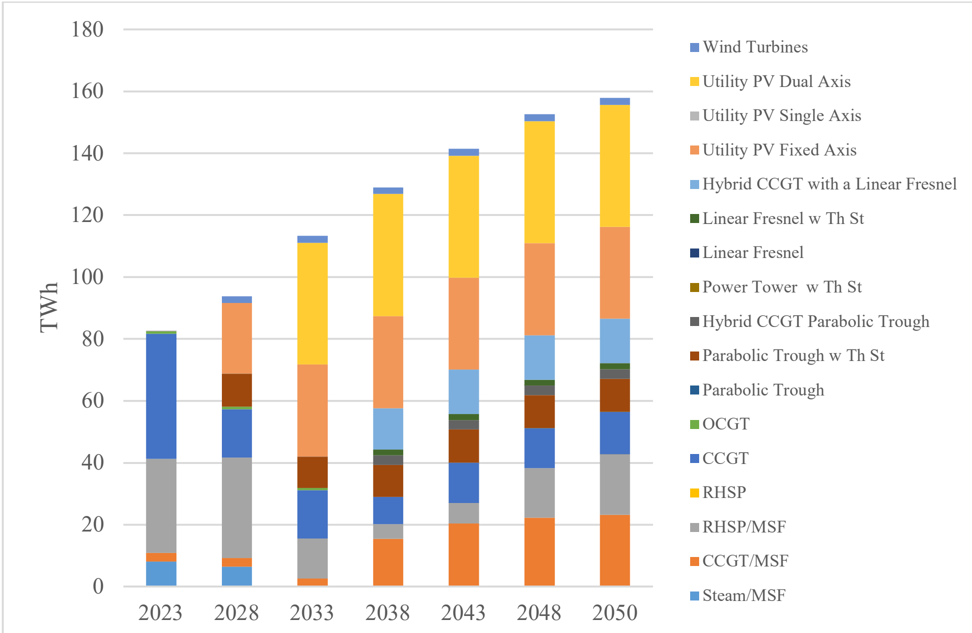

Figure 7-6 Electricity supply by source of generation – RE+EFF scenario

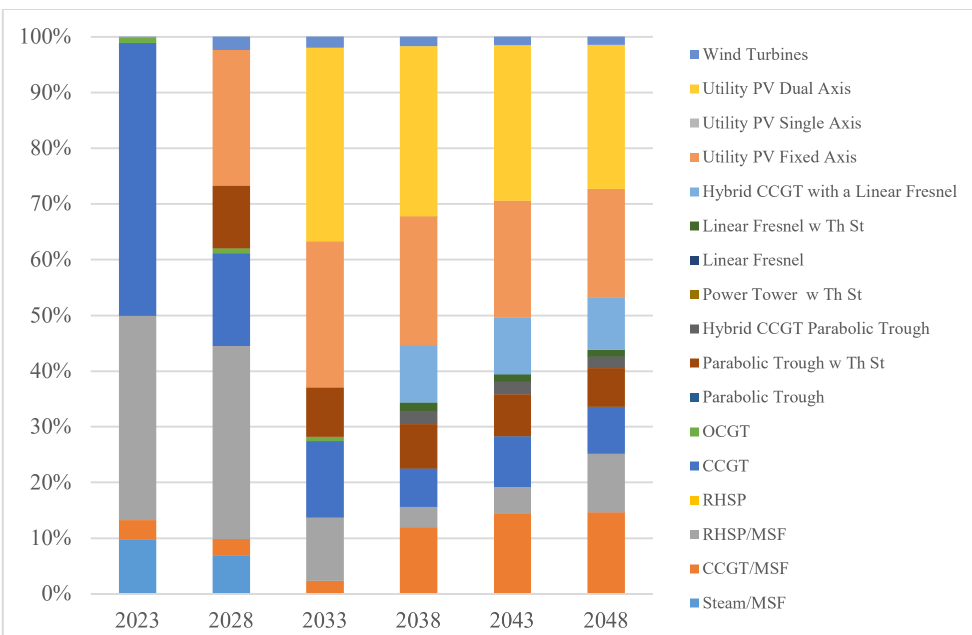

Figure 7-7 Generation technology contribution to the electricity supply – RE+EFF scenario

7.3.3 Seawater desalination

One key advantage of implementing end-use efficiency improvement measures in KEWSM is that the model can choose between enhancing water use efficiency and expanding desalination technologies to meet increasing potable water demand. The model also makes this choice through system optimisation and balancing the energy requirements for desalination with the capital costs of new capacities in order to find the least-cost pathway for meeting potable water demand. Therefore, decisions regarding water supply are fundamentally tied to the decarbonisation potential of the entire power sector. KEWSM projections show how an integrated strategy of renewables and end-use efficiency improvements can accelerate the transition away from carbon-intensive seawater desalination towards more efficient technologies (Figure 7-8).

The REF scenario, representing a business-as-usual path with high demand and no renewables, illustrates the consequences of inaction. To meet rising water demand, the model invests heavily in thermal desalination. Model projections show the oil-fired SPP/MSF capacity to increase from 1.9 million m^3/day in 2023 to 3.7 million m^3/day by 2048. Similarly, gas-fired CCGT/MSF capacity is projected to increase from 0.4 million m^3/day to 1.5 million m^3/day for the same period. While CCGT/MSF capacity remains relatively stable for the final decade of the modelled horizon, the SPP/MSF desalination capacity continue to increase. This comes as a result of complete utilisation of all available natural gas and imported LNG supplies. Hence, the model continues to invest and utilise SPP/MSF technologies. This trajectory represents a deepening technical “lock-in” to carbon-intensive technologies for meeting Kuwait’s potable water needs, with almost no expansion in RO technologies.

The introduction of renewables in the Reference RE scenario begins to break this lock-in. By providing a new source of electricity, seawater desalination decouples water production from electricity generation. Renewables create flexibility in the system which heavily invests in grid-connected RO capacities. Consequently, RO desalination capacities are projected to be deployed early on with a capacity of 0.6 million m^3/day in 2027, peaking at 2.8 million m^3/day in 2035, representing 68% of that year’s desalination capacity. The model then shifts its desalination investments towards expanding the CCGT/MSF.

The model's decision to reprioritise cogeneration and cap the expansion of RO reflects its system-wide optimisation. This optimisation seeks to achieve the least-cost pathway to simultaneously meet three distinct and competing demands of electricity baseload, peak electricity, and total potable water production requirements. This shows that while RO and renewables are highly competitive, a renewed investment in modern cogeneration emerges as the most economically optimal strategy to balance the grid and provide firm capacity in the long term, limiting the ultimate market share of RO in a cost-optimised system.

By 2048, RO desalination capacity drops slightly to 2.6 million m^3/day, accounting for a 47% share of the total desalination capacity. The remainder of the desalination mix is composed of thermal technologies, with CCGT/MSF providing 1.8 million m^3/day and the SPP/MSF plants providing 1.1 million m^3/day.

Finally, the RE+EFF scenario projections show the role of end-use efficiency improvements in securing a sustainable and economically sound potable water supply. Initial demand reductions from end-use efficiency measures are substantial enough to delay the need for any significant RO capacity until 2033. This deferral of major capital investment is a significant benefit of demand-side efficiency improvements, providing over a decade of planning flexibility.

For the first decade of the RE+EFF projection, the system is able to meet demand primarily by utilising its existing thermal desalination with minimal expansion in its capacities. The SPP/MSF desalination capacity averages around 1.8 million m^3/day, while the CCGT/MSF peaks in 2026 at 0.3 million m^3/day before declining again. Commencing in 2033, RO capacity replaces retired SPP/MSF and accounts for 66% of the total desalination capacity. This share remains relatively steady for the remainder of the model time horizon, with gradual increases in CCGT/MSF capacity serving to replace the retiring SPP/MSF plants. By 2048, the total seawater desalination capacity reaches 3.5 million m^3/day, with RO representing 46%, CCGT/MSF 29%, and SPP/MSF 25%. This 2048 capacity under the RE+EFF is comparable to the REF 2033 capacity but more diversified in its mix.

These results show that end-use efficiency improvements can transform the optimal pathway for securing Kuwait's potable water supply. By successfully curbing underlying water demand, the RE+EFF scenario avoids the fossil-fuel-only Reference (REF) scenario's heavy reliance on expanding thermal cogeneration. Instead, it creates the flexibility to meet future water needs through a more balanced portfolio of desalination technologies. KEWSM is not only able to meet demand but does so with a diversified mix balanced between thermal and membrane desalination technologies. This confirms that managing water at the point of use level is an enabler of a more sustainable and decarbonised water system. And that incorporating water end-use and efficiency measures into the TIMES model can alter the model's optimisation decisions, thus introducing a wider horizon that allows for a more cost-effective and ambitious decarbonisation of the energy-water nexus.

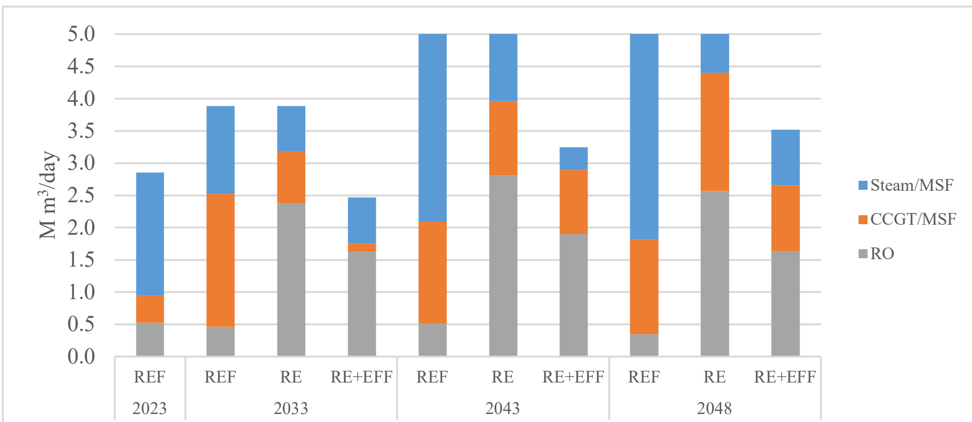

Figure 7-8 Projection of seawater desalination capacities

7.3.4 Interaction between desalination and batteries

With a high penetration of renewables, the model must determine how to best utilise the abundance of cheap intermittent daytime electricity. KEWSM output in Figure 7-9 shows a strategy where RO desalination and battery storage are treated as complementary tools with distinct operational roles rather than competitors. RO serves as the primary dispatchable load to absorb solar generation during the day, while batteries serve as the time-shifting mechanism to move surplus energy to the night.

7.3.4.1 Desalination

During daytime periods of high solar production, such as the second half of a summer day (SuD2), electricity generation peaks at 31 TWh. This period's surplus energy actively charges batteries with 7 TWh and supplies RO desalination with its electricity needs of 900 GWh. This pattern demonstrates that the model treats the RO plant as a large, flexible electricity consumer. Therefore, by producing desalinated water when power is cheapest and storing this water in tanks for later use, the RO desalination plant functions as a Virtual Energy Storage (VES) system. In this configuration, surplus solar generation acts as the charging mechanism, where the stored volume of potable water acts as the vessel, and the ability to meet later water demand without running the plant serves as the discharge.

The contrast between day time periods and night time periods confirms these distinct roles. At night, when solar generation ceases (N1 periods), RO electricity consumption drops to a minimal level. This is when the batteries are dispatched to meet the nighttime load. The pattern is most evident in the Summer Night period (SuN1), where battery discharge peaks at 5.1 TWh.

In summary, the model's cost-optimisation logic establishes a clear order for RO and batteries utilisation based on cost-effectiveness as evident from the above analysis and technology deployment projections (Figure 7-10). The model prioritises using low-cost solar electricity to directly power flexible loads like RO plants, then only the surplus generation that remains after direct uses are met is used to charge electrochemical batteries, which are reserved as time-shifters for energy to periods when solar is unavailable.

7.3.4.2 Batteries

The model's strategy for utilising RO as daytime load and batteries for nighttime demand is clear. However, a deeper analysis of model output shows the presence of seasonally driven dynamics and constraints, resulting from the model's balancing of supply and demand throughout the year.

Battery charging is the last resort for surplus energy, occurring only after other direct uses are saturated. This is most evident in the summer period. During the first half of the summer day (SuD1), when solar production is substantial but not at its peak, the model meets all RO demand but charges no batteries. Only during the absolute peak of solar production later in the day (SuD2) when generation reaches 31 TWh and RO consumption is already maximised, does the model finally commence charging batteries with 7 TWh. This shows that electrochemical storage is treated as the most expensive sink for surplus solar, utilised only when cheaper VES options like water production are fully exhausted.

The winter period (Wi) balances generation and network demand with tight margins (Figure 7-11), leaving no electricity surplus for battery storage. During the winter daytime periods (WiD1 and WiD2), electricity production is 6 TWh and 36 TWh, respectively, which closely matches network demand of 6.1 TWh and 34.7 TWh. The tight margins result from the cost-optimisation strategy that minimises electricity capacity investment. There is no spare generation to charge the batteries.

This lack of daytime surplus in winter quantifies a seasonal imbalance. The system, which is built with enough renewable capacity to generate a large surplus during summer peaks (7 TWh surplus in SuD2), operates with minimal reserve margin during winter. This highlights a key challenge for a solar-dominant system in a region with high seasonal demand variance. While the installed capacities are sufficient, the lower winter solar irradiance means they can only cover the basic load. This means the system must rely on non-solar resources to meet nighttime demand in the winter, but less so in the summer.

Finally, a comparison between the intermediate seasons (I1 and I2) shows the model actively managing this seasonal trade-off. In the cooler first season (I1), the model follows a classic time-shifting pattern with moderate battery cycling. However, in the warmer second season (I2), which has higher demand, daytime battery charging (2.6 TWh in I2D2) is far greater in preparation for a much larger required nighttime discharge (1.7 TWh in I2N1). This demonstrates the model's optimisation framework, adjusting the batteries' charging and discharging cycles in response to system conditions across all time slices.

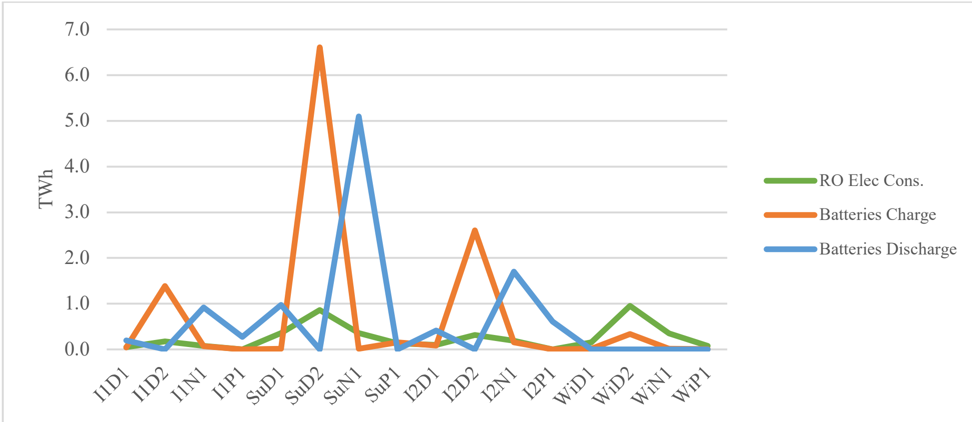

Figure 7-9 Batteries charge, discharge, and RO electricity consumption - RE+EFF Scenario year 2048

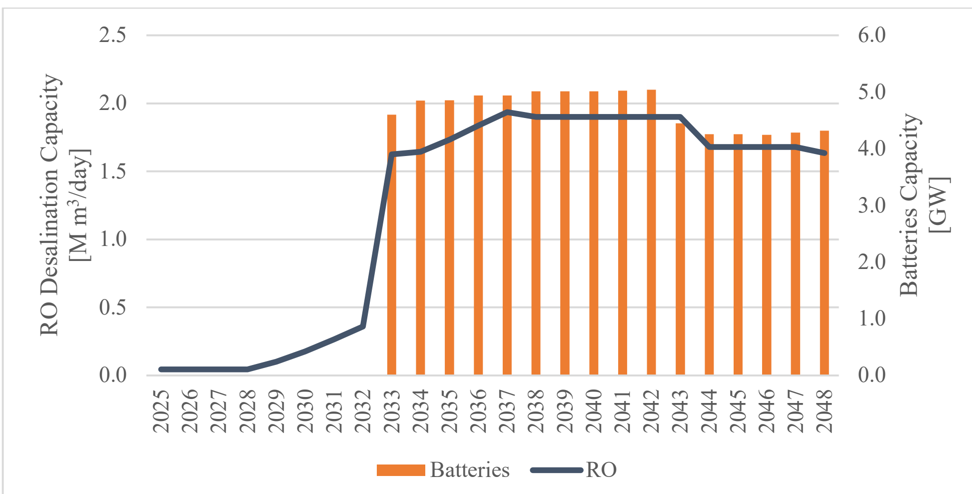

Figure 7-10 RO desalination and batteries capacities deployment

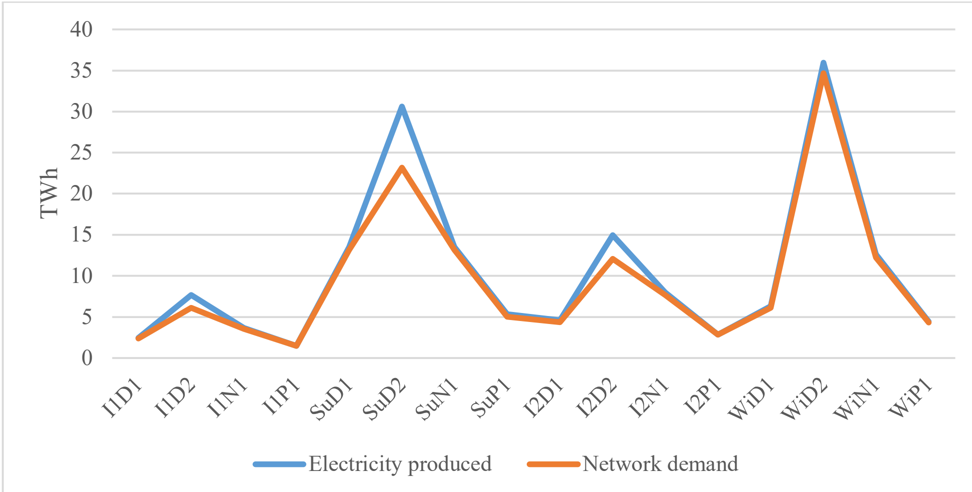

Figure 7-11 Electricity produced and network demand - RE+EFF Scenario year 2048

7.3.5 Levelised cost of electricity

The term "levelised cost of electricity" (LCOE) refers to the minimum price at which a power-generating system must sell electricity to cover its costs and achieve financial breakeven during its operational lifespan (Papapetrou et al., 2022). The LCOE is calculated by KEWSM using the TIMES model generator methodology. This methodology takes into consideration all costs that affect the selection of a technology, including capital, operational, fuel, and other expenses as well as the efficiency of the technology (Loulou et al., 2016, Ghose et al., 2018). This methodology is represented in equation (11) and a worked example is provided in Appendix F.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{IC_t}{(1+r)^{t-1}} + \frac{\sum_i FC_{i,t} + OC_t + FD_{i,t}}{(1+r)^{t-0.5}}}{\sum_{t=1}^{n} \frac{\sum_m MO_{m,t}}{(1+r)^{t-0.5}}} \tag{11}$$

Where:

- r = discount rate
- IC_t = investment expenditure in the beginning of year t
- OC_t = fixed operating expenditure in year t
- FC_{it} = fuel-specific operating expenditure for fuel i in year t
- FD_{it} = fuel-specific acquisition expenditure for fuel i in year t
- MO_{mt} = output of main product m in year t

- *t-0.5:* mid-year discounting for continuous streams of annual expenditures

Projections of LCOE for all generation technologies help explain the logic driving the model's investment decisions. For the RE+EFF scenario, Figure 7-12 projects cost reductions across all renewable technologies. These reductions align with well-established trends, thus validating the KEWSM's representation of the competitive landscape. Figure 7-13 and Figure 7-14 project LCOE for cogeneration and for thermal technologies for the RE+EFF scenario, respectively.

7.3.5.1 Utility-Scale Solar PV

The most profound trend is the large sustained cost decline of utility-scale PV. KEWSM projects that the LCOE for the most cost-effective option, fixed-axis PV, will fall by over 60% from an already competitive 24 US$/MWh in 2025 to 9 US$/MWh by 2040. While these projections appear aggressive when compared to current global LCOE benchmarks for solar PV (Lazard (2025) reported LCOE at 38 US$/MWh to 78 US$/MWh). KEWSM projections are validated by the realised pricing of recent, large-scale projects within the GCC region itself.

For instance, the Sakaka solar PV plant in Saudi Arabia has an electricity price of just $23.40/MWh (Bellini, 2024), a figure that is almost identical to the KEWSM's 2025 LCOE projection. Even with recent market volatility, which saw the weighted average LCOE in Saudi Arabia increase by 18% to 44 US$/MWh in 2023, this figure is projected to decline further (IRENA, 2024). Therefore, the KEWSM's projections of a continued decline towards 10 US$/MWh by 2040 represent the anticipated trajectory for a maturing regional market. KEWSM LCOE projections also show a rational cost hierarchy within the utility-scale PV portfolio, where tracking systems (both single and dual-axis) carry a justifiable cost premium over fixed-axis due to their higher energy yield.

7.3.5.2 Concentrated Solar Power

Examining the concentrated solar power (CSP) technologies (linear Fresnel and parabolic trough) LCOE projections must be contextualised by the technology's learning curve. IRENA (2024) reports the global weighted average LCOE for CSP has already fallen by 70%, from 393 US$/MWh in 2010 to 117 US$/MWh in 2023. KEWSM's projections show the LCOE for the linear Fresnel to decline from 148

US$/MWh in 2025 to 74 US$/MWh in 2040, while the parabolic trough falls from 162 US$/MWh to 68 US$/MWh. KEWSM's starting points already align with reported figures from the US market between 112 US$/MWh and 142 US$/MWh range (IEA, 2020). Projections (Figure 7-12) show a competitive sorting among the various technologies. Hybrid Gas CSP plants and standalone CSP without storage exhibit persistently high LCOE, making them uncompetitive against a more optimised portfolio that combines cheap PV with dedicated storage. Therefore, the projected LCOE for CSP technologies with thermal storage have different and lower starting points around 84 US$/MWh. This reduction in LCOE aligns with existing literature, which suggests that incorporating thermal storage with CSP can reduce the cost of supplying electricity by 16% (Miron et al., 2023). Hence, KEWSM invests in these technologies during the initial renewables deployment (accepting a cost premium) because of their ability to ensure supply stability in the evening. This provides a system value that is more cost-effective than relying on other dispatchable options such as fossil-fuel peaking plants.

7.3.5.3 Onshore Wind Turbines

For wind turbines, KEWSM projects a relatively flat LCOE. The LCOE for wind declines only modestly from 47 US$/MWh in 2025 to 42 US$/MWh by 2040. This comes as a result of the model's limited deployment of wind capacities that does not expand even as electricity demand grows. Nevertheless, initial projections align with Al-Nassar et al. (2021) real-world study on Kuwait's pilot project, Shagaya wind farm. The study reports the LCOE at 46 US$/MWh, which is almost identical to KEWSM's 2025 starting value. Furthermore, KEWSM's long-term projection aligns within the established global LCOE range for new onshore wind projects, which is reported to be between 37 US$/MWh and 86 US$/MWh (Lazard, 2025).

Finally, the fixed deployment of wind turbines indicates that Kuwait's wind resources are a cost-effective component of the initial decarbonisation portfolio. At scale, however, wind becomes a resource-limited technology. This explains why the model relies on the initial tranche of wind for its generation diversity but then switches to the more scalable resource (utility-scale solar PV) to meet long-term growth in a land-constrained but solar-rich environment.

7.3.5.4 Conventional Generation

KEWSM projections (Figure 7-13) show that the most cost-effective conventional technology in Kuwait's EWS is the Combined Cycle Gas Turbine with MSF Desalination (CCGT/MSF). The projections values (119 US$/MWh in 2025 and 129 US$/MWh in 2045) are notably higher than those reported by Lazard (2025) for standalone CCGTs in the US market (between 48 US$/MWh and 109 US$/MWh). However, KEWSM's projections align almost perfectly with findings specific to Kuwait. Ramadhan et al. (2013) reported that the LCOE for CCGT is between $110/MWh and $130/MWh. The cost premium over some global averages is explained by the added complexity and capital cost of integrating the plant with large-scale thermal desalination.

Standalone CCGT and Open Cycle Gas Turbine (OCGT), which are used to meet peak demand, are projected to have LCOE consistent with global benchmarks for gas peak generation plants (Figure 7-14), which range between 149 US$/MWh and 251 US$/MWh (Lazard, 2025). Similarly, the legacy Reheat Steam Power Plants (RHSP) have a projected LCOE of over $250/MWh, which is broadly consistent with real-world assessments for Kuwait's older thermal plants (Al-Nassar et al., 2021).

The main insight from this analysis is that the high cost of conventional technologies creates an opportunity for system transition. The LCOE of even the most efficient conventional option (CCGT/MSF) sets an achievable benchmark for cost-competitive baseload renewables. And finally, the extremely high and rising cost of the system's dedicated peaking power technology (OCGT) creates an economic incentive to deploy dispatchable renewables or storage that can avoid the need to run these expensive plants.

7.3.5.5 The influence of the residential efficiency measures on the LCOE

The influence of residential efficiency measures on the LCOE is examined in Table 7-2. Comparing the LCOE of the RE+EFF scenario with the RE-only scenario shows some level of variation between the two scenarios. Since the LCOE values are endogenously calculated by the TIMES model, these values reflect a technology's system-wide value and optimal utilisation rate, which changes depending on the scenario. Efficiency measures alter the size and shape of electricity demand, which in turn reshape the least-cost investment and dispatch solution. Therefore, the observed LCOE changes are a direct result of these system effects. For example, wind technology has a higher LCOE in the RE+EFF scenario compared to the RE-only scenario in the year 2035. This increase is because of lower overall demand that reduces its optimal utilisation rate, and therefore, spreads its fixed costs over fewer kilowatt-hours. At the same time, a technology like a hybrid gas plant experiences a decrease in LCOE because the new demand profile makes it more competitive and increases its role in the system.

Table 7-2 Influence of residential efficiency measures on the LCOE

	2025		***2035***		***2040***		***2045***	
	RE	**RE+EFF**	**RE**	**RE+EFF**	**RE**	**RE+EFF**	**RE**	**RE+EFF**
CCGT/MSF	116	119	126	121	128	126	129	129
RHSP/MSF	167	171	163	165	163	165	163	164
CCGT	162	168	161	162	162	166	160	164
OCGT	300	295	331	323	341	337	344	345
RHSP	247	250	253	254	258	258	253	253
Power Tower w Th St	100	108	45	46		31		
Linear Fresnel Hybrid Gas	205	196	209	199	204	201		203
Linear Fresnel	138	148	86	90	73	74	71	71
Linear Fresnel w Th St	79	84	47	47	38	38		
Parabolic Trough Hybrid Gas	182	173	173	162		162		
Parabolic Trough	150	162	84	89		68		
Parabolic Trough w Th St	76	83		42				
Utility PV Dual Axis	34	34	17	17		12		
Utility PV Fixed Axis	24	24	12	12		9		
Utility PV Single Axis	31	32	15	16		11		
Wind Turbine		47	39	44		42		

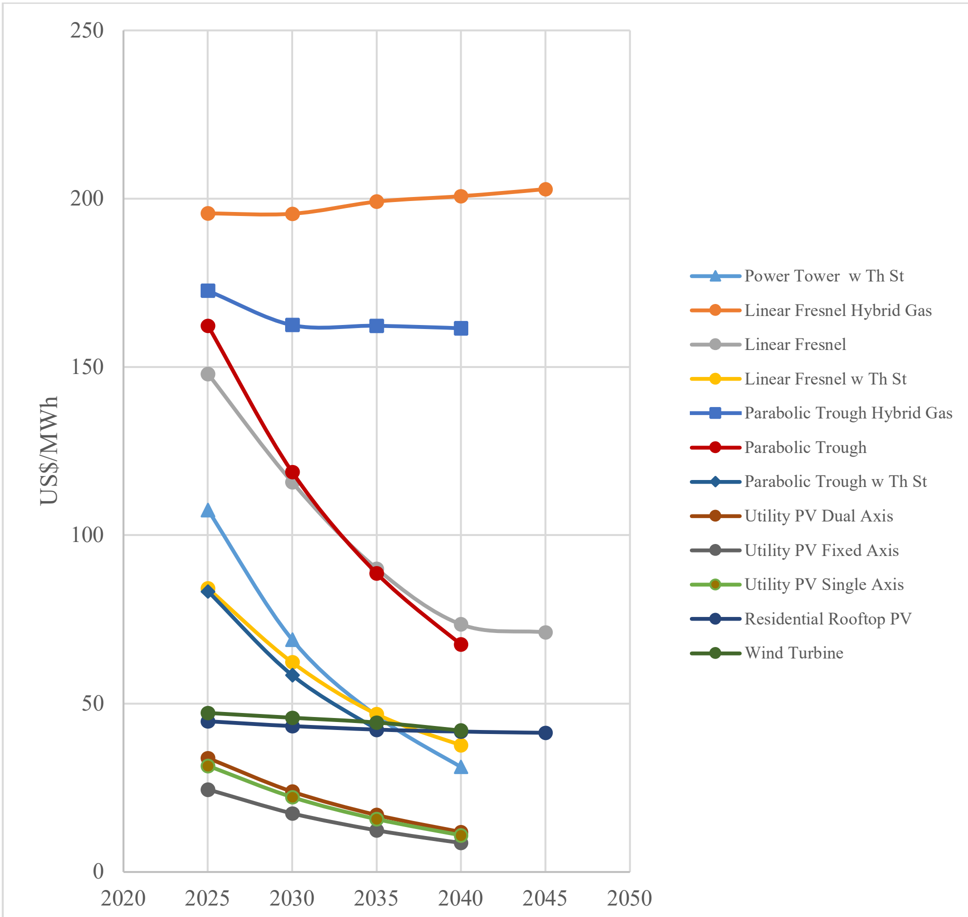

Figure 7-12 LCOE projections for renewable technologies - RE+EFF scenario

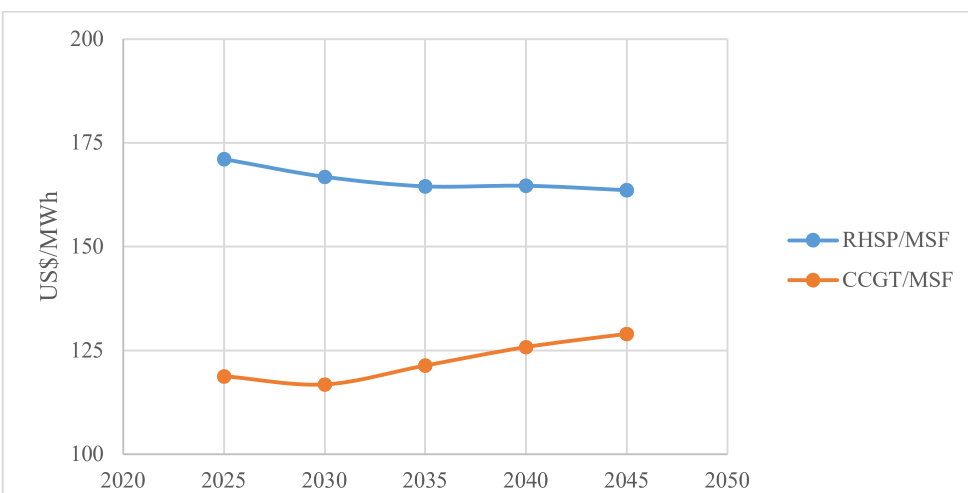

Figure 7-13 LCOE projections for cogeneration technologies - RE+EFF scenario

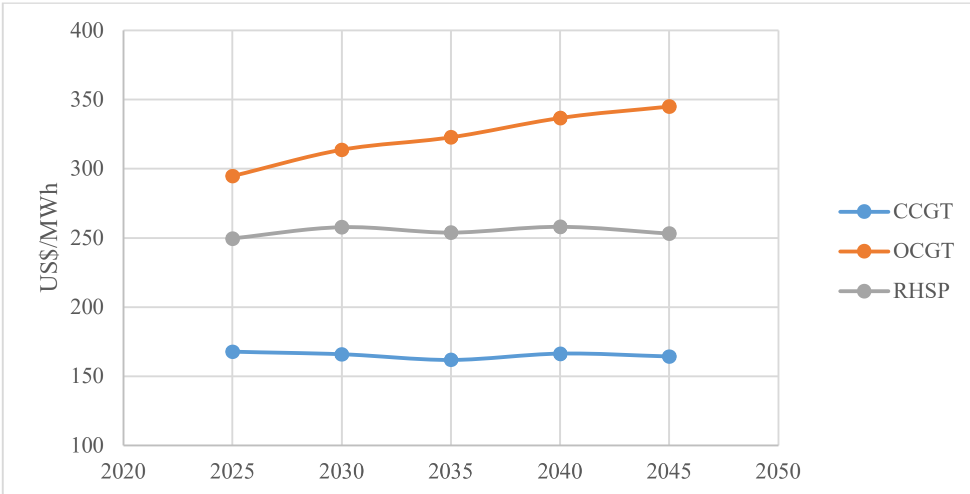

Figure 7-14 LCOE projections for thermal technologies - RE+EFF scenario

7.3.6 Fossil fuel consumption

Renewable deployment and end-use efficiency improvements in the RE+EFF scenario lead to a large transformation of the primary energy mix required for power and water production. Figure 7-15 projects a transition away from hydrocarbons, followed by a period of maximum decarbonisation, and a later stage where fossil fuels return to the mix in order to meet growing demand and maintain a stable potable water supply.

The initial period between 2023 and 2038 shows the benefits of growth in renewable energy capacity. This growth results in renewable energy resources producing energy that amounts to 10 Mtoe by 2038, displacing fossil fuels. The consumption of crude oil, the system's marginal fuel, is driven down from 11 Mtoe in 2023 to zero by 2038. Similarly, domestically-produced natural gas is completely phased out of the power generation mix by 2028. This establishes imported LNG (fixed at 6.7 Mtoe) as the sole thermal energy source during this peak decarbonisation phase.

KEWSM's decision to phase out the use of domestic natural gas entirely while retaining the full volume of imported LNG is a direct outcome of the fuel price assumptions detailed in Chapter 3. Based on the oil-indexed pricing methodology used in this study, the projected cost of Kuwait's domestic natural gas (reaching 16.75 US$/MBtu in 2028) is higher than the price of imported LNG (at 11.47 US$/MBtu in the same year). The price disparity reflects the high production and processing costs associated with Kuwait's domestic gas, which is predominantly sour associated gas co-produced with oil. This makes Kuwait's natural gas more expensive than LNG from international suppliers with lower production costs. Based on this, the cost-optimisation framework of KEWSM makes the rational decision of displacing the high-cost domestic natural gas in favour of renewables, retaining the cheaper imported LNG to provide the dispatchable capacity for the system.

However, the period after 2038 period shows the long-term challenge of meeting the continued electricity and water demand growth. The most cost-effective pathway for Kuwait's EWS is to reintroduce fossil fuels, bringing back indigenous hydrocarbons to the fuel mix with crude oil and natural gas reaching 5.5 Mtoe and 0.5 Mtoe respectively by 2048. Nevertheless, a direct comparison with the fossil-fuel-only Reference (REF) scenario shows the large potential of introducing renewables and efficiency improvement measures to support Kuwait's Net Zero by 2060 Strategy. Figure 7-16 shows the scale of fossil fuels saved by integrating these measures into Kuwait's EWS.

The RE+EFF scenario reduces the consumption of domestic crude oil by 76% and natural gas by over 94% compared to the fossil-fuel-only REF case. Consequently, the fuel mix in 2048 under the RE+EFF scenario is significantly changed by having the consumption of domestically produced hydrocarbons down to only 26% of the total primary energy consumed by plants (23.1 Mtoe). This reduction is a complete inversion of the REF scenario in which domestic hydrocarbons account for 80% of the total primary energy consumed by plants (39.7 Mtoe). The consequence of this shift is projected in Figure 7-17, where the portion of national oil production consumed by the EWS is drastically lower in the RE+EFF scenario. Therefore, this illustrates that a combined strategy of efficiency and renewables is effective at displacing Kuwait's most carbon-intensive and valuable exportable commodities, all while maintaining the balanced and diversified potable water production mix detailed in Section 7.3.3.

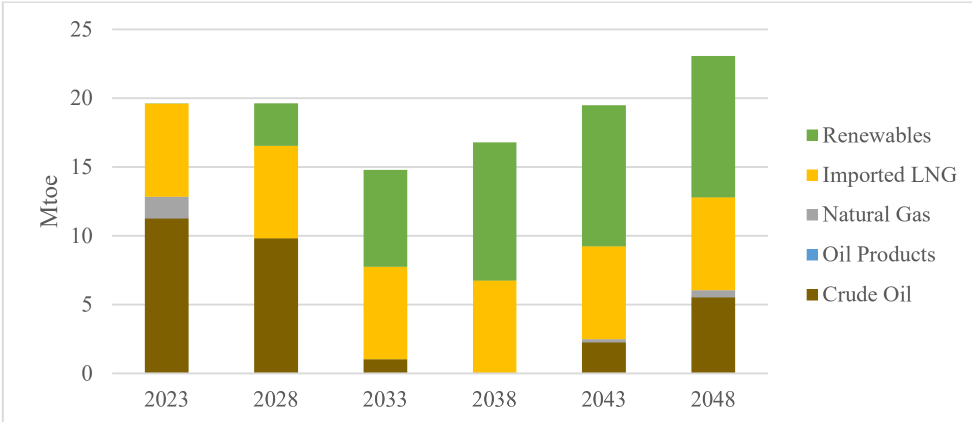

Figure 7-15 Primary energy consumption in plants – RE+EFF scenario

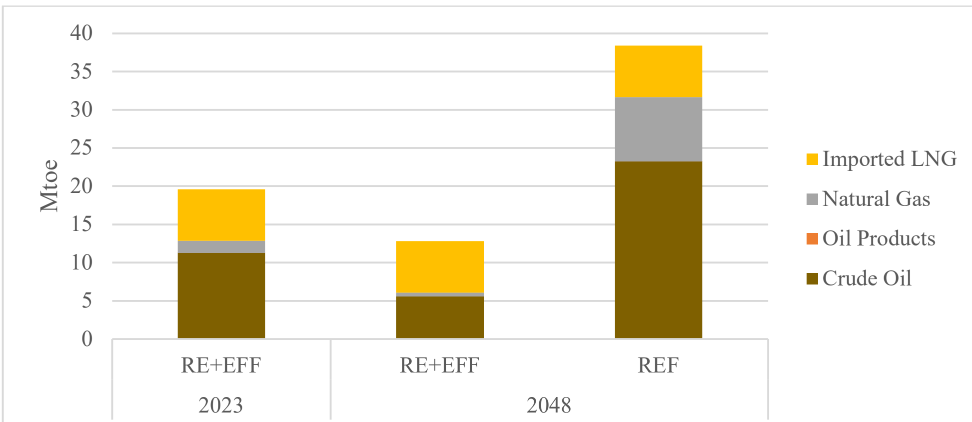

Figure 7-16 Fuel consumption in plants in 2048 for RE+EFF and REF scenario

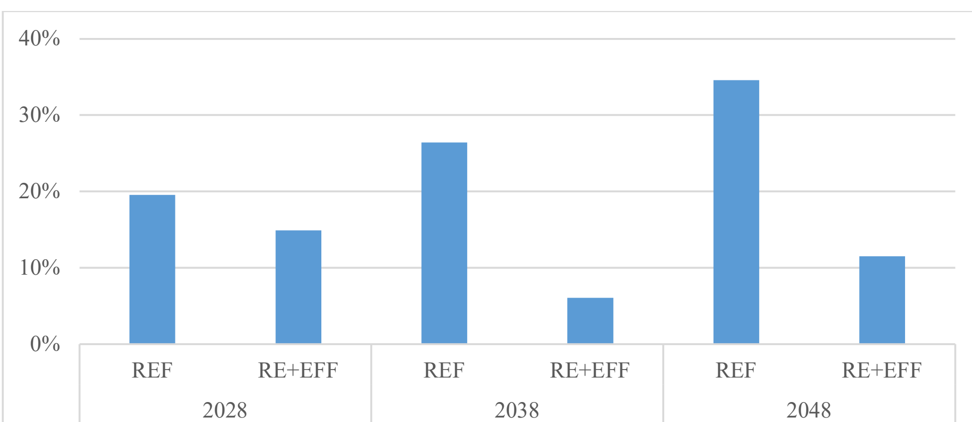

Figure 7-17 Comparison of fossil energy required by the EWS as a share of existing oil production capacity

7.3.7 Generation costs

The system transformation detailed in the prior analysis results in a significant reshaping of the system's cost and cost structure (Figure 7-18 and Figure 7-19). By implementing renewables with end-use efficiency improvements, the system experienced significant decarbonisation in a pathway that emerges as the least-cost for Kuwait's EWS. While the fossil-fuel-only REF scenario projects total annual generation costs to reach US$34.3 Bn by 2048, the RE+EFF scenario cuts these costs by 55% to just US$15.5 Bn.

A closer examination of these costs show that the savings are primarily from the fuel expenditures. In the fossil-fuel-only REF case, fuel costs are the dominant expense, accounting for US$26 Bn (over 75% of the total 2048 cost). The introduction of renewables alone in the Reference RE scenario cuts the fuel costs to US$14 Bn. However, the synergy of renewables and efficiency in the RE+EFF scenario reduces the 2048 fuel cost to US$7.8 Bn (70% lower than REF scenario and 45% lower than the Reference RE's).

The cost reductions are accompanied by a very important fundamental change in the economic structure of the electricity-water system, as shown by the cost distribution in Figure 7-19. The fossil-fuel-only REF scenario presents an EWS financially dominated by volatile fuel costs (76% of total). The RE+EFF scenario completely inverts this structure by creating a system dominated by a predictable capital investment (43% of total). This shift from an OPEX-heavy to a CAPEX-heavy system is the signature of the energy transition. It demonstrates that the decarbonisation pathway not only lowers the total cost of energy but also fundamentally de-risks the system by trading the uncertainty of global fossil fuel markets for the stability of long-term capital assets. And by doing so, Kuwait's potable water supply becomes insulated from the volatility of global energy prices and is instead secured by long-term capital investments.

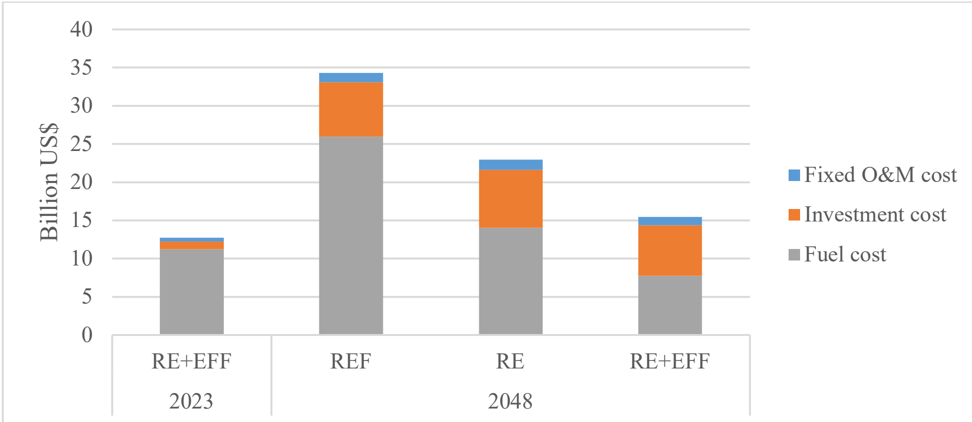

Figure 7-18 Generation costs under different scenarios

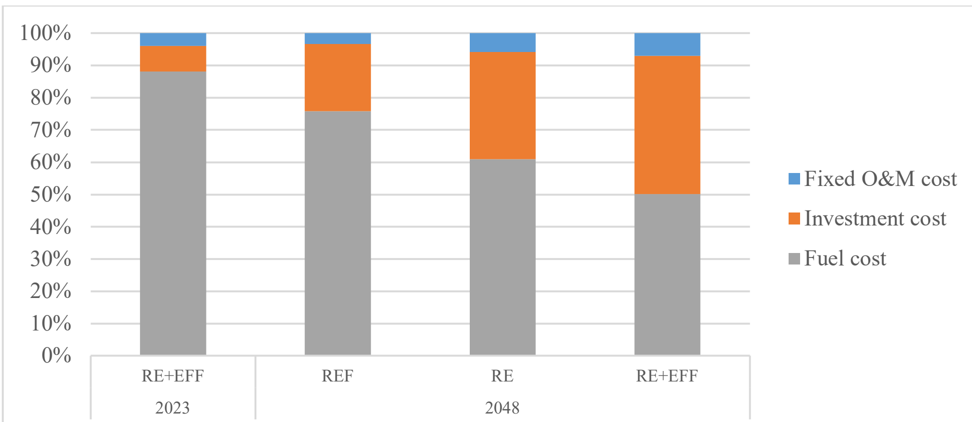

Figure 7-19 Generation costs distribution under different scenarios

7.3.8 Marginal prices of electricity and water

Comparing the total system costs from the previous section with the marginal electricity and water prices (Figure 7-20 and Figure 7-21) provides interesting insights. While the RE+EFF scenario cuts down the total annual generation costs by 55%, the average marginal price of electricity in 2048 remains high at 123 US$/MWh. This figure is only slightly lower than in the REF scenario. This, seemingly a contradiction, actually reveals an insight into the fundamental characteristics of a cost-optimised high-renewable pathway for Kuwait's integrated electricity-water system.

The main observation is the creation of a volatile price environment driven by the alternating periods of energy surplus and scarcity. This feature is a common characteristic of a renewables-dominated system. The total annual cost drops because this average includes the massive volume of daytime electricity produced by solar at a very low marginal cost. However, the average marginal price remains high because it is heavily influenced by the significant number of hours of darkness. At night, the system must rely on its dispatchable thermal capacities (oil/gas-fired plants). Thus, thermal capacities set the high marginal price.

However, another more distinctive characteristic is observed from the model's investment decisions for desalination. Even with a massive deployment of renewables, the cost-optimal solution for the system is not to completely phase out thermal cogeneration in favour of grid-connected RO desalination. Instead, the model retains thermal desalination and expands the capacities by switching from SPP/MSF to CCGT/MSF. By maintaining these dispatchable, high-capacity-factor assets, the model ensures it can provide both essential baseload power and potable water when intermittent renewables are unavailable. The consequence of this choice is that these relatively expensive thermal plants remain on the system and are frequently setting the marginal price, even in a system with 67% renewable capacity. Therefore, the persistently high marginal price is not a sign of scenario failure. Rather, it is the economic signature of an optimal and least-cost solution to the dual challenge of balancing an intermittent grid while guaranteeing the integrity of a national potable water supply.

This dynamic of high marginal electricity prices is mirrored in the average marginal price of water. In the year 2048, the price of producing a cubic metre of water is around 4.8 US$/$m^3$ in both decarbonisation scenarios. This level is very close to the REF scenario price of 5.1 US$/$m^3$. It demonstrates how strong the economics of electricity and water are linked, with the marginal price of electricity acting as the primary transmission mechanism for this price stability. It shows that in a system where RO is frequently the marginal source of desalination, the cost of producing an additional cubic metre of water is determined by the marginal price of the electricity required to run the RO plant. Since the average marginal price of electricity remains high across all scenarios, it results in that the marginal price of water also remains high and stable.

In conclusion, end-use efficiency improvements and renewable energy resources can significantly lower the cost of producing electricity and water. However, these measures do not eliminate the EWS reliance on conventional thermal cogeneration plants. And since the cost of running these plants is what ultimately sets the price, the marginal cost of water and electricity remains high even in a system with a much lower total average cost.

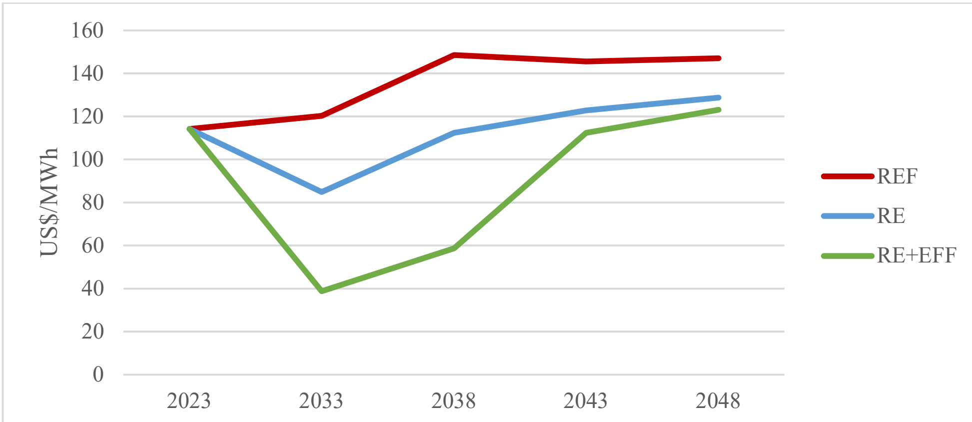

Figure 7-20 Average marginal price of electricity

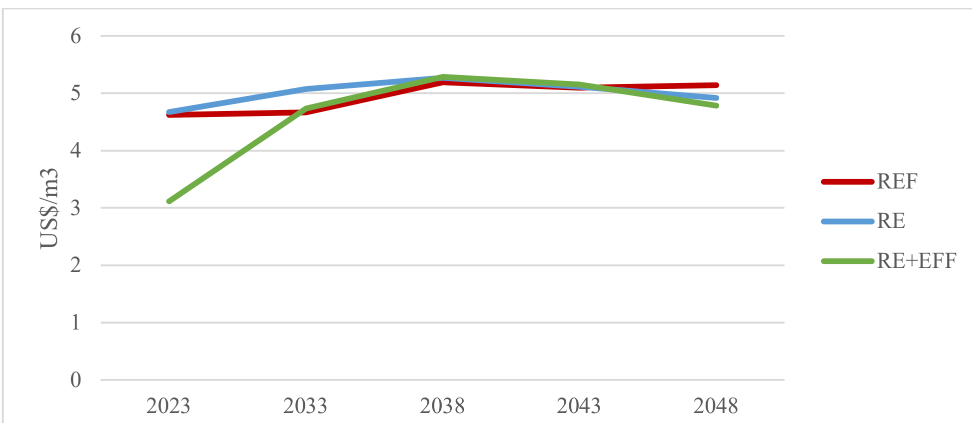

Figure 7-21 Average marginal price of water

7.3.9 CO_2 emissions

The supply-side transformation and fuel displacement lead to a reduction in CO_2 emissions from Kuwait's electricity-water system. Projections in Figure 7-22 show that while an integrated strategy of deploying renewables and end-use efficiency improvement can provide the deepest decarbonisation pathway, the trajectory is not a simple linear decline. Instead, the trajectory reflects the complex interplay between technological deployment, demand growth, and resource constraints.

Under the REF scenario, which has no renewables or new efficiency policies, emissions are projected to nearly double, rising from 59 $MtCO_2$ in 2023 to 110 $MtCO_2$

by 2048. This trajectory establishes the scale of the climate challenge by demonstrating a state of strong coupling where rising electricity and water demand is met almost entirely by increased fossil fuel generation. As the country develops and the population grows, driving higher electricity and potable water demands, a proportional increase in carbon emissions follows.

The introduction of renewables in the RE scenario drives a rapid decline in CO_2 emissions. The initial deployment of solar power in the period between 2023 and 2033 cuts emissions by nearly a half to 30 $MtCO_2$ in 2033. However, in the period after 2033, emissions begin to rise again, reaching 55 $MtCO_2$ by 2048. This U-shaped trajectory shows effect of model's cost-optimisation and the absence of any constraints on emissions. After deploying renewable capacities, the model identifies that the optimal pathway to simultaneously provide electricity and potable water is through the investment in thermal cogeneration (CCGT/MSF). Because this new thermal capacity is fossil-fuelled, its deployment to meet demand growth causes CO_2 emissions to rebound. While this scenario still cuts 2048 emissions by 50% compared to the REF case, it demonstrates that a renewables-only strategy cannot achieve continuous decarbonisation in a system with growing demand for both power and water.

Finally, it is the RE+EFF scenario that provides the deepest and most sustained decarbonisation pathway. Demand reduction from end-use efficiency facilitates the lowering of carbon emissions to a lower point compared to the other scenarios and sustains it further into the future. Emissions in this scenario drop to 16 $MtCO_2$ in 2038. Although emissions also begin to rise again in the final decade due to the same growth and constraint dynamics, they remain on a much lower trajectory. Carbon emissions reach 35 $MtCO_2$ in 2048, which represents a 68% reduction compared to the REF case.

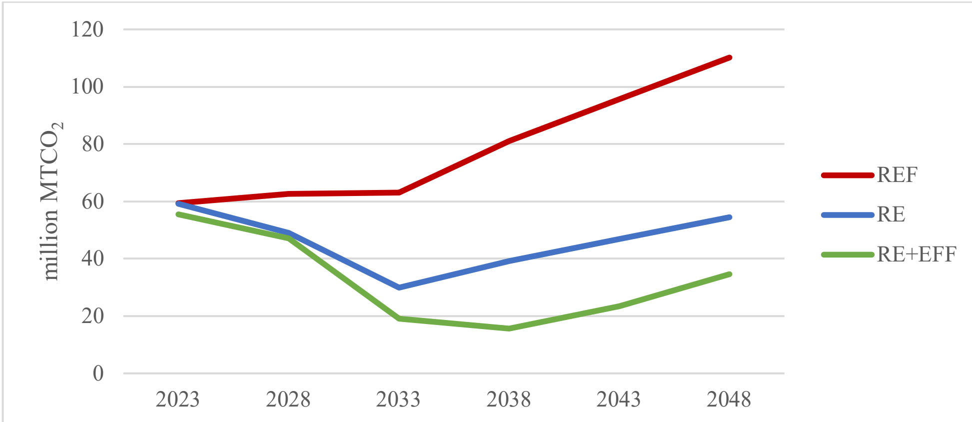

Figure 7-22 Carbon Dioxide emission

7.3.10 Carbon intensity

In addition to reducing total emissions, the decarbonisation scenarios alter the carbon intensity of the final services delivered to the consumer. This metric helps understand the progress towards decarbonisation at the system level. Figure 7-23 projects the electricity carbon intensity and Figure 7-24 projects the water carbon intensity.

For electricity, all scenarios exhibit a very high carbon intensity in 2023 of approximately 0.72 $kgCO_2/kWh$. This level is comparable to other hydrocarbon-heavy systems in the region such as 0.650 $kgCO_2/kWh$ Saudi Arabia (Hamieh et al., 2022), 0.46 $KgCO_2/kWh$ in the UAE (BP, 2022), and in other parts of the world with similar climatic conditions such as the 0.5 $KgCO_2/kWh$ in Australia (EMBER, 2023). In the REF scenario, while there are minor improvements from generation modernisation and fuel switching, the intensity remains high at 0.68 $kgCO_2/kWh$ in 2048.

In contrast, the carbon intensity in both the RE and RE+EFF scenarios reduces until the mid-2030s. The RE+EFF scenario achieves the lowest intensity by dropping over 80% to 0.13 $kgCO_2/kWh$ in 2038. This level is on par with some of the European grids (European Environment Agency, 2025). This is followed by a rebound discussed previously, where the reintroduction of marginal fossil fuel plants to meet growth causes the intensity to rise again. Nevertheless, the intensity remains at a much lower level of 0.24 $kgCO_2/kWh$ in 2048.

As for water, the behaviour is slightly different with a different starting point and some level of reordering of the scenario performance. For instance, the 2023 carbon intensity of water in the RE+EFF scenario is the highest of all scenarios at 26 $kgCO_2/m^3$. This is explained by the fact that demand reductions which became available for the model beginning from 2020 (as stated in Chapter 6) allow the system to meet its water needs primarily with existing thermal desalination plants, while delaying the deployment of new cleaner technologies.

However, as the transition accelerates, this hierarchy inverts. The intensity of water in the RE+EFF scenario only drops to 4.8 $kgCO_2/m^3$ by 2038 before rising steadily to 9.5 $kgCO_2/m^3$ by 2048. In contrast, the REF scenario's water intensity remains steadily high, reaching 18.8 $kgCO_2/m^3$. It is noteworthy that the RE and RE+EFF scenarios ultimately achieve a 2048 water carbon intensity that is approximately half that of Saudi Arabia's current level (Hamieh et al., 2022). Therefore, it can be concluded that decarbonisation efforts enabled by renewables and accelerated by end-use efficiency can help decouple water from fossil fuels, and thereby improving the sustainability of potable water supply.

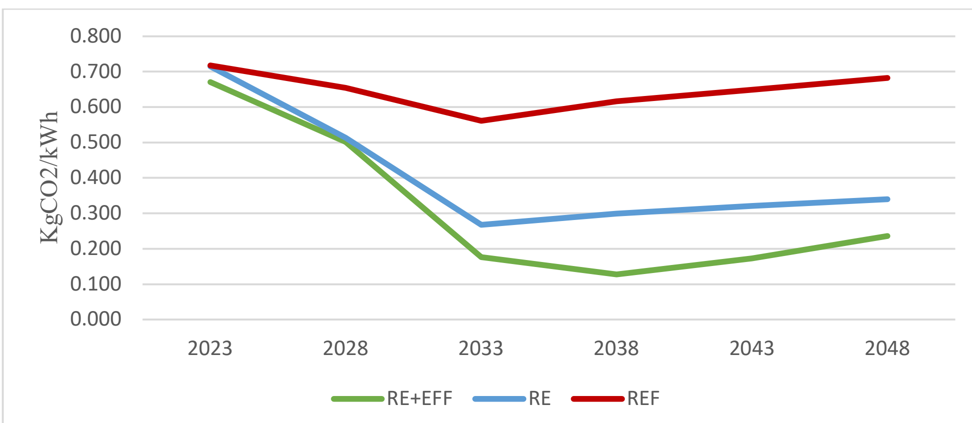

Figure 7-23 Carbon intensity of electricity

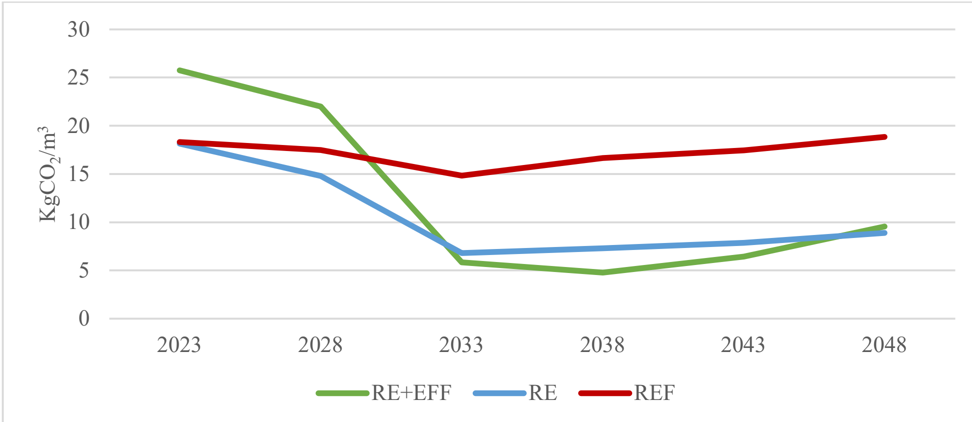

Figure 7-24 Carbon intensity of water

7.3.11 Sensitivity demands

A series of sensitivity analyses are conducted to assess the decarbonisation pathway under the RE+EFF scenario. These tests are applied to this particular scenario as it represents the optimal pathway identified in the preceding analysis. This analysis seeks to investigate how dependent the optimal technology mix and decarbonisation outcomes are on assumptions regarding fuel prices, varying levels of national development, land availability, and the absence of battery technologies. The results in Table 7-3 show that the optimal decarbonisation pathway is dynamic in its response to different pressures placed on the electricity-water system.

7.3.11.1 Land Constraint

When the land limitation is removed, the renewables deploy at a scale that leads to a near-total decarbonisation of the EWS. Total renewable capacity reaches 105 GW, representing 94% of the total projected capacity in 2048. This expansion is almost exclusively composed of utility-scale PV, which is the cheapest available technology. By 2048, utility-scale PVs constitute over 95% of the renewable mix. This large investment in PV is paired with 7 GW of battery capacity to manage intermittency. As a result, the water production becomes almost fully electrified with a 93% share of RO. Consequently, carbon emissions drop to just 4 Mt. In theory, land availability is a binding constraint that prevents the Kuwait EWS from achieving near 100% decarbonisation with solar PVs and batteries.

7.3.11.2 Batteries

To compensate for the lack of electrochemical storage, the model is forced to reconfigure its entire generation portfolio towards dispatchable assets. The share of Parabolic Trough CSP (with thermal storage and hybrid-gas), nearly doubles to 21% of the renewable mix. More significantly, the model secures the reliability of the electricity-water nexus by increasing its reliance on thermal cogeneration. The share of CCGT/MSF in the water supply mix grows from 29% to 50%. Therefore, in the absence of batteries, the model finds that the most cost-effective pathway is to steer away from energy-efficient RO desalination and increase the capacities of gas-fired CCGT/MSF cogeneration in order to maintain electricity and water supplies.

Perhaps the valuable insight of the batteries removal scenario is that it highlights the transitional challenge for fossil-dominated systems. By disabling the batteries under this scenario, the system produces nearly 18% lower carbon emissions compared to when the system had batteries (RE+EFF scenario). Closer examination of the generation projections reveal that by removing the batteries, the model has less reliance on oil-fired thermal plants and more reliance on CCGTs in addition to the CCGT/MSFs. By removing the batteries, the resulting oil displacement lowers emissions under central development conditions to levels equivalent to the low-development conditions.

7.3.11.3 Energy prices and socioeconomic development

Finally, a comparison of the low and high development scenarios from Section 0 shows how future demand levels dictate different investment and technology deployment strategies. The low development scenario (reduced water and electricity demands, low energy prices), requires less new capacity overall. Its renewable share is the highest of all constrained scenarios at 84%. However, its technology mix relies more on renewables (PV and Parabolic Trough) and on legacy thermal plants

(SPP/MSF) for desalination, since there is less pressure to invest in expensive new capacities.

In contrast, the high development scenario is defined by the urgent need for large-scale new capacities. The renewable share drops to 65% as the model deploys significant number of combined cycle gas turbines (CCGTs) to meet the higher demand. The renewable mix shifts towards high-capacity Linear Fresnel technology (29% with thermal storage and 24% hybrid gas, totalling 53% of renewables), and the water system is almost entirely electrified with a 95% RO share. This shows that higher economic growth forces a more capital-intensive transition focused on building the most productive new assets, while lower growth allows for a more cost-cautious approach. However, this transition is only feasible through the electrification of seawater desalination. The feasibility of this pathway depends on a broader national strategy that extends beyond energy policy to include the stability of the membrane desalination supply chain, its operational resilience and long-term environmental sustainability.

In conclusion, this sensitivity analysis shows that the optimal pathway for Kuwait's decarbonisation is highly dynamic and defined by a series of trade-offs. First, land availability ultimately determines the maximum achievable renewable penetration. Thus, land availability sets the ceiling for emissions reduction. Second, the availability of energy storage (batteries) and RO desalination dictate the extent to which renewables can displace thermal cogeneration. Finally, the analysis demonstrates how the RE+EFF scenario represents a balanced, cost-optimal configuration.

Table 7-3 RE+EFF Scenario sensitivity analysis

Observed year: 2048	*RE+EFF Central Case*	*Low E. P. Low Dev.*	*High E. P. High Dev.*	*No L.C.*	*No Batteries*
Total renewables capacity [GW]	33.0	31.7	34.8	105.2	32.5
Renewables share of total capacity [%]	67%	84%	65%	94%	63%
Technology mix (% of RE capacity):					
Parabolic Trough	12.0%	23.7%	9.4%	3.1%	21.0%
Solar Tower	0.0%	0.0%	0.0%	0.0%	0.0%
Linear Fresnel	11.5%	0.0%	53.4%	0.0%	11.4%
Utility-scale PV	71.4%	71.0%	32.4%	95.3%	62.5%
Rooftop PV	3.1%	3.3%	3.0%	1.0%	3.2%
Wind	2.0%	2.0%	1.9%	0.6%	2.0%
Batteries capacity [GW]	4.3	5.6	3.6	7.2	0.0
Water supply capacity [M m3/day]	3.5	2.0	4.9	3.5	3.5
Water supply mix [%]:					
RO	46%	43%	95%	93%	43%
CCGT/MSF	29%	3%	0%	0%	50%
SPP/MSF	25%	55%	5%	7%	7%
Land used [% of total available land]	20%	20%	20%	60%	20%
CO_2 emission [Mt]	34.6	17.3	31.4	3.7	28.3

E. P. = Energy Prices; L.C. = Land Constraint.

7.3.12 Cost-effectiveness

The final method used to present the cost-effectiveness results of different scenarios in this study is the Marginal Abatement Cost Curve (MACC). The MACC is a widely adopted analytical framework utilised in economic and environmental policy assessment (Jimenez Gomez, 2023, McKinsey, 2023). This method provides a visual representation of the economic efficiency and potential impact of various emission reduction measures.

In this method, each intervention is represented by a block whose height signifies the marginal cost of abatement (US$/t$CO_2$), while its width represents the total annual abatement potential (Million tCO_2). By illustrating both cost and impact, the MACC helps decision-makers identify which measures offer the greatest emission reductions for the least cost, while also drawing attention to the trade-offs between economic efficiency and mitigation potential.

To construct the MACC for this study, two key parameters were calculated for each intervention. First, the abatement potential was quantified by calculating the scenarios' undiscounted lifetime emissions savings. Concurrently, the marginal abatement cost was derived using a simplified approach where the Net Present Value (NPV) of the measure's costs was divided by the undiscounted sum of its lifetime emissions savings. Finally, all measures were ranked in ascending order based on their marginal cost, presenting the most cost-effective pathway for reducing emissions.

The cost-effectiveness and scale of carbon savings vary across the different decarbonisation pathways, as shown in Figure 7-25. Implementing residential efficiency measures alongside renewables in the RE+EFF increases the total volume of carbon removed and decreases the marginal cost compared to the renewables-only (RE) scenario. This confirms that residential efficiency measures act as a decarbonisation accelerator.

The MACC data also show the constraints facing Kuwait's energy transition. Land availability is a significant barrier to deep and cost-effective decarbonisation. When this constraint is removed, reductions in carbon emissions are projected at the lowest marginal abatement cost of any of the scenarios. This demonstrates that land availability is a bottleneck that forces the system to rely on more expensive or less-efficient abatement strategies when land for low-cost solar PV is scarce.

The role of electrochemical storage highlights an economic trade-off within the system. The no batteries scenario (RE+EFF No Batteries) achieves a greater carbon savings at a marginally lower abatement cost than the central RE+EFF case. In the batteries' presence, the model continues to operate oil-fired SPP/MSF cogeneration plants as the most cost-optimised pathway to produce electricity and water. In the absence of batteries, the role of oil-fired cogeneration diminishes as the model switches to gas-fired CCGT/MSF cogeneration plants. This finding suggests that when batteries are modelled at the system level, they may be optimised for grid temporal cost optimisation in a way that is not strictly aligned with maximal decarbonisation in a thermal based EWS like Kuwait's. Future KEWSM work could therefore investigate the impact of modelling batteries as dedicated renewable energy storage, restricting their charging to surplus renewable generation.

Finally, the abatement costs presented in Figure 7-25 are above the very low-cost options identified by the IPCC (2022) of around 100 US$/t$CO_2$ capable of cutting global 2019 emissions by around half by 2030. They do, however, remain below the levels typically associated with the final stages of deep decarbonisation, estimated at around 200 to 300 US$/t$CO_2$ by mid-century (Mahone et al., 2018, IEA, 2021).

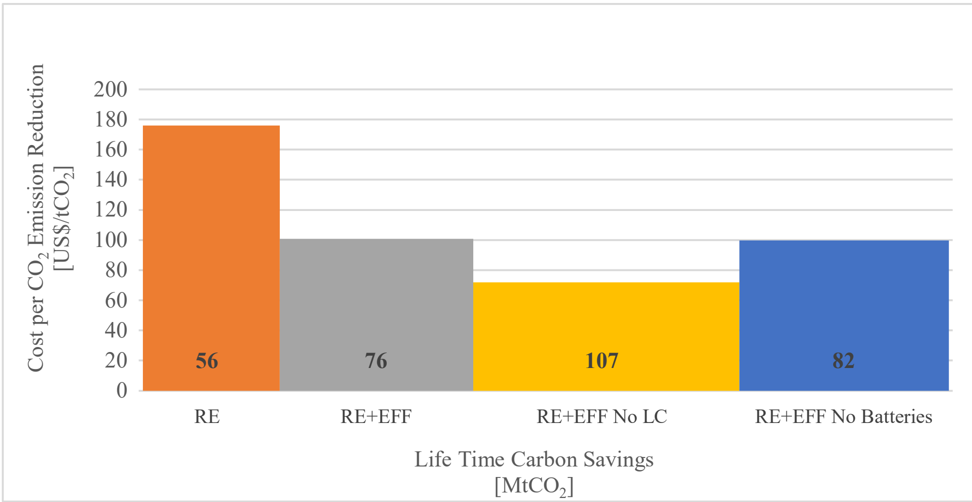

Figure 7-25 Estimation of cost-effectiveness of scenario options

7.4 Discussion

This discussion interprets these results through the following main themes: the complementary relationship between end-use efficiency and renewables, the reshaping the supply mix, the decoupling and displacement of fossil fuels, and trade-offs between average and marginal costs.

7.4.1 The complementary relationship between end-use efficiency and renewables

The results of this chapter demonstrate that an integrated demand-side efficiency improvement across the entire electricity-water system (EWS) is a critical enabler that unlocks system transition. The comparative analysis of the Reference RE and the RE+EFF scenarios demonstrates that efficiency does not only add to the benefits of renewables but increases their effectiveness. By incorporating water end-uses and efficiency options into TIMES model, a powerful synergistic relationship is unlocked for optimal decarbonisation pathway. Results suggest that for water-scarce countries heavily relying on seawater desalination technologies for potable water supplies, water end-use and efficiency can act as a decarbonisation accelerator by creating headroom for faster and deeper energy transition.

The most evident example of this synergy is in the scale and pace of renewable deployment. The RE+EFF scenario leads to a renewable capacity deployment by 2035 (10 years from the initial technology availability) that achieves 30% higher deployment than the RE-only case. This projection, where reducing demand accelerates the uptake of renewables, underscores the systemic advantages of an integrated approach within a coupled electricity–water system. It demonstrates that demand-side efficiency and supply-side transformation are mutually reinforcing components of a coherent decarbonisation pathway.

This synergy unfolds through two interrelated mechanisms. First, and most significantly, the large reductions in water demand cuts the system's rigid dependency on thermal cogeneration. By reducing the need for new desalination capacity, water efficiency liberates the power system from the requirement to build and run inflexible, fossil-fuelled steam and oil/gas-fired MSF plants, which would otherwise be necessary to maintain the water supply. Second, the efficiency measures directly reduce the sharp summer peaks driven by air conditioning. This reduction peak demand contributes to the reduced need for fossil fuel peaking plants, diverts gas resources to more efficient gas-fired cogeneration and phases out oil-fired cogeneration.

Together, these two effects create a significant flexibility for system planning. With a lower and flatter demand curve, the requirement for fossil-fuelled thermal cogeneration is reduced. The upfront capital cost of intermittent renewables become more economically competitive against the avoided operational and capital costs of their fossil-fuelled alternatives. Therefore, by reducing the total and peak energy demand, the efficiency measures make the high upfront capital cost of solar capacity a more economically attractive investment for the model compared to the long-term operational and fuel costs of building new fossil fuel capacities.

Furthermore, this deployment leads to a significant level of decarbonisation. While the RE-only scenario achieves a 50% reduction in emissions by 2048, its U-shaped trajectory highlights the system limitation. After exhausting the most cost-effective and renewable options, the model must still satisfy the inflexible growing demands of the electricity-water nexus. In order to meet the demand requirements, the model deploys thermal cogeneration as the least-cost solution, causing emissions to rebound. The RE+EFF scenario breaks through this barrier. By managing the underlying demand growth, the model pushes the system to a much lower emissions in 2048 that are 36% lower than in the renewables-only case.

Finally, the analysis shows a level of synergy between demand-side efficiency and land-use optimisation for renewable deployment. While land availability is a binding constraint in both decarbonisation scenarios, end-use efficiency alters how the model responds to that constraint. In the high-demand Reference RE scenario, the high capital cost of land-efficient technologies makes their deployment economically suboptimal. The model therefore finds it more cost-effective to meet the remaining demand by building additional fossil-fuelled thermal cogeneration capacities.

In the RE+EFF scenario, however, a different outcome emerges. By lowering total demand and creating savings from avoided fuel and thermal cogeneration capacity, efficiency measures create the necessary conditions for a renewables-focused investment decisions. In consequence, the model deploys the higher-yield utility scale dual-axis PVs and at a larger scale. Generation from dual-axis PV increase significantly from just 7.8 TWh in the RE scenario to 39.4 TWh in the RE+EFF scenario, becoming the largest source of renewable electricity.

Based on this, it can be concluded that while efficiency does not remove the land constraint, it unlocks the capital required to overcome the land constraint through technically superior generation options. It makes it economically rational for the system to pay a premium for more advanced solar technologies that maximise the productive output of every square metre of the scarce land.

7.4.2 Reshaping Kuwait's supply mix

The transition to a deeply decarbonised system, as optimised by KEWSM, is not a simple substitution of one technology for another, but the construction of a sophisticated portfolio where different technologies are assigned distinct and complementary roles based on their cost and operational characteristics. Analysis of the capacity investments and production dispatch decisions show a strategy in implementation. First, intermittent renewable generation deployed as major primary energy source, a hierarchy of dispatchable and storage assets, and a modernisation of firm cogeneration capacity.

Under all scenarios, the role of bulk low-cost energy production is assigned to utility-scale solar PVs. The LCOE analysis confirms that this technology is the cheapest source of MWhs, hence explaining the aggressive deployment. However, the model's choice within the PV portfolio reveals a deeper level of optimisation. The late-stage shift to a more expensive but higher-yield dual-axis PVs in the RE+EFF scenario demonstrates that the response is due to binding land constraint. Such trade-off becomes economical viable because of the system-wide savings unlocked by the demand-side efficiency improvements.

The challenge of managing PV's intermittency is met by a clear hierarchy of electricity storage and dispatchable assets. The model's lowest-cost tool is the virtual energy storage (VES) via reverse osmosis desalination plants. These plants serve as a flexible load to absorb surplus daytime solar. The results indicate that only when the VES is saturated, the low-cost power is diverted to the physical storage options. Electrochemical batteries are therefore reserved for managing short-term nighttime demand as their charging and discharging cycles dynamically adjust to seasonal load profiles. However, during the early deployment of renewables and prior to the expansion of RO capacities, the model invests in concentrated solar power (CSP) with thermal storage. These technologies are deployed to serve the predictable evening demand peak and thus act as a medium-duration time-shifter.

Finally, the analysis underscores the continued and significant role of modernised thermal cogeneration within the transition pathway. The model does not fully phase out fossil fuels. Instead, it systematically replaces old, inefficient steam/MSF plants with modern, efficient CCGT/MSF units. This outcome reflects a cost-optimisation process constrained by Kuwait's demand for desalinated water. Projections show that even in a decarbonising world, maintaining capacities of dispatchable cogeneration plants emerges as the most cost-effective solution to simultaneously guarantee baseload power and secure the integrity of the potable water supply. This positions modern cogeneration as an essential component of a least-cost for ensuring system reliability and safeguarding the electricity-water nexus.

7.4.3 Desalination

The results show that potable water supply is a central and complex challenge facing the future of Kuwait's electricity-water system energy transition and the nation's carbon neutrality objectives. The scenario analysis and sensitivity tests show multiple pathways for how the system can optimally produce potable water.

The fossil-fuel-only Reference (REF) scenario shows a future where unchecked demand growth forces the system deeper into a carbon "lock-in" by expanding the capacities of oil-fired and gas-fired thermal cogeneration plants. The introduction of renewable energy begins to break this dependency. By providing a source of electricity decoupled from thermal generation, renewables create the initial flexibility for the system to invest in grid-connected RO desalination. The model then rapidly deploys this technology to a peak share of 68%. However, the analysis also shows that even with renewables, the model eventually reprioritises and expands modern thermal CCGT/MSF cogeneration. This insight shows that in a cost-optimised system facing competing demands for baseload power and water, a full transition to RO is not the most economic pathway. However, it chooses to 'modernise' the thermal cogeneration capacities by switching from SPP/MSF to CCGT/MSF. Thus, fossil-fuelled thermal capacities remain essential for ensuring system-wide reliability, and therefore, placing a ceiling on the ultimate share of RO.

The RE+EFF scenario, however, shows the most powerful driver for overcoming the constraints identified above, which is the residential sector efficiency improvements. By substantially cutting down water demand, efficiency measures help delay the need for major RO desalination capacity by up to 15 years. This deferral is far more than a simple cost saving, and significantly beneficial as a de-risking strategy in the context of membrane desalination technologies in countries relying completely on seawater desalination for their potable water needs. It provides an important temporal window for more advanced and efficient membrane technologies to mature, for countries to develop a domestic membrane supply chain to mitigate global market risks, and for innovative solutions like brine mining to become commercially viable to mitigate the environmental effects of the technology.

Finally, the analysis shows how a high-renewable system could customise its utilisation of desalination as a way of managing the solar resource. The model establishes a clear operational hierarchy between RO desalination and batteries, using them as complementary tools in a symbiotic relationship. RO plants are treated as a virtual energy storage, the primary dispatchable load that absorbs massive volumes of low-cost daytime solar by converting it into stored potable water. This is the model's preferred and cheapest method for managing solar intermittency. Only when this virtual storage is saturated with power does the model turn to its more expensive option, charging electrochemical batteries. Batteries are thus reserved for their highest-value function of time-shifting the remaining electricity surplus to meet nighttime electricity demand.

7.4.4 Restructuring of Kuwait's EWS economics

A key insight to emerge from this analysis is the complete restructuring of Kuwait's electricity-water system's economics. The RE+EFF pathway demonstrates this through a shift in the cost structure, from reductions in the total system production costs driven by the transition away from operational expenditure (fuel-based generation) to capital expenditure (capacity-based investments), while the short-run marginal price of electricity and water remains high. This persistence in the marginal price is the result of them being anchored to the thermal cogeneration capacities that provide system reliability. Understanding this divergence is crucial for interpreting the economic realities of a high-renewable grid.

The shift in the cost structure is enabled by the cost-competitiveness of Kuwait's solar resources. The LCOE analysis confirms that the projected decline of utility-scale PV to around 10 US$/MWh level (a trajectory validated by recent regional PPAs (Bellini, 2024)) strengthens its role as the least-cost source of bulk energy based on land and fuel supply constraint conditions examined in KEWSM.

However, this dramatic drop in the aggregate cost (which under the RE+EFF scenario cuts down the total annual generation cost by 55% and de-risks the system from the volatile global fuel markets) conceals a more complex pricing dynamic. The analysis of marginal prices reveals that even in a system with 67% renewable capacity, the average marginal price of electricity remains high at 123.2 US$/MWh. This is a direct consequence of the "zero-and-high" price environment that characterises systems with large renewables capacities.

The average marginal price is a blend of thousands of daytime hours where a surplus of solar drives the price to near-zero, and a significant number of solar scarcity hours when the system's reliability depends on its most expensive dispatchable assets. The model's investment decisions show precisely what sets this high marginal price during scarcity periods. The LCOE analysis shows that in order to meet demand when cheap PV is unavailable, the model initially prefers dispatchable CSP with thermal storage over CCGT or OCGT peaking plants. The model then manages the surplus electricity by deploying RO desalination as virtual energy storage, followed by batteries as time-shifters.

More strategically, the model chooses to maintain and even expand thermal desalination capacities by switching from oil-fired SPP/MSF cogeneration to gas-fired CCGT/MSF cogeneration plants. This is a critical optimisation outcome. These thermal assets are retained not because they are the cheapest source of bulk energy, but because they provide the least-cost solution to the system's biggest constraint which is potable water demand.

Therefore, it is the short-run marginal cost of these thermal plants that ultimately anchors the high marginal price for both electricity and, by extension, potable water. This demonstrates that the core economic challenge of the energy transition is not just reducing the aggregate cost of energy, but also finding the most cost-effective way to invest in and operate the dispatchable assets required to guarantee system reliability when intermittent renewables are unavailable.

7.4.5 Decoupling and displacement of fossil fuels

The decarbonisation pathways analysed in this thesis reveal a central strategic priority for Kuwait. Specifically, the nation must mitigate the long-term structural vulnerabilities of a hydrocarbon-exporting state by decoupling its domestic prosperity from its domestic hydrocarbon consumption. The results show that an integrated strategy of demand-side efficiency improvements and supply-side renewable deployment is not just a climate policy. It also serves as a tool for strengthening Kuwait's economic sovereignty and energy security, particularly given that the nation's potable water supply remains tied to hydrocarbon consumption. The results show two key dynamics that reshape Kuwait's electricity–water system, and they are the displacement of the marginal fuel and the decoupling of electricity and water production.

The model consistently identifies domestic crude oil as the system's high-cost, high-carbon marginal fuel for the EWS. It means that under any scenario of demand growth, every unit of energy saved through efficiency or generated by a renewable source delivers a disproportionately high benefit by directly freeing up a unit of exportable hydrocarbon. This finding reframes fuel savings from a simple environmental benefit to a key element of Kuwait's broader economic strategy. By displacing the most expensive and most polluting fuel in the system, the RE+EFF pathway generates a dual benefit by maximising potential export government revenues while simultaneously delivering the deep carbon reductions.

This marginal fuel displacement is enabled by the decoupling of water and power production. The results show that a renewables-only pathway is ultimately constrained by the inflexible operational lock-in of thermal cogeneration. It is the introduction of water end-use efficiency improvements within Kuwait's residential sector that cuts this dependency. Decoupling water from power production thus unlocks the flexibility to transition water production to the more energy-efficient, grid-connected RO desalination technology. Which, as a result, enables the system to accommodate a much larger share of intermittent renewables.

The ultimate success of this integrated strategy is quantified in the final carbon intensity metrics. By achieving a 2048 electricity carbon intensity of 0.235 $kgCO_2/kWh$ and a water carbon intensity of 9.5 $kgCO_2/m^3$, the system reaches levels that are dramatically lower than the REF case and highly competitive with regional benchmarks. Therefore, the RE+EFF scenario provides a tangible, model-driven pathway. It shows that it is possible to break the historic strong coupling of economic growth and emissions. And this breaking is done by re-engineering the relationship between the demand for services and the primary energy required to provide them. This transformation would ultimately insulate Kuwait's EWS from its risky dependencies which are the volatility of global fossil fuel prices and the opportunity cost of burning valuable, exportable hydrocarbons for domestic needs.

7.5 Summary

This chapter examined research question 4: "What are possible decarbonisation and emissions reduction pathways while maintaining the integrity of the potable water supply?"

Based on this research question, two renewable energy scenarios were developed and solved through KEWSM. Analysis of KEWSM projections provided insights into the role of solar technologies and efficiency improvement measures in decarbonising the electricity-water system and improving the overall system sustainability. Furthermore, this chapter's results illustrated the benefit gained by incorporating water end-use services, along with electricity end-use services, into TIMES model, particularly for countries where potable water relies on seawater desalination technologies and investigating the potential role of solar technologies in their energy mix.

KEWSM projections highlighted the broader implications of transitioning towards a decarbonisation pathway. Solar technologies will play an increasing role in the future of Kuwait's energy-water nexus. The analysis showed that the deployment of solar technologies will enhance the sustainability of Kuwait's energy system by substantially reducing fossil fuels consumption, decreasing generation costs and cutting carbon emissions. However, the scale and pace of their deployment are significantly influenced by demand-side efficiency measures.

A key finding is that residential electricity and water efficiency have a powerful synergistic relationship with renewables. By substantially cutting water demand, efficiency measures act as a decarbonisation accelerator, breaking the system's rigid dependency on thermal cogeneration. This creates the operational flexibility needed to integrate a larger share of intermittent solar power. Furthermore, it facilitates a broader competition among solar technologies and enables a more extensive range of solar technologies to play a role in Kuwait's decarbonisation track. This ultimately decouples Kuwait's electricity-water system from indigenous hydrocarbons, the most valuable national commodity for export.

Thermal desalination will continue to play a vital role in securing Kuwait's potable water supply. KEWSM projections indicate that thermal desalination can be part of the transition towards decarbonisation. However, this will be constrained by the availability of natural gas supplies to meet the requirements of the electricity-water system. Electrification of seawater desalination is a fundamental component for achieving decarbonisation within electricity-water systems. In a high-renewables system, membrane desalination technologies, such as reverse osmosis, can function as a complementary flexibility option to battery storage. This enables an effective utilisation of surplus renewable generation and enhancing the system's decarbonisation potential.

Ultimately, all of the aforementioned synergies enable a restructuring of Kuwait's electricity-water system. It breaks the system's dependence on thermal generation, decouples potable water supply from fossil fuel availability, and insulates potable water production costs from the variable price of fossil fuels in the global market. Furthermore, it displaces crude as a high-cost, high-carbon marginal fuel, thus driving deep decarbonisation and supporting government efforts towards the Net-Zero Emissions by 2050 strategy.

Chapter 8

CONCLUSIONS

8.1 Introduction

This chapter restates the research problem and summarises key conclusions for each of the research questions. Limitations of the research and suggestions for future studies are then presented. Finally, the originality and contribution of this work are presented.

8.2 Restatement of the research problem

Seawater desalination technology offers an opportunity to overcome the natural freshwater constraints and meet national development aspirations. In the oil-rich Kuwait, water scarcity represents a fundamental challenge to economic and social development. Large-scale seawater desalination technologies enabled the country to grow and meet its national development aspirations.

The electricity-water system in Kuwait has multiple challenges starting with the reliance on indigenous oil reserves to produce potable water. The reliance on fossil fuels ties potable water availability to fuel availability. Additionally, it exposes the cost of producing potable water to the variable price of fossil fuels in the global market. Furthermore, oil revenue represents 90% of the government's income, and therefore, using indigenous oil reserves to produce potable water is considered a missed opportunity in the global markets.

Another challenge facing Kuwait's electricity-water system is the interlinkage between electricity and water production. Desalination processes are either integrated with electricity generation processes or grid-connected, thus, making potable water inseparably linked to electricity. Furthermore, while electricity generation and water production processes are coupled, demand for these services is not.

The largest consumer of electricity and water is the residential sector, accounting for 60% of total electricity demand and 87% of the water demand. This represents a challenge for system planners in a developing country where about 70% of the population is composed of migrant workers susceptible to government spending on national development plans.

This thesis evaluated the role of residential end-use efficiency improvement measures and renewable energy resources in improving the sustainability of Kuwait's potable water supply by answering the following research questions:

1. What are the potential demand pathways for electricity and water in Kuwait?
2. What influence will residential efficiency improvements have on demand for electricity and water?
3. To what extent will end-use efficiency improvement influence the electricity-water supply mix?
4. What are possible decarbonisation and emissions reduction pathways while maintaining the integrity of the potable water supply?

8.3 Summary of findings

The main findings are summarised by the following:

1. Very little information about electricity and water end-use within the residential sector is available. In order to model electricity and water end-use, an estimation process was conducted, and estimates were calibrated, taking into account variations in housing typology and demographics.

2. Electricity and water demands are subject to a high level of uncertainty due to the nature of the population composition and the drivers behind the composition growth. A sophisticated housing demand model for projecting Kuwait's housing demand that accounts for changes in the demographic structure was developed and verified. Housing demand projections are used to project end-use appliances stock, and electricity and water services demand.

3. Water and electricity production in Kuwait are closely linked. Previous energy system modelling studies have focused on the supply side and have not considered water end-uses. The aim of this study was to understand the dynamic relationship between supply and demand and examine the influence of end-use efficiency improvement on the supply-side and the overall system. The gap in energy system modelling with regards to the residential water end-use was closed by the development of the Kuwait Electricity Water System Model (KEWSM).

4. Under multiple socioeconomic conditions, projections for electricity and water demand in Kuwait indicate an upward trend in consumption. The residential sector maintains a significant consumption share even under negative socioeconomic growth. A change in government housing policy, development priorities, or spending can influence the population composition and migrant workers' demographic characteristics. These changes would significantly influence the housing demand and growth of different archetypes.

   KEWSM results projects electricity consumption under the reference scenario at 134 TWh in 2043, 30% lower for the same year under the low-development scenario and 42% higher under the high-development scenario. Water consumption is projected in 2043 to reach 1,788 million m^3 under the reference scenario. The low-development scenario projects water consumption to be 39% lower, and the high-development scenario projects it to be 29% higher.

5. KEWSM projections establish several fundamental dynamics of Kuwait's electricity-water system: Consumption levels correlate closely with socioeconomic development of the country; Electricity demand is significantly more sensitive to socioeconomic development shifts than water consumption; Shifts in consumption are not uniform changes across sectors, but rather focused within the residential sector.

6. Across all socioeconomic growth trajectories, the residential sector would dominate the demand for electricity and water. A continuation in current consumption trend would lead the apartments' segment to become the largest residential consumer. KEWSM results under the reference scenario show that the apartments segment share of electricity and water consumption could grow from less than 38% share in 2013 to more than half of the total consumption in 2043. However, this segment is the most sensitive to socioeconomic fluctuations and is subject to growth uncertainty.

7. Incorporating an expansive inventory of residential end-use technologies into TIMES model highlighted Kuwait's residential sector inefficiencies and potential for efficiency improvement. The per capita consumption under the reference scenario declines for electricity from 15,034 kWh/Cap in 2018 to 12,375 kWh/Cap in 2043 and water from 187 m^3/Cap in 2018 to 165 m^3/Cap in 2043. Under efficiency improvement policy scenarios introducing changes to buildings' characteristics and technologies availability, the reduction in electricity demand ranging between 3% and 14% is achieved within ten years of measures availability. Water reduction achieved ranges between 12% and 42% in the same year.

8. The divergence between KEWSM's projected stable per capita consumption pathway and the rising real-world consumption is the "efficiency gap". This gap quantifies the considerable potential for resource savings that are not being utilised under current market conditions and behavioural patterns. This gap can be interpreted as a direct cost of a policy and regulatory void.

9. Given the policy and regulatory void, this research findings position the Public Authority for Housing Welfare (PAHW) as a potential champion for energy efficiency.

10. Investment apartment sector is a key leverage point for a high-potential water conservation strategy. Such a strategy would require a different set of tools that extend to the landlord-tenant regulations and plumbing codes to capture its savings potential.

11. Modelling water end-use and efficiency improvement measures highlighted the influence of water demand on electric power generation and technologies cost-effectiveness, providing new insights from model projections.

12. Due to the inefficiencies surrounding consumption in Kuwait, implementing the residential sector efficiency improvement measures resulted in a reduction in capacities, capacities investments, and fuel consumption.

13. Solar technologies will play an increasing role in the future of Kuwait's energy-water nexus. The analysis showed that the deployment of solar technologies will enhance the sustainability of Kuwait's energy system by substantially reducing fossil fuels consumption, decreasing generation costs and cutting carbon emissions. However, the scale and pace of their deployment are significantly influenced by demand-side efficiency measures.

14. Incorporating residential electricity and water end-use technologies increase the renewable energy resources penetration in the energy mix. KEWSM projections show higher penetration of solar technologies compared to TIMES-KPW.

15. By reducing water demand, efficiency measures act as a decarbonisation accelerator breaking the system's rigid dependency on thermal cogeneration. This creates the operational flexibility needed to integrate a larger share of intermittent solar power.

16. Incorporating end-uses and efficiency options in the cost-optimisation model facilitated broader competition among solar technologies and enables a more extensive range of solar technologies to be deployed by the model.

17. Thermal desalination will continue to play a vital role in securing Kuwait's potable water supply, and can be part of a decarbonisation pathway given the availability of stable natural gas supplies.

18. Incorporating residential electricity-water end-use technologies improved the allocation of solar generation and seawater desalination technologies. With end-use technologies enabled, KEWSM projections show CCGT/MSF desalination capacities expanding along with RO desalination at a varying rate.

19. Electrification of seawater desalination is a fundamental component for achieving decarbonisation within electricity-water systems. Grid-connected desalination technologies, such as reverse osmosis, can function as a complementary flexibility option to battery storage.

20. There is a symbiotic relationship between RO desalination and batteries. RO plants can function as virtual energy storage, the primary dispatchable load that absorbs volumes of low-cost daytime solar by converting it into stored potable water. While batteries function as time-shifting mechanism for the remaining electricity surplus to meet nighttime electricity demand.

21. Enabling efficiency measures in combination with solar technology reduced generation fuel consumption significantly, thereby improving the integrity of Kuwait's electricity-water system and the sustainability of potable water supply.

22. Decarbonisation of Kuwait's electricity-water system is viable when solar power generation is coupled with residential efficiency improvement measures that can be implemented through updating buildings codes and appliances efficiency standards.

23. Decarbonisation of Kuwait's electricity-water system could break the dependence on thermal generation, decouple potable water supply from fossil

fuel availability, and insulate potable water production costs from the variable price of fossil fuels in the global market.

8.4 Limitation and future work

Improve electricity end-use technologies: Due to the time constraint, data availability, and scope of this work, some household electrical appliances were aggregated and not modelled individually. Therefore, disaggregating appliances would improve the model. A focus on expanding air-conditioning technologies taking into account refrigerant type and the degrading performance during the time of the year, would improve model output.

Improve houses efficiency pathways: Cladding options for different house types would provide new insights regarding buildings' efficiency.

Impose environmental constraints: Emissions to air and effluents to sea are incorporated in the model and projected, but there are currently no constraints on their release. However, environmental protection regulations and actual capacity of shores could potentially impede emissions and effluents beyond a certain level. As a result, imposing limits or costs on emissions and effluents would create an opportunity for other technologies on both the supply and demand sides to compete.

Expansion of demand sectors: KEWSM extended TIMES-KPW by incorporating the residential sector and the residential sector electricity and water end-use. The model can be improved by disaggregating the demand-side further. The industrial sector provides an opportunity for model expansion, given the size of this sector and the data availability. The industrial sector falls under the oversight of the Public Authority for Industry, which also provides the utilities for the sector and publishes detailed reports on the sector's activities.

Incorporate water storage: The integrity of potable water supply relies on the Ministry of Electricity & Water storage capacities. Since storage capacities serve as a buffer between production and consumption, factoring in water storage capacities could improve the electricity-water supply model. This includes both operational reserves storage and large-scale strategic reservoir options.

Incorporate electric vehicles: KEWSM already accounts for vehicles as part of the car washing activity. With the current trend towards electric vehicles, incorporating electric vehicles into KEWSM would provide new insights regarding Kuwait's electricity-water system.

Incorporate Carbon Capturing and Storage (CCS) and Direct Air Capture of CO_2 (DAC): The carbon footprint of Kuwait and other GCC countries is high compared to other developed countries. Some GCC countries are experimenting CCS and DAC in the oil sector in an effort to promote the offering of "clean" fossil fuels. Multiple pilot projects are underway in Saudi Arabia, Qatar and the UAE. Therefore, the technology is already in the region. Utilising CCS and DAC can help reduce the carbon footprint of electric power generation and seawater desalination. Incorporating CCS and DAC into KEWSM would provide new insights regarding Kuwait's decarbonisation pathways.

Incorporate regional trade: Previous studies such as Amorim et al. (2014) have shown that closed systems can result in underinvestment in renewables. With the recent launch of the Gulf Cooperation Council Interconnection Authority interconnector in Kuwait (2023), electricity import and possibly trade will be available in the coming years. KEWSM assumes Kuwait's electricity-water system to be closed, and no electricity trade is included. Extending KEWSM to an open system to allow trade would provide new insights into Kuwait's solar generation and seawater desalination pathways.

8.5 Originality and contribution

This thesis addresses the gap in energy system optimisation modelling by developing a supply-demand model focused on the electricity-water interactions in coastal energy-rich countries experiencing extreme freshwater scarcity. The novelty of this research lies in incorporating residential water end-use and efficiency technologies into TIMES (The Integrated MARKAL-EFOM System) model in order to explore decarbonisation projections that integrate both supply and demand sides in a coherent modelling framework for the first time.

The developed model, KEWSM, is relevant for other countries in the region, such as Saudi Arabia, Qatar, and the UAE (Dubai, Abu Dhabi…), since all these countries share similar demand patterns for electricity and water, similar electricity-water systems structure, buildings typology, and demographic profiles.

Additionally, a method for projecting Kuwait's housing demand under different socioeconomic assumptions was developed.

Furthermore, this research provides valuable information appended to this thesis for researchers interested in Kuwait's electricity-water system. The information consists of: Disaggregated housing stock inventory and housing stock projections; electrical and water appliances inventory and demand projections; electricity and water demand projections under different socioeconomic scenarios; generation fuel demand projections; carbon and pollutants emissions projections.

Outside academia, this research provides valuable insights for policymakers and system planners. It provides them with a tool for analysing system pathways under uncertainty, insights into the potential of efficiency improvement measures, and insights for robust decarbonisation pathways while maintaining the integrity of the potable water supply.

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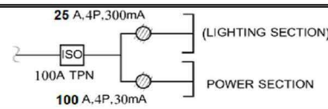
APPENDIX A: PAHW HOUSE MODEL H4

Standard government house (GH) floor plan

DB-G1 : GROUND FLOOR

(10 WAYS,TPN,SPLIT B.B.)

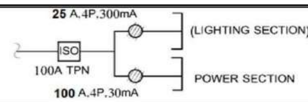


Section	Way No.	Way Ph.	MCB Rating	wire size mm²	Location	DESCRIPTION NO. OF FITTING (NO. X WATTS/FITT.)	Load in Watt R	Load in Watt Y	Load in Watt B
LIGHTING SECTION	1	R	10A	1.5	حمام(2)+المغاسل	L19-L23 (5X100) / S14-S15 , EF-4(1X100) / S16 , L2A (1X100) / S2A	700		
		Y	10A	1.5	الديوانية	L13-L15 (3X100) / S9-S10 , L16-L18 (3x100) / S11-S12		600	
		B	10A	1.5	استقبال	L4-L7 (4x100) / S4-S5			400
	2	R	10A	2.5	مدخل رئيسي	Lo1-Lo4 (4x100) / So1 , Lo1A-Lo5A (1x100) / So1	900		
		Y	10A	1.5	مغاسل الإستقبال	L8-L10 (3X100) / S6		300	
		B	10A	1.5	اضاءة خارجية	Lo18 (1x100) / S13 , Lo14-Lo16 (3x100) / So5+So5A			400
	3	R	10A	1.5	إضاءة خارجيه	Lo5-Lo6 (2x100) / So2	200		
		Y	10A	1.5	اضاءة خارجية	Lo7-Lo10 (4x100) / So3+So3A		400	
		B	10A	1.5	حمام (1)	L11-L12 (2x100) / S7 , EF-1(1X100) / S8 , L1A (1X100) / S1A			400
	4	R	16A	1.5	الدرج	LS1-LS11 (11X100) / SS1,SS2+SS2A,I	1100		
		Y	10A	1.5	نوم سائق+حمام(3)	L24-L27 (4X100) / S17-S18 , EF-2(1X100) / S19 , L3A (1X100) / S3A		600	
		B	10A	1.5	المدخل وصالة المدخل +ممر(1)	L1-L3 (3x100) / S1,S2+S3			300
	5	R	10A	1.5	مخزن	L29 (1X100) / S22	100		
		Y	10A	-	SPARE	-		-	
		B	16A	-	SPARE	-			-
POWER SECTION	6	R	25A	4	الديوانية	JB-AC3 (S-AC3) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM	3200		
		Y	25A	4	الديوانية	JB-AC4 (S-AC4) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM		3200	
		B	25A	4	استقبال	JB-AC1 (S-AC1) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM			3200
	7	R	20A	4	حمام (2)	JB-H2 (SH-2) / 1X1000 20A JB& D.P SW FOR WATER HEATER	1000		
		Y	25A	4	استقبال	JB-AC2 (S-AC2) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM		3200	
		B	25A	4	نوم سائق	JB-AC9 (S-AC9) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM			3200
	8	R	16A	-	SPARE	-	-		
		Y	16A	2.5	استقبال	P5-P7 / 3X100 , P8 / 1(2X100) 13A,SW SOCKET, GEN USE		500	
		B	16A	2.5	الديوانية	P1-P3 / 3X100 , P4 / 1(2X100) 13A,SW SOCKET, GEN USE			500
	9	R	20A	4	حمام (1)	JB-H1(SH-1) / 1X2000 20A JB& D.P SW FOR WATER HEATER	2000		
		Y	16A	2.5	الدرج + مخزن	P24-25 / 2X100 13A,SW SOCKET, GEN. USE		200	
		B	16A	2.5	نوم سائق	P10-P11 / 2X100 , P12 / 1(2X100) 13A,SW SOCKET, GEN USE			400
	10	R	16A	-	SPARE	-	-		
		Y	16A	-	SPARE	-		-	
		B	16A	-	SPARE	-			-
	TOTAL CONNECTED LOAD (In Summer) =					27.00 KW	9200	9000	8800
	TOTAL CONNECTED LOAD (In Winter) =					27.00 KW	9200	9000	8800

H4 ground floor electrical load plan

DB-G2 : GROUND FLOOR

(10 WAYS,TPN,SPLIT B.B.)

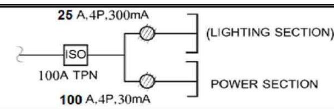


Section	Way No.	Ph.	MCB Rating	wire size mm²	Location	DESCRIPTION NO. OF FITTING (NO. X WATTS/FITT.)		Load in Watt R	Y	B
LIGHTING SECTION	1	R	10A	1.5	ممر (2)	L28 (1X100) / S20		100		
		Y	10A	1.5	غرفه متعددة الإستخدام	L30-L31 (2X100) / S23-S24			200	
		B	16A	-	SPARE	-				-
	2	R	10A	1.5	مخزن (1)	L32 (1X100) / S21		100		
		Y	10A	1.5	إضاءة خارجيه	Lo11-Lo13 (3x100) / So4+So4A			300	
		B	10A	-	SPARE	-				-
	3	R	10A	1.5	مطبخ رئيسي	L33-L38 (6X100) / S25-S26 , EF-3(1X200) / S27		800		
		Y	10A	-	SPARE	-			-	
		B	10A	-	SPARE	-				-
	4	R	10A	-	SPARE	-		-		
		Y	10A	-	SPARE	-			-	
		B	10A	-	SPARE	-				-
POWER SECTION	5	R	25A	4	مطبخ رئيسي	JB-AC6 (S-AC6) / 1X3200	AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC	3200		
		Y	25A	4	مطبخ رئيسي	JB-AC7 (S-AC7) / 1X3200	AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC		3200	
		B	25A	4	مخزن (1)	JB-AC5 (S-AC5) / 1X3200	AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC			3200
	6	R	25A	4	غرفه متعددة الإستخدام	JB-AC8 (S-AC8) / 1X3200	AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC	3200		
		Y	20A	4	مطبخ رئيسي	JB-H4(SH- 4) / 1X3000	20A JB& D.P SW FOR WATER HEATER		3000	
		B	20A	4	حمام (3)	JB-H3(SH- 3) / 1X2000	20A JB& D.P SW FOR WATER HEATER			2000
	7	R	20A	-	SPARE	-		-		
		Y	16A	2.5	غرفه متعددة الإستخدام	P13-P15 / 3X100 , P16 / 1(2X100)	13A,SW SOCKET, GEN USE		500	
		B	16A	2.5	مخزن (1)	P21-P22 / 2X100 , P23 / 1(2X100)	13A,SW SOCKET, GEN USE			400
	8	R	16A	-	SPARE	-		-		
		Y	16A	-	SPARE	-			-	
		B	16A	2.5	مطبخ رئيسي	P17 / 1(2X100) , P18 / 1X500 , P19 / 1(2X500) , P20 / 1X100	13A,SW SOCKET REFREG.& GEN USE			1800
	9	R	16A	-	SPARE	-		-		
		Y	16A	-	SPARE	-			-	
		B	16A	-	SPARE	-				-
	10	R	25A	-	SPARE	-		-		
		Y	25A	-	SPARE	-			-	
		B	25A	-	SPARE	-				-
	TOTAL CONNECTED LOAD (In Summer) =					22.00 KW		7400	7200	7400
	TOTAL CONNECTED LOAD (In Winter) =					22.00 KW		7400	7200	7400

H4 ground floor (b) electrical load plan

DB-F :FIRST FLOOR

(10 WAYS,TPN,SPLIT B.B.)



Section	Way No.	Way Ph.	MCB Rating	wire size (mm²)	Location	DESCRIPTION: NO. OF FITTING (NO. X WATTS/FITT.)	Load in Watt R	Load in Watt Y	Load in Watt B
LIGHTING SECTION	1	R	10A	1.5	ممر(1)+ممر(3) + مخزن	L11-L12 (2X100) / S11-S12 , L24 (1X100) / S22	300		
		Y	10A	1.5	معيشة	L13-L16 (4X100) / S13-S14 , L25 (1X100) / S14		500	
		B	10A	1.5	غرفة نوم(3)+حمام(3)	L6-L10 (5X100) / S6-S9 , EF-6(1X100) / S10 , L6A-L7A (1X100) / S6A-S7A			800
	2	R	10A	1.5	تحضيري+غرفة نوم(2)	LK1 (1x100) / SK1 , EF-5(1X100) / S23 , L22-L23 (2X100) / S20-S21	400		
		Y	10A	1.5	ممر(2)+حمام(2) +غرفة نوم(1)	L17-L21 (5X100) / S15-S16,S18-S19 , EF-8(1X100) / S17 , L5A (1X100) / S5A		700	
		B	10A	1.5	غرفة نوم رئيسيه +ملابس +حمام (1)	L1-L5 (5X100) / S1-S4 , EF-7(1X100) / S5 , L4A (1X100) / S4A			700
	3	R	10A	-	SPARE	-	-		
		Y	10A	-	SPARE	-		-	
		B	10A	-	SPARE	-			-
POWER SECTION	4	R	25A	4	غرفة نوم رئيسيه	JB-AC1 (S-AC1) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM	3200		
		Y	25A	4	غرفة نوم (1)	JB-AC5 (S-AC5) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM		3200	
		B	25A	4	غرفة نوم (2)	JB-AC4 (S-AC4) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM			3200
	5	R	25A	4	غرفة نوم (3)	JB-AC2 (S-AC2) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM	3200		
		Y	25A	4	معيشة	JB-AC6 (S-AC6) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM		3200	
		B	25A	4	تحضيري	JB-AC3 (S-AC3) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM			3200
	6	R	16A	2.5	غرفة نوم رئيسية	P1-P3 / 3X100 , P4 / 1(2X100) 13A,SW SOCKET, GEN USE	500		
		Y	20A	4	تحضيري	JB-H8 (SH-8) / 1X1500 20A JB& D.P SW FOR WATER HEATER		1500	
		B	16A	2.5	معيشة	P9-P11 / 3X100 , P12 / 1(2X100) 13A,SW SOCKET, GEN USE			500
	7	R	20A	4	حمام (2)	JB-H6(SH- 6) / 1X2000 20A JB& D.P SW FOR WATER HEATER	2000		
		Y	20A	4	حمام (1)	JB-H5 (SH- 5) / 1X2000 20A JB& D.P SW FOR WATER HEATER		2000	
		B	20A	4	حمام (3)	JB-H7(SH- 7) / 1X2000 20A JB& D.P SW FOR WATER HEATER			2000
	8	R	16A	2.5	تحضيري	P21-P22 / 2X100 , P23 / 1(2X500) 13A,SW SOCKET GEN&REFREG. USE	1200		
		Y	16A	2.5	مخزن	P24 / 1X100 13A,SW SOCKET, GEN. USE		100	
		B	16A	2.5	غرفة نوم (2)	P17-P19 / 3X100 , P20 / 1(2X100) 13A,SW SOCKET, GEN USE			500
	9	R	16A	2.5	غرفة نوم (1)	P13-P15 / 3X100 , P16 / 1(2X100) 13A,SW SOCKET GEN&REFREG. USE	500		
		Y	16A	-	SPARE	-		-	
		B	16A	2.5	غرفة نوم (3)	P5-P8 / 4X100 13A,SW SOCKET, GEN. USE			400
	10	R	16A	-	SPARE	-	-		
		Y	16A	-	SPARE	-		-	
		B	16A	-	SPARE	-			-
					TOTAL CONNECTED LOAD (In Summer) =	33.80 KW	11300	11200	11300
					TOTAL CONNECTED LOAD (In Winter) =	33.80 KW	11300	11200	11300

H4 first floor load plan

	DB-R : ROOF FLOOR (8 WAYS,TPN,SPLIT B.B.)					25 A,4P,300mA (LIGHTING SECTION); ISO 100A TPN; 100 A,4P,30mA POWER SECTION			
	Way		MCB Rating	wire size mm²	Location	DESCRIPTION NO. OF FITTING (NO. X WATTS/FITT.)	Load in Watt		
	No.	Ph.					R	Y	B
LIGHTING SECTION	1	R	16A	-	SPARE	-	-		
		Y	10A	1.5	غسيل	L9 (1X100) / S9 , EF-10 (1X100) / S10		200	
		B	16A	1.5	كي + مخزن+موزع	L3-L4 (2X100) / S3-S4 , L1-L2 (2X100) / S1-S2			400
	2	R	16A	-	SPARE	-	-		
		Y	16A	-	SPARE	-		-	
		B	10A	1.5	إضاءة خارجيه	LR1-LR3 (3X100) / SR1			300
	3	R	10A	1.5	حمام	L7-L8 (2X100) / S7 , EF-9(1X100) / S8	300		
		Y	10A	1.5	خادمة	L5-L6 (2X100) / S5-S6		200	
		B	10A	1.5	مخزن	L10(1X100) / S11			100
POWER SECTION	4	R	25A	4	خادمة	JB-AC1 (S-AC1) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM	3200		
		Y	25A	4	كي	JB-AC2 (S-AC2) / 1X3200 AS PER TYPICAL INSTALLATION FOR EACH A/C MINI SPLIT UNIT SHOWN IN SCHEMATIC DIAGRAM		3200	
		B	20A	4	غسيل	JB-H9 (SH-9) / 1X3000 20A JB& D.P SW FOR WATER HEATER			3000
	5	R	16A	4	غسيل	P10 / 1X1500 15A,SW SOCKET, WASHING MACH.	1500		
		Y	16A	4	غسيل	P11 / 1X1500 15A,SW SOCKET, WASHING MACH.		1500	
		B	16A	4	غسيل	P12 / 1X1500 15A,SW SOCKET, WASHING MACH.			1500
	6	R	16A	2.5	كي + مخزن (1)	P4-P5 / 2X100 , P6-P7 / 2X100 13A,SW SOCKET, GEN USE	400		
		Y	16A	2.5	خادمة	P1-P2 / 2X100 , P3 / 1(2X100) 13A,SW SOCKET, GEN USE		400	
		B	16A	2.5	مخزن + الدرج	P9 / 1X100 , P12 / 1X100 13A,SW SOCKET, GEN USE			200
	7	R	16A	2.5	موزع	P8 / 1X100 13A,SW SOCKET, GEN USE	100		
		Y	16A	-	SPARE	-		-	
		B	16A	-	SPARE	-			-
	8	R	16A	-	SPARE	-	-		
		Y	16A	-	SPARE	-		-	
		B	16A	-	SPARE	-			-
	TOTAL CONNECTED LOAD (In Summer) =					16.50 KW	5500	5500	5500
	TOTAL CONNECTED LOAD (In Winter) =					16.50 KW	5500	5500	5500

H4 roof floor load plan

APPENDIX B: RENEWABLE ENERGY TECHNOLOGY & BATTERIES PARAMETERS FOR KEWSM

Solar technologies parameters

Technology	***Life*** *Years*	***Construction Time*** *Years*	***Investment Cost 2025*** *$/kW*	***Investment Cost 2033*** *$/kW*	***Investment Cost 2043*** *$/kW*	***Annual O&M 2025-2033*** *$/kW*	***Annual O&M 2033-2043*** *$/kW*	***Annual Availability*** *%*	***Capacity Credit*** *%*
Tower w/ storage	30	2	5,656	3,215	1,587	112 – 64	64-33	37%	50%
Trough	30	2	4,513	3,044	1,861	77 – 52	52-32	23%	20%
Trough w/ storage	30	2	4,340	2,686	1,475	69 – 42	42-25	37%	50%
Trough hybrid	30	2	4,013	2,484	1,364	68 – 42	42-23	23%	100%
Fresnel	30	2	4,161	3,173	2,261	83 – 64	64-45	23%	20%
Fresnel w/ storage	30	2	4,674	3,310	2,150	83- 64	64-45	37%	50%
Fresnel hybrid	30	2	3,950	3,147	2,203	58 – 44	33	23%	100%
Stirling engine	30	2	4,655	3,712	2,797	93 – 72	72-56	23%	20%
Utility-scale PVs:									
Fixed-axis	30	1.5	688	388	189	7.2-4	4-2	17%	20%
Single axis	30	1.5	1,080	609	297	7.3-4	4-2	17%	20%
Dual axis	30	1.5	1,197	675	330	7.4-4.2	4.2-2	17%	20%
Residential rooftop PVs	3	1	655	622	605	7.7-7.3	7.3-7.1	17%	20%
Wind (onshore)	30	1	1,590	1,489	1,484	41-39	39-38	28%	20%

Source: Adapted from O. Alsayegh et al. (2012), IRENA (2023), IRENA (2024), and NREL (2024)

Renewable technologies cost assumptions:

Technologies life time, construction time, annual availability and capacity credit are based on O. Alsayegh et al. (2012). Investment costs and annual operating and maintenance costs were developed based on market data and trends published in IRENA (2023), IRENA (2024), and when technologies cost was not available in these reports it was taken from NREL (2024).

Comparable regions were selected from the reports. For instance, when Saudi Arabia or UAE costs were available, they were selected. Otherwise, the global weighted average was chosen. Cost projections were based on trend average between 2019 and 2023. For NREL (2024) data, the "advanced case" projection costs were selected.

Seasonal and diurnal capacity factors for solar technologies

	WD1	WD2	WP	I1N	I1D1	I1D2	I1P	I2N	I2D1	I2D2	I2P	SN	SD1	SD2	SP
Solar Thermal Parabolic Trough plants	0%	30%	0%	0%	7%	36%	80%	0%	15%	34%	80%	7%	14%	38%	75%
Solar Thermal Parabolic Trough with storage 6.5-h plants	0%	46%	25%	0%	7%	67%	80%	0%	16%	66%	80%	3%	16%	69%	90%
Solar Thermal Parabolic Trough Field	0%	30%	0%	0%	7%	36%	80%	0%	15%	34%	80%	7%	14%	38%	75%
Solar Thermal Power Tower with thermal storage plant	0%	46%	25%	0%	7%	67%	80%	0%	16%	66%	80%	3%	16%	69%	90%
Solar thermal Fresnel panels	0%	30%	0%	0%	7%	36%	80%	0%	15%	34%	80%	7%	14%	38%	75%
Solar thermal Fresnel panels with storage plant	0%	46%	25%	0%	7%	67%	80%	0%	16%	66%	80%	3%	16%	69%	90%
Solar Thermal Fresnel Field	0%	30%	0%	0%	7%	36%	80%	0%	15%	34%	80%	7%	14%	38%	75%
Solar thermal Stirling Parabolic Dish	0%	30%	0%	0%	7%	36%	80%	0%	15%	34%	80%	7%	14%	38%	75%
Utility-scale PVs:*															
Fixed-axis	0%	0%	36%	0%	0%	11%	59%	34%	0%	9%	59%	32%	1%	22%	63%
Single axis	0%	0%	43%	0%	1%	22%	64%	46%	0%	16%	64%	48%	2%	42%	67%
Dual axis	0%	0%	45%	0%	1%	23%	64%	47%	0%	16%	64%	48%	2%	43%	69%
Residential Rooftop Solar PV	0%	28%	0%	0%	4%	22%	48%	0%	9%	20%	48%	4%	8%	22%	43%
Wind (onshore)*	35%	36%	30%	38%	40%	34%	32%	30%	33%	27%	21%	25%	59%	48%	50%

Source: Adapted from O. Alsayegh et al. (2012); For utility-scale PVs and wind: Renewables.ninja (2025)

Battery technologies parameters

Technology	*Life* *Years*	*Efficiency*	*Discharge Time* *Hr*	*Energy Cost 2025 $/kWh*	*Energy Cost 2050 $/kWh*	*Annual O&M 2025 $/kW*
Lead-acid batteries	8	80%	4	178	146	4.6
Li-ion batteries	10	90%	1	241	234	4.6
NaS batteries	15	85%	4	318	281	4.6

Technology parameters based on: Simoes et al. (2013)

APPENDIX C: WATER CONSUMPTION PER HOUSING SEGMENT UNDER DIFFERENT DEMAND CONSERVATION SCENARIOS

Residential end-use water consumption for different household categories in REF scenario

[M m^3]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Bathroom	36	41	54	57	61	64	67	70	72
Kitchen	14	15	24	31	33	36	39	43	47
Laundry	8	9	13	18	19	21	22	24	27
Outdoor	7	8	12	16	17	18	20	22	24
Carwash	10	11	16	21	23	25	27	29	32
Total	75	84	119	142	153	164	176	188	201
Residential GO									
Bathroom	23	29	44	62	74	87	101	117	135
Kitchen	9	11	19	35	42	51	61	74	90
Laundry	5	6	11	20	24	29	35	42	51
Outdoor	5	6	10	18	21	26	31	38	46
Carwash	5	6	10	18	22	27	33	40	48
Total	47	58	95	152	183	218	261	312	371
Residential PH									
Bathroom	69	73	65	52	52	51	49	48	46
Kitchen	27	27	27	27	26	26	26	26	27
Laundry	15	15	16	15	15	15	15	15	15
Outdoor	13	14	14	13	13	13	13	13	13
Carwash	35	35	36	35	35	34	35	35	35
Total	158	165	158	142	141	140	139	137	135
Residential IA	**119**								
Bathroom	119	133	196	318	377	459	547	611	657
Kitchen	19	29	34	55	66	81	96	108	116
Laundry	6	11	12	19	23	28	34	38	41
Outdoor	0	0	0	0	0	0	0	0	0
Carwash	5	7	8	14	16	20	24	26	29
Total	148	180	250	406	482	588	701	783	842

Residential end-use water consumption for different household categories in MN-CM scenario

[M m³]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Bathroom	36.11	40.98	54.05	46.66	42.66	45.06	47.19	48.97	50.38
Kitchen	13.99	15.33	23.67	27.03	29.30	31.73	34.54	37.54	40.89
Laundry	7.90	8.65	13.38	17.52	18.99	20.57	22.40	24.36	26.55
Outdoor	7.06	7.73	11.96	15.65	16.96	18.37	20.01	21.76	23.72
Carwash	9.53	10.97	16.14	21.13	22.90	24.81	27.01	29.38	32.02
Total	75	84	119	128	131	141	151	162	174
Residential GO									
Bathroom	23.47	29.15	43.91	52.08	51.19	60.21	70.23	81.21	93.09
Kitchen	9.09	10.99	19.49	30.25	36.59	44.21	53.71	65.14	79.18
Laundry	5.14	6.20	11.02	19.60	23.71	28.66	34.83	42.27	51.42
Outdoor	4.59	5.54	9.85	17.51	21.18	25.61	31.12	37.76	45.94
Carwash	4.82	5.82	10.34	0.92	1.11	1.34	1.63	1.98	2.41
Total	47	58	95	120	134	160	192	228	272
Residential PH									
Bathroom	68.64	73.09	65.25	42.13	37.59	36.89	35.92	34.71	33.29
Kitchen	26.59	27.17	27.44	23.21	23.16	23.10	23.16	23.18	23.25
Laundry	15.02	15.34	15.52	15.04	15.01	14.98	15.02	15.04	15.10
Outdoor	13.42	13.70	13.86	13.43	13.41	13.38	13.42	13.44	13.49
Carwash	34.55	35.28	35.69	1.73	1.73	1.72	1.73	1.73	1.74
Total	158	165	158	96	91	90	89	88	87
Residential IA									
Bathroom	118.56	133.05	195.66	307.22	355.59	433.00	515.79	576.25	619.39
Kitchen	18.56	29.45	34.10	48.81	58.19	71.24	85.20	95.40	102.67
Laundry	6.49	10.55	11.95	19.30	23.00	28.17	33.69	37.72	40.59
Outdoor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carwash	4.56	7.41	8.39	0.68	0.81	0.99	1.18	1.32	1.43
Total	148	180	250	376	438	533	636	711	764

Residential end-use water consumption for different household categories in HN-CM scenario

[M m^3]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Bathroom	36.11	41.02	54.05	46.66	42.66	45.06	47.19	48.97	50.38
Kitchen	13.99	15.33	23.67	3.28	3.56	3.84	4.17	4.51	4.89
Laundry	7.90	8.65	13.38	17.52	18.99	20.57	22.40	24.36	26.55
Outdoor	7.06	7.73	11.96	15.65	16.96	18.37	20.01	21.76	23.72
Carwash	9.53	10.96	16.14	22.79	22.90	24.81	27.01	29.38	32.02
Total	75	84	119	106	105	113	121	129	138
Residential GO									
Bathroom	23.47	29.19	43.91	52.08	51.19	60.21	70.23	81.21	93.09
Kitchen	9.09	10.99	19.49	3.67	4.44	5.35	6.48	7.83	9.47
Laundry	5.14	6.20	11.02	19.60	23.71	28.66	34.83	42.27	51.42
Outdoor	4.59	5.54	9.85	17.51	21.18	25.61	31.12	37.76	45.94
Carwash	4.82	5.82	10.34	0.92	1.11	1.34	1.63	1.98	2.41
Total	47	58	95	94	102	121	144	171	202
Residential PH									
Bathroom	68.64	73.13	65.25	42.13	37.59	36.89	35.92	34.71	33.29
Kitchen	26.59	27.17	27.44	2.82	2.81	2.80	2.79	2.79	2.78
Laundry	15.02	15.34	15.52	15.04	15.01	14.98	15.02	15.04	15.10
Outdoor	13.42	13.70	13.86	13.43	13.41	13.38	13.42	13.44	13.49
Carwash	34.55	35.28	35.69	1.73	1.73	1.72	1.73	1.73	1.74
Total	158	165	158	75	71	70	69	68	66
Residential IA									
Bathroom	118.56	133.10	195.66	307.22	355.59	433.00	515.79	576.25	619.39
Kitchen	18.56	29.45	34.10	16.82	20.05	24.55	29.37	32.88	35.39
Laundry	6.49	10.55	11.95	19.30	23.00	28.17	33.69	37.72	40.59
Outdoor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carwash	4.56	7.41	8.39	0.68	0.81	0.99	1.18	1.32	1.43
Total	148	181	250	344	399	487	580	648	697

Residential end-use water consumption for different household categories in GHGO-CM scenario

[M m^3]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Bathroom	36.11	41.00	54.05	46.66	42.66	45.06	47.19	48.97	50.38
Kitchen	13.99	15.33	23.67	27.03	29.30	31.73	34.54	37.54	40.89
Laundry	7.90	8.65	13.38	17.52	18.99	20.57	22.40	24.36	26.55
Outdoor	7.06	7.73	11.96	15.65	16.96	18.37	20.01	21.76	23.72
Carwash	9.53	10.97	16.14	21.13	22.90	24.81	27.01	29.38	32.02
Total	75	84	119	128	131	141	151	162	174
Residential GO									
Bathroom	23.47	29.16	43.91	52.08	51.19	60.21	70.23	81.21	93.09
Kitchen	9.09	10.99	19.49	30.25	36.59	44.21	53.71	65.14	79.18
Laundry	5.14	6.20	11.02	19.60	23.71	28.66	34.83	42.27	51.42
Outdoor	4.59	5.54	9.85	17.51	21.18	25.61	31.12	37.76	45.94
Carwash	4.82	5.82	10.34	18.39	22.24	26.89	32.67	39.65	48.23
Total	47	58	95	138	155	186	223	266	318
Residential PH									
Bathroom	68.64	73.10	65.25	52.37	51.78	50.77	49.35	47.58	45.51
Kitchen	26.59	27.17	27.44	26.52	26.47	26.40	26.46	26.49	26.57
Laundry	15.02	15.34	15.52	15.04	15.01	14.98	15.02	15.04	15.10
Outdoor	13.42	13.70	13.86	13.43	13.41	13.38	13.42	13.44	13.49
Carwash	34.55	35.28	35.69	34.59	34.54	34.45	34.55	34.60	34.73
Total	158	165	158	142	141	140	139	137	135
Residential IA									
Bathroom	118.56	133.07	195.66	317.77	376.81	458.98	546.85	611.04	656.83
Kitchen	18.56	29.45	34.10	55.20	65.81	80.57	96.36	107.89	116.12
Laundry	6.49	10.55	11.95	19.30	23.00	28.17	33.69	37.72	40.59
Outdoor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carwash	4.56	7.41	8.39	13.56	16.16	19.79	23.66	26.50	28.52
Total	148	180	250	406	482	588	701	783	842

APPENDIX D: WATER CONSUMPTION PER APPLIANCE UNDER DIFFERENT DEMAND CONSERVATION SCENARIOS

Detailed Residential end-use water consumption REF Scenario

	2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Bathroom									
Faucet	29.0	30.6	33.5	48.0	56.2	67.3	79.1	88.1	94.8
Ablution faucet	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Shower head	113.8	130.8	171.2	223.6	256.3	298.4	343.1	379.1	408.2
Sprayer	10.4	11.9	16.6	23.9	27.9	33.2	38.9	43.2	46.5
Toilet	70.7	81.5	115.5	170.4	199.5	238.8	280.8	312.6	336.5
Bathroom	247	278	360	489	563	661	765	846	909
Kitchen									
Faucet - drinking	2.3	2.7	3.8	5.7	6.7	8.0	9.5	10.6	11.4
Faucet - dishwashing	65.9	80.3	100.9	141.4	160.8	185.7	214.2	241.2	268.6
Dishwashers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen	68	83	105	147	168	194	224	252	280
Laundry	35	41	52	71	81	92	106	119	134
Outdoor use									
Carwash	53.5	59.8	70.6	87.7	95.8	105.9	117.9	130.1	143.5
Faucet	25.1	27.0	35.7	46.6	51.6	57.4	64.5	73.0	83.1
Outdoor use	79	87	106	134	147	163	182	203	227

Detailed residential end-use water consumption MN-CM Scenario

	2008	*2013*	*2018*	*2023*	*2028*	*2033*	*2038*	*2043*	*2048*
Bathroom									
Faucet	29.0	30.9	33.0	33.3	29.6	35.4	41.6	46.4	49.9
Ablution faucet	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Shower head	113.8	130.8	171.2	197.6	207.1	244.8	284.9	316.1	340.3
Sprayer	10.4	11.9	16.6	23.9	27.9	33.2	38.9	43.2	46.5
Toilet	70.7	81.5	115.5	170.4	199.5	238.8	280.8	312.6	336.5
Bathroom	247	278	359	448	487	575	669	741	796
Kitchen									
Faucet - drinking	2.3	2.7	3.8	5.7	6.7	8.0	9.5	10.6	11.4
Faucet - dishwashing	65.9	80.3	100.9	0.0	0.0	0.0	0.0	0.0	0.0
Dishwashers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen	68	83	105	6	7	8	9	11	11
Laundry	35	41	52	71	81	92	106	119	134
Outdoor use									
Carwash	53.5	59.8	70.6	24.5	26.5	28.9	31.6	34.4	37.6
Faucet	25.1	27.0	35.7	46.6	51.6	57.4	64.5	73.0	83.1
Outdoor use	79	87	106	71	78	86	96	107	121

Detailed residential end-use water consumption HN-CM Scenario

	2008	2013	2018	2023	2028	2033	2038	2043	2048
Bathroom									
Faucet	29.0	30.4	33.7	35.4	29.6	35.4	41.6	46.4	49.9
Ablution faucet	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Shower head	113.8	130.8	171.2	139.1	151.9	177.2	204.0	225.5	242.8
Sprayer	10.4	11.9	16.6	23.9	27.9	33.2	38.9	43.2	46.5
Toilet	70.7	81.5	115.5	170.4	199.5	238.8	280.8	312.6	336.5
Bathroom	247	278	360	392	432	508	588	651	699
Kitchen									
Faucet - drinking	2.3	2.7	3.8	5.7	6.7	8.0	9.5	10.6	11.4
Faucet - dishwashing	65.9	80.3	100.9	0.0	0.0	0.0	0.0	0.0	0.0
Dishwashers	0.0	0.0	0.0	4.8	5.4	6.2	7.1	8.0	9.0
Kitchen	68	83	105	11	12	14	17	19	20
Laundry	35	41	52	71	81	92	106	119	134
Outdoor use									
Carwash	53.5	59.8	70.6	12.5	8.2	9.0	9.9	10.9	12.0
Faucet	25.1	27.0	35.7	26.3	21.5	23.9	26.9	30.4	34.6
Outdoor use	79	87	106	39	30	33	37	41	47

Detailed residential end-use water consumption GHGO-CM Scenario

	2008	2013	2018	2023	2028	2033	2038	2043	2048
Bathroom									
Faucet	29.0	30.8	33.2	45.1	52.2	62.8	74.0	82.4	88.5
Ablution faucet	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Shower head	113.8	130.8	171.2	206.5	219.9	257.3	297.0	327.7	351.3
Sprayer	10.4	11.9	16.6	23.9	27.9	33.2	38.9	43.2	46.5
Toilet	70.7	81.5	115.5	170.4	199.5	238.8	280.8	312.6	336.5
Bathroom	247	278	359	469	522	615	714	789	846
Kitchen									
Faucet - drinking	2.3	2.7	3.8	5.7	6.7	8.0	9.5	10.6	11.4
Faucet - dishwashing	65.9	80.3	100.9	76.8	86.5	99.9	114.5	125.1	132.7
Dishwashers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen	68	83	105	83	93	108	124	136	144
Laundry	35	41	52	71	81	92	106	119	134
Outdoor use									
Carwash	53.5	59.8	70.6	87.7	95.8	105.9	117.9	130.1	143.5
Faucet	25.1	27.0	35.7	46.6	51.6	57.4	64.5	73.0	83.1
Outdoor use	79	87	106	134	147	163	182	203	227

Detailed residential end-use water consumption IA-CM Scenario

	2008	2013	2018	2023	2028	2033	2038	2043	2048
Bathroom									
Faucet	29.0	30.7	33.2	37.5	35.0	41.3	48.0	53.3	57.4
Ablution faucet	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Shower head	113.8	130.8	171.2	223.6	256.3	298.4	343.1	379.1	408.2
Sprayer	10.4	11.9	16.6	23.9	27.9	33.2	38.9	43.2	46.5
Toilet	70.7	81.5	115.5	170.4	199.5	238.8	280.8	312.6	336.5
Bathroom	247	278	360	478	542	635	734	811	871
Kitchen									
Faucet - drinking	2.3	2.7	3.8	5.7	6.7	8.0	9.5	10.6	11.4
Faucet - dishwashing	65.9	80.3	100.9	90.8	100.5	111.8	125.8	142.3	162.1
Dishwashers	0.0	0.0	0.0	1.1	1.4	1.7	2.0	2.2	2.4
Kitchen	68	83	105	98	109	122	137	155	176
Laundry	35	41	52	71	81	92	106	119	134
Outdoor use									
Carwash	53.5	59.8	70.6	24.5	26.5	28.9	31.6	34.4	37.6
Faucet	25.1	27.0	35.7	46.6	51.6	57.4	64.5	73.0	83.1
Outdoor use	79	87	106	71	78	86	96	107	121

Detailed residential end-use water consumption MB-CM Scenario

	2008	2013	2018	2023	2028	2033	2038	2043	2048
Bathroom									
Faucet	29.0	30.6	33.4	48.0	56.2	67.3	79.1	88.1	94.8
Ablution faucet	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9	22.9
Shower head	113.8	130.8	171.2	136.3	156.3	181.9	209.2	231.1	248.9
Sprayer	10.4	11.9	16.6	23.9	27.9	33.2	38.9	43.2	46.5
Toilet	70.7	81.5	115.5	170.4	199.5	238.8	280.8	312.6	336.5
Bathroom	247	278	360	402	463	544	631	698	750
Kitchen									
Faucet - drinking	2.3	2.7	3.8	5.7	6.7	8.0	9.5	10.6	11.4
Faucet - dishwashing	65.9	80.3	100.9	141.4	160.8	185.7	214.2	241.2	268.6
Dishwashers	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Kitchen	68	83	105	147	168	194	224	252	280
Laundry	35	41	52	71	81	92	106	119	134
Outdoor use									
Carwash	53.5	59.8	70.6	43.8	47.9	53.0	59.0	65.1	71.8
Faucet	25.1	27.0	35.7	31.1	34.4	38.2	43.0	48.6	55.4
Outdoor use	79	87	106	75	82	91	102	114	127

APPENDIX E: ELECTRICITY CONSUMPTION PER HOUSING SEGMENT UNDER DIFFERENT DEMAND CONSERVATION SCENARIOS

Residential electricity end-use energy consumption for different household categories in REF scenario

[PJ]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Air conditioning	8.6	9.5	14.6	19.2	20.8	22.5	24.5	26.6	29.0
Lighting	2.3	1.4	2.1	2.1	1.5	1.6	1.8	1.9	2.1
Refrigerators, freezers, and water coolers	1.5	1.5	2.2	2.8	3.0	3.3	3.6	3.9	4.2
Space heating & water heaters	1.6	1.8	2.8	3.6	4.0	4.3	4.7	5.1	5.5
Other appliances	0.9	1.3	1.6	2.1	2.3	2.5	2.7	2.9	3.2
Total	15	15	23	30	32	34	37	40	44
Residential GO									
Air conditioning	6.1	7.4	13.1	23.2	28.1	34.0	41.3	50.1	61.0
Lighting	1.6	1.1	1.9	3.4	3.3	2.5	3.0	3.6	4.4
Refrigerators, freezers, and water coolers	1.0	1.2	2.0	3.4	4.2	5.0	6.1	7.4	9.0
Space heating & water heaters	1.2	1.4	2.5	4.4	5.4	6.5	7.9	9.5	11.6
Other appliances	0.7	1.1	1.4	2.5	3.1	3.7	4.5	5.5	6.6
Total	11	12	21	37	44	52	63	76	93
Residential PH									
Air conditioning	22.9	23.4	23.7	22.9	22.9	22.8	22.9	22.9	23.0
Lighting	6.0	3.4	3.3	1.3	1.3	1.3	1.3	1.3	1.3
Refrigerators, freezers, and water coolers	3.9	3.8	3.7	3.4	3.4	3.4	3.4	3.4	3.4
Space heating & water heaters	4.4	4.5	4.5	4.4	4.4	4.4	4.4	4.4	4.4
Other appliances	2.5	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5
Total	40	38	38	35	34	34	34	35	35
Residential IA									
Air conditioning	15.4	23.9	27.1	43.8	52.2	63.9	76.4	85.5	92.0
Lighting	4.0	3.5	3.6	2.2	2.6	3.2	3.8	4.3	4.6
Refrigerators, freezers, and water coolers	2.6	3.5	3.9	6.1	7.2	8.9	10.6	11.9	12.8
Space heating & water heaters	2.9	4.5	5.1	8.3	9.9	12.1	14.5	16.2	17.5
Other appliances	1.7	2.8	3.1	5.0	5.9	7.2	8.7	9.7	10.4
Total	27	38	43	65	78	95	114	128	137

Residential electricity end-use energy consumption for different household categories in MN-CM scenario

[PJ]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Air conditioning	8.6	9.5	14.6	17.8	18.8	18.8	18.9	19.9	21.3
Lighting	2.3	1.4	1.8	1.3	1.5	1.6	1.7	1.9	2.0
Refrigerators, freezers, and water coolers	1.5	1.5	2.2	2.8	3.0	3.3	3.6	3.9	4.2
Space heating & water heaters	1.6	1.8	2.8	3.6	4.0	4.3	4.7	5.1	5.5
Other appliances	0.9	1.2	1.6	2.1	2.3	2.5	2.7	2.9	3.2
Total	15	15	23	28	29	30	32	34	36
Residential GO									
Air conditioning	6.1	7.4	13.1	21.5	25.3	28.5	31.7	37.2	44.7
Lighting	1.6	1.1	3.7	1.6	2.0	2.4	2.9	3.6	4.3
Refrigerators, freezers, and water coolers	1.0	1.2	2.0	3.4	4.2	5.0	6.1	7.4	9.0
Space heating & water heaters	1.2	1.4	2.5	4.4	5.4	6.5	7.9	9.5	11.6
Other appliances	0.7	1.1	1.4	2.5	3.1	3.7	4.5	5.5	6.6
Total	11	12	23	34	40	46	53	63	76
Residential PH									
Air conditioning	22.9	23.4	23.7	21.5	20.8	19.7	18.6	17.8	17.6
Lighting	6.0	3.4	1.5	1.3	1.3	1.3	1.3	1.3	1.3
Refrigerators, freezers, and water coolers	3.9	3.8	3.7	3.4	3.4	3.4	3.4	3.4	3.4
Space heating & water heaters	4.4	4.5	4.5	4.4	4.4	4.4	4.4	4.4	4.4
Other appliances	2.5	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5
Total	40	38	36	33	32	31	30	29	29
Residential IA									
Air conditioning	15.4	23.9	27.1	41.0	47.3	55.2	62.4	67.8	72.1
Lighting	4.0	3.5	1.7	2.1	2.5	3.1	3.7	4.2	4.5
Refrigerators, freezers, and water coolers	2.6	3.5	3.9	6.1	7.2	8.9	10.6	11.9	12.8
Space heating & water heaters	2.9	4.5	5.1	8.3	9.9	12.1	14.5	16.2	17.5
Other appliances	1.7	2.7	3.1	5.0	5.9	7.2	8.7	9.7	10.4
Total	27	38	41	62	73	86	100	110	117

Residential electricity end-use energy consumption for different household categories in HN-CM scenario

[PJ]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Air conditioning	8.6	9.5	14.6	17.0	17.4	17.4	18.2	19.6	21.3
Lighting	2.3	1.4	1.8	1.3	1.3	1.1	1.2	1.3	1.4
Refrigerators, freezers, and water coolers	1.5	1.5	2.2	2.8	3.0	3.3	3.6	3.9	4.2
Space heating & water heaters	1.6	1.8	2.8	3.6	4.0	4.3	4.7	5.1	5.5
Other appliances	0.9	1.2	1.6	2.1	2.3	2.5	2.7	2.9	3.2
Total	15	15	23	27	28	29	30	33	36
Residential GO									
Air conditioning	6.1	7.4	13.1	19.9	21.7	24.1	26.1	31.3	38.0
Lighting	1.6	1.1	3.7	1.5	1.8	1.7	2.1	2.6	3.1
Refrigerators, freezers, and water coolers	1.0	1.2	2.0	3.4	4.2	5.0	6.1	7.4	9.0
Space heating & water heaters	1.2	1.4	2.5	4.4	5.4	6.5	7.9	9.5	11.6
Other appliances	0.7	1.1	1.4	2.5	3.1	3.7	4.5	5.5	6.6
Total	11	12	23	32	36	41	47	56	68
Residential PH									
Air conditioning	22.9	23.4	23.7	20.6	19.6	18.4	17.8	17.6	17.6
Lighting	6.0	3.4	1.5	1.3	1.3	1.3	1.3	1.3	1.3
Refrigerators, freezers, and water coolers	3.9	3.8	3.7	3.4	3.4	3.4	3.4	3.4	3.4
Space heating & water heaters	4.4	4.5	4.5	4.4	4.4	4.4	4.4	4.4	4.4
Other appliances	2.5	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5
Total	40	38	36	32	31	30	29	29	29
Residential IA									
Air conditioning	15.4	23.9	27.1	41.1	48.5	58.6	69.0	76.6	82.2
Lighting	4.0	3.5	1.7	2.1	2.5	3.1	3.7	4.2	4.5
Refrigerators, freezers, and water coolers	2.6	3.5	3.9	6.1	7.2	8.9	10.6	11.9	12.8
Space heating & water heaters	2.9	4.5	5.1	8.3	9.9	12.1	14.5	16.2	17.5
Other appliances	1.7	2.8	3.1	5.0	5.9	7.2	8.7	9.7	10.4
Total	27	38	41	63	74	90	106	119	127

Residential electricity end-use energy consumption for different household categories in GHGO-CM scenario

[PJ]	2008	2013	2018	2023	2028	2033	2038	2043	2048
Residential GH									
Air conditioning	8.6	9.5	14.6	17.8	18.8	18.8	18.9	19.9	21.3
Lighting	2.3	1.4	1.8	1.3	1.3	1.1	1.2	1.3	1.4
Refrigerators, freezers, and water coolers	1.5	1.5	2.2	2.8	3.0	3.3	3.6	3.9	4.2
Space heating & water heaters	1.6	1.8	2.8	3.6	4.0	4.3	4.7	5.1	5.5
Other appliances	0.9	1.3	1.6	2.1	2.3	2.5	2.7	2.9	3.2
Total	15	15	23	28	29	30	31	33	36
Residential GO									
Air conditioning	6.1	7.4	13.1	21.5	25.3	28.5	31.7	37.2	44.7
Lighting	1.6	1.1	3.7	1.5	1.8	1.7	2.1	2.6	3.1
Refrigerators, freezers, and water coolers	1.0	1.2	2.0	3.4	4.2	5.0	6.1	7.4	9.0
Space heating & water heaters	1.2	1.4	2.5	4.4	5.4	6.5	7.9	9.5	11.6
Other appliances	0.7	1.1	1.4	2.5	3.1	3.7	4.5	5.5	6.6
Total	11	12	23	33	40	45	52	62	75
Residential PH									
Air conditioning	22.9	23.4	23.7	21.6	21.5	21.5	21.5	21.6	21.7
Lighting	6.0	3.4	3.3	1.3	1.3	1.3	1.3	1.3	1.3
Refrigerators, freezers, and water coolers	3.9	3.8	3.7	3.4	3.4	3.4	3.4	3.4	3.4
Space heating & water heaters	4.4	4.5	4.5	4.4	4.4	4.4	4.4	4.4	4.4
Other appliances	2.5	2.6	2.6	2.5	2.5	2.5	2.5	2.5	2.5
Total	40	38	38	33	33	33	33	33	33
Residential IA									
Air conditioning	15.4	23.9	27.1	41.1	49.0	60.0	71.8	80.4	86.5
Lighting	4.0	3.5	3.6	2.1	2.5	3.1	3.7	4.2	4.5
Refrigerators, freezers, and water coolers	2.6	3.5	3.9	6.1	7.2	8.9	10.6	11.9	12.8
Space heating & water heaters	2.9	4.5	5.1	8.3	9.9	12.1	14.5	16.2	17.5
Other appliances	1.7	2.8	3.1	5.0	5.9	7.2	8.7	9.7	10.4
Total	27	38	43	63	75	91	109	122	132

Appendix F: Levelised Cost of Electricity Calculation Example

Utility-scale solar PV fixed-axis technology specifications for sample LCOE calculation

Component	***Description***
Technology	Utility-Scale Solar PV Fixed Axis
Start year	2025
Observed Year	2025
Discount rate	7.8%
Investment cost	688 US$/kW
Fixed operating expenditure	7.16 US$/kW
Fuel-specific operating expenditure	0 US$
Fuel-specific acquisition expenditure	0 US$
Output	26 GWh

$$LCOE = \frac{\frac{688\ US\$/kW}{(1+0.078)^{(1-1)}} + \frac{7.16\ US\$/kW + 0 + 0}{(1+0.078)^{(1-0.5)}}}{\frac{26\ \times 10^{6}\ kWh}{(1+0.078)^{(1-0.5)}}} = 27.34\ US\$/MWh$$

LCOE calculated by model for the same year = 24.5 US$/MWh