Kuwait Residential Energy Outlook

Modeling the Diffusion of Energy Conservation Measures

by

Turki Rakan M. J. Alajmi

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Graduate Supervisory Committee:

Patrick E. Phelan, Chair
Kamil Kaloush
Huei-Ping Huang
Liping Wang
Ali Hajiah

ARIZONA STATE UNIVERSITY

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ABSTRACT

The residential building sector accounts for more than 26% of the global energy consumption and 17% of global CO2 emissions. Due to the low cost of electricity in Kuwait and increase of population, Kuwaiti electricity consumption tripled during the past 30 years and is expected to increase by 20% by 2027. In this dissertation, a framework is developed to assess energy savings techniques to help policy-makers make educated decisions. The Kuwait residential energy outlook is studied by modeling the baseline energy consumption and the diffusion of energy conservation measures (ECMs) to identify the impacts on household energy consumption and CO2 emissions.

The energy resources and power generation in Kuwait were studied. The characteristics of the residential buildings along with energy codes of practice were investigated and four building archetypes were developed. Moreover, a baseline of end-use electricity consumption and demand was developed. Furthermore, the baseline energy consumption and demand were projected till 2040. It was found that by 2040, energy consumption would double with most of the usage being from AC. While with lighting, there is a negligible increase in consumption due to a projected shift towards more efficient lighting. Peak demand loads are expected to increase by an average growth rate of 2.9% per year. Moreover, the diffusion of different ECMs in the residential sector was modeled through four diffusion scenarios to estimate ECM adoption rates. ECMs' impact on CO2 emissions and energy consumption of residential buildings in Kuwait was evaluated and the cost of conserved energy (CCE) and annual energy savings for each measure was calculated. AC ECMs exhibited the highest cumulative savings, whereas lighting ECMs showed an immediate energy impact. None of the ECMs in the study were cost effective due to the high subsidy rate (95%), therefore, the impact of ECMs at different subsidy and rebate rates was studied. At 75% subsidized utility price and 40% rebate only on appliances, most of ECMs will be cost effective with high energy savings. Moreover, by imposing charges of $35/ton of CO2, most ECMs will be cost effective.

This dissertation is dedicated to

my mother and late father,

and to my beloved daughters

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1. INTRODUCTION

Global warming is one of the most significant threats facing the world today. Increasing global temperatures put enormous strain on ecosystems across the planet, causing frequent extreme weather events, sea level rise, and resource shortages [1]. Therefore, countries across the world have decided to cooperate in order to mitigate this threat. The recent Paris Climate conference (COP 21) led to an action plan that hopes to keep the global average temperature rise below 2°C [2]. This plan involves reducing carbon dioxide and other Green House Gas (GHG) emissions while fostering sustainable development.

The building sector accounts for more than 35% of the global energy consumption [3]. Over the last forty years, the energy demand associated with residential and commercial buildings has increased steadily at an annual rate of 1.8% [4]. Given the rising population and increased urbanization, the building sector is expected to continue growing globally for decades to come [5]. Energy use in buildings is projected to increase by 32% between 2015 and 2040 [6]. This increase is largely accredited to developing countries where infrastructure development is a key priority.

Of the various types of buildings, residential buildings account for nearly 75% of the overall energy consumption [6]. This sector presents significant opportunities for improving energy efficiency. As can be seen in Figure 1, there is marked variation in energy consumption patterns within residential buildings across the world. It can be seen that the energy demand from such buildings fluctuates between 20% in the developed world to 35% in developing countries [7]. This sector is crucial both in terms of present size and future expected growth. Therefore, any energy saving intervention in this sector can have far reaching positive consequences.

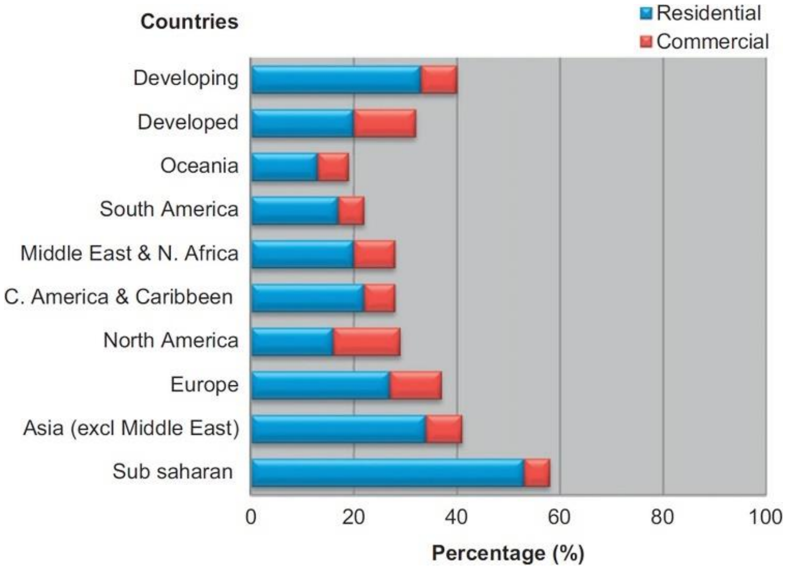


Figure 1 Percentage of buildings energy consumption in different regions of the world [8].

The building sector accounts for nearly a third of the energy-related greenhouse gas (GHG) emissions [9]. The residential sector represents around 17% of global CO_2 emissions [10]. It is well known today that carbon dioxide (which is the major emission from fossil-fuel-based energy) is the main GHG responsible for global warming [8]. Clearly, there is a massive potential in the residential sector for decreasing global total energy-consumption and CO_2 emissions.

The importance of exploring ways to minimize energy consumption in residential buildings is well established from the data provided above. The most common research approach is to consider residential energy use as a function of per capita energy consumption, which in turn is based on income or per capita GDP. However, it is known that residential energy demand is a complex construct, depending on largely individual household characteristics and energy profiles [11]. Additionally, gauging the effectiveness of various energy conservations measures (ECMs) in the residential sector is challenging. This study therefore attempts to understand and subsequently project residential energy use and CO_2 emissions with the aid of a dynamic systems model based on a detailed description of the underlying drivers of residential energy use in Kuwait as a case study.

1.1. Motivation

Kuwait has experienced a steady increase in its population since the 1960s, however with the turn of the century, an exponential rise has been observed as per Figure 2 [12]. This steep increase, along with economic growth, has resulted in higher electrical consumption, exceeding approximately 30 TWh per annum since 2000, whereas the highest level in the 1980s was less than 10 TWh [13]. Besides the high population growth, and rise in new construction, Kuwait has also a high energy use per capita, as shown in Figure 3 [14]. This is mainly driven because of the heavy subsidization of the cost of electricity. Having more than doubled since the early 1990s, per capita energy consumption poses a serious problem [14]. Considering the demand for labor, and the fast-paced development trend in the region, both Figure 2 and Figure 3 clearly indicate the impact created on the electrical load for Kuwait. In addition, according to the Ministry of Energy and Water (MEW), the peak demand is expected to reach 30,000 MW by 2030, whilst 70% of this is attributed to residential new construction [15]. Another significant factor that effect the energy consumption and demand in Kuwait is the harsh climate conditions. The weather in Kuwait is hot and humid during summer, with an average temperature of 38 ° C in August and maximum of 50 ° C. This led to 55 to 60% of the peak demand is attributed to air-conditioning [16].

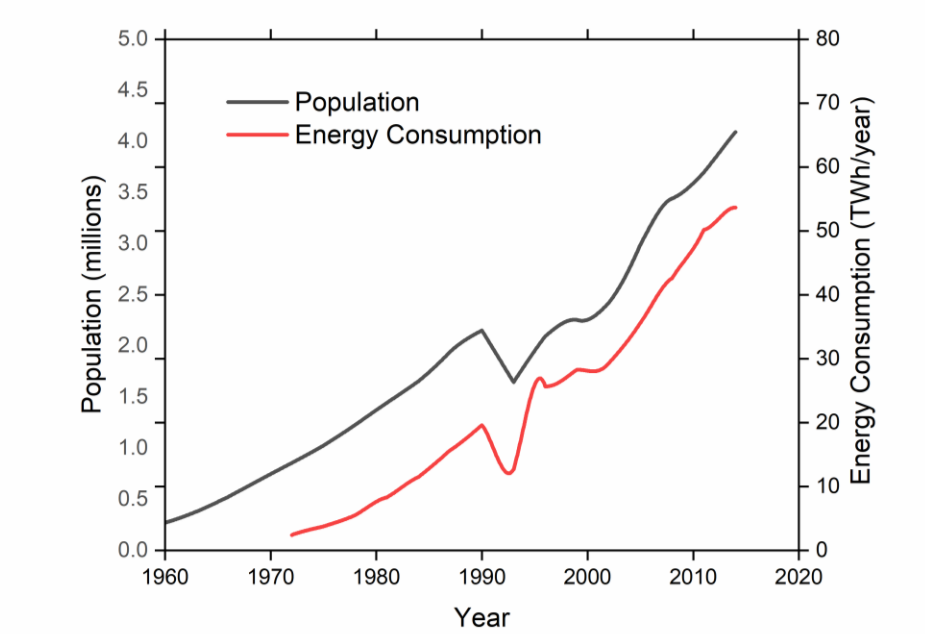


Figure 2 Population and electricity growth trends in Kuwait from 1960 to 2015 [17].

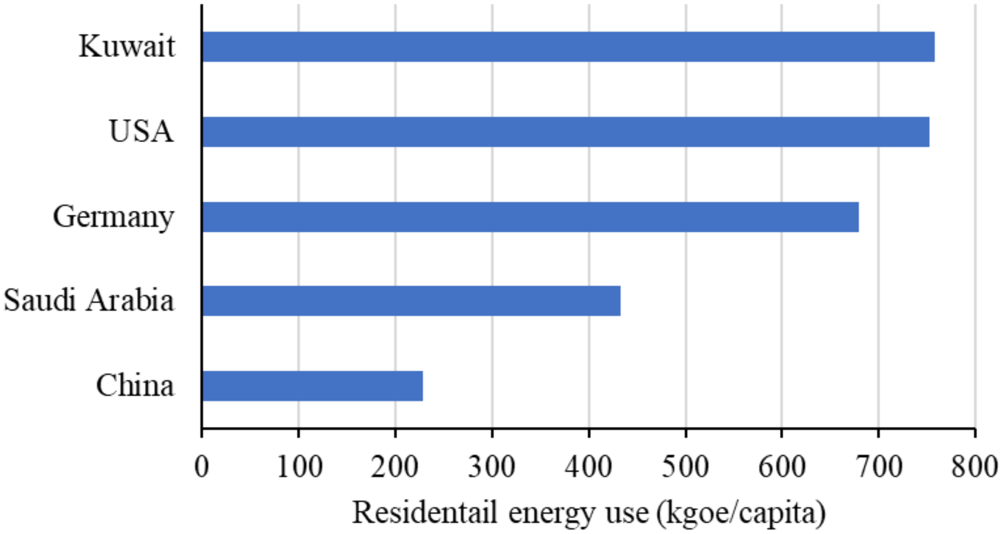


Figure 3 Residential energy use per capita in 2014 (kg of oil equivalent per capita) [14].

Given the growing population, along with high energy consumption per capita, these growth trends create a risk for the stability of the electrical grid and meeting the national demand. While extensive studies have been published on building energy use in Kuwait [18–20], most have been observed to be geared towards evaluation of certain policies, or retrofit programs related to energy efficiency. A missing link in these studies is the lack of benchmarking analyses and the lack of information about the end use distribution of electricity consumption in households. Should a breakdown of energy end-uses be analyzed, a better forecast of the building energy use can be strategized, as well as more effective codes and standards. Given that 57% of the energy consumption is attributed to the residential sector, it is crucial to assess the baseline energy consumption patterns in the residential sector [20]. Moreover, plenty of energy conservation measures are available in the Kuwait market that can be applied in the residential sector. Modeling the adoption of these measures in the housing stock and evaluating their impact on energy consumption and CO_2 emissions is crucial.

1.2. Research objective

The aim of this research is to develop a dynamic model of the socio-technical systems of energy consumption and carbon emissions of the Kuwait residential building stock with a tool capable of modeling the diffusion of different energy conservation measures (ECMs) in the residential sector. This will improve the understanding of the complex nature of household energy consumption and carbon emissions in Kuwait. A number of energy scenarios are constructed to illustrate the possible futures of energy consumption and GHG emissions in the Kuwait residential building stock. These scenarios are used to explore the diffusion of different ECMs in the housing stock.

The specific objectives to achieve the aim of this research are to:

1. Identify the social and technical variables influencing household energy consumption and CO_2 emissions in Kuwait.
2. Investigate the energy sector in Kuwait and the residential building characteristics.
3. Model the baseline energy consumption and demand in the Kuwait residential building stock by end-use and technology type.
4. Review the modelling approaches used in modeling and forecasting household energy consumption and CO_2 emissions.

5. Forecast the baseline energy consumption and demand in the Kuwait residential building stock by end-use and technology type.
6. Model the diffusion and adaption of different ECMs in the national building stock in Kuwait.
7. Establish a common framework to evaluate and prioritize the impact of ECMs.
8. Evaluate available energy-efficiency technologies and assess the energy and CO_2 impacts of ECMs on the national building stock using the adoption scenarios.

1.3. Overview of the thesis

This thesis divided into five chapters and Appendices. Chapter 1 is the general introduction of the thesis, which includes the aim and motivation behind this research. It also includes the objectives to achieve this aim.

Chapter 2 gives an overview of the national energy sector in Kuwait. It shed some light on energy resources and power generation in Kuwait. The historical energy consumption and peak demand in Kuwait were discussed. Furthermore, the characteristics of the residential buildings stock along with energy codes of practice were investigated. Based on these characteristics, four archetypes, that represent the residential housing stock in Kuwait, were developed.

Chapter 3 aims to model the baseline energy consumption and demand. A bottom-up model was developed to estimate the energy usage and peak demand by end-use. In this model, end-uses were broken out into air conditioning, lighting, appliances, and space heating and water heating, and further sub-categorized by different equipment types and technologies. Furthermore, the baseline energy consumption and demand were projected till the year 2040.

Chapter 4 models the diffusion of different energy conservation measures (ECMs) in the residential sector. Four diffusion scenarios were created to estimate the measures adoption rates. The impact of these measures to the CO2 emissions and the energy consumptions of the baseline residential building markets in Kuwait were evaluated. The cost of conserved energy (CCE) and annual energy savings for each measure were calculated. In addition, some policy scenarios were created to make the most energy savings ECMs cost effective.

Chapter 5 introduces the conclusions of this research; it summarizes the key findings of the work and offers recommendations for future work.

2. OVERVIEW OF ENERGY DEMAND AND HOUSING STOCK CHARACTERISTICS IN KUWAIT

Kuwaiti electricity consumption tripled during the past 30 years, and the MEW estimates that electricity consumption will increase by an additional 20% by 2027 [13,21]. Per capita electricity consumption was 15 MWh in 2014, with Kuwait ranking as the sixth highest consumer of electricity in the world [22]. Figure 4 shows a comparison of per capita electricity consumption for several countries.

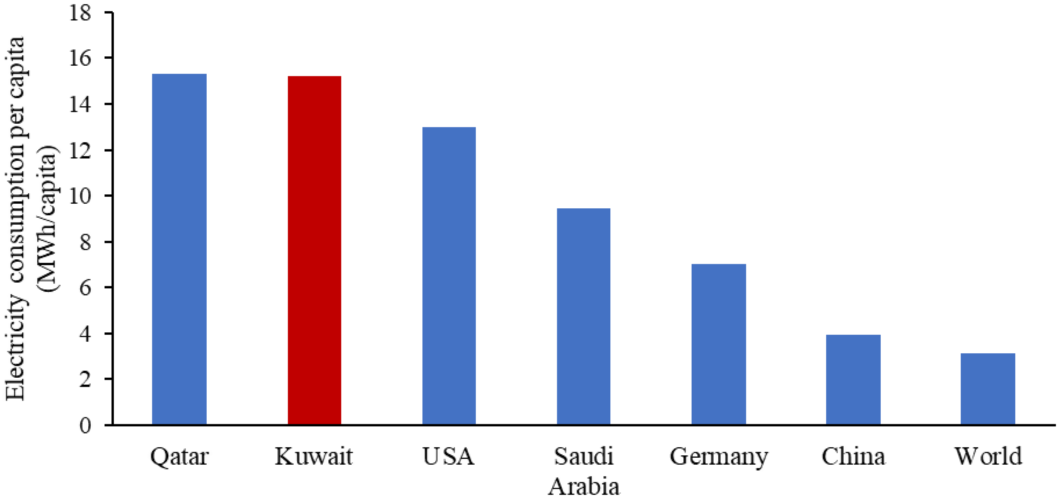


Figure 4 Electricity consumption per capita in 2014 for different countries [22].

In 2017, 70% of all total primary energy consumption and 45% of electricity were consumed by buildings in Kuwait [23]. Most of this electricity is used in cooling due to Kuwait's severely hot summers. And with almost 95% of the electricity bill subsidized by the government, there is little incentive for prudent consumption [23]. Driven by population, economic growth and a construction boom, the share of buildings in electricity consumption is likely to increase over the next decades. Excessive electricity consumption is not without problems: the Kuwaiti grid is continuously struggling to keep up with both the total electricity demand and peak power demand, with blackouts and brownouts becoming common occurrences. Continuous investment in power generation capacity, energy subsidies and imports of natural gas all represent a major burden on the government's finances, and Kuwait is also the world's fourth biggest CO_2 emitting country on a per capita basis [24].

Demand for electricity services is driven by a set of physical and social determinants, and policy makers have at their disposal a range of measures to influence electricity demand, such as construction codes, appliance efficiency standards and retrofit programs. The biggest challenge often lies in selecting the most cost-effective instruments, and this study will attempt to provide a better understanding of residential energy demand in Kuwait and help decision-makers set effective policies.

The chapter starts with an introduction about Kuwait's energy resources and their role in the economy, followed by a presentation of the country's growing residential electricity demand problem, as well as measures taken to tackle it, both from the supply and demand sides; special attention is given to building codes in Kuwait. Finally, the chapter describes the Kuwaiti urban landscape and the housing stock characteristics, which have been used to create four archetypes that represent the residential building stock in Kuwait.

2.1. Kuwait’s primary energy sources

Kuwait holds the eighth largest oil reserves in the world. It is also the eighth largest producer of oil [21]. The country’s revenues from petroleum exports in 2017 represent a share of 91.5% of all exports and 42.5% of GDP [25]. Despite the prominence of oil, natural gas is becoming an increasingly important fuel. Figure 5 shows Kuwait’s total primary energy supply by type of fuel.

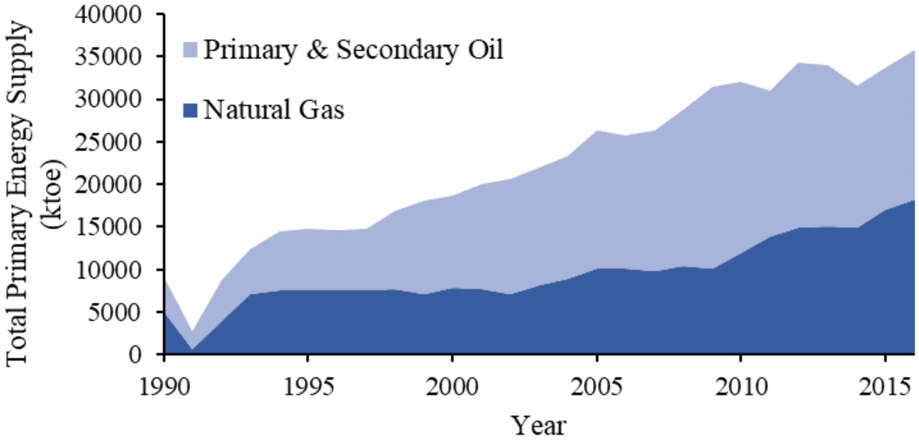


Figure 5 Kuwait’s total primary energy supply by fuel [14].

Natural gas consumption increased by almost 140% between 1996 and 2016 [14]. With reserves of 1.7 trillion cubic meters, Kuwait owns the 19th largest reserves of natural gas but domestic gas production is constrained by the complex geological nature and lack of foreign investment [26]. Natural gas is critical for the growing sectors of power generation, desalination and enhanced oil recovery, and demand from these sectors overtook domestic production in 2009, forcing Kuwait to import natural gas for the first time in almost two decades. Since that year, Kuwait has relied on imports to meet a growing share of domestic demand for gas, estimated at 22.9% in 2016 [14,21].

Despite Kuwait's very high rate of annual solar irradiance, electricity generated from solar sources was less than 3% of all electricity generation and 0.05% of total energy consumption in 2016 [14,21,27]. However, there is an increased focus on solar power generation, with the MEW aiming to generate 15% of total energy consumed from renewable sources [13].

2.2. Electricity demand in Kuwait

Ever since commercial oil drilling started in Kuwait in 1938, the country embarked on an energy-intensive development path that was only briefly interrupted by the Iraqi invasion of 1990. Oil became the primary source of income, and the urban landscape and patterns of consumption changed a lot. Kuwaitis started living in single-family detached homes; districts expanded horizontally very quickly, and the lack of public transport also led to private vehicles becoming the main form of transportation.

Summers in Kuwait are very harsh, with temperatures sometimes exceeding 50°C, and homes are liberally cooled to shield the occupants from the excessive heat. For decades, very little attention was given to energy efficiency, and residential energy demand is very high. The rising living standards also imply an accumulation of appliances and equipment, and the efficiency of these appliances was not given much attention either. Electricity subsidies are also very generous, equal to a surprising $1760 per capita in

2013, demotivating thrifty consumption and defeating the feasibility of most energy conservation measures [23].

Kuwait's economic growth also engendered an influx of foreign workers, and in 2017 the foreign population outnumbered Kuwaiti nationals by a ratio of more than 2:1 [28]. Figure 6 shows the growth of the national and foreign populations in Kuwait since 1995.

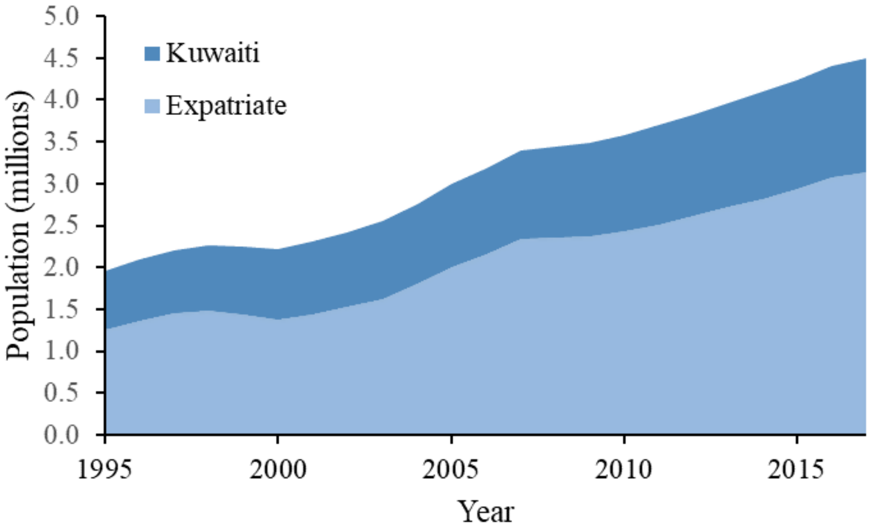


Figure 6 National and foreign populations in Kuwait [28].

The high rate of population growth is fueling the construction sector, which is struggling to keep up with the demand, especially for the single-family detached homes favored by Kuwaitis. While 90% of Kuwaiti nationals live in single-family detached houses, 70% of expatriates live in apartment complexes. Figure 7 shows the growth of the construction sector during the period 2005-2017.

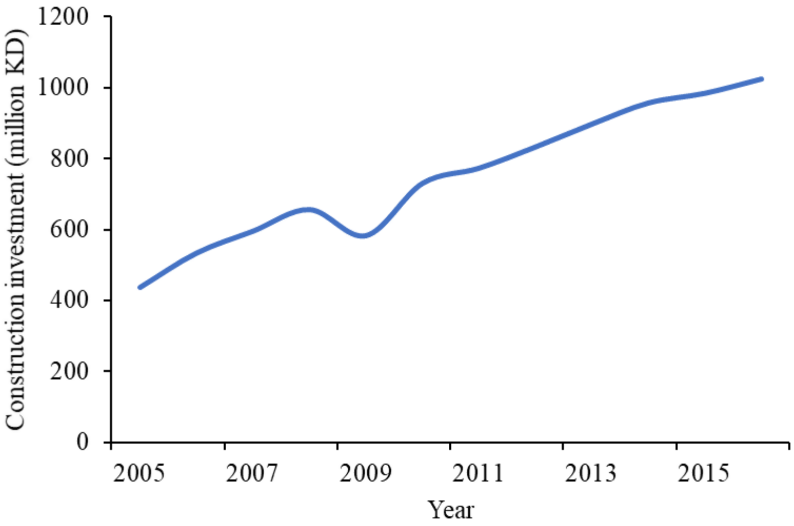


Figure 7 Size of the construction sector in million Kuwaiti dinars (1 KD = 3.29 2018 USD) [29].

The residential sector is a major consumer of energy in Kuwait. In 2017, buildings consumed 70% of the total primary energy supply (almost double the world average) and 45% of electricity [23,29]. The main culprit is air conditioning, which takes up more than two-thirds of a household's consumption [30]. The harsh weather is not the only reason behind this: Buildings' characteristics, many of which are not optimal for energy conservation, as well as negligent usage both play a role. Other lesser but significant electricity services are lighting and appliances. For Kuwait, electricity demand can be broken down into two distinct challenges, total electricity consumption and peak power demand.

2.2.1. Total electricity consumption

Kuwait's consumption is very high even compared to its Gulf neighbors with similar climatic and economic conditions [31]. Figure 8 shows the high growth rate of the total electrical energy consumption in Kuwait from the period 1997-2016 [13].

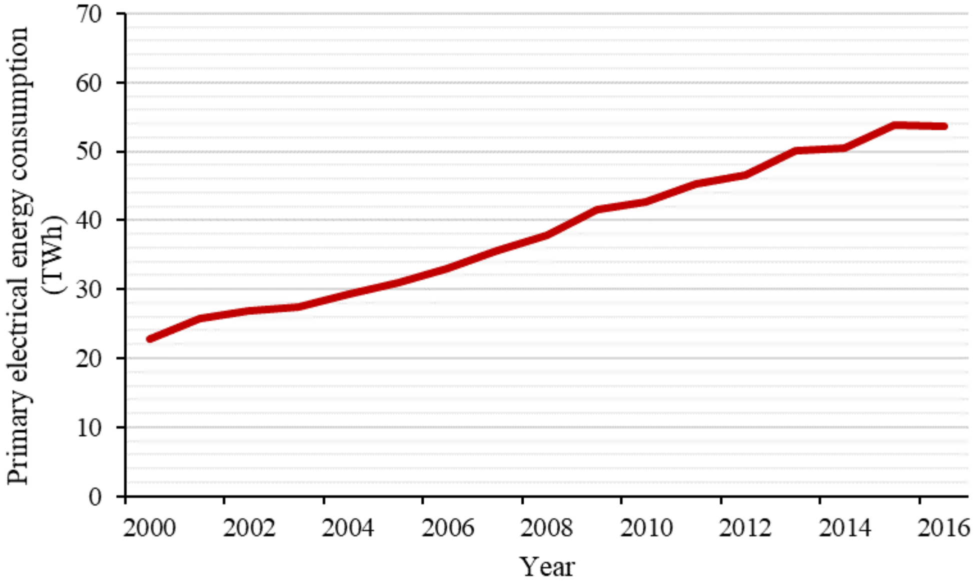


Figure 8 Total primary energy consumption in Kuwait [13].

Assuming the generation capacity exists, meeting electricity demand is still very costly in terms of fuel and other variable costs: In 2016, fuel cost the MEW 1 billion Kuwaiti dinars, equivalent to $3.3 billion at the time of writing. Electricity and water sales revenues in the same year were however a meager 200 million KD, covering one-fifth of fuel charges due to the very low tariffs that have not changed since 1966 [13]. The massive cost to the state treasury is not the only problem, however. Since Kuwait almost totally relies on fossil fuels to generate electricity, this consumption translates into massive amounts of CO_2 emissions. In 2016, CO_2 emissions per capita for Kuwait was

25.06 metric tons. It is a primary policy objective of Kuwait to reduce its CO_2 emissions, both because of its international obligations and because of the threat climate change represents for Kuwait [13,32].

The harm of excessive electricity consumption is not limited to finances and CO_2 emissions. Increasingly large quantities of the country's main export must be diverted for power generation in addition to the import of natural gas for the same purpose. Kuwait is also water-poor and has to rely on desalination to meet around 90% of water demand, but desalination is an energy-intensive process, and combined with power generation causes a threat to economic sustainability and energy security [32].

2.2.2. Peak demand

Electricity providers are not only expected to satisfy total electricity demand (in kWh), but also to have enough spare capacity to satisfy *peak* power demand (in MW). An elevated ratio of peak to average power demand is particularly challenging because utilities are required to invest in power generation assets that are seldom used. Furthermore, to fill peak demand, utilities often must resort to fuels with higher marginal cost of production. Failing to satisfy peak demand leads to blackouts and brownouts [33].

Peak power demand is especially problematic in Kuwait during hot days when coinciding demand for cooling services is very large. Table 1 shows annual peak loads against maximum temperature during peak load. Since the beginning of the decade, power outages became something of a common occurrence and the grid is continuously growing both in terms of reserves and transmission capacities in order to keep up with demand.

Table 1 Annual peak load against maximum temperature during peak load [13].

Year	**Peak Load (MW)**	**Maximum temperature at peak load (°C)**
1997	5,360	48
1998	5,800	49
1999	6,160	48
2000	6,450	50
2001	6,750	43
2002	7,250	50
2003	7,480	49
2004	7,750	50
2005	8,400	51
2006	8,900	49
2007	9,070	47
2008	9,710	50
2009	9,960	48
2010	10,890	50
2011	11,220	50
2012	11,850	50
2013	12,060	49
2014	12,410	49
2015	12,810	49
2016	13,390	49

Figure 9 shows the high growth rate in peak load from 1997 to 2016 and the future projections of peak demand in Kuwait by the MEW [13]. Peak demand, combined with the growing demand for new homes are putting a lot of pressure on the Ministry, which is adding significant generation capacity almost every year.

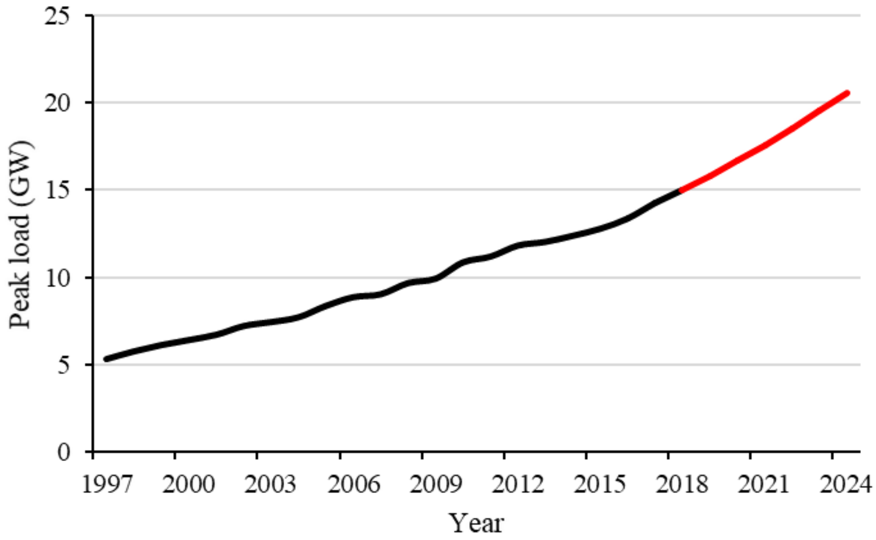


Figure 9 Peak load history and projected growth in Kuwait [13].

2.2.3. Power generation

Power generation in Kuwait relies on fossil fuels; the four types of fuel typically used are crude oil, heavy fuel oil, gas oil and natural gas. There are four types of generation plants: Steam turbines with a total capacity of 8970 MW, combined cycle with a total capacity of 2294 MW and gas turbines with a total capacity of 7586 MW; gas turbines are meant for operation during peak times and emergencies. Apart from fossil fuel plants, there is a small but growing renewable energy base of 20 MW. Table 2 shows the most recent figures for installed capacity.

Table 2 Installed power generation capacity in Kuwait as of the end of 2016 [13].

Stations	Available Thermal Plants Capacity (MW)			Available Renewables Capacity (Wind and PV)	Total Available Capacity
	Gas Turbines	Steam Turbines	Combined Cycle Gas Turbines		
Shuwaikh	252	-	-	-	252
Shuaiba South	-	720	-	-	720
Shuaiba North	660	-	216	-	876
Doha East	108	1050	-	-	1158
Doha West	141	2400	-	-	2541
Az-Zour South	1040	2400	560	-	5806
	111				
	825		370		
	500				
Sabiya	250.2	2400	647	-	5867
	250				
	1320				
	500				
	500				
Az-Zour North	1129	-	502	-	1631
Shygaya	-	-	-	20	20
Total	7586	8970	2294	20	18870

Since 2004, the MEW has been expanding the power generation and distribution capacity almost every year to keep up with the ever-growing demand. Figure 10 shows growth in generation capacity since 1976. The construction sector is growing steadily, which translates into an increasing number of households and thus consumers.

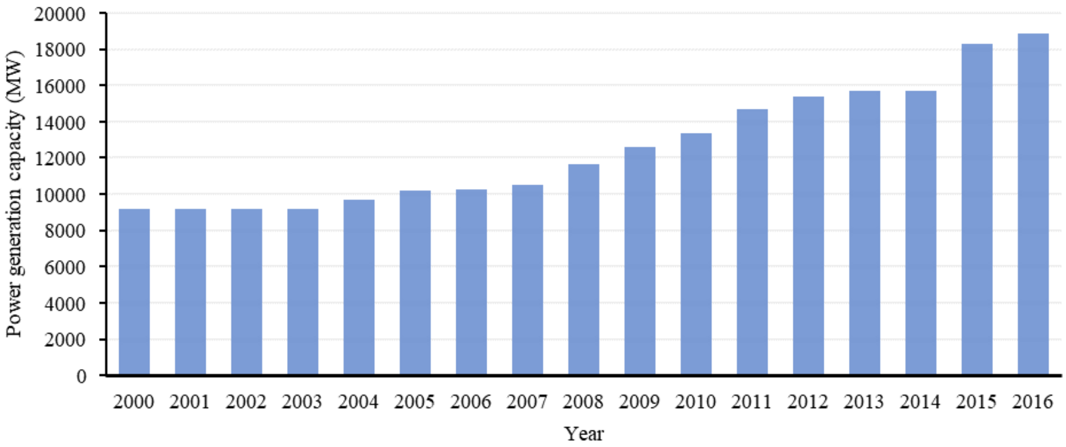


Figure 10 Power generation capacity in Kuwait [13].

Electricity demand is expected to grow by 20% until 2027, and the Ministry of Water and Electricity is planning further thermal capacity additions, improvements in power generation efficiency and a larger share of electricity from renewables as a pillar of its new strategy. However, capacity cannot grow indefinitely in response to demand and peaks in consumption; this is why the MEW has its eyes set on energy efficiency to curtail demand as the second pillar of its strategy [13].

2.3. Energy efficiency in Kuwait

Electricity demand is driven by consumer demand for the services it can provide such as cooling or lighting, and it is also shaped by the technical characteristics of the powered devices and the environment in which they operate. For example, electricity consumption for cooling is driven by consumers' desire for comfort, their favorite set temperature as well as the efficiency of their air conditioners and the thermal performance of the building envelope.

Some energy efficiency measures have the potential to modify the load profile and total demand cost-effectively. Policies that prioritize energy efficiency are needed because consumers may not be aware of the demand they impose on the grid, they may not know the best practices, they may have little motivation to act or there may be conflicts of interest at work [29]. Energy efficiency measures are numerous and many countries around the world have implemented programs for different purposes. To realize its ambitious energy efficiency targets, the EU is relying on a bundle of instruments including energy efficiency standards and labeling for appliances, and the deployment of 200 million smart meters [34]. And in Japan, the shutdown of nuclear power plants after the Great East Japan Earthquake led to a shortage of electricity, especially in Tokyo and Tohoku. The government's response included a demand-side energy conservation program. Measures included reducing usage of air conditioners and adjusting temperature settings, adjusting TV screen brightness and managing the standby mode of electronic devices. The program was highly successful, and its effects persisted several years later [35]. A third notable example is Thailand's Efficient Lighting program, which successfully replaced fluorescent tube lamps with highly efficient thin-tube fluorescent lamps through negotiations with local producers and importers as well as a public awareness campaign. Estimated savings were in the order of 2 TWh per year at the time of implementation in 1993 [29].

Demand-side management (DSM) is often associated with energy efficiency policies. DSM is the planning and implementation of activities that can influence electricity consumers in ways that will produce change in the utility's load shape. DSM interventions can be technological, behavioral, legislative or institutional and they range from the most intuitive (raising prices) to the most exotic (thermostats remotely-controlled by the utility). Managing electricity demand can reduce peak loads, and thus the investment in power generation assets. It would also lead to a reduction in fuel costs as well as CO_2 emissions and improve reliability of service.

Concerns about energy efficiency are not new in Kuwait, which was the first Gulf country to issue an energy efficiency code. The original code, issued in 1983, included several measures to control consumption. The 2014 revision aims to ensure energy efficiency is taken into consideration from the earliest stages through a better-performing building envelope, better HVAC sizing and control, and limits on peak power density for lighting. A number of measures have been proposed in Kuwait to improve energy efficiency or alter the load profile, examples of which are listed below.

2.3.1. Lighting

Lighting occupies second place after air conditioning in terms of residential electricity consumption, and incandescent bulbs are still widely used. Al-Enezi estimates that a program to replace incandescent lamps with compact fluorescent lamps would have substantial impact on both energy use and peak demand (in the order of 16.5% to 19% in energy savings and 14.5% to 16.8% in peak reduction per household) but his results may be slightly outdated, with the most recent code of practice setting the lighting power density at 7 W/m2 for the residential sector instead of the 15.7 W/m2 stipulated at the time of the study [29].

2.3.2. Appliance efficiency standards

Energy efficiency standards classify and regulate the energy performance/consumption of household equipment. Even if consumers are not very much concerned with their electricity bills, the least appliance efficiency standards can do is eliminate inefficient equipment in the retail market. Efficiency standards coupled with replacement programs for old appliances can ensure that consumers don’t just accumulate equipment at home. Al-Enezi found that appliance efficiency standards would save 4.6% of total consumption and reduce peak demand by 2.2% [29].

2.3.3. Thermostat setting

Al-Enezi found that setting the thermostat to 25.6°C instead of 23.9 would have a high benefit-to-cost ratio because it can reduce peak demand by around 15% through an awareness program. Changing the thermostat setting does not involve any cost other than the overheads of an awareness program [29]. Thermostats are already mandatory in all new homes, but it is questionable whether occupants currently set them at an optimal temperature.

2.3.4. Cool thermal storage

The very high energy consumption of air conditioning systems in Kuwait is well established. One method to at least reduce air conditioning peak load is cool thermal storage, a system that shifts air conditioners’ energy-intensive operations to low-demand hours such as late night or early morning. Sebzali evaluated different thermal storage systems and recommends chilled water storage systems for medium-sized buildings because of the reduction in both peak power and overall consumption they provide [32]. The 2014 Code already stipulates thermal storage systems for buildings with plant production capacity of 500 RT and above.

2.3.5. Pricing

The government of Kuwait subsidies 95% of the cost of electricity, leaving little incentive for conservation. An obvious and oft-repeated policy recommendation is to make electricity tariffs more realistic, but it may be politically difficult to implement. A second-best option would be to charge households not only for overall consumption but also for peak power consumption. This would encourage consumers to stagger their equipment usage and reduce coincident demand.

2.3.6. Distributed generation

Kuwait has one of the highest rates of solar irradiance in the world, and single-family detached dwellings have flat roofs that would be very convenient for installing PV panels and generating part of their own consumption. It is especially notable that the demand for residential cooling tends to match the profile of PV power generation. Solar water heaters may also be a cost-effective proposition. However, the initiative would have a very long payback period for the consumers because of the low electricity tariffs. Alternatively, such a measure could be financed through grants and other financing instruments from the MEW if found to be cost-effective.

2.4. Building energy codes of practice

Building codes are an important instrument to control excessive energy consumption and promote energy efficiency in buildings. Building codes are sets of rules that protect public health and safety and enhance sustainability and social welfare. They address issues such as buildings’ structural integrity, lighting, electrical and mechanical installations, HVAC and fire safety during the various phases of the building’s life.

2.4.1. Integration of energy conservation measures in building codes

Not only are buildings large consumers of electricity but they also have very long, useful lives (in the order of several decades) and any energy savings would accrue over this long life, potentially translating into nationwide reductions in energy consumption [36]. For example, the US Department of Energy estimates that during the period from 1992 to 2012, energy efficiency codes led to 1230 TWh in energy savings and $44 billion in cost savings to consumers [37].

Integrating energy conservation measures in building codes provide three key benefits: First, they emphasize energy efficiency as a design criterion during planning, a phase where the designers’ choices will determine the building’s energy consumption throughout its lifetime. Energy efficiency measures that may be easy to implement at this stage can later become prohibitively expensive or even impossible to implement. Second, due to diverging interests between different stakeholders, the reduction of building capital costs is often emphasized during construction at the expense of the building’s future operating costs (which will be incurred by occupants). Energy efficiency codes thus introduce a balance between the interests of these stakeholders. Third, the expertise, tools and data required to make sensible energy efficiency decisions are scarce. For example, some energy efficiency measures are complex and may require special expertise and information. Some measures may be simple, but the designers may not be aware of them. In such cases, a building code guides designers in the decision-making process and compensates for this lack of information [36].

It is also very important for energy efficiency codes to include refurbishments and renovations in their scope because they represent rare opportunities to improve an existing building's energy efficiency at relatively low cost [36].

2.4.2. The Kuwaiti energy codes of practice

The first Kuwaiti energy conservation code of practice was issued in 1983, motivated by the growing burden of electricity subsidies. The code sets standards for residential and commercial buildings' air conditioning systems and also addresses glazing, lighting and thermal resistance for the building envelope [18]. An evaluation of the code's impact conducted by the MEW was very positive, estimating the code saved KD 2.25 billion through energy conservation and reduction of peak power [18].

The code was revised in 2010, some 27 years later, to set more stringent energy efficiency requirements as well as to address new requirements such as thermostats, motor efficiency and seawater use for condensers. The code was again revised in 2014. Similar in spirit to its predecessors, it is mainly concerned with the building envelope and

HVAC because air conditioning load is attributed to 70% of the peak load in the summer months. The code is applicable to residential, commercial and public buildings. It regulates new construction projects as well as new portions of buildings and HVAC system renovations. Below is a summary of the code's requirements:

2.4.2.1. Building Envelope

The building envelope is a term that describes the parts surrounding the conditioned spaces of the building. The building envelope plays a critical role in controlling heat gains (losses) from (to) the external environment because it is the interface between conditioned spaces and the exterior. To minimize heat gains, the code sets maximum allowable heat transfer coefficients for walls and roofs; it also sets glazing requirements and imposes limits for air infiltration. Measures to control air infiltration include revolving or double-doors and back-draft dampers for exhaust fans.

2.4.2.2. HVAC

The optimal sizing of HVAC systems both minimizes capital and running costs and ensures the comfort of occupants. To ensure correct load estimation, the code gives examples of acceptable methods and software packages. Since 2010, the code separates Kuwait into two climate regions, coastal and interior, with different sets of design conditions for each. The code makes the use of water-cooled chillers mandatory for projects with total operating plant capacity of 500 RT and above in the interior region of Kuwait and projects with total operating plant capacity of 1,000 RT and above in the coastal region. It also makes the use of cooling recovery units and thermal storage mandatory under certain conditions.

2.4.2.3. HVAC Control Systems

Since wasteful use of air conditioners can often be attributed to human error, the use of automatic control systems can promote energy efficiency. The code mandates the use of programmable thermostats for all spaces with part-day occupancy. Building automation systems are mandatory for all projects with cooling capacity above 500 RT; programmable thermostats are acceptable for smaller projects.

2.4.2.4. Lighting

Lighting can be a major electricity consumer in households. Not only do indoor lighting systems consume electricity when operating, they are also sources of heat gain inside the building that raise the cooling load on the air conditioning system. The code sets limits for peak wattage per square meter for lighting systems according to the type of building (residential villa, mosque, shopping mall, etc.). Since automatic controls can reduce the demand for lighting, the code also stipulates the installation and replacement of all lighting systems with LED lights with occupancy sensors and time-of-day-control for government buildings. The use of building automation systems that allow monitoring and control of lighting systems is mandatory for all projects with cooling capacity of 500 RT and above; for smaller projects, programmable lighting controls are mandatory.

Optimization of window size and placement can make use of daylight and reduce the need for artificial lighting. However, this is not addressed in the code.

2.4.2.5. Water Conservation

The code also stipulates the use of seawater or grey water in water-cooled plants. The use of seawater for condenser cooling is compulsory for plants in coastal regions with cooling capacity of 10,000 RT and above. The use of grey water (i.e. waste water from taps, showers and laundries) is also compulsory for both regions as long as it satisfies quantity and quality requirements.

2.4.2.6. Electric Motors

The code sets minimum requirements for electric motors' full-load power factor and efficiency, imposing the most stringent requirements on government buildings.

2.4.2.7. Renewables

Solar energy can play a significant role in improving a building's energy efficiency: Solar thermal collectors could be used to heat water, or rooftop solar generation could meet part of the building's electricity demand. This is especially feasible in Kuwait's sunny climate, but it has been omitted in this revision of the code. However, some mosques and schools have already started using solar energy to improve efficiency [13].

2.4.2.8. Appliances

Appliances are not only significant users of electricity whether on standby mode or during operations, they also release heat in the conditioned space, increasing the cooling load. This is especially pronounced in the case of large, inefficient appliances. The code does not directly address specific requirements for appliances but sets a maximum limit for total peak electrical power per unit area for the building.

2.4.2.9. Enforcement

There are several reasons why codes can fail to achieve their purpose. They may be obsolete, insufficient in their scope, ambiguous in their requirements or unenforced. Aware of this fact, the MEW attempts to mitigate these risks by committing to create a regulatory authority to be responsible for the proper implementation of the code, from the design phase to construction. It will also hold consulting offices responsible for the full compliance and accurate implementation of the code during the design and construction stages. The Ministry will update the code regularly in order to keep up with technological advances.

The code lists the role of three different governmental authorities in the enforcement of the code: The MEW is responsible for approving all electrical engineering documents including power density calculations, equipment data sheets and drawings. Kuwait Municipality will check window-to-wall ratios, glazing specifications and insulation materials. The Ministry of Public Works will test and certify all building materials and insulation.

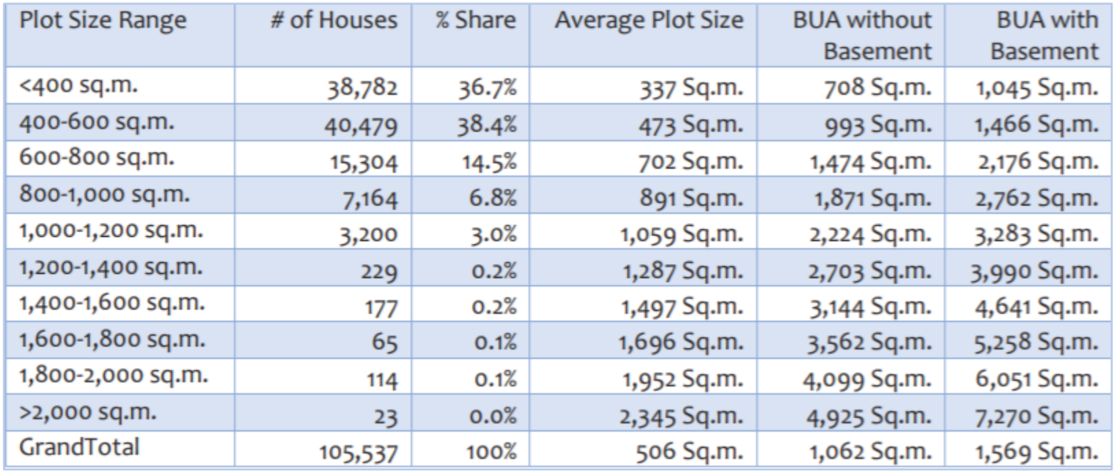
Table 23, in Appendix A, shows a comparison of the main requirements of the three revisions of the Energy Conservation Program Code of Practice [31].

2.5. Kuwait’s urban landscape and housing stock characteristics

The origins of Kuwait’s contemporary urban landscape can be traced back to 1952, when the Kuwait Master Plan was first implemented. Neither reflecting Kuwaitis’ housing customs at the time nor Kuwait’s desert climate, the Master Plan was the creation of British architectural firm Minoprio, Spencely and Macfarlane. The Plan, inspired by the Garden Cities movement, still plays a major role in shaping not only the urban but also the social landscape and, of course, electricity consumption [38,39].

The Master Plan essentially created two types of suburbs: The first type, Model residential suburbs, are groups of a few hundred to 1000 single-family detached homes with associated services such as a clinic, a police station and a supermarket; today these suburbs house 90% of Kuwaiti nationals. The second type, Investment suburbs, comprises commercial districts and apartment blocks that house most of the foreign population. Apart from these two new types, some traditional courtyard and palaces survive, but they are few in number and of little importance in terms of electricity consumption [30,38]. Table 3 shows the distribution of houses in Kuwait with their plot size range [40].

Table 3 Distribution of houses in Kuwait with their plot size [40].



Plot Size Range	# of Houses	% Share	Average Plot Size	BUA without Basement	BUA with Basement
<400 sq.m.	38,782	36.7%	337 Sq.m.	708 Sq.m.	1,045 Sq.m.
400-600 sq.m.	40,479	38.4%	473 Sq.m.	993 Sq.m.	1,466 Sq.m.
600-800 sq.m.	15,304	14.5%	702 Sq.m.	1,474 Sq.m.	2,176 Sq.m.
800-1,000 sq.m.	7,164	6.8%	891 Sq.m.	1,871 Sq.m.	2,762 Sq.m.
1,000-1,200 sq.m.	3,200	3.0%	1,059 Sq.m.	2,224 Sq.m.	3,283 Sq.m.
1,200-1,400 sq.m.	229	0.2%	1,287 Sq.m.	2,703 Sq.m.	3,990 Sq.m.
1,400-1,600 sq.m.	177	0.2%	1,497 Sq.m.	3,144 Sq.m.	4,641 Sq.m.
1,600-1,800 sq.m.	65	0.1%	1,696 Sq.m.	3,562 Sq.m.	5,258 Sq.m.
1,800-2,000 sq.m.	114	0.1%	1,952 Sq.m.	4,099 Sq.m.	6,051 Sq.m.
>2,000 sq.m.	23	0.0%	2,345 Sq.m.	4,925 Sq.m.	7,270 Sq.m.
GrandTotal	105,537	100%	506 Sq.m.	1,062 Sq.m.	1,569 Sq.m.

Houses or plots of lands in the Model residential suburbs were provided as a form of wealth distribution for the Kuwaiti citizenry. Today, Kuwaitis perceive owning and living in a single-family detached house as a de facto right, one that is an increasingly heavy burden for the State. The Public Authority for Housing Welfare (PAHW) has been unable to keep up with housing demand for decades, such that the backlog is in the order of 100,000 units, a number comparable to all housing units built since the inception of the program [30]. Considering the very high electricity consumption rate of single-family villas in Kuwait, meeting the increasing demand is ominous for the Kuwaiti power sector and economy. Table 4 shows a comparison between the consumption of residential energy consumption in Kuwait and the UK [38].

Table 4 Comparison of residential electricity consumption in Kuwait and the UK [41].

KUWAIT					UK (2013)	
Dwelling type	Number of dwellings	Electricity consumed			Average kWh/ dwelling/annum	Average kWh/m^2/ dwelling/ annum
		Share	Average kWh/ dwelling/ annum	Average kWh/m^2/ dwelling/ annum		
Villas	105,764	88%	145,44	264	4,170 (electricity) 14,829 (gas) Total 18,999	209
Flats	170,815	12%	20,278	127		

In the context of electricity consumption, the distinction between single-family detached houses and apartments is both necessary and useful: The differences range from electrical consumption patterns and appliance ownership rates, occupancy behavior, to different utility rate structures. While approximately 90% of the Kuwaiti households would fall under the single-detached home category, roughly 70% of the non-Kuwaiti families live in apartments in the Investment district. The electrical rate for the residential sector, which includes the single-family detached dwellings, is set at a trivial 2 fils/kWh ($0.006/kWh), which leads to little concern for conservation. The rate for the Investment sector, which includes multi-family homes is approximately 250% more compared to the residential sector. Another difference is that the average household size for Kuwaiti homes is roughly eight persons, whereas the non-Kuwaiti homes are smaller, at around four persons [28,42]. Furthermore, the average growth rate of the expatriate population between 2000 and 2016 is 5.2%, compared to 2.9% for the Kuwaiti population [28]. Figure 11 shows the growth of the two types of dwellings since 2007.

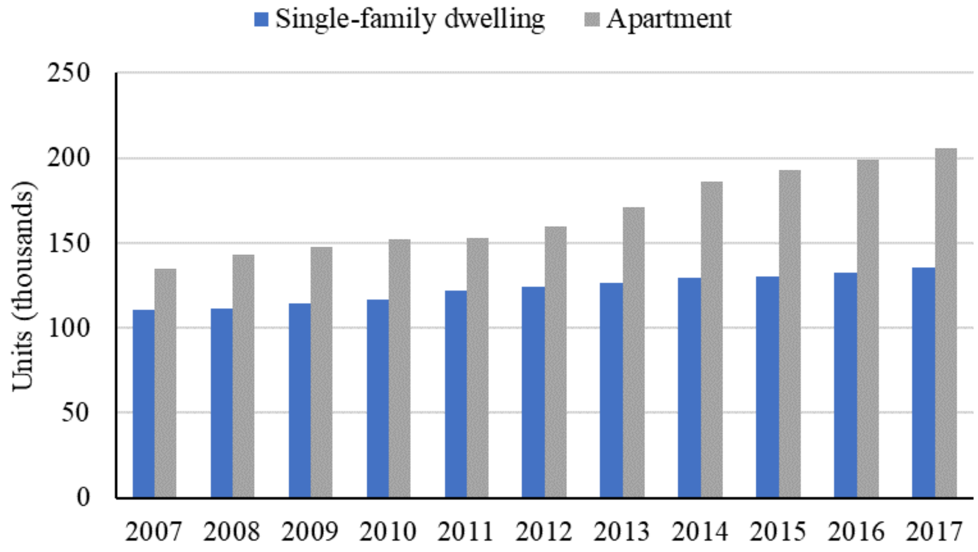


Figure 11 Growth of single-family dwellings and apartments since 2007 [28].

2.5.1. Archetypes

Modeling the housing stock at a high spatial resolution would be very beneficial. Interventions could be introduced in stages (for example, a retrofit program could be introduced only in certain neighborhoods or certain dwelling types), savings could be quantified for each type of dwelling, and measures with the largest return on investment could be identified.

However, modeling the housing stock is still very challenging. There is a huge variation among residential buildings not only in terms of geometry but also in terms of applicable building codes, floor plans, materials of construction and age. Modeling the residential building stock using only one archetype would severely limit both the versatility of the model and the validity of the simulation results. At the opposite end of feasibility, it is not practical to enter the characteristics of each building individually; it is very time consuming, data is not available, and the simulation would impose massive computational demands [30,43].

A common solution is to classify the building stock according to specific criteria and to represent each class with an archetype, an abstraction that would reduce each building to its most essential and relevant characteristics. To do so, we need characteristics that capture the thermal properties of the house and that describe most of the housing stock. Fortunately, many building characteristics can be inferred from high-level information such as year of construction and applicable code. Single-family detached houses went through several milestones since the Master Plan was first implemented:

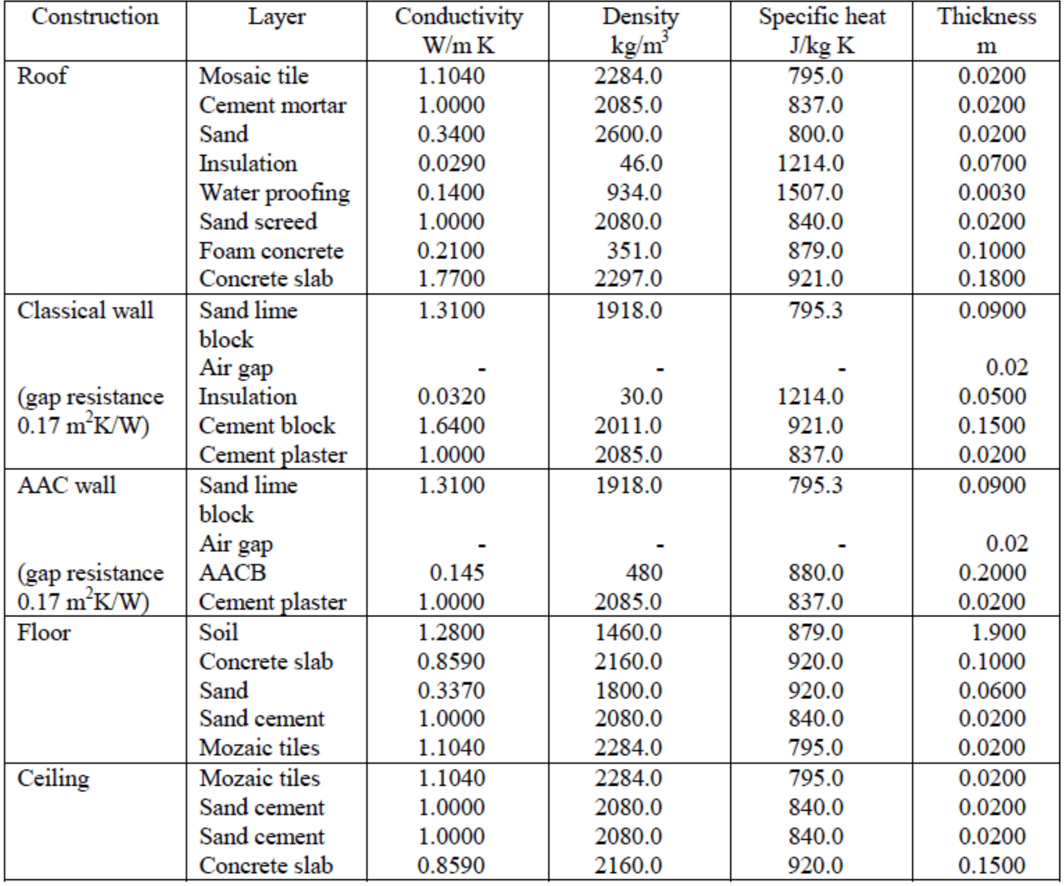
First, between 1967 and 1984, housing was allocated according to a two-tier system of low- and middle-income families. The two main differences were the size of the house and the option of receiving instead a plot of land and a loan. The two-tier system was discontinued in 1984. Also, until 1984, houses were either designed and built by the PAHW or the owners; after that year, the PAHW has handled most of the design and construction activities.

Second, the year of build also reveals the applicable energy efficiency codes; the first was issued in 1983 and it underwent two revisions since then, one in 2010 and the other in 2014. For the residential sector the difference between the two is inconsequential for our purpose.

Third, the year of build also provides some information about surface area because amendments in the Municipality Code in the years 1996, 2000 and 2002 increased the permissible built-up floor area.

Fourth, the materials of external walls, which represent an important characteristic for thermal models, can be inferred from the year of build. According to Al-Ajmi and Hanby, regular concrete blocks with cement mortar were used for external walls since the 1940s, with thermal insulation added in the 1970s [19]. Autoclaved aerated concrete, a type of foam concrete, was introduced in the Kuwait market in the 1980s and has practically replaced regular concrete since that time. The authors also point out that virtually all roofs in Kuwait are of the flat type because they are cheap, convenient for vertical expansion and required by the NHA, the predecessor to the PAHW.

Table 5 Physical properties of wall and roof materials [44].



Construction	Layer	Conductivity W/m K	Density kg/m^3	Specific heat J/kg K	Thickness m
Roof	Mosaic tile	1.1040	2284.0	795.0	0.0200
	Cement mortar	1.0000	2085.0	837.0	0.0200
	Sand	0.3400	2600.0	800.0	0.0200
	Insulation	0.0290	46.0	1214.0	0.0700
	Water proofing	0.1400	934.0	1507.0	0.0030
	Sand screed	1.0000	2080.0	840.0	0.0200
	Foam concrete	0.2100	351.0	879.0	0.1000
	Concrete slab	1.7700	2297.0	921.0	0.1800
Classical wall	Sand lime block	1.3100	1918.0	795.3	0.0900
	Air gap	-	-	-	0.02
(gap resistance 0.17 m^{2}K/W)	Insulation	0.0320	30.0	1214.0	0.0500
	Cement block	1.6400	2011.0	921.0	0.1500
	Cement plaster	1.0000	2085.0	837.0	0.0200
AAC wall	Sand lime block	1.3100	1918.0	795.3	0.0900
	Air gap	-	-	-	0.02
(gap resistance 0.17 m^{2}K/W)	AACB	0.145	480	880.0	0.2000
	Cement plaster	1.0000	2085.0	837.0	0.0200
Floor	Soil	1.2800	1460.0	879.0	1.900
	Concrete slab	0.8590	2160.0	920.0	0.1000
	Sand	0.3370	1800.0	920.0	0.0600
	Sand cement	1.0000	2080.0	840.0	0.0200
	Mozaic tiles	1.1040	2284.0	795.0	0.0200
Ceiling	Mozaic tiles	1.1040	2284.0	795.0	0.0200
	Sand cement	1.0000	2080.0	840.0	0.0200
	Sand cement	1.0000	2080.0	840.0	0.0200
	Concrete slab	0.8590	2160.0	920.0	0.1500

According to the available information and based on detailed study as part of the Kuwait-MIT signature project on sustainability of Kuwait’s built environment, four archetypes for the single-family detached houses were chosen [43]:

1. Original 1960s-80s villas: this is the era of the two-tier system so there is some variation in built area as well as the design (government or private).
2. 1960s-80s retrofitted villas: renovated government villas, where shadings or new windows were added and some façade treatment carried out.
3. 1980s-2010s modern villas: designed (and some were built) by PAHW according to the 1983 code.

4. 2010-present villas: designed and built according to the 2010 code.

As pointed out earlier, traditional courtyard houses and palaces as well as villas built before 1960 were left out. Table 6 summarizes the archetype parameters used in the simulation.

Table 6 Archetype parameters [16,45].

Parameters	**Original**	**Retrofit**	**Modern**	**Code**
Construction year	60s-80s	60s-80s	80s-Present	10s-Present
Wall U-value (W/m^2.K)	2.53	2.53	0.62	0.32
Roof U-value (W/m^2.K)	1.56	0.53	0.53	0.40
Window U-value (W/m^2.K)	5.96	2.89	2.89	2.33
Window SHGC	0.86	0.76	0.37	0.65
HVAC COP	2.00	2.20	2.40	2.90
Infiltration (ACH)	0.80	0.80	0.50	0.30
Stock share (%)	20%	28%	42%	10%

After defining the archetypes and their relative numbers in the Kuwaiti building stock, the next step is to create thermal models for said archetypes using the DesignBuilder simulation tool. Figure 12 shows a screenshot of DesignBuilder software interface for one of the archetype models created.

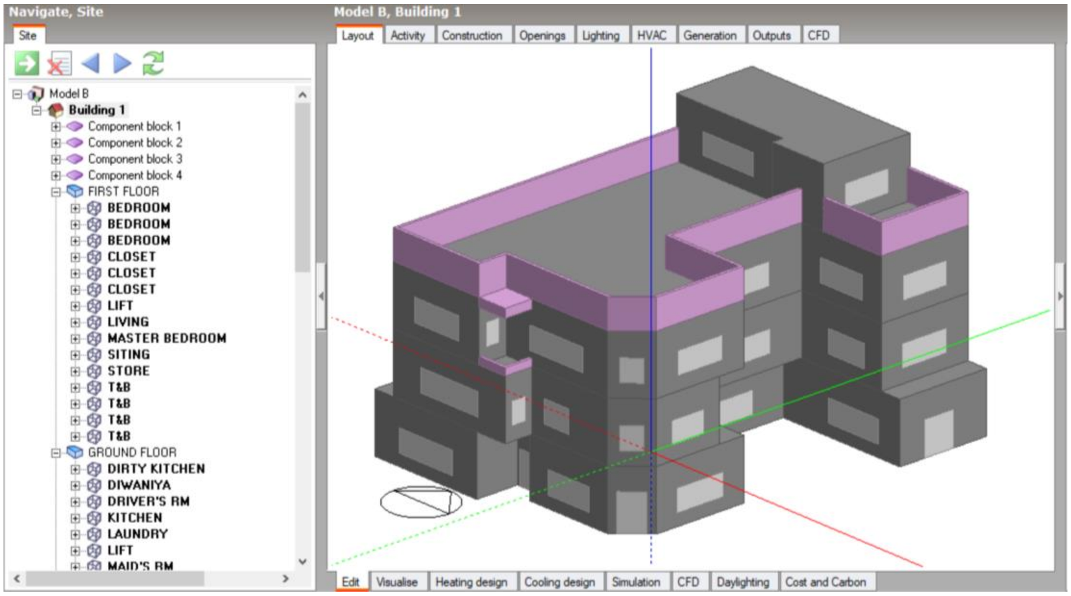


Figure 12 Screenshot of DesignBuilder software interface of an archetype model.

2.6. Conclusion

This chapter has shown the nature and extent of Kuwait's excessive electricity consumption. There are numerous measures that policy makers can use to improve residential energy performance in general, and especially building envelopes. In order to prioritize, select and coordinate between different energy efficiency measures, a proper understanding of the baseline energy consumption patterns in the residential sector is necessary. However, assessing the effectiveness of various energy conservation measures in the residential sector is challenging because of the variation in characteristics of the building stock as well as the lack of data. This study will use the four archetypes developed above to help in modeling residential energy use and CO_2 emissions in Kuwait.

3. BASELINE ENERGY CONSUMPTON AND DEMAND MODEL

Before identifying energy goals and polices, energy use profile must be developed for the building stock. This profile can serve as a baseline for energy planning efforts and provide insight of the types and scale of energy use within the housing stock. Building energy savings and CO_2 emission reduction strategies and policies requires the application of building stock models that have the ability to: (a) estimate the baseline energy consumption of the existing building stock, (b) explore the distribution of the energy consumption by fuel type, end use or technology type (if applicable).

While extensive studies have been published on the building energy use in Kuwait, most have been observed to be geared towards evaluation of certain policies, or retrofit programs related to energy efficiency. A missing link in these studies is the lack of benchmarking analyses. Should a breakdown of energy end-uses be analyzed, a better forecast of the building energy use can be strategized, as well as more effective codes and standards. Given that 57% of the energy consumption is attributed to the residential sector, it is crucial to assess the baseline energy consumption patterns for the residential sector [20].

3.1. Review of literature

A number of different models are available for studying residential energy consumption [46–50]. These models depend on accurate input data to calculate or simulate corresponding results. The availability of accurate and reliable input data can vary significantly, leading researchers to choose appropriate modelling techniques to best exploit available data.

These modelling techniques can broadly be divided into ‘‘top-down’’ and ‘‘bottom-up’’ approaches as shown in Figure 13 [51,52]. These approaches differ in how they estimate residential energy consumption. The top down approach assesses or estimates the energy requirements for the entire residential sector, and then, if needed, calculates individual energy consumption from that data [53,54]. The bottom up approach does just the opposite. In such an approach, individual or house hold energy consumption is first obtained and then aggregated to obtain the energy demand for the entire sector [55,56]. Both these approaches find applications in building energy modelling.

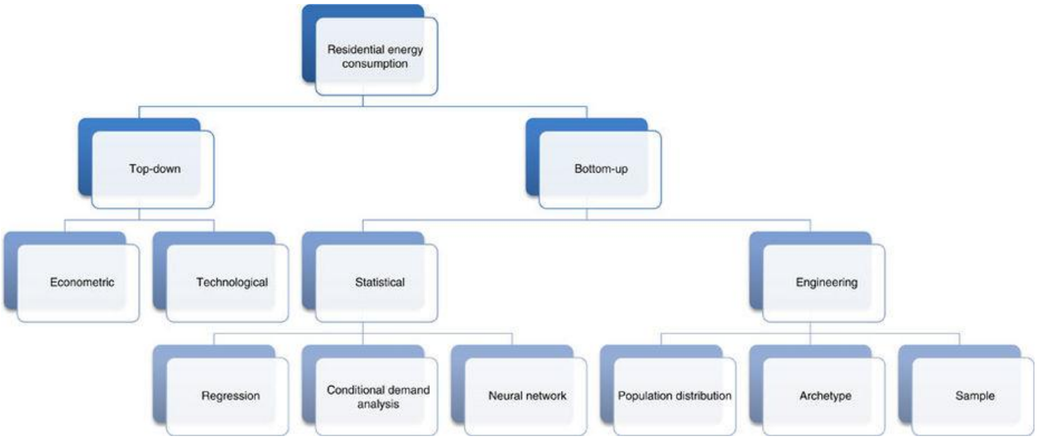


Figure 13 Modeling techniques for estimating the residential energy consumption.

One bottom up approach commonly used in building energy analysis is engineering method (EM) [52]. This method (EM), which accounts for energy consumption of the end-uses based on their ratings or characteristics is perhaps the only method that models energy consumption without reliance on historic data. A simple example of this approach would involve calculating the overall heat load based on the location climate, thermodynamics, and heat transfer analysis for all end users in a particular building. Since this method is based on end user characteristics, it offers a great degree of flexibility and dynamic range when compared to other equivalent methods. The only constraint is that end user behavior needs to be assumed. This may not be a convenient approach as individual users may have varied behavior patterns and therefore, different energy consumption patterns.

Another approach that is also within the bottom-up framework is statistic method (SM) which identifies a sample household and then scales the data from that house to the entire system. Relationship between the end user and energy consumption is then regressed using one of the many statistical techniques available [57]. SM models can employ macroeconomic variables, energy price and income, and other geographic or political indicators, thus imbibing the strength of top down approach as well. In comparison, the EM relies on firsthand information provided by end users. For example, appliance ownership, rating, and appliance efficiency can be used to calculate energy usage patterns. This direct access to end user information such as power rating of appliances or thermodynamic analysis based on ambient conditions makes EM extremely versatile when it comes to characterizing residential energy usage. Either of the bottom up models may be employed to characterize a single unit and then aggregated to generate residential energy consumption data pertaining to the entire political or geographic sector.

One example of such a study by Capaso et al. [58] generated an appliance use profile for the residential sector by using data generated from a housing survey. This study combined data pertaining to demographic and lifestyle patterns of the population with engineering specifications corresponding to appliances employed. The model was then applied to the entire region and generated results comparable to that of the actual load patterns.

The INSTRUM-R simulation tool uses historic energy consumption, price, behavioral parameters, distribution levels of technologies, and quantification of appliance unit energy consumption, cost, and availability as inputs [59]. This tool works by modelling each individual consumer application from the data available and then aggregating it to get the overall residential energy usage. In addition to these characteristics, this tool can also assess the viability of housing stock, identify retrofit potential, if any, and retire old housing stock. It can also include simulations representing purchase of new applications. The researchers also included lifecycle cost assessment and does not assume perfect knowledge across space and time.

Kadian et al. [60] developed an energy consumption model for the Delhi residential sector that utilizes macro level and distributed data sources. This detailed model accounts for each unique application such as lighting, water heating, air conditioning, refrigeration, cooking, and washing in addition to other subjective loads. Using a simplified end use consumption equation, they manage to incorporate penetration and use factors of all households without compromising on the data from individual end users.

In the literature, end-use energy consumption for residential buildings in Kuwait have been identified in studies that utilize archetypes. Baqer and Krarti [23] have modeled a prototypical Kuwaiti villa and carried out a series of analyses to ascertain the effectiveness of certain energy policies, and the impact of various energy efficiency measures on energy use and peak demand. It was observed that air conditioning accounts for 72% of the total electrical usage, whereas lighting and miscellaneous household appliances account for 22% of the energy consumption combined.

Another study, conducted by Krarti & Hajiah [20], examines the impact of daylight time savings (DST) on energy use for various types of buildings. Similarly, the analysis is based on a series archetypical models that represent the buildings in the residential and commercial sectors. According to their results, space cooling represents a majority of the usage and peak demand, at 48% of annual energy use, and representing a peak load of 64%.

For forecasting energy demand, a study by Wood and Alsayegh [61] has modeled the electrical demand until 2030 using a top-down approach. It was developed based on historic data of oil income, gross domestic product (GDP), population and electric load. However, a forecasting model of the energy consumption and demand by end use using a bottom-up approach have not, to best of our knowledge, been developed yet. Should a breakdown of energy end-uses be analyzed and forecasted, a better building energy use can be strategized, as well as the development more effective codes and standards. Given that 57% of the energy consumption is attributed to the residential sector, it is crucial to assess the baseline energy consumption patterns [20].

3.2. Methodology

This work presents a bottom-up approach for modelling and forecasting end-use energy consumption and demand in Kuwait's residential buildings until 2040. The methodology relies on information pertaining to the energy consumption of specific household equipment and appliances, where factors such as quantity, operating hours, and power requirements are accumulated, and extrapolated to a national scale to ultimately estimate the usage patterns in Kuwait. Therefore, energy consumption and demand are calculated at the individual level and aggregated to estimate the national consumption and demand. In this model, end-uses were broken out into air conditioning, lighting, appliances, and space heating and water heating, and further sub-categorized by different technologies. Moreover, each end-use category was further broken down by different equipment and appliances with corresponding data on diffusion rates and energy efficiency ratings. The rate of diffusion was based on data obtained from surveys, and available literature [11,12]. The driver variables of this model are based on macroeconomic variables such as population, household size and income, and engineering variables like unit energy consumption, and efficiency ratings. This study uses a stock-and-flow model rather than calculating the energy consumption per household using simulation tools. This approach gives the benefit of estimating the stock of each equipment and the replacement rates, which can help policy makers in estimating energy savings from different energy efficiency scenarios, like replacing old or broken appliances with more efficient ones. It also can take advantage of the sales or shipments data if it comes available, for more accurate estimation, rather than dealing with few archetypes that represent the whole buildings stock. Figure 14 illustrate the modelling structure.

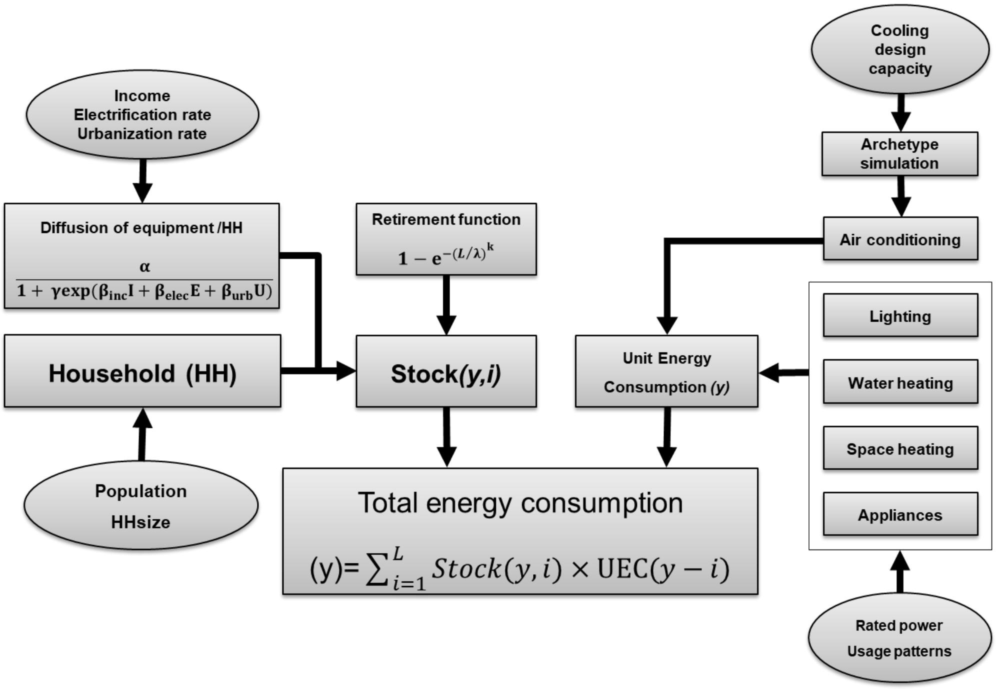


Figure 14 Flow chart of the baseline energy consumption model.

The initial step is to model the quantity of equipment owned and the initial present stock. The sales and stock turnover are then derived from first purchases and replacements. The first purchases are driven by growth in population and increase in ownership, while replacements are calculated based on the age of equipment and a retirement function. Next, an average Unit Energy Consumption (*UEC*) and unit power demand (*UPD*) per equipment are derived and the total energy consumption and peak demand are modelled using the following general equations:

$$Total\ Energy\ Consumption(y) = \sum_{i=1}^{L} Stock(y,i) \times UEC(y-i) \quad (1)$$

$$Peak\ Load\ Demand(y) = \sum_{i=1}^{L} Stock(y,i) \times UPD(y-i) \quad (2)$$

where *Stock*(*y*,*i*) represents the quantity of equipment of vintage (*i*) remaining annually in year (*y*). The variable *UEC* (*y*, *i*) on the other hand, denotes the unit energy consumption at the corresponding year of purchase (y – i) and the *UPD (y, i)* is the unit demand power during the peak time. Lastly, the overall useful life of the equipment is represented by L. Due to the lack of published information, acquiring data on sales volumes of equipment, efficiency ratings, ownership details, and daily consumption patterns are all infeasible for the state of Kuwait. This analysis therefore utilizes an array of surveys that include national statistics, and numerous reports published by the government [13,28,62].

3.2.1. Stock and diffusion rate

Since the overall consumption of electricity is impacted by the total quantity of equipment, it is crucial to calculate the adoption rates for the population, as well as the total sales numbers of end-use equipment. The stock of any equipment in year *y* equals the equipment sales at the same year plus the previous year stock. The sales are the sum of initial purchases of equipment, and the replacement purchases, which includes replacements-on-burnout and early retirements. The calculations for replacements involve the age of the equipment within the stock and a retirement function, which represents the percentage of failed equipment in a vintage stock:

$$Stock(y) = Sales(y) + Stock(y-1) \tag{3}$$

$$Sales(y) = First\ purchases(y) + Replacements(y) \tag{4}$$

First purchases, shown in Equation (4) represents an increase in the stock quantity which can be due to new construction projects, such as housing subsidies by the Public Authority of Housing Welfare (PAHW), or an increased rate of equipment diffusion per household as shown in Equation (5):

$$First\ purchases(y) = H(y)D(y) \tag{5}$$

where *H(y)* represents the number of new households based on [28]. *D(y)* is the equipment diffusion rate per household. Equipment diffusion rates are not available as input data, but are projected according to a macroeconomic model using a logistic function [63,64]:

$$D(y) = \frac{\alpha}{1+\gamma+e^{-(\beta_1 I(y)+\beta_2 E(y)+\beta_3 U(y))}} \tag{6}$$

I(y) denotes the average annual income per household *(y)*, whereas *E(y)* is the electrification rate, *U(y)* is the urbanization rate and γ and β are parameters for scale. For the case of Kuwait, since income, electrification and urbanization rates are relatively high, diffusion rates for equipment are reflective of this phenomenon in the analysis. The logistic function, by definition, has a maximum value of one at which the saturation level is reached. However, some households have more than one appliance or equipment of the same type. Therefore, the logistic function is scaled by the parameter α, as seen in Equation (5), which is the saturation level [63]. Because the climate conditions directly impact the air conditioner ownership rates, cooling degree days (CDD) are used instead of an urbanization rate in the equation above to calculate the diffusion rates of AC units. For some appliances, the sale price affects the diffusion rate as purchases depend on affordability. Therefore, a price variable was added for some appliances based on [65].

Replacement stock are attained from previous sales as in Equation (7):

$$Replacements(y) = \sum_{i=1}^{L} Sales(y - i) \times Retirements(i) \tag{7}$$

In Equation (8), *Retirements(i)* represents the probability of the equipment retiring at a given lifetime for each year up to its entire lifetime *(L)*, and it is modeled using a Weibull distribution [54,66]:

$$Retirements(i) = 1 - e^{-(i/\lambda)^{k}} \tag{8}$$

where *i* is the number of years after the equipment is purchased, *λ* is a scale parameter and *k* is a shape parameter, which determines the way the failure rate changes through time. Table 7 shows a sample of these parameters for some appliances. These parameters were estimated for each equipment based on [67,68]. Figure 15 shows a sample of the projected sales for residential refrigerators.

Table 7 Shape and scale parameters of retirement function for some appliances [69].

Appliance	**Shape factor (k)**	**Scale parameter (λ)**	**Mean Life (μ)**
Dishwasher	2.18	14.22	12.59
Refrigerator	2.15	18.76	16.62
Freezer	2.46	21.36	18.95
Clothes washer	2.31	18.63	16.51
Clothes dryer	2.57	18.26	16.21

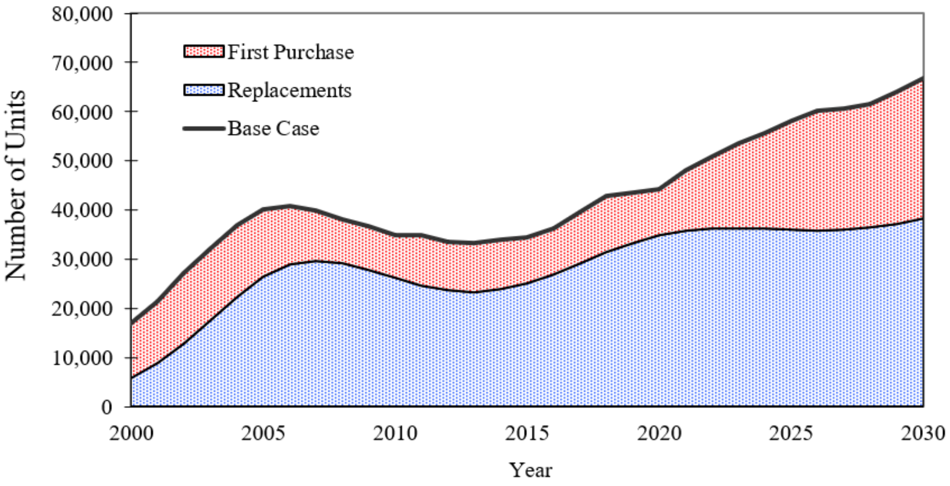


Figure 15 Sales of residential refrigerators in Kuwaiti households.

3.2.2. Unit energy consumption

The next section describes the methods and assumptions for determining the average unit energy consumption (*UEC*) for each equipment. *UEC* depends on the typical product used (size and rated power), use patterns and equipment efficiency. Therefore, the *UEC* model includes information on equipment usage and lifetime profiles, stock energy efficiencies by vintage and efficiency improvement profiles [23,70]. The assumption of the efficiency improvement of the appliances over time is made based on [71,72], and the likely improvement is 1–5%, depending on the equipment, considering the technical limitation of the technology.

3.2.2.1. Air conditioning

Space conditioning is a large driver of energy consumption in residential buildings and it is affected by many variables like weather, building envelope efficiency, building size, equipment types and occupant behaviors. Therefore, it is challenging to determine the *UEC* for AC units and some additional complexity is required for modelling space conditioning in order to obtain reasonable accuracy. Simulation tools was used to estimate the *UEC* for AC using the four archetypes developed in chapter 2 and the result is shown in Table 8.

Table 8 Annual cooling energy use for different residential archetypes in Kuwait.

	Archetype			
	A	B	C	D
Cooling Energy Use (kWh/m2/year)	201.08	184.73	130.43	113.57

A less computationally-intensive method to estimate the energy requirements for heating and cooling purposes in a building is the bin method. *UEC* for air conditioning systems using this method is derived as the following equations:

$$UEC = \frac{Q_{design} EFLH}{COP} \tag{9}$$

where Q_{design} represents the cooling system capacity, and *EFLH* is the equivalent full-load hours, where *COP* is the coefficient of performance of the air conditioning unit. The equivalent full-load hours of operation of the air conditioning system are therefore calculated as follows [73,74]:

$$EFLH = \frac{\sum_{i=1}^{m} N_{bin,i} \cdot (T_{o,i} - T_{bal})}{(T_{ODC} - T_{bal})} \tag{10}$$

where $N_{bin,i}$ represents the total number of hours in which a dry bulb temperature is within bin i, m is the total number of bins depending on the minimum and maximum temperatures of the month, $T_{o,i}$ is the midpoint of bin i, and T_{ODC} is the outdoor design temperature, which is 46 °C for Kuwait [75]. The building balance-point temperature, T_{bal}, is the outdoor temperature above which cooling is required. The building balance-point temperature is influenced by indoor temperature, building type and construction and internal heat gains by occupants, electric equipment, and lighting. It is expressed as follows:

$$T_{bal} = T_i - \frac{Q_i}{UA} \tag{11}$$

where T_i is the indoor temperature (thermostat set-point temperature), Q_i is the internal heat gains. U is the overall heat transfer coefficient for the building envelope and A is the total area. The major sources of internal heat gains (Q_i) into a building are occupancy, electric equipment, lighting and solar radiation through windows. Table 9 shows the internal heat gains assumptions for the residential building stock in Kuwait.

Table 9 Internal heat gain parameters for residential buildings in Kuwait [45].

Internal heat gain	**Value**
Occupancy density (Occ/m2)	0.012
Plug load (W/m2)	10.80
Lighting load (W/m2)	12.30

The U values can be defined by the thermal resistance of the building envelope components (i.e., walls, windows, roof, etc.). The U values for a multi-layered structure is modeled as:

$$U = \frac{1}{\frac{1}{h_i}+\sum_{j=1}^{N}\frac{e_j}{k_j}+\frac{1}{h_o}} \tag{12}$$

The indoor and outdoor heat transfer coefficients for the building surfaces are represented by h_i and h_o and are set at 10 and 20 W m^{-2} K^{-1}, respectively [56]. The thickness and the thermal conductivity of the materials in layer j is represented by e_j and k_j respectively.

Although this method is based on a simple steady-state energy balance where we use a constant balance temperature, its reasonable results compared to the archetype method made it a favorable method when dealing with a national level building analysis.

3.2.2.2. Water heaters

The unit energy consumption for a water heater was estimated through Equation (12) [76]:

$$UEC = \frac{Usage \times c_p(T_{supply} - T_{tank})}{EF} \tag{13}$$

where usage is the household hot water usage in gallon per day, c_p is the volumetric specific heat of water ($Jm^{-3}K^{-1}$), T_{supply} is the incoming cold-water (C) assumed to be 20 °C, T_{tank} is the tank temperature (C) and EF is the energy factor of the water heater.

Energy Factor (EF) is a measure of water heater overall efficiency, based on the ratio of useful energy output from the water heater to the total amount of energy delivered to the water heater. Typical electric-resistance water heaters (include tankless) have EFs that range from 0.90 to 0.99, where is gas water heaters have EFs that ranges from 0.57 to 0.82 [77,78]. The EF takes into account standby losses for the water heater tank. Since electricity is the only fuel used for water heating in residential buildings in Kuwait, EF is assumed to be 0.904 for standard electric water heaters and 0.95 for high efficiency ones. The water heating usage is assumed to be 20 gal.person^{-1}.day^{-1} based on [23].

3.2.2.3. Lighting

Since all electrified households use electricity for lighting, the model assumes that lighting diffusion is equal to the national electrification rate, which is almost 100% for Kuwait [1]. However, the lighting energy is largely determined by the number of lighting fixtures, type of lamps and usage patterns. Therefore, the residential lighting stock was broken down by lamp types based on the 2010 lighting stock data in Kuwait [79,80] as shown in

Table 10. Figure 16 shows that almost 50% of the lighting stock in Kuwait is incandescent bulbs and around 37% is compact fluorescent lamps (CFL). Based on residential surveys and audits [29,70], the daily average use of light bulbs is estimated to be 7 hours.

Table 10 Residential lighting stock in Kuwait [79].

Lamp Type	**Average Wattage**	**Lifetime**	**Stock**
Incandescent	60	1,000	27,758,352
Tungsten Halogen	52	2,000	5,752,156
Compact Fluorescent	15	10,000	10,738,022
Linear Fluorescent	32	18,000	9,373,571
High Intensity Discharge	50	10,000	26,382
Total			53,648,484

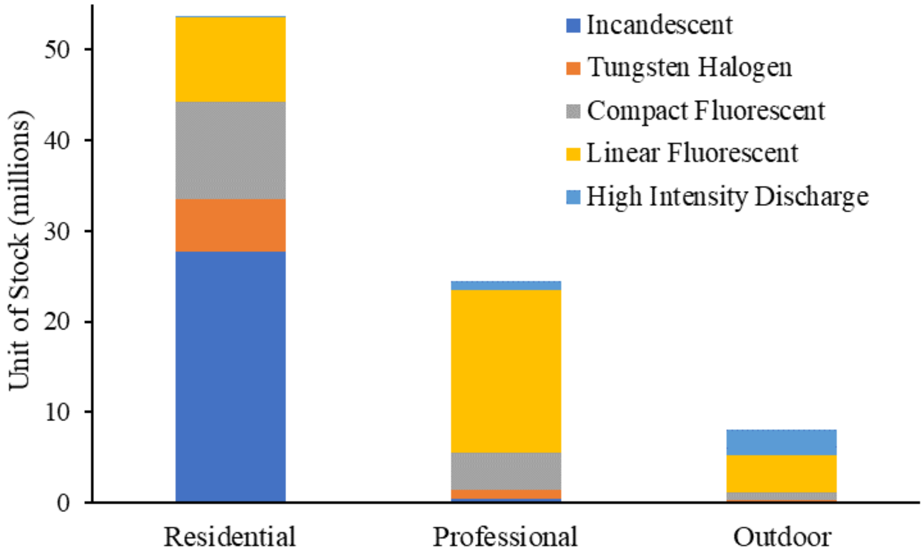


Figure 16 Total Kuwait lighting stock in 2010 [79].

3.2.2.4. Appliances

The home appliances end-use in residential households includes electric appliances like refrigerators, televisions, computers, and others. The *UEC* for appliances is the product of the nameplate wattage and the usage hours. Most appliances have different types and sizes, resulting in different energy usage. For the specific case of Kuwait, all the literature, surveys and government statistical data are based on an average appliance sizes and types. Therefore, we can only calculate the average unit energy consumption of each appliance, until more detailed surveys or sales data become available. For products with multiple modes like standby mode, energy consumption for each mode is calculated separately and added to obtain the total energy consumption in all modes. The average hours use, rated wattage and life span for most of the appliances is estimated based on [62,67,70]. Table 11 lists the various metrics that are used to calculate the modelled energy usage broken down by appliances.

Table 11 List of household appliances metrics that include corresponding power requirements, average run-time, and useful life.

Appliance	**Rated power (W)**		**Usage (hours/ week)**	**Useful lifetime (years)**	**Notes**
Washer	500		11	10	Source [23,62,81]
Dryer	2790		6	13	Source [81–83]
Iron	1000		7	7	Source [23,62]
Microwave	1000		7	9	Source [23,62,81]
TV	138		35	7	Source [23,70]
PC	300		21	5	Source [23,70,83]
Refrigerator	907	kWh/year		13	Source [23,81]
Freezer	1037	kWh/year		11	Source [23,81]
Water cooler	799	kWh/year		10	Source [23], EERNGY STAR calculator (2.19kWh/day)

3.2.3. Unit power demand

Unit Power Demand (UPD) is determined in a similar way to *UEC*, but it only focuses on the equipment operating at the peak load period (i.e. summer in Kuwait), and can be expressed as [84]:

$$UPD = P \times RLF \times CDF \tag{14}$$

where *P* is the nameplate power per unit, Rated Load Factor (*RLF*) is the ratio of maximum operating demand of equipment to the rated input power. For example, air conditioners that operate above their rated input power could result in an *RLF* greater than one. The coincidence diversity factor (*CDF*) is used to account for the fact that not all stock units are operating at the peak time. The coincidence diversity factor is defined as the peak demand of a population of units at the system peak time to the peak demand of an individual unit, and can be expressed as [85]:

$$CDF = \frac{kW_{pop}}{\sum_{i=1}^{n}(kW_i \times RLF_i)} \tag{15}$$

where kW_{pop} is the peak demand of the population of units, kW_i is the nameplate rating of unit *i*, and RLF_i is the rated load factor of unit *i*. For the specific case of Kuwait, there is no sufficient data for the peak demand of individual equipment or even by end-use. Therefore, we assumed 100% CDF for AC since the peak demand happens in summer and the major contributor is AC [13]. We used Equation 15 to calculate single CDF for the rest of equipment, using the actual total peak demand and the rated power of all the equipment stock.

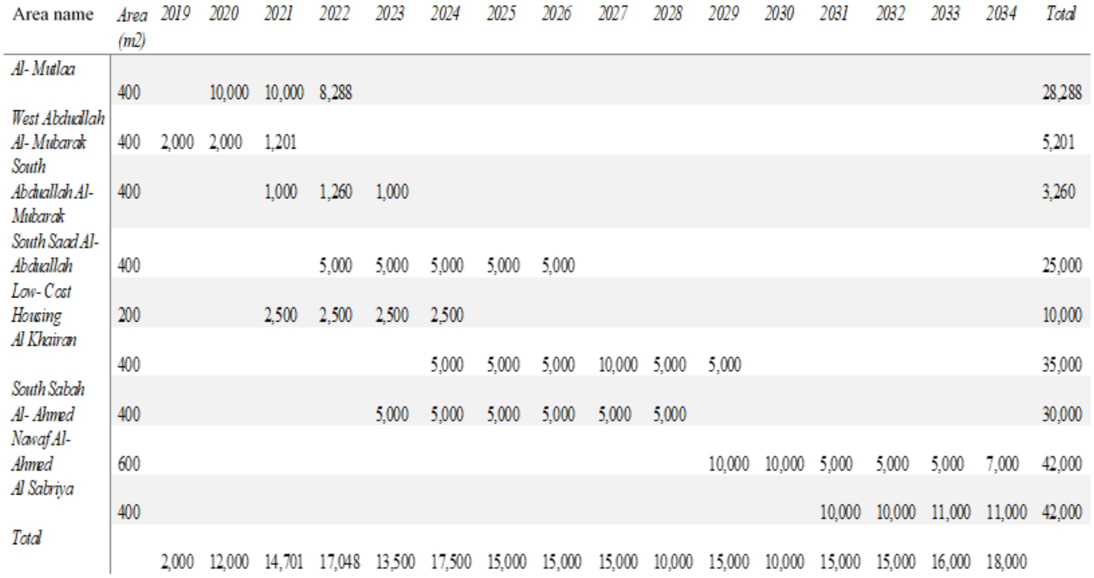
3.2.4. Forecast analysis

To predict a business-as-usual case, the forecast model relies on the main driving variables of national energy consumption, *UEC* and *Stock*. With projected values of *UEC* and *stock* for each equipment, we can use the same equations mentioned previously (Equation 1 and 2) to forecast the energy consumption and demand. Depending of the equipment type, *UEC* is assumed to improve 1% - 5% in efficiency per year based on [71,72]. The forecast of the equipment stock is mainly driven by the diffusion rate *D(y)* and new housing construction. The diffusion rate *D(y)*, as modelled in Equation 5, yields a high saturation rate rendering a maximum rate of diffusion since it is based on the assumed high levels of:

1) Income
2) Electrification rate
3) Urbanization rate

In addition to the population data mentioned in the introduction, Table 12 shows the amount of housing subsidies provided by the Public Authority of Housing Welfare (PAHW) each year, until 2034. The housing subsidy values are another driving variable used to estimate the stock included in the model by *First purchases(y)* in Equation 3.

Table 12 Total housing subsidies provided by PAHW for various cities in Kuwait until the year 2034 [65].



Area name	Area (m2)	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	Total
Al- Mutlaa	400		10,000	10,000	8,288													28,288
West Abdullah Al- Mubarak	400	2,000	2,000	1,201														5,201
South Abdullah Al-Mubarak	400			1,000	1,260	1,000												3,260
South Saad Al-Abdullah	400				5,000	5,000	5,000	5,000	5,000									25,000
Low- Cost Housing	200			2,500	2,500	2,500	2,500											10,000
Al Khairan	400						5,000	5,000	5,000	10,000	5,000	5,000						35,000
South Sabah Al- Ahmed	400					5,000	5,000	5,000	5,000	5,000	5,000							30,000
Nawaf Al-Ahmed	600											10,000	10,000	5,000	5,000	5,000	7,000	42,000
Al Sabriya	400													10,000	10,000	11,000	11,000	42,000
Total		2,000	12,000	14,701	17,048	13,500	17,500	15,000	15,000	15,000	10,000	15,000	10,000	15,000	15,000	16,000	18,000	

This forecast model represents a business-as-usual scenario where no energy efficiency measures or polices are implemented. Nevertheless, even with base case scenarios, the efficiency of equipment and appliances tend to improve over the years. This was considered by assigning an efficiency improvement rate for each equipment and appliance in the model. In addition, some new technologies will diffuse into the market and replace old ones that can be less efficient. LED lighting is a good example of that since it was introduced in Kuwaiti market couple of years ago. A Bass model was used to estimate the adoption rate of LED lighting and incorporated into the baseline model. Since no historical sales data of LED are available for Kuwait, the Bass model parameters were estimated by analogy to CFL bulbs that have past shipment data and similar diffusion characteristics with LED [86]. The ordinary least squares (OLS) method was used to estimate the Bass model parameters (i.e. the coefficient of innovation (*p*) and imitation (*q*)) in Table 13.

Table 13 Coefficients of innovation and imitation of Bass model.

Parameter	**p**	**q**
Estimated value	0.0073	0.1686

3.3. Results and discussion

Based on the specified inputs explained in the previous section, Figure 17 shows a bubble plot of the unit energy consumption of home appliances against the total stock to reveal the energy usage. The additional dimension, the size of the bubble, represents the total annual energy consumption. Household appliances included in the analysis consist of televisions (TV), personal computers (PC), washers, irons, microwave, refrigerator, freezer, water cooler, and dryers.

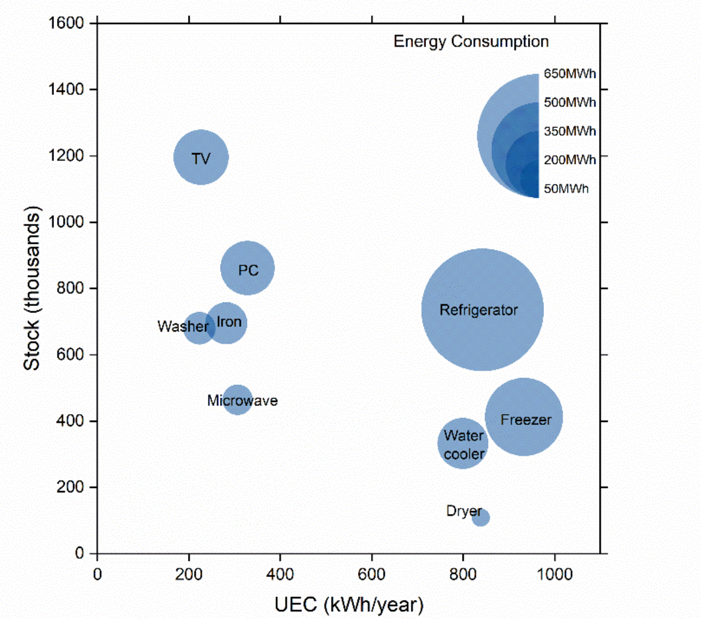


Figure 17 Electrical energy consumption of selected household appliances in Kuwait.

It can be observed that two major data clusters emerge with similar *UEC*s. One contains the following household appliances: TVs, PCs, washers, irons, and microwaves. The *UEC* for this group ranges from approximately 200 kWh/year to 400 kWh/year. Despite the relatively low unitary electrical consumption of TVs, the quantity of the stock raises the level of impact. With approximately a thousand sets at a *UEC* of roughly 250 kWh per year, TVs represent a significant portion of the domestic energy use in Kuwait.

The second group consisting of higher *UEC*s, contains the following household appliances: water coolers, refrigerators, dryers, and freezers. Unlike refrigerators, freezers, and water coolers, dryers have low duty cycles and therefore consume less energy in a year--hence the smaller bubble. Moreover, in contrast, this group has a higher *UEC* range starting from approximately 800 kWh/yr. to 1000 kWh/yr. Collectively, despite being less in stock, the overall impact is almost equally relevant due to the higher electrical consumption. This is partly due to the components that require significant power to operate, such as compressors in refrigeration systems, or resistive heaters commonly found in irons and electrical dryers.

Table 14 and

Table 15 display the *UEC*, stock quantity, and the total energy consumption for specific household appliances for Kuwaiti homes. Due to the differences in energy use patterns between Kuwaiti and non-Kuwaiti homes, a similar analysis was conducted utilizing equal usage parameters, but with different stock quantities. The *UEC* values for the listed household appliances were calculated as outlined in the methodology section and remain unchanged for both models. The highest *UEC* is noted to be freezers, refrigerators, and dryers, respectively, while PCs, washers, and TVs have *UEC*s that are less than a third that of freezers.

Table 14 Total energy consumption of modeled household appliances with corresponding stock quantities for Kuwaiti residential homes.

Plug loads	**UEC (kWh/year)**	**Stock**	**Total energy consumption (GWh)**
Refrigerator	907.20	524,045	475.41
Freezer	1,036.80	315,747	327.37
Washer	297.48	459,011	136.54
Dryer	882.57	89,540	79.03
Iron	375.95	470,321	176.82
Microwave	408.80	313,862	128.31
TV	251.85	926,505	233.34
PC	328.50	597,563	196.30
Water cooler	799.35	274,276	219.24
Total			1,972.36

The results indicate that the energy consumption for the listed appliances total 1,972.36 GWh for Kuwaiti households. Approximately 40% of the total consumption is attributed to refrigerators and freezers. The high energy consumption for these appliances were expected, as the *UEC* values were high to begin with. However, due to the relatively high stock quantities, TVs also represent a significant load on the grid. Despite their low *UEC*s, the impact is offset by the volume, adding up to 926,505 TV sets, the highest stock quantity in all the listed appliances.

Utilizing the same list of appliances, along with their *UEC*, Table 4 displays the total energy consumption for specific household appliances for non-Kuwaiti homes.

Table 15 Total energy consumption of modeled household appliances with corresponding stock quantities for expatriate residential homes.

Plug loads	**UEC (kWh/year)**	**Stock**	**Total energy consumption (GWh)**
Refrigerator	907.20	211,349	191.74
Freezer	1,036.80	96,724	100.28
Washer	297.48	221,084	65.77
Dryer	882.57	19,156	16.91
Iron	375.95	224,538	84.42
Microwave	408.80	150,111	61.37
TV	251.85	269,446	67.86
PC	328.50	264,107	86.76
Water cooler	799.35	58,097	46.44
Total			721.53

According to the results, the distribution of the electricity consumption in residential households in Kuwait differs vastly, since the stock quantity weighs in heavily. Kuwaiti households account for roughly 70% of the total electrical consumption of the modeled appliances, whereas the remaining 30% is attributed to non-Kuwaiti household usage at 721.53 GWh. Parallel to the Kuwaiti profile, the results governing the expatriate households indicate that the top two energy-consuming appliances are refrigerators and freezers. The energy consumption of these two appliances make up approximately 40% of the overall energy usage for the expatriate household appliances.

On a broader perspective, the electrical consumption and demand distribution in residential households in Kuwait is broken down by the following main usage categories: lighting, air conditioning, space heating, water heating and miscellaneous loads. Electrical consumption patterns remain heavily dependent on air-conditioning, as it represents the biggest slice within the pie charts shown in Figure 18. Air conditioning accounts for two thirds of the residential household consumption. However, although it is as little as 4.5%, space heating still accounts for a small load.

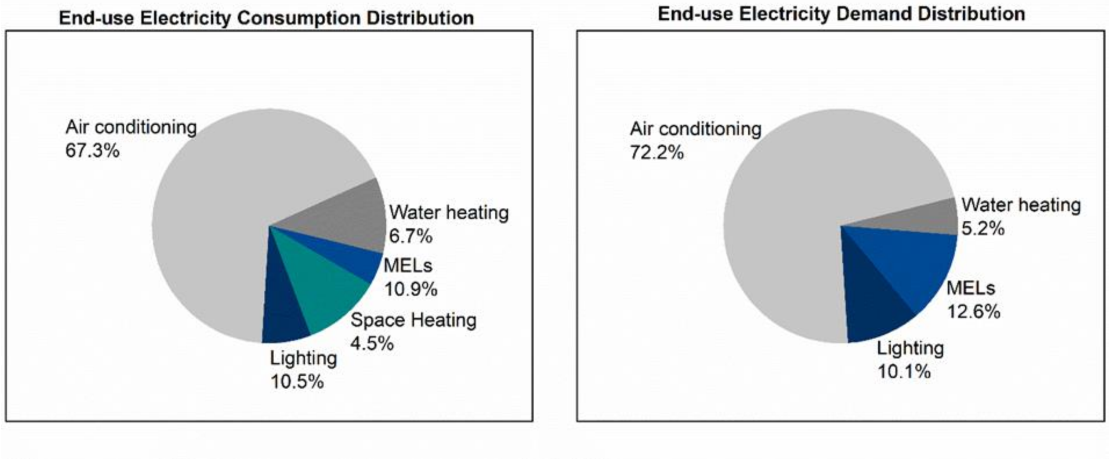


Figure 18 Distribution of on-site residential energy use and demand in Kuwait.

As seen in the distribution for residential electricity consumption, air conditioning makes up the bulk of the demand for Kuwaiti households at 66% whereas the rest of the categories (miscellaneous loads, water heating, and lighting) range from 5% to 13%.

Utilizing the methodology outlined in this paper, the forecast of the residential energy consumption end-use was modeled and plotted in Figure 19. Revealing a similar trend observed in the household electrical consumption distribution and the household electricity demand distribution, air conditioning load is one of the highest loads for households. As per the results of the analysis, it is expected to rise exponentially from the year 2022 onwards, reaching an estimated load of 60 TWh. Lighting is predicted to rise as well, but much flatter, unlike the trend in air conditioning, mainly because the diffusion of LED lighting in the residential stock. The dashed line represents the actual total energy consumption from 2005-2017. The comparison between the actual and forecast points show an accurate model starting from 2005 until 2017. The model results agree with the actual historical data, as the error is less than 5%. In terms of electrical demand, Figure 20 displays the growth for the air conditioning load, as it comprises a significant portion of the annual power demand. The results are also presented in a tabular form in Table 16. Figure 21 displays the forecast of electrical consumption for Kuwaiti and expatriate (non-Kuwaiti) households until the year 2040. Despite the slow growth in population, the forecast analysis indicates that the Kuwaiti energy consumption per capita is significantly higher than that of the expatriates, reaching levels of 15 MWh. The values for expatriates is almost stagnant, staying well below 1.5 MWh, despite the growing population figures that are expected to reach 4 million, more than doubling since 2005. The results are also represented in a tabular form in Appendix B.

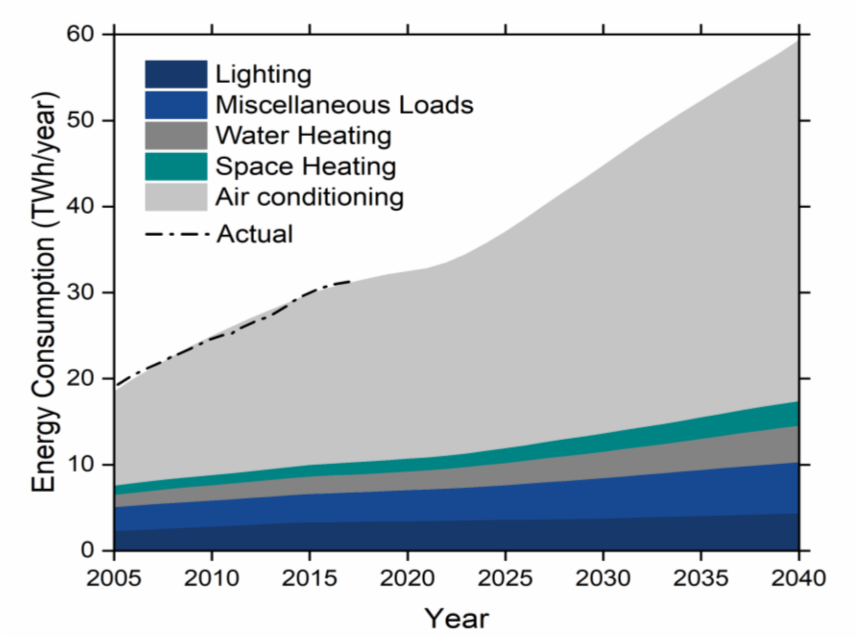


Figure 19 Forecast of on-site residential energy consumption by end use.

Table 16 Forecast of end-use residential energy consumption until the year 2040 in Kuwait.

	Residential Energy Consumption (GWh)					
	2017	2020	2025	2030	2035	2040
Miscellaneous Loads						
Kuwaiti	1,687.61	1,805.81	2,100.36	2,587.74	3,095.81	3,537.81
Expatriate	452.18	509.93	610.29	700.97	792.76	888.22
Total	2,139.78	2,315.74	2,710.65	3,288.71	3,888.58	4,426.04
Water Heating						
Kuwaiti	1,821.13	1,893.24	2,244.82	2,692.32	3,184.99	3,762.42
Expatriate	252.54	286.16	340.38	384.51	436.12	486.02
Total	2,073.67	2,179.40	2,585.20	3,076.83	3,621.10	4,248.44
Space Heating						
Kuwaiti	1,672.00	1,749.44	2,026.52	2,524.51	2,987.72	3,435.29
Expatriate	195.53	221.44	257.48	296.7	333.74	371.42
Total	1,867.53	1,970.88	2,284.00	2,821.21	3,321.47	3,806.71

Air Conditioning						
Kuwaiti	18,879.39	19,554.17	22,474.09	28,068.57	33,333.43	38,070.25
Expatriate	2,027.28	2,250.95	2,697.75	3,098.75	3,486.88	3,894.83
Total	20,906.67	21,805.12	25,171.84	31,167.32	36,820.31	41,965.08
Lighting	3,527.00	3,864.00	3,866.00	3,941.00	4,246.00	4,574.00
Total	30,514.51	32,135.44	36,617.78	44,295.47	51,897.46	59,020.41

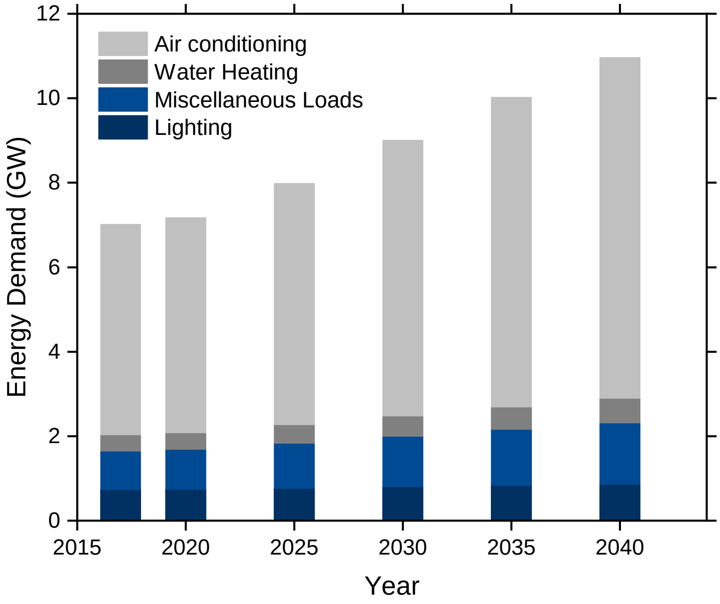


Figure 20 Forecast of on-site residential energy demand by end use in Kuwait.

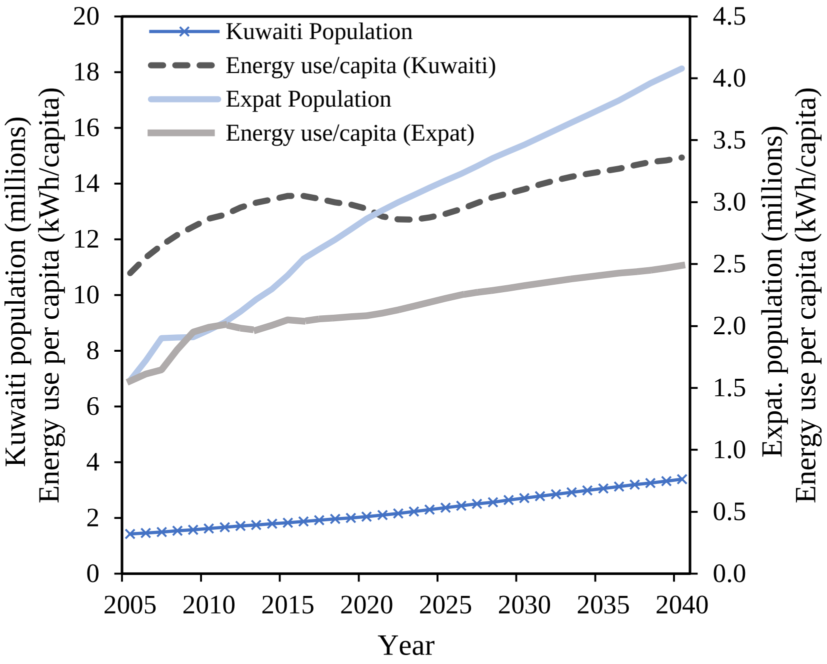


Figure 21 Forecast of population and residential energy consumption per capita.

3.4. Conclusion

Kuwait has one of the highest energy consumption per capita levels in world. This large-scale consumption is negatively impacting its natural resources and the environment. The building sector alone accounts for 57% of the electrical consumption. It is therefore important to study the driving impacts in a building's energy consumption in Kuwait. Utilizing end-use baseline information for residential loads sets an important foundation to help understand the residential consumption patterns. Based on the specified end-use equipment and certain parameters, a forecasting analysis was conducted to estimate the end-use distribution of electrical consumption for the state of Kuwait until the year 2040. In the model, end-uses were broken down into the following: air conditioning, lighting, miscellaneous loads, and space heating and water heating.

The resulting Unit Energy Consumption (*UEC*) of home appliances was plotted against the total stock which illustrated the impact of each of the specified home appliances. Refrigeration units, out of all appliances, held the highest *UEC* by far, as they were high in both stock and *UEC* values. A forecast model was then plotted to reveal the end-use energy consumption and peak demand in Kuwait until 2040. The air conditioning loads are expected to rise in the future with an average annual growth rate of 2.9%. Meanwhile, the rise in lighting energy consumption is much flatter due to an expected gradual shift towards more efficient lighting. The total residential energy consumption is expected to double by the year 2040. Furthermore, based on the forecast results, the differences between the Kuwaiti and expatriate (non-Kuwaiti) residential loads have been observed. These results provide opportunities for the development of more effective energy policies, as well as opportunities for energy efficiency initiatives for the future.

4. ADOPTION MODEL OF ENERGY CONSERVATION MEASURES

It is often noted that assessing the national impact of any energy saving technology specific to buildings is a challenging task. This is often compounded by the fact that technology-specific impact studies may not rely on the same basic assumptions about the buildings being studied. Therefore, before aggregating the results, the findings should be normalized. This time-consuming process often hampers impact assessment. The model presented in this work hopes to eliminate this difficulty by qualitatively assessing the energy and GHG impact of energy-efficiency measures on the national building stock in Kuwait. The measures are characterized by the timeline of market entry and exit, unit performance levels, lifespan, and the cost associated with the equipment. The model developed is capable of characterizing building stock across a timeline for new projects and retrofits while accounting for equipment replacement, and new technology interventions under varied adoption scenarios.

4.1. Review of literature

The presence or distribution of a technology is often represented by a factor termed as *technology* diffusion rate. This factor can be calculated using techniques such as diffusion of innovation models. A review of technology diffusion models is provided by Rao and Kishore [87]. The study also discusses the impact of economics and energy policies. The Bass model [88] is a common approach for describing technology diffusion on markets. This model is modified by Higging et al. [89] to accommodate financial and non-financial benefits, ceilings of adoption and interactions between intervention options.

McNeil and Letschert [63] study diffusion of household appliances, and try to assess the importance of macroeconomic drivers in this regard. Similarly, Tao and Yu [90] and Schade et al., etc. [91] assess future energy demand of various household electrical appliances. Such an approach, when combined with factors such as specific energy demand and market diffusion rate, can be employed to predict household demand.

Meier and Rosenfeld [92,93] concentrated on developing tools and methods for classifying energy conservation measures based on their economic savings potential and their levelized cost of conserved energy (LCCE). These early works also introduced an accounting system such that households or organizations using multiple energy saving measures can keep track of the effects of each without missing or double counting the effects of any one measure. Other research focused on factors such as economic potential and a time frame of one or two decades to assess the possibility of satisfying any future domestic service using more energy efficient technologies. These studies identify crucial opportunities to save energy over a 10-year horizon by 16-28% [94] and over a 20-year horizon by 23-32% [95] employing energy saving measures that are commercially viable at the time of their research.

The U.S. Department of Energy recently developed a tool to assess the energy and CO_2 impact of an energy efficiency measure in the building sector [96]. This tool, named *Scout*, is an improvement on the unit performance and/or lifetime operational costs of an equipment stock baseline calculated from the U.S. Energy Information Administration Annual Energy Outlook (AEO) [97]. Scout is capable of combining and analyzing multiple energy efficiency measures available to the U.S. Department of Energy (DOE). This tool is perhaps a significant step forward in building stock assessment, capable of using AEO projections for new construction, retrofit, and equipment replacements, and competes technologies within market segments for varied scenarios. Scout was built upon a prioritization tool called the P-Tool [98] that aggregates and analyzes many building efficiency measures available in the U.S. market.

4.2. Methodology

The impact of Energy Conservation Measures (ECMs) to the CO_2 emissions and the energy consumptions of the baseline residential building markets in Kuwait is modelled. Figure 22 illustrates the modelling structure of the impact evaluation. Each ECM has a set of data that includes the applicable market, year when the measure was introduced/phased out from the market, incremental cost, measure performance, and Estimated Useful Life (*EUL*). These data are determined from the ECMs survey data and literature [18,98].

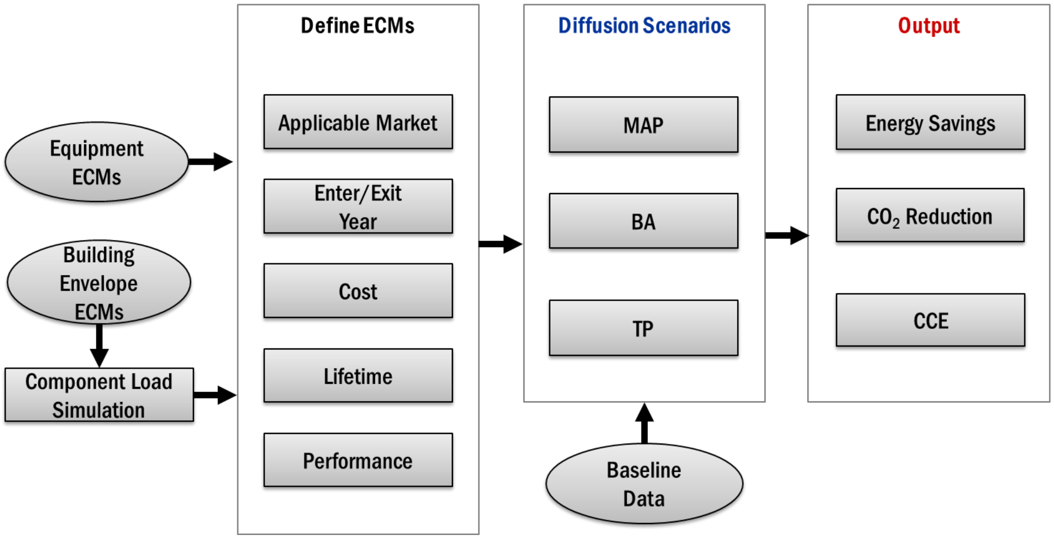


Figure 22 Flow chart of the measure impact evaluation.

The energy performances of the envelope ECMs are calculated from component load simulation [99] and the performances of equipment ECMs are developed from the ECMs survey data. Then the applicable ECMs are applied to the baseline markets, which are established from the earlier chapter for the residential building sector in Kuwait. The rate that the market adapt to each ECM is determined by three technology adoption models: The Technical Potential (TP), Maximum Adoption Potential (MAP), and Bass Adoption model (BA) [88,96,98]. Both the impacts of individual measures, and the overall impacts of combined measures to the baseline building stock, are presented.

4.2.1. Baseline markets and market dynamics

To properly evaluate the impact of the ECMs, a reasonable baseline market is essential. Various researchers have studied the baseline building stock in the U.S. [54,100,101], however, there is very little research that has examined the Kuwait building market. Since the building composition, available technologies and climate of Kuwait are significantly different from those of the U.S., a proper baseline must be established to account for the building type, energy end use, and available technology for Kuwait. The baseline energy data for each market are generally derived from the earlier chapter. The baseline markets were established from a bottom-up approach for forecasting the energy consumption and demand. The energy consumption end uses are divided into air conditioning, lighting, appliances, space heating, water heating and other. Each end-use category is consistent of different technologies available for the Kuwait residential market. Another important factor to establish the baseline is the market adoption rate, which is based on the data obtained from surveys and available literature [62,102]. The population, household size and income, or engineering variables such as unit energy consumption and efficiency ratings are vital parameters for determining the baseline. The detailed description and modeling approach for establishing the baseline can be found in the earlier chapter and Appendix A.

4.2.2. Measure definitions

An ECM is defined by five parameters: 1) applicable market; 2) years when the measure was introduced/phased out from the market; 3) incremental cost; 4) measure performance, and 5) EUL. The definitions of each parameter are listed below. The critical factor to ensure the accuracy of an ECM impact is to ensure the same definition is consistently applied to all the technologies for ECMs.

Applicable market: The ECMs usually have their own applicable market. For example, a high efficiency heat pump system is unlikely to be available in the Kuwait market since little heating is required in this region, instead, portable space heaters are more typical for handling the small heating load in the Kuwait region. The applicable market is obtained from the ECMs survey.

Market entry and exit year: Efficiency measures typically have a limited period when they are available to the market. The entry year is typically dependent on the local building code, the price of the technologies etc. The exit of one technology typically occurs when a more stringent code is adapted by the government that requires a higher efficiency than the ECM can provide. If there is no existing legislation or building codes, the measure entry and exit year is typically dictated by competition of similar ECMs.

The ECM incremental cost includes the material and labor cost for installing the ECMs. They are typically presented in the form of cost per equipment or cost per square meter for envelope ECMs. For new construction or retrofit, the incremental cost is the cost difference of the ECM relative to the standard efficiency system or existing equipment cost. For add-on measures, where the measure only adds to the existing system to improve its performance, and the existing system is not replaced, such as adding low-e window films, the baseline installed cost is zero and the measure’s incremental installed cost is the same as its installed cost.

The ECM performance describes its performance (typically energy performance), such as U-value and solar heat gain coefficient for a window or coefficient of performance (COP) for air conditioning system (AC). The measure performance can also be described as a percentage of savings relative to standard efficiency equipment. The measure performance value is used to calculate the UEC of the ECM equipment as shown in the following equation:

$$UEC_{measure} = \frac{\text{Efficiency (or U} - \text{value, SHGC etc.)of ECM}}{\text{Efficiency (or U} - \text{value, SHGC, etc.) of Baseline}} \times UEC_{baseline} \tag{16}$$

The EUL is the estimated useful life of an equipment in years. There are various sources to identify the EUL. To ensure consistency, the EUL should come from the same data source as the measure incremental cost whenever possible.

Table 17 summarizes some sample ECMs which cover a variety of end uses. The applicable market for most of these measures is the total residential stock. For solar water heaters, the applicable market is single-family dwellings only. Since no R&D measures were considered when modelling these measures, the exit year, when the measure is replaced with a more efficient one, is not specified. Also, the entry year is assumed to be 2018 for most of the measures since they are already available on the market.

Table 17 Sample of residential energy conservation measures.

ECMs	**Performance**	**Cost (2018 USD)**	**Lifetime (yr)**	**Source**
ENERGY STAR Refrigerator	55% savings	\$873	13	[23,103,104]
ENERGY STAR Freezer	30% savings	\$995	11	[23]
ENERGY STAR Computers	40% savings	\$616	4	[105]
ENERGY STAR TV	27% savings	\$618	7	[106]
ENERGY STAR Water Cooler	30% savings	\$140	10	[106]
ENERGY STAR Washer	25% savings	\$400	10	[106]
ENERGY STAR Dryer	20% savings	\$475	8	[106]
Microwave (Max-tech)	20% savings	\$155	9	[103]
ENERGY STAR WH (HPWH)	EF = 2.1	\$1500	10	[78]
Efficient WH	EF = 0.96	\$700	13	[78]
Solar with Electric Backup	EF = 1.9	\$3200	20	[78]
ENERGY STAR Central AC	COP =3.6	\$2761/TR	15	[106]
ENERGY STAR Split AC	COP = 3.8	\$2874/TR	15	[106]
ENERGY STAR Room AC	10% savings	\$200/unit	10	[107]
Smart Thermostats	10% savings	\$250/unit	10	[103,106]
Programmable thermostats	4% savings	\$150/unit	10	[103]
Exterior wall insulation (Code 2014)	R-10	\$12/m^2	25	[23,29]
Exterior roof insulation (Code 2014)	R-14	\$16/m^2	25	[23,29]
ENERGY STAR Window	U-factor=0.4, SHGC=0.26	\$29/m^2 (incremental cost)	30	[96,108]
Reduce infiltration	ACH =0.3	\$1.4/m^2	30	[96]

4.2.3. Envelope components load simulation

The energy savings of the ECMs are a result of either the demand or supply side of the energy reduction. For the ECMs that contribute to the supply side savings, the equipment typically consumes energy directly, such as AC units. On the other hand, ECMs that contribute to the demand side savings typically do not consume energy directly. Instead, they yield savings by reducing the building load, such as providing higher insulation level to the roof to reduce the heating and cooling load, which in the end reduces the AC and space heating energy consumption. These types of ECMs are usually refer to as ‘envelope’ ECMs.

Since the envelope ECMs do not consume energy directly, building simulations are needed to estimate the energy impact of each envelope ECMs. To estimate the average impact of each envelope ECM, the four archetype models from chapter 2 were used.

The simulations calculated and reported the heating and cooling loads for each model. Then, to isolate the building load contributed by each component, such as the walls, roof, and windows, we conducted parametric simulations by setting the envelope property of one ECM to first adiabatic and then setting it to the appropriate baseline value [99]. The difference between the adiabatic run and the baseline run is the heating or cooling load contributed by that envelope component. Then the component load for each archetype was applied to the whole building stock based on the proportion each archetype represents. Figure 23 shows the monthly energy heat balance of the main envelope components. The contribution of each envelope components to the building cooling load is shown in Figure 24. Figure 35, in Appendix B, shows the annual energy heat balance of the main envelope components.

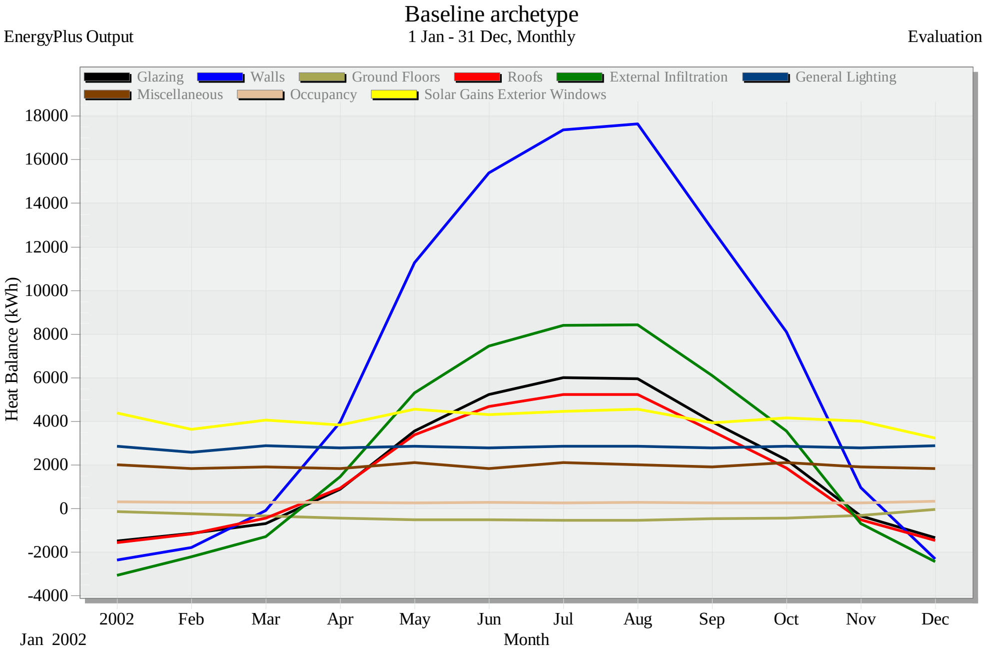


Figure 23 Simulated energy heat balance of the main envelope components of a typical residential building in Kuwait.

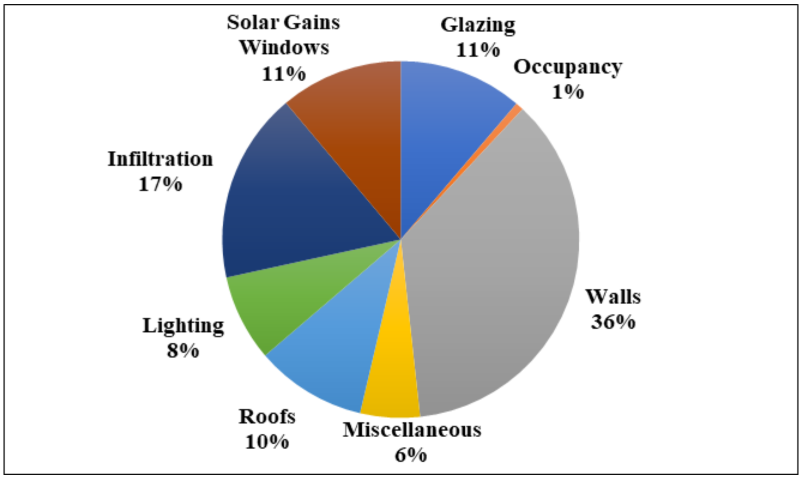


Figure 24 Contribution of envelope components to the annual cooling load in a typical residential building in Kuwait.

4.2.4. Measure adoption scenarios

For the measure to have an impact on the baseline building market, it must be adopted by the market. The adoption rate is impacted by various parameters. We used three different adoption models, The Technical Potential (TP), Maximum Adoption Potential (MAP), and Bass Adoption model (BA) to generate three different adoption rates. The Technical Potential (TP) scenario assumes that the ECM will replace all the existing equipment that has lower performance than the ECM and is adopted in all new constructions as soon as the entry year of the ECM. The TP represents the maximum impact that a measure could realize, and it is only limited by its baseline market size. The MAP scenario assumes that an ECM replaces an existing system at the end of the life of the existing system, and the ECM is also adopted by all new construction as soon as its market entry year. The MAP therefore represents a measure’s maximum impact given realistic stocks-and-flows. The third scenario is based on the Bass model [103,109–111]. The Bass model defines the fraction of sales $F(y)$ in year y to represent the adoption rate of a measure as follows:

$$\frac{dF(y)}{dt} = (p + qF(y))(1 - F(y)) \tag{17}$$

where p represents the external factors that drive the market to adopt a new technology, such as advertisement, and q is often termed the “word-of-mouth” effect from the early adopters to encourage the “imitators” to adopt the ECMs [88]. In order to use the Bass model to forecast the adoption of a new product or technology, the parameter p (innovators), q (imitators) and the potential market size need to be estimated. Since no historical sales data of ECMs are available for Kuwait, these parameters were estimated by analogy to similar products that have past sales data and similar diffusion characteristics with the targeted products based on [112,113]. The Bass scenario was divided into two models; Bass 1 and 2. Bass 1 model the normal diffusion of ECMs with no energy policy efforts While Bass 2 incorporate the effect of these energy policies. Based on Anderson et al. [103,111], energy policy efforts like the deployment of ENERGY STAR labeling, increase the innovation coefficient by 0.0139. Table 18 shows the coefficients used in both models.

Table 18 Coefficients of innovation and imitation of Bass model.

Scenario	**p**	**q**
Bass 1	0.00047	0.17230
Bass 2	0.01447	0.17230

4.2.5. Economic analysis

The Cost of Conserved Energy (*CCE*) is used to determine the cost-effectiveness of ECMs in Kuwait. The CCE is defined as the cost of per unit energy savings [114], as shown in the equation below:

$$CCE = \frac{Incremental\ cost}{Present\ value\ of\ the\ energy\ saved\ through\ the\ EUL\ of\ the\ ECM} \qquad (18)$$

Since the energy savings of the ECM occurs throughout its entire life, we need to convert the life time energy savings to the present value to account for inflation. The present value of energy savings is:

Present value of the total energy savings = Annual Energy Savings (kWh) / CRF (19)

And the Capital-Recovery Factor CRF is calculated as

$$CRF = \sum_{n=1}^{L} \frac{1}{1/(1+\mathrm{r})^{n}} = \frac{d}{1-(1+d)^{-L}} \tag{20}$$

where r is the discount rate and L is the period of the analysis, which is typically the lifetime of the equipment [114,115].

For an ECM to be cost effective, the *CCE* of that measure should be larger than the current utility rate (i.e., the retail cost of the energy source such as the cost of electricity). For example, if the *CCE* of an air conditioning ECM is \$0.07, and the utility rate is \$0.11, then this ECM is cost effective and will provide \$0.04 savings per unit energy saved. Therefore, if multiple ECMs in the same measure category are available for the market, the measures with the lowest *CCE* and highest energy savings would be preferable.

It should be noted that the utility cost in Kuwait is heavily subsidized. The MEW of Kuwait reported the actual cost of electricity generation and distribution is \$0.133 per kWh, however, the utility rate has been held constant at \$0.007 per kWh since 1966 [23]. With the subsidized utility rate, almost no ECMs will be cost effective. Therefore, we compared the *CCE* to both the subsidized and unsubsidized Kuwait utility rates to prevent biased results when subsidization is considered.

4.2.6. Measures interaction

As mentioned in the previous sections, there are certain measures that not only reduce the end use energy consumption, but also change the building load, which results in a change in the HVAC system energy consumption. Such measures include efficient lighting measures and high efficiency appliance measures. In Kuwait, there is typically little heating load, therefore, by reducing the building load through high efficiency lighting and appliances, the cooling energy use can also be reduced. To account for the interactive effects of those measures, we introduce HVAC interaction factors for measures that have secondary influences on HVAC system energy [96,98]. The HVAC interaction factor is defined as the ratio of the change in the HVAC electricity consumption per unit energy change in the measure energy consumption. The HVAC interaction factors are calculated from building energy simulation programs through parametric runs using the archetype buildings models mentioned in earlier sections. We run the baseline simulation and record the energy consumption of lighting and cooling system. We then apply the lighting ECM by reducing the lighting power density (LPD) to values that represent efficient light bulbs like LED or efficient CFL. We also need to change the heating properties of the light bulbs based on Table 19, since efficient light bulbs tend to radiate less heat [116].

Table 19 Heating properties of light fixtures [116].

	Incandescent	**Fluorescent**	**LED**
Visible light fraction	0.08	0.21	0.25
Radiant heat fraction	0.73	0.37	-
Convective heat fraction	0.19	0.42	0.75

Then we run the simulation and record the energy consumption of lighting and cooling system when ECM is applied. The HVAC interaction factor (HIF) is calculated based on the following equation:

$$HIF = \frac{\Delta\, HVAC\ energy\ consumption\ (kWh)}{\Delta\, Lighting\ energy\ consumption\ (kWh)} \tag{21}$$

Table 20 shows the HVAC interaction factors from replacing incandescent light bulbs with CFL or LED bulbs.

Table 20 Calculated HVAC interaction factor for lighting ECM.

HVAC Interaction Factor	**Archetype**			
	A	B	C	D
CFL	0.28	0.37	0.41	0.49
LED	0.24	0.23	0.38	0.46

4.3. Results and discussion

This section shows the results and discussion of the energy savings for various ECMs in Kuwait under different scenarios and their cost effectiveness based upon local utility rates, first cost and useful life and proposes several policies according to the outcome of this investigation.

4.3.1 Energy savings under different adoption models

Figure 25 shows the annual primary energy consumption for refrigeration, air conditioning, water heater and lighting ECMs under various adoption models through 2035. These ECMs was chosen because of their high energy savings and low *CCE*. The increase in annual energy consumption in the baseline scenario is primarily due to the population growth, and hence the increase of the number of units in each ECM. For the different adoption models, the population growth also exists, however, due to the adoption of more efficient equipment, the increase in energy consumption is slower than the baseline. The TP model represents the scenario where all the existing equipment will be replaced in the first year with the high efficiency equipment, regardless of the age or condition of the existing equipment. This scenario, albeit unrealistic, represents the maximum savings for each ECM and provides the lower bound of the energy consumption. As shown in Figure 25, there is a significant drop in the first year of the analysis, due to all the existing equipment being replaced by the energy efficient ones. The energy consumption in the following years will increase due to the population growth. However, the slope is smaller than the baseline because the energy efficient equipment consumes less energy than the baseline equipment per unit.

The MAP model represents the scenario where all the standard efficiency equipment will be replaced at the end of their useful life with the higher efficiency ones. This scenario represents the maximum impact of each ECM given realistic stocks-and-flows. Theoretically, which is also shown in Figure 25, the TP and MAP scenarios converge eventually after the analysis period exceeds the life time of the standard efficiency equipment because all the standard efficiency equipment will be replaced by the energy efficient ones in both scenarios.

Additionally, this study also investigated two scenarios using the Bass diffusion model. “Bass 1” simulates the scenario where the energy efficient equipment will be adapted under the normal diffusion rate in Kuwait without any policy, regulation or incentives. Compared to the MAP scenario, the Bass model assumes only a certain percentage of the existing equipment will be replaced with energy efficient ones. As shown in Figure 25, the Bass 1 model closely follows the baseline, indicating the adoption of the energy efficient equipment will be slow without any policy or regulation in Kuwait. Bass 2 denotes the scenario with government efforts to promote the energy efficient equipment, such as through ENERGY STAR labeling. The difference between Bass 1 and Bass 2 model is the p coefficient used in Equation 16 [103,111]. As shown in Figure 25, the Bass 2 scenario has lower energy consumption than Bass 1 because with the promotion from the government, more people would choose energy efficient equipment over standard efficiency equipment.

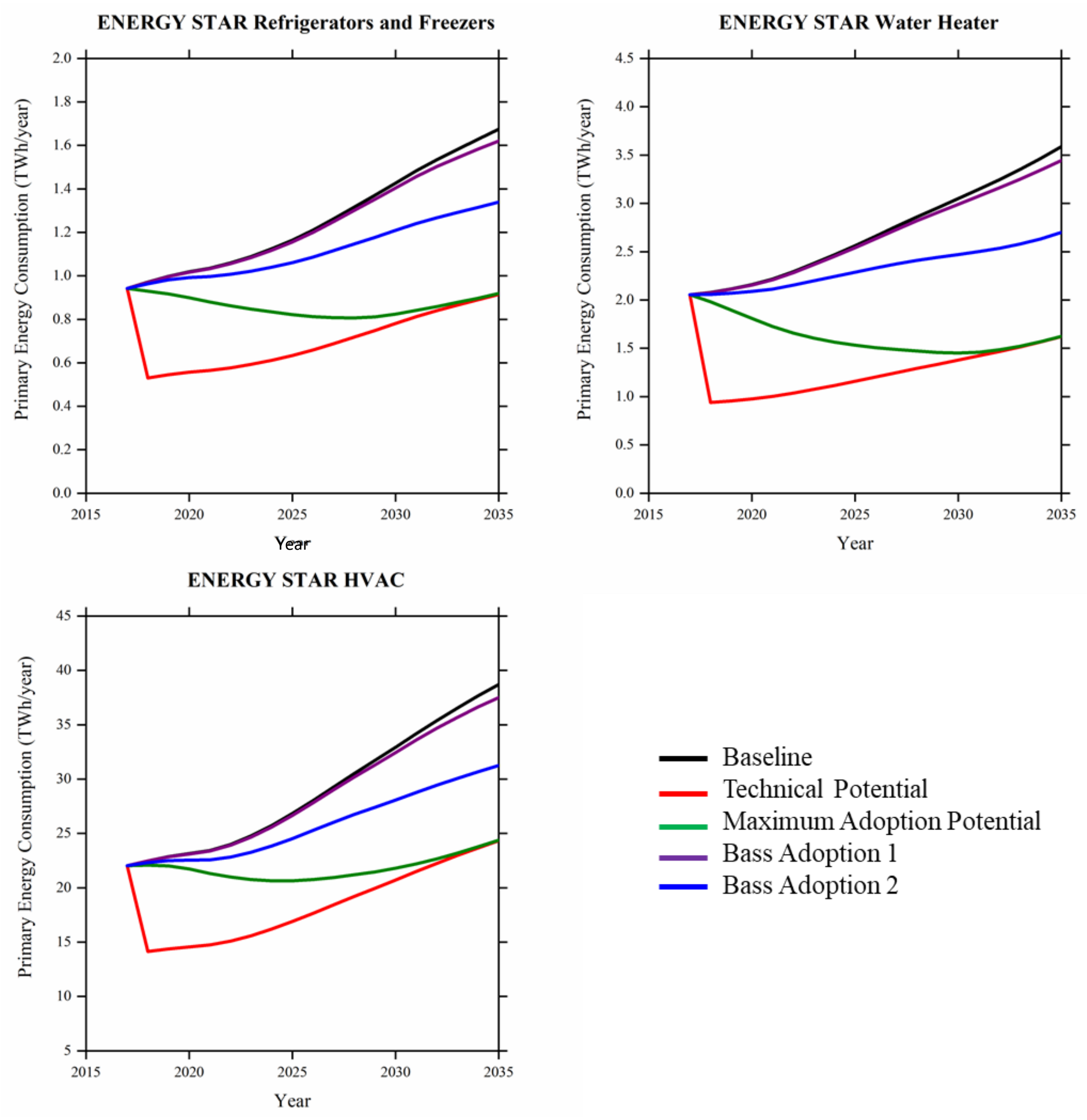


Figure 25 Primary energy consumption of ECMs under TP, MAP and Bass scenarios for ENERGY STAR AC, water heater and refrigerators and freezers.

Figure 26 shows the primary energy consumption for lighting measures. Since the standard light bulbs (incandescent bulbs) have low useful life (less than 2 years), all the used scenarios will result in almost the same diffusion patterns. Therefore, this study only analyzed the lighting measures using one scenario. MAP scenario was chosen, where all the baseline light bulbs will be replaced by CFLs or LEDs by the end of their lifetime (i.e. in the first two years of the analysis). Since LED light bulbs was introduced in the Kuwaiti market couple of years ago, the baseline forecast model assumes some diffusion of LED light bulbs in the baseline market using Bass model as shown in Chapter 3.

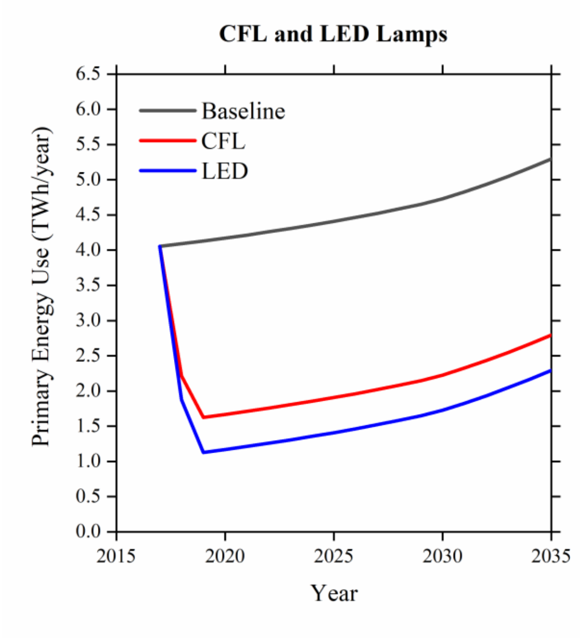


Figure 26 Primary energy consumption of lighting measures under the MAP scenario.

4.3.2. Sensitiviy analysis of innovation and imitation coefficients.

Modeling the diffusion of new products, which has not yet saturated the market, poses the difficulty of conducting parameter estimations based on similar products. Since the innovation and imitation coefficients in this study were estimated based on products that we think share similar adoption characteristics [112,113], more insight would be provided by conducting sensitivity analyses on these coefficients.

Figure 27 shows the annual and cumulative sales of refrigerators with different values of the innovation coefficients (p). As we can see form figure, the change of p affects slightly the sales, while it affects directly the diffusion time required to reach the critical mass. As the p values increases, the time to reach the critical mass decreases. The critical mass refers to the point where sufficient number of adopters of an innovation is reached, so that the rate of adoption becomes self-sustaining and creates further growth. After this point, the subsequent adoption would no longer rely on external variables and the mass itself becomes a growth power that attracts imitators.

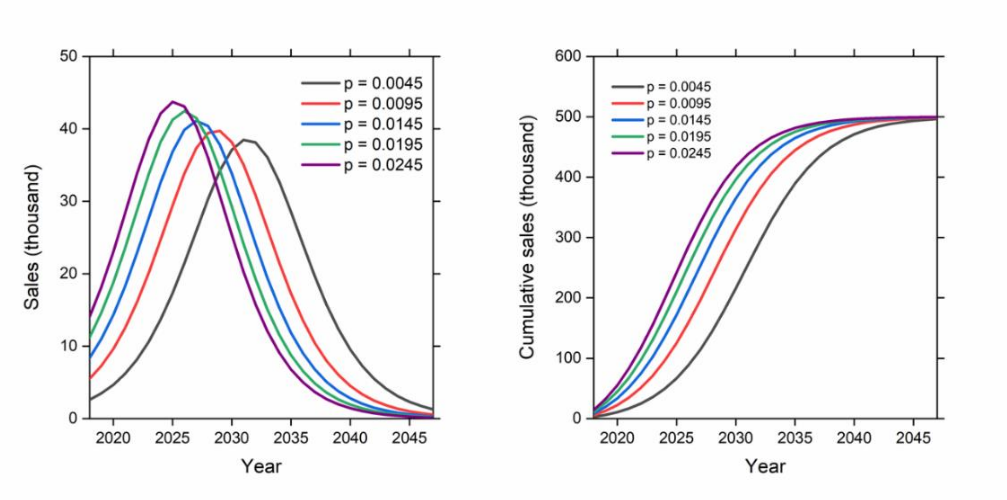


Figure 27 Sensitivity analysis of innovation coefficients (p).

Figure shows the annual and cumulative sales of refrigerators with different values of the imitation coefficients (q). We can see from both figure that the change of q affects slightly the time required for the sales to reach the critical mass but affects significantly the maximum sales. As we increase the q values, the annual maximum sales increases. In addition, the slope of the diffusion curves is changing, after reaching the critical mass point, with different values of *q*. This means that changing the imitation coefficient has a significant effect in the time to reach the saturation level.

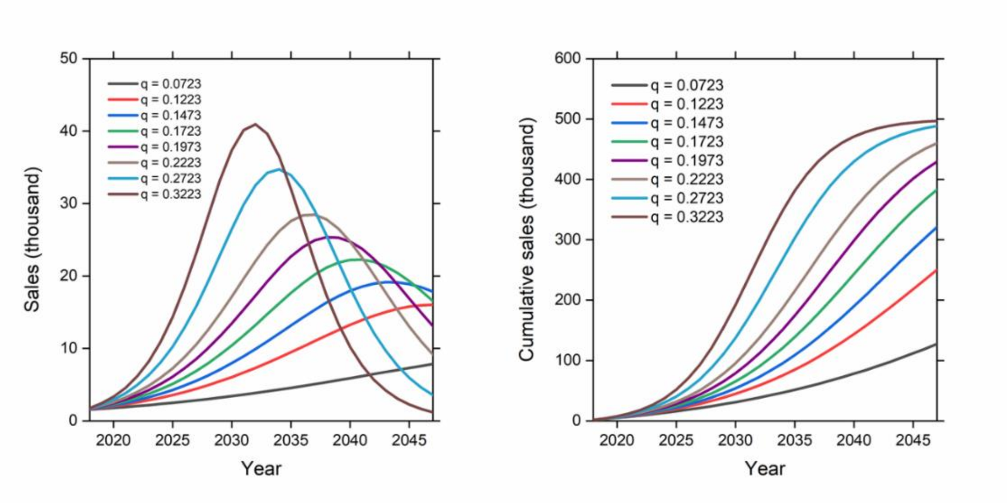


Figure 28 Sensitivity analysis of imitation coefficients (q).

Figure 29 shows the annual CO_2 emissions reduction resulting from different ECMs under the MAP scenario. As shown in Figure 29, the AC yeilds the maximum emissions reduction by 2040 caused by the reduction in electricity consumption (i.e., not casued by the release of refrigerants). However, during the initial period of the anlaysis, lighting shows higher emissions reduction than AC. The MAP model assumes the energy efficient equipment will replace the existing equipment at the end of their useful life. Therefore, for lightings technologies, due to their short lifetime, the majority of the replacement will happen in the early stage of the analysis, thus resulting in higher emissions reduction in the early stages and remaining stable throughout the entire analysis period. Compared to ACs or water heaters, which have longer lifetimes, the adoption of high efficiency equipment happens over a longer period of time, resulting in an increase in emissions reduction over time. Figure 29 can provide useful informaiton for policy makers to determine which measure to proritize or promote depending on the need for immeidate or long-term impact.

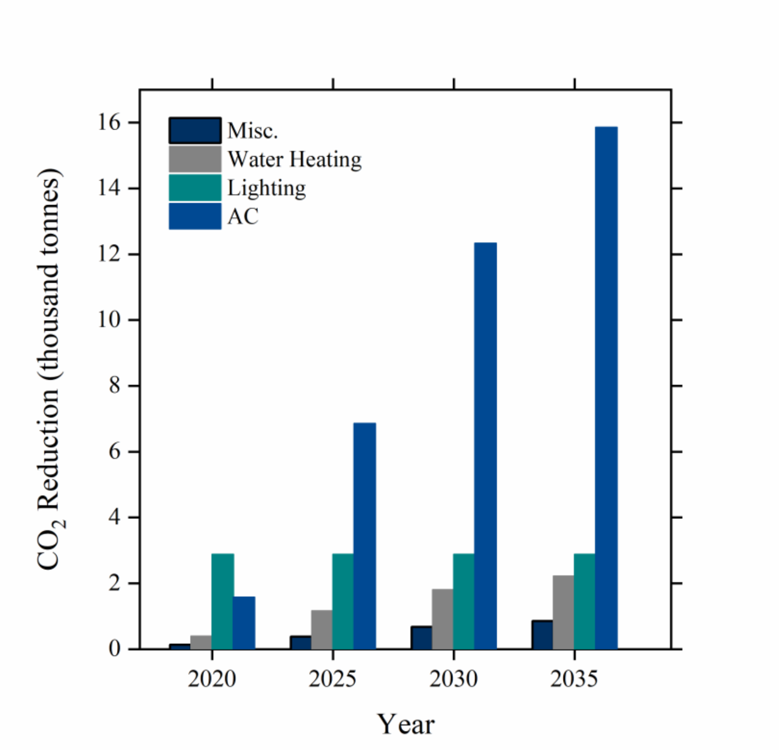


Figure 29 Residential energy-related CO$_2$ emissions cumulative reduction by end-use, projected by MAP scenario to 2035.

Figure 30 shows the projected energy consumption for the entire building stock in Kuwait under the MAP scenario. The outline of all shaded area is the baseline energy projection through 2035. With the market switching to energy efficient equipment at the end of the existing equipment lifetime, the projected energy consumption will be reduced, as shown in the blue, green, dark gray and purple shaded areas for AC, lighting, water heater and refrigerator/freezer measures respectively. The AC contributes to nearly 40% of the total savings for all the measures, with the lighting measure coming in second, accounting for approximately 30% of the total savings. Due to their large energy savings, these two measures should be an area of focus for policy makers to incentivize and promote. According to MEW, the electricity transmission and distribution losses in Kuwait is around 10-15% [13]. Therefore, to convert from site to primary energy, a source-site ratio equals to 1.85 was assumed for this study.

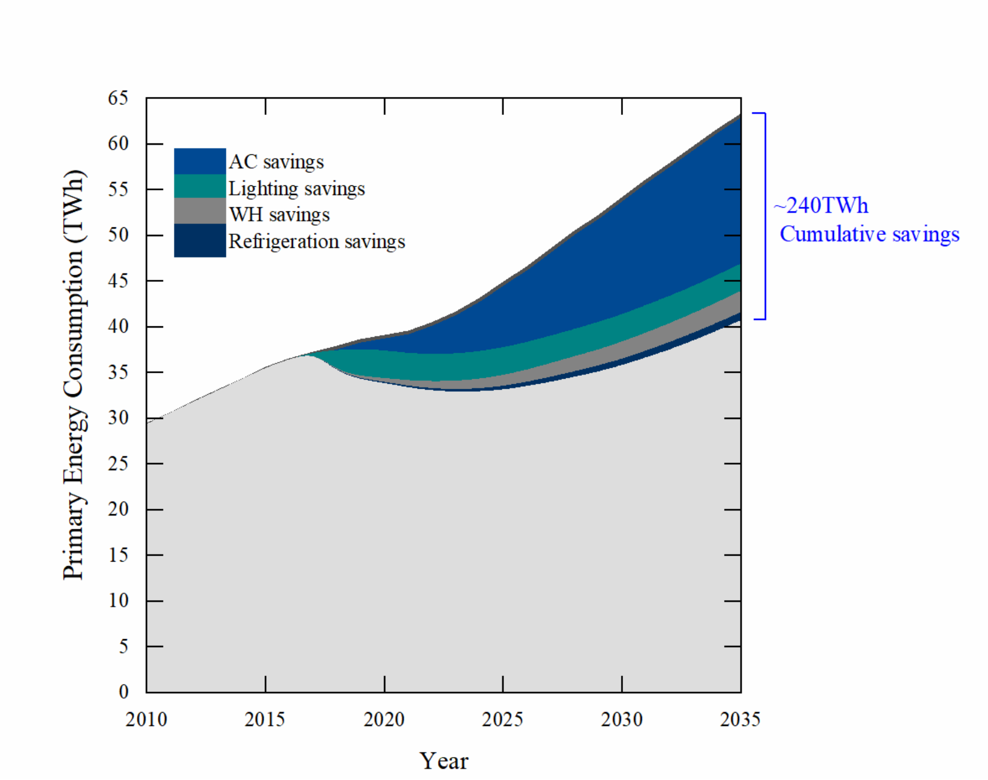


Figure 30 Residential primary energy savings forecast by end use, projected by the MAP scenario to 2035.

Table 21 shows the cumulative energy savings under different diffusion scenarios through 2035. These savings come from only applying four ECMs to the residential building stock: ENERGY STAR AC, water heater, refrigerators and freezers and LED lamps. The projected energy consumption for these measures is also shown in Figure 31, where the cumulative savings under different adoption scenarios in 2035 is presented on the top right of the figure. As mentioned earlier, the TP model represents the maximum impact in terms of cumulative energy savings of all measures. Although the MAP model converges with the TP model because all the standard efficiency equipment will eventually be replaced by high efficiency equipment in the end, the cumulative savings of the MAP model is smaller than that of the TP model.

Table 21 Cumulative primary energy savings from different ECM adoption scenarios.

Scenario	**Cumulative savings (GWh)**			
	2020	2025	2030	2035
TP	42,856	121,068	213,137	320,312
MAP	12,335	56,535	193,502	240,719
Bass 1	101	850	3,139	8,948
Bass 2	1,513	11,763	36,875	79,676

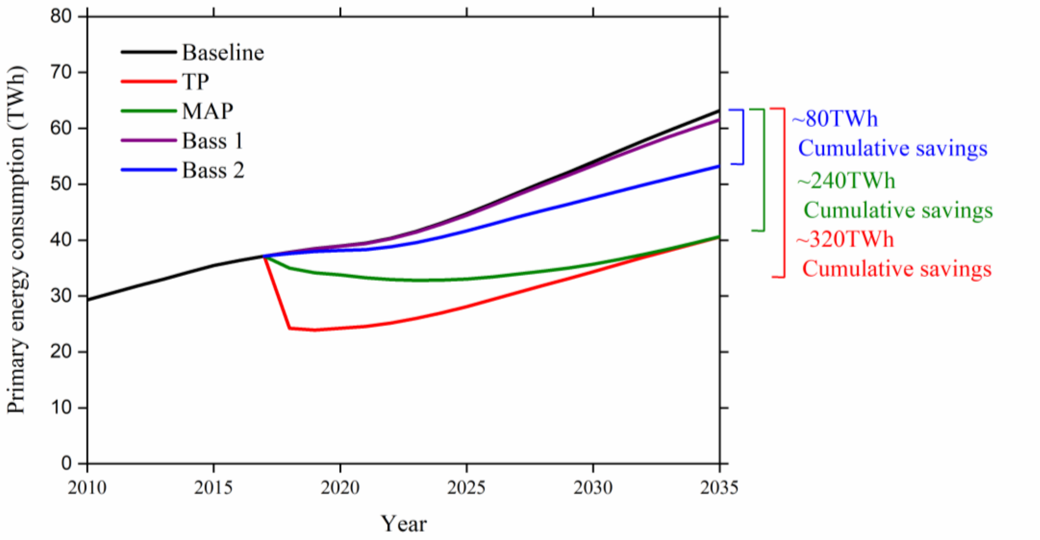


Figure 31 Cumulative primary energy savings for AC, water heater, refrigeration and lighting ECMs from different adoption scenarios.

4.3.2. Economic impact

This section discusses the economic impact of the ECMs, considering their incremental cost, lifetime, energy savings and utility price. This study uses Cost of Conserved Energy (CCE), which denotes the additional cost of an ECM compared to a baseline to achieve one unit of energy savings, as the economic metric for the ECMs. The CCE can be compared directly to the utility rates to determine the cost-effectiveness of the measure. If the CCE of a certain measure is lower than the utility rate, then this measure will be cost effective under the current market.

Table 22 shows the CRF (Capital Recovery Factor), CCE and the annual energy savings for each measure analyzed in this paper. The CRF is related to the lifetime of the equipment and discount rate, which in this study is assumed to be 5% [23], as shown in Equation 18. The CCE considers the ratio of incremental cost of the higher efficiency equipment compared to the standard efficiency equipment and the energy savings adjusted by the CRF as shown in Equation 17.

Table 22, insulation, thermostats, room AC replacement and infiltration measures have the lowest CCE, indicating they are most cost effective in Kuwait. On the other hand, solar water heaters have the highest CCE due to their high incremental cost, despite their large energy savings. The ENERGY STAR AC is also a good candidate to promote because it has both high savings per unit equipment and low CCE.

Table 22 Cost of Conserved Energy (CCE) of different ECMs (Lowest to highest CCE, TP scenario).

ECMs	Savings/Equipment (kWh/year)	CRF	CCE ($/kWh)
ENERGY STAR Room AC per TR	335.70	0.13	0.01
Predictive thermostats per TR	55.95	0.13	0.01
Programmable thermostats per TR	22.38	0.13	0.01
R-10 wall insulation per m^2	34.65	0.07	0.01
Reduce infiltration per m^2	10.46	0.07	0.01
ENERGY STAR Water Cooler	239.81	0.13	0.02
Efficient CFL	98.55	0.92	0.02
ENERGY STAR Window per m^2	74.64	0.07	0.02
Efficient Electric WH	172.18	0.11	0.03
LED	113.88	0.38	0.03
ENERGY STAR CAC per TR	1,983.68	0.1	0.03
ENERGY STAR Split AC per TR	2,288.86	0.1	0.03
R-14 roof insulation per m^2	26.15	0.07	0.03
ENERGY STAR PC	131.40	0.28	0.04
ENERGY STAR TV	68.00	0.17	0.04
ENERGY STAR Washer	150.51	0.13	0.04
ENERGY STAR WH (HPWH)	2,035.66	0.11	0.04
ENERGY STAR Refrigerator	515.70	0.11	0.05
ENERGY STAR Freezer	316.80	0.12	0.06
ENERGY STAR Dryer	176.51	0.15	0.06
Microwave (Max-tech)	81.76	0.17	0.13
Solar WH with Electric Backup	1,770.08	0.11	0.15
Discount rate = 5%			

Figure 32 shows the CCE and total energy savings of selected ECMs compared to the utility price in Kuwait. The utility price in Kuwait is 95% subsidized, which renders all the ECMs non-cost effective due to the low electricity price. With 90% subsidy, the thermostat measure becomes cost effective. Another factor that policy makers should pay attention to is the total energy savings. Although the thermostat measure is cost effective with 90% subsidized utility price, it will not generate a significant amount of energy savings for the entire building stock. To achieve a large impact on energy consumption, the policy makers should also focus on making ECMs on the right side of the figure cost-effective, such as ENERGY STAR Central AC system. On the other hand, the ECMs that are located towards the top left corner are relatively less important because they are less cost-effective and cannot yield large savings compared to other ECMs.

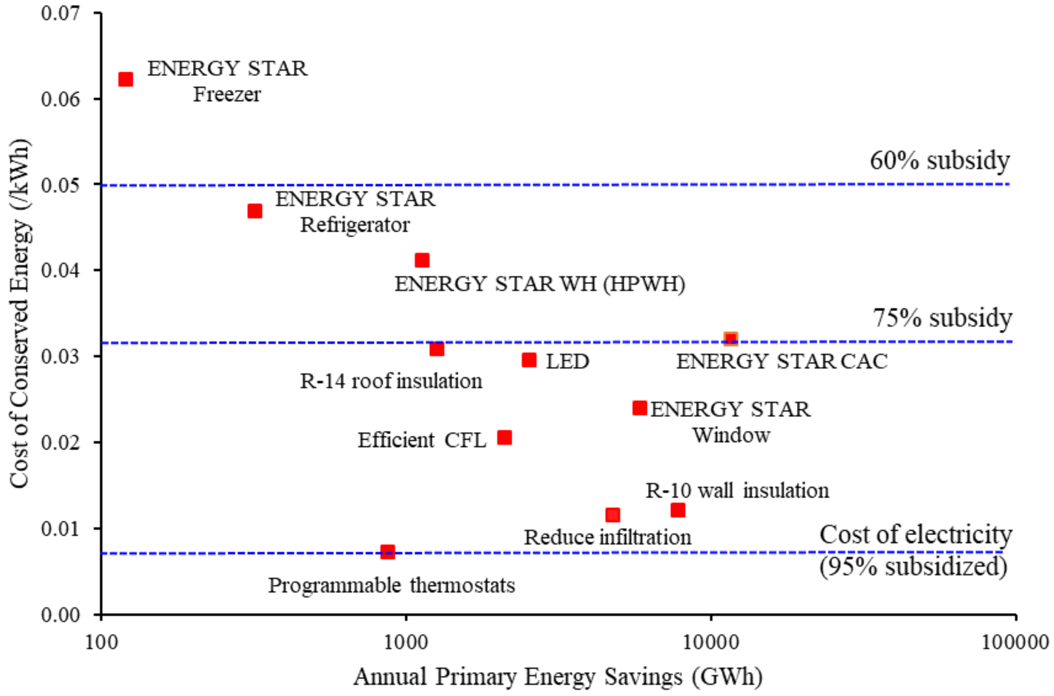


Figure 32 Primary energy savings versus cost of conserved energy (CCE) of selected ECMs for Kuwait.

Based on the discussion above, there are two ways to make an ECM cost effective: reducing the subsidy on the electricity price (increase utility cost) or provide a rebate on purchasing the energy efficient equipment (reduce incremental cost). Additionally, policy makers can adopt both methods at the same time to maintain a balanced budget by moving the money that's originally allocated for utility subsidization to providing consumer rebates for energy efficiency measures. Figure 33 shows the CCE for LED and ENERGY STAR ECMs with different levels of rebate under various subsidy scenarios. To make an ECM cost effective, the policy maker can provide rebates and reduce the subsidy for the utility price. Under the 85% subsidized utility price, all the measures shown in Figure 33 need a 60% rebate on the purchase price to make them cost effective. On the contrary, with a 65% subsidy, all the ECMs shown in Figure 33 will be cost effective without any rebate on the purchase price.

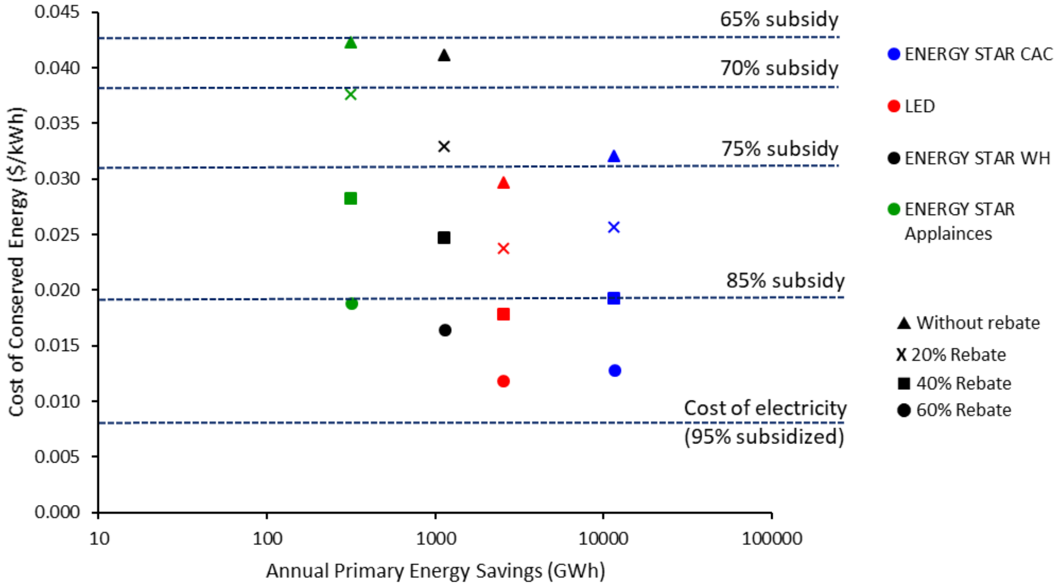


Figure 33 CCE with rebates for selected ECMs.

Figure 36, in Appendix B, shows a residential building energy efficiency supply curve of different ECMs.

4.3.3 Sample policies for energy efficiency program incentives

This study intends to develop a framework to assess the cost-effectiveness and energy savings for various ECMs in Kuwait. The parameters in the adoption model, baseline and ECM characteristics can be refined with more detailed survey data relevant to Kuwait once they become available. However, for the purpose of illustrating the benefit of this tool to policy makers to make informed decisions, this section will use the results shown above as an example to develop several policies with various targets.

Policy #1: Reducing the subsidy of the utility price to make ECMs cost effective

The major prohibitor for ECMs to be cost effective in Kuwait is the heavily subsidized utility price. Currently, the electricity price is 95% subsidized, rendering all ECMs investigated in this study non-cost-effective. The most straightforward way to make ECMs cost-effective is to reduce the subsidy of the utility price. For example, if the subsidy is reduced to 75%, Figure 32 shows that lighting, AC and wall insulation ECMs, etc. will become cost-effective. However, the limitation of this policy is that it should be accompanied with extensive marketing or education campaigns to inform people about the cost-effectiveness of the ECMs. Additionally, this policy cannot make certain ECMs of interest more attractive to the customer, because cost-effectiveness is already determined by the incremental cost, lifetime of the equipment and their energy savings.

This method is a one-size fits all solution for promoting ECMs. Additionally, the increase in utility price might introduce complaints from the customers who are accustom to the low utility price.

Policy #2: Adding fees for CO_2 emissions to the utility price

This policy is similar to reducing the subsidy of the utility price, with the difference being that the utility company will charge an extra fee to the current subsidized price. Based on the current grid mix, the CO_2 emission is 0.805 kg/kWh in Kuwait, corresponding to $7.44/ton of CO_2 based on the cost of electricity generation without any subsidy [18,117]. By charging different levels of fees on the CO_2 emissions, policy maker can achieve the same effect as reducing the subsidy as shown in Figure 34. The difference between this policy and reducing subsidy is that the psychological impact on the customers. Seeing an extra charge on the CO_2 emission is more likely to make the customer to be conscious about their energy consumption and to look for ways to reduce the CO_2 emission. Therefore, this method is more likely to be effective than simply reducing the subsidy on the utility price.

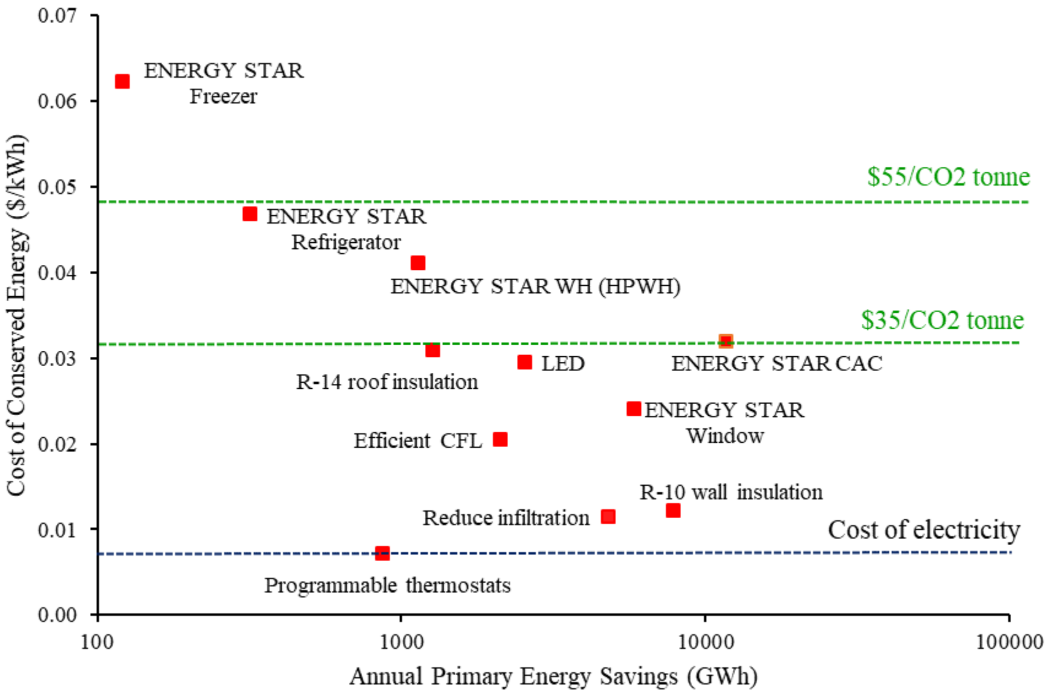


Figure 34 CCE and energy savings for select ECMs with CO2 emissions fees.

Policy #3: Providing rebates for certain ECMs

Instead of increasing the cost of the utility, policy makers can also reduce the incremental cost of the high efficiency equipment by providing rebates. This method offers more flexibility for policy makers to promote certain ECMs of interest by providing higher rebates for them. For example, the ENERGY STAR CAC measure has high energy savings, however, compared to programmable thermostats it is less cost effective. The policy makers can provide a high rebate for this measure to encourage the customers to purchase high-efficiency CAC. For measures that are already cost-effective or have low savings, the rebate amount can be reduced. Additionally, providing rebates has a psychological impact on the consumer's decision making. People tend to purchase a piece of equipment if they can receive money by doing so [118]. This method also requires less education campaign than the other two policies because a rebate is easier to be accepted by a typical consumer. Apart from this, this method can have a positive effect on the diffusion of ECMs, since it increases the innovation coefficient (q) of the Bass model. The drawback of this measure is that in addition to providing a subsidy to the utility price, policy makers need to allocate budget for offering rebates on the ECMs.

Policy #4: Combination of any of the policies above

By combining any of the policies above, the government or utility company can reduce the impact of their overall budget by allocating the additional revenue from the recovered subsidy on the utility price to providing rebates on the energy efficient equipment. Additionally, combining different policies will offer more flexibility to promote certain ECMs to the customer to reach the energy savings target.

4.4. Conclusion

This chapter presents the energy savings and cost effectiveness of the selected ECMs in Kuwait using the tools developed in this study. The intent of this thesis is to develop a framework to assess the energy savings and cost-effectiveness of the various ECMs in Kuwait and help policy makers to make informed decisions. As an example, this study investigated several measures in Kuwait using this tool and the major findings are given below:

1. The AC ECMs will yield the highest cumulative savings throughout their lifetimes.
2. The Lighting ECM will have an immediate energy impact due to the short lifetime of the baseline fixtures.
3. With the current subsidized utility price, none of the ECMs in this study is cost effective without any form of rebate.
4. The ECMs with the lowest CCE in this investigation become cost effective with 90% subsidized utility price. However, their energy savings impact is small.
5. This chapter provides a preliminary assessment on measure cost-effectiveness in Kuwait and identified AC and lighting as the major ECMs that could achieve significant impact on the energy savings.
6. Various policies were developed based on the results of this study considering the cost-effectiveness and energy savings of the measures.
7. The framework of the ECM assessment tool for Kuwait has been developed and users can improve it by using additional survey data, adding new ECMs of interest to expand the investigation.

5. CONCLUSION

Due to the low cost of electricity in Kuwait and increase of population, Kuwaiti electricity consumption tripled during the past 30 years and is expected to increase by an additional 20% by 2027. In this dissertation, we aim to develop a framework to assess the energy savings techniques and help policy makers to make educated decisions. The Kuwait residential energy outlook was studied by modeling the baseline energy consumption and the diffusion of various energy conservation measures with the aim of identifying the social and technical impacts on the household energy consumption and CO2 emission.

In Chapter 2, we extensively investigated the Kuwait's energy resources, the growth of residential electricity demand and consumption, and the opportunities of energy efficiency. Additionally, we reviewed the building energy codes of practice for building envelope, HVAC, lighting, appliances, etc. In view of Chapter 2, the excessive residential electricity consumption per capita in Kuwait can be mostly mitigated by either enforcing different energy efficiency techniques or governing several energy codes and policies. With an eye to select, evaluate, and then compare different energy efficiency approaches, an accurate understanding of the current baseline electricity consumption is crucial.

In Chapter 3, we developed a baseline of end-use electricity consumption and demand of Kuwait residential buildings. In our model, the end-uses (residential electrical equipment) were categorized into air conditioning, lighting, water heating, space heating, and miscellaneous loads. These categorizes were furthermore categorized into sub-categories based on its diffusion rates, unit energy consumption (UEC), and unit power demand. Our result showed that refrigerators held the highest UEC and stock values compared with all other appliances. Our forecast model shows that air conditioning loads are expected to increase by an average growth rate of 2.9% per year. Unlike AC units, there is a negligible increase in the lighting energy consumption due to the projected shift towards more efficient lighting. Furthermore, our model revealed that non-citizens consume much less energy per capita compared to citizens which provide opportunities for more effective energy policies and initiatives in the future.

In Chapter 4, we presented the impact of the energy conservation measures (ECMs) on energy saving and CO2 reduction in Kuwait based on our baseline model and a selected diffusion scenario. Each ECM has a dataset (determined from survey data) that includes the application market, enter/exit year, cost, lifetime, and performance. Three diffusion scenarios were considered, namely, maximum adoption potential (MAP), technical potential (TP), and Bass adoption (BA). Our results showed that air conditioning ECMs exhibit the highest cumulative savings during the course of its lifetime. On the other hand, lighting ECMs show an immediate energy impact due to its short lifetime. Moreover, we examined the impact ECM at different subsidy and rebate rates since none of the ECMs in the study is cost effective due to the high subsidy rate (current electrical utility prices are 95% subsidized). At 90% subsidized utility price, the ECMs with the lowest conserved cost effective (CCE) come to be cost effective even though their associated energy savings are small. Similarly, at 75% subsidized utility price and 40% rebate, all central air conditioning (CAC) and LED become completely cost effective with high energy savings. Meanwhile, most of the water heater (WH) and other appliances are cost effective at lower energy savings. Likewise, by imposing charges of $35/ton of CO2, most of AC, lightings, and other appliances will be cost effective except for WHs, freezers, and refrigerators which are at lower energy savings.

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APPENDIX A

COMPARATIVE SUMMARY OF KUWAIT ENERGY COSERVATION CODES OF PRACTICE

Table 23 Main features of the 2014 energy conservation code of practice compared to previous revisions – table updated from [31].

Requirements	Code of Practice 1983	Code of Practice 2010	Code of Practice 2014
Design Weather Conditions	Only one set of design weather conditions for all sites in Kuwait	Two sets of design weather conditions are use: interior and coastal sites.	Two sets of design weather conditions are use: interior and coastal sites.
Wall Thermal Insulation	Maximum U-value depending on mass and color levels (Refer to Table A-1 in Appendix A)	Maximum U-value depending on mass and color levels (Refer to Table A-2 in Appendix A)	Maximum U-value depending on mass and color levels.
Roof Thermal Insulation	Maximum U-value depending on mass and color levels (Refer to Table A-1 in Appendix A)	Maximum U-value depending on mass and color levels (Refer to Table A-2 in Appendix A)	Maximum U-value depending on mass and color levels
Window to Wall Ratio/Glazing type	Maximum WWR value depending on glazing type and orientation (Refer to Table A-1 in Appendix A)	Maximum WWR value depending on glazing type and orientation (Refer to Table A-3 in Appendix A)	Maximum WWR value depending on glazing type. Min. acceptable glazing type 6 mm double-tinted, max. acceptable SHGC 0.4, max acceptable visible transmittance dropped to 0.61 Government buildings shall apply most stringent requirements.
Thermal Bridges	Not Mentioned	Columns and beams should be insulated.	Columns and beams shall be insulated. Windows shall have thermal

		Windows should have thermal breaks.	breaks. [Unchanged]
Lighting Density		Maximum lighting power density depending on space type (Refer to Table A-4 in Appendix A)	Maximum lighting power density depending on space; more stringent requirements than previous edition.
Ventilation Rate	ASHRAE Requirements of Standard 62 1979	ASHRAE Requirements from Standard 62 2001 (Refer to Table A-5 in Appendix A)	ASHRAE 62.1 (latest) or 0.25 ACH, whichever value is highest.
Programmable Thermostats	Not mentioned	Recommended for buildings with part-day occupancy levels with 5°C offset with switching off of air-circulating fans during non-occupancy periods as long as thermal comfort is maintained during occupancy periods.	Building Automation System mandatory for projects with cooling capacity ≥ 500 RT. Programmable thermostats and lighting controls mandatory for projects < 500 RT.
Motor Efficiency		Minimum efficiency rating depending on motor type and size (Refer to Table 5)	Minimum efficiency rating depending on motor type and size. Most stringent requirements applicable to government buildings.
Power Factor		Minimum power factor for motor and fluorescent lighting systems (refer to Table A-6 in Appendix A)	Minimum power factor for motor. Most stringent requirements applicable to government buildings.

			Only LED lights with occupancy sensors and time-of-day-control allowed in government buildings.
A/C Energy Efficiency	Minimum efficiency for select systems (refer to Table A-1 in Appendix A)	Minimum efficiency rating depending on A/C system type (Refer to Table A-7 in Appendix A)	Minimum efficiency rating depending on A/C system type.
Water vs. Air Cooled A/C Systems		Water cooled A/C systems are required for buildings with cooling capacity of 1000 RT or above in the coastal areas and of 500 RT or above for interior areas.	Water cooled A/C systems are required for buildings with cooling capacity of 1000 RT or above in the coastal areas and of 500 RT or above for interior areas. [Unchanged]
A/C Capacities	Maximum power capacity depending on the building and air conditioning system types	Maximum capacity depending on the building and Air Conditioning System Types (Refer to Table A-4 in Appendix A)	Maximum capacity depending on the building and Air Conditioning System Types. Requirements slightly more stringent.
Cooling Recovery Units	Not Mentioned	Required Rotary-wheel cooling recovery units with a minimum efficiency of 75% for all buildings in the coastal areas and for buildings with high ventilation needs (940 L/s or 2000 cfm or above) in the interior areas.	Mandatory when recoverable exhaust air quantity ≥ 2,000 CFM for all buildings in the coastal region and when recoverable exhaust air quantity ≥ 3,000 CFM for buildings in the interior region.

		Exceptions apply for health reasons	Exceptions apply for health reasons.
Variable Speed Drives	Not Mentioned	Required for fan motors of cooling towers	Fan motors of cooling towers shall either have VSD or power factor optimization devices. Water temperature sensor also mandatory.
Cool Storage Systems	Not Mentioned	Required for buildings with part-day occupancy and more than 100 RT cooling peak load	Mandatory for buildings with cooling capacity ≥ 500 RT; recommended for others.
District Cooling	Not Mentioned	Recommended based on cost analysis for large complexes such as university campuses and residential neighborhood.	Not mentioned. TBC
Seawater *and grey water* use for condensers	Not Mentioned	*Sea water* recommended for water-cooled plants of more than 5000 RT capacity in coastal areas	Seawater mandatory for plants with cooling capacity ≥ 10,000 RT in coastal regions. Grey water mandatory for all other water-cooled plants (when feasible).

APPENDIX B

SIMULATED ANNUAL ENERGY HEAT BALANCE OF ENVELOPE COMPONENTS

RESIDENTIAL BUILDING ENERGY EFFICIENCY SUPPLY CURVE

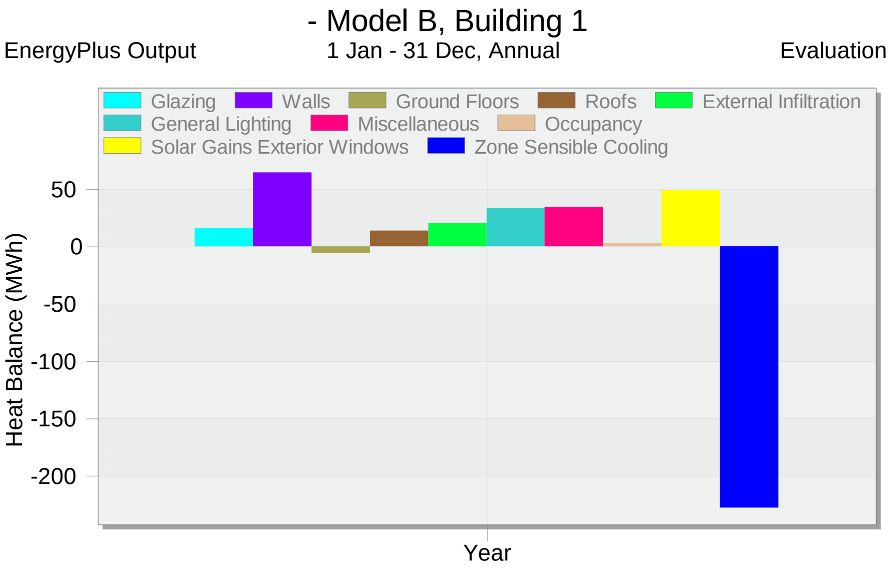

Figure 35 Simulated annual energy heat balance of the main envelope components of a typical residential building in Kuwait.

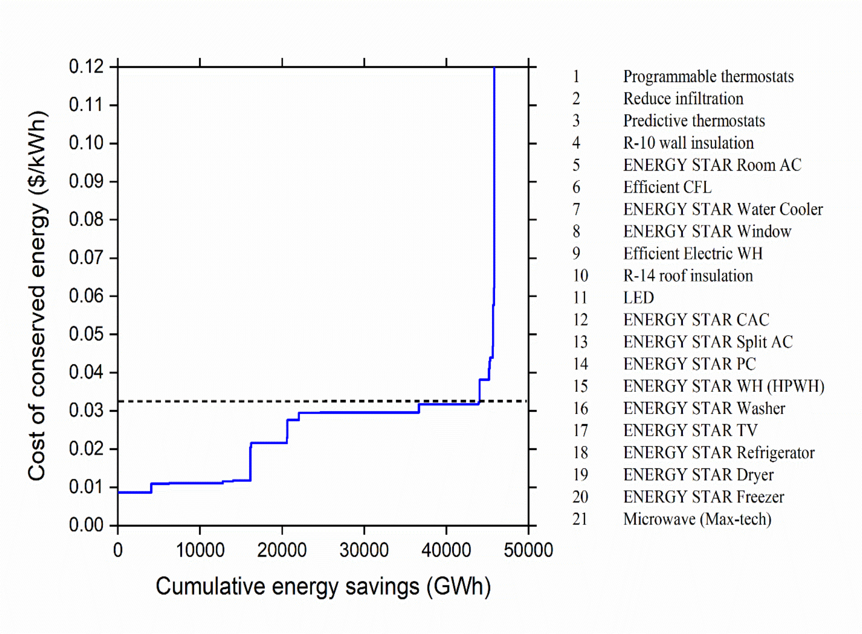

Figure 36 Residential building energy efficiency supply curve.