Using a Calibrated Detailed Building Energy Simulation Model to Compare the Potential Contribution of Energy Efficiency and Renewable Energy in the Kuwaiti Residential Sector

by

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ABSTRACT

Due to extreme summer temperatures that regularly reach 122°F (50°C), cooling energy requirements have been responsible for 70% of peak demand and 45% of total electricity consumption in Kuwait. It is estimated that 50%-60% of electric power is consumed by the residential sector, mostly in detached villas. This study analyzes the potential impact of energy efficiency measures (EEM) and renewable energy (RE) measures on the electric energy requirements of an existing villa built in 2004. Using architectural plans, interview data, and the eQUEST building energy simulation tool, a building energy model (BEM) was developed for a villa calibrated with hourly energy use data for the year 2014. Although the modeled villa consumed less energy than an average Kuwaiti villa of the same size, 26% energy reductions were still possible under compliance with 2018 building codes. Compliance with 2010 and 2014 building codes, however, would have increased energy use by 19% and 3% respectively. Furthermore, survey data of 150 villas was used to generate statistics on rooftop solar area availability. Accordingly, it was found that 78% of the survey sample's average total rooftop area was not suitable for rooftop solar systems due to shading and other obstacles. The integration of a solar canopy circumvents this issue and also functions as a shading device for outdoor activities and as a protective cover for AC units and water tanks. Combining the highest modeled EEMs and RE measures on the villa, the energy use intensity (EUI) would be reduced to 15 kWh/m^2/year from a baseline value of 127 kWh/m^2/year, close to net zero. Finally, it was determined that EEMs were able to reduce the entire demand profile whereas RE measures were most effective at reducing demand around mid-day hours. In future studies, more effort should be spent on collecting hourly data from multiple villas to assist in the development of a detailed hourly bottom-up residential energy modeling methodology.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

1.1 Objective and Scope of Study

Building Energy Models (BEM) can provide valuable insight on the drivers and patterns of energy use. Such models produce outcomes that usually have a degree of uncertainty depending on the level of detail provided in the input data. BEM can produce outputs with high-level accuracy when calibrated with hourly data or smaller resolution timeframes. For countries with harsh summer climates, BEM can be used to investigate promising strategies that reduce energy consumption and peak loads and keep demand at low stable levels. Since buildings in hot climates require more energy in the summer for air-conditioning, integrating Distributed Energy Resources (DER) such as a rooftop solar system can play a significant role in reducing costly peak loads.

Kuwait summer temperatures are among the highest in the world, making cooling demand extremely high. Global warming will continue to increase global average temperatures and thus, increased demand for cooling loads. One of the outcomes of the Kuwait Energy Outlook (KEO) 2018 report states the need to improve the stock of inefficient residential buildings in Kuwait due to the sector’s high share of total national energy consumption. This thesis investigates strategies that reduce energy and peak loads in residential buildings by developing a BEM for an existing villa calibrated with hourly data. Results will contribute to the framework on improving the energy efficiency of residential building stock models for Kuwait by filling data gaps [1].

Residential energy consumption has been increasing steadily for the past decades with no sign of slowing down. This has resulted in a deficit in the national budget due to the continued subsidization of fuel and energy prices. Furthermore, local oil consumption attributed to electricity generation continues to increase its share from that of total oil production. Current motivations to reduce local oil consumption could be aligned with other environmental obligations of achieving an renewable energy portfolio (RPS) of 15% by 2030. However, due to a lack of state emission reduction strategies and targets, there is little incentive or reward for using energy efficiently.

A literature review revealed that there are no studies to date that investigate the effect of the updated 2014 and 2018 building residential codes. The studies that did investigate the application of the building codes looked at the implications of retrofitting existing buildings to comply with the 1983 and 2010 building codes [2][3]. In general, estimates corresponding to the implementation of existing codes, which are normally only applied to new buildings in Kuwait, allow for an understanding of the potential benefits of enforcing them on older buildings. Evidently, the building codes were made specifically for Kuwait weather conditions. As such, the developed building model will provide an opportunity to investigate the effectiveness of these codes when applied to older buildings built under previous codes. The current stock of villas consists mostly of buildings that comply with the first building code enforced in 1983. The new 2014 and 2018 codes have more stringent requirements and minimum compliance could potentially reduce energy consumption of existing buildings.

Kuwait benefits from high levels of solar irradiance yet DERs are under-utilized due to their low economic benefits to electric consumers who benefit from subsidized electricity prices. As such, the added benefits of rooftop solar were investigated by studying rooftop survey drawings and extracting quantitative data on available solar areas of typical rooftops. The survey sample was taken from a government funded pilot project that installed 150 solar energy systems on the rooftops of residential villas. Using this data enabled an assessment of the average available rooftop area in a typical Kuwaiti villa that can be utilized for solar generation. Overall, the paper focuses on:

1. Evaluating the potential of newer building codes in reducing energy consumption of buildings built under older building codes.
2. Assessing the effects of incorporating energy reducing strategies such as improving thermal quality of building envelope, using efficient cooling, and lighting technology.
3. Investigating the benefits of adding or increasing rooftop solar capacity and their potential in reducing high peak loads that are the most expensive electric loads to supply.

The issues mentioned above were investigated using a building model of an existing villa and a solar simulation tool. Developing a base case for the building model was necessary prior to alternative scenario modelling. The villa was modeled and calibrated using actual hourly energy data for an entire year. In addition, realistic policy-based measures were identified from engineering analysis to assist in lowering residential building's high energy consumption and peak demands as well as increase sustainability.

1.2 Overview of Methodology

The analysis begins with a preliminary simulation made using eQUEST to model the energy consumption of an existing building built in 2004 [44]. Results were calibrated with actual hourly energy data for an entire year (2014). The building parameters were deduced through a detailed survey from the building owner to obtain accurate input data for the model. After calibration, the model was used to estimate the energy saving benefits of using the updated 2010, 2014, and 2018 building codes. A design that incorporates additional realistic efficiency measures was also modeled to determine the extent of further savings which could be achieved. Finally, a solar system was added to the building model under several rooftop area configurations to analyze peak demand reductions. The steps taken to perform this analysis are shown in Figure 1:

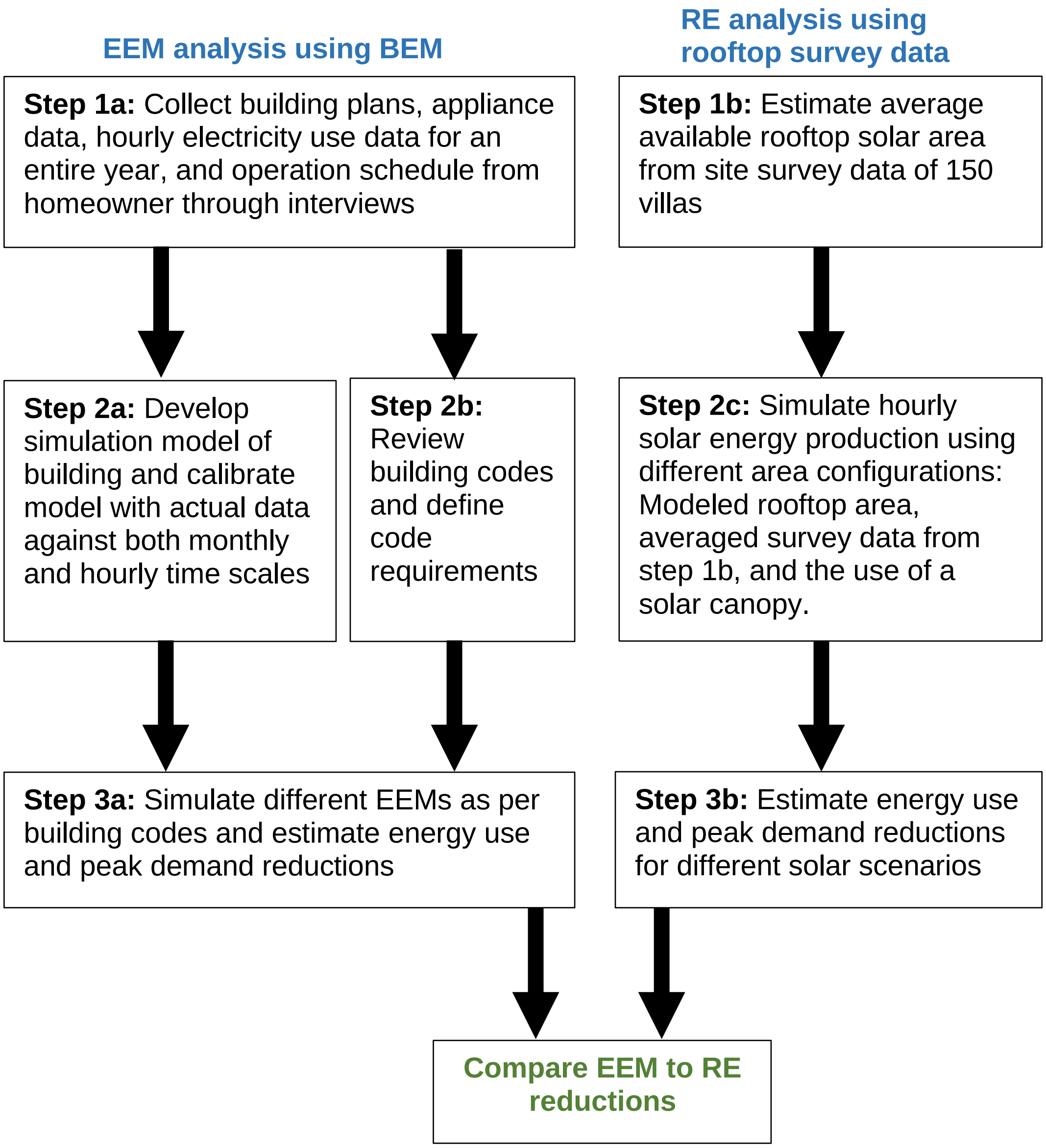


Figure 1 Flowchart of steps performed in the analysis

CHAPTER 2

BACKGROUND

2.1 Residential Energy in Hot Climates

The residential sector is one of the major energy consuming sectors for countries around the world and especially in regions with hot climates where cooling energy use is high. Figure 2 shows the share of energy consumed by the residential sector for fourteen countries as well as worldwide average. The residential sector energy share in Saudi Arabia is almost 50% of the entire country's energy consumption due to extreme climate conditions and building cooling energy use. Kuwait, which shares a border with Saudi Arabia, has similar climate conditions. Most of the building energy consumption in Kuwait; 70% of peak demand and 45% of total annual electricity consumption are due cooling loads [4]. The hourly load for Kuwait in 2016 shown in Figure 3, illustrates the impact of AC usage on power demand levels where electric loads in the summer are almost twice the loads in winter.

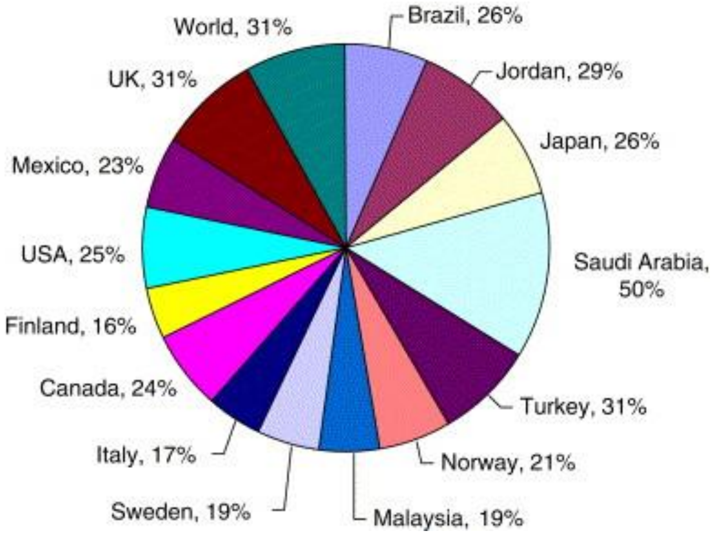


Figure 2 Residential sector energy consumption of total energy for a few countries [5]

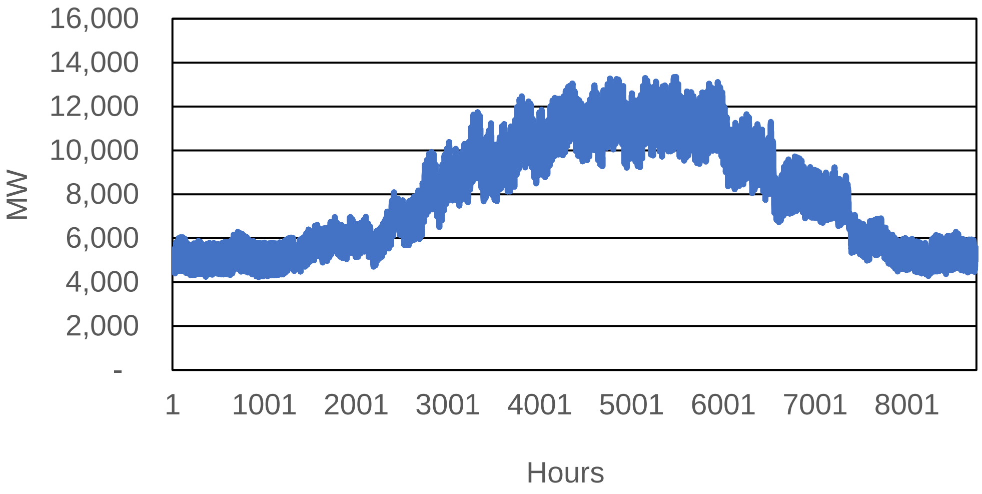


Figure 3 Kuwait's Electricity Load Profile in 2016

The main drivers of high energy consumption in Kuwait’s residential buildings are due to: (a) highly subsidized energy prices, (b) existing stock of inefficient buildings,(c) lack of strict building regulations, and (d) the continued addition of new buildings [2] [6] [7] [8] [9]. Although building energy demand is not the only driver of total energy use, it is one of the main contributors that make Kuwait one of the highest energy consuming countries per capita worldwide. Figure 4 shows the energy use per capita of several countries around the world in 2014 according to the World Bank. Out of all the countries in the World Bank data, Kuwait ranks among the top 5 countries in terms of energy use per capita.

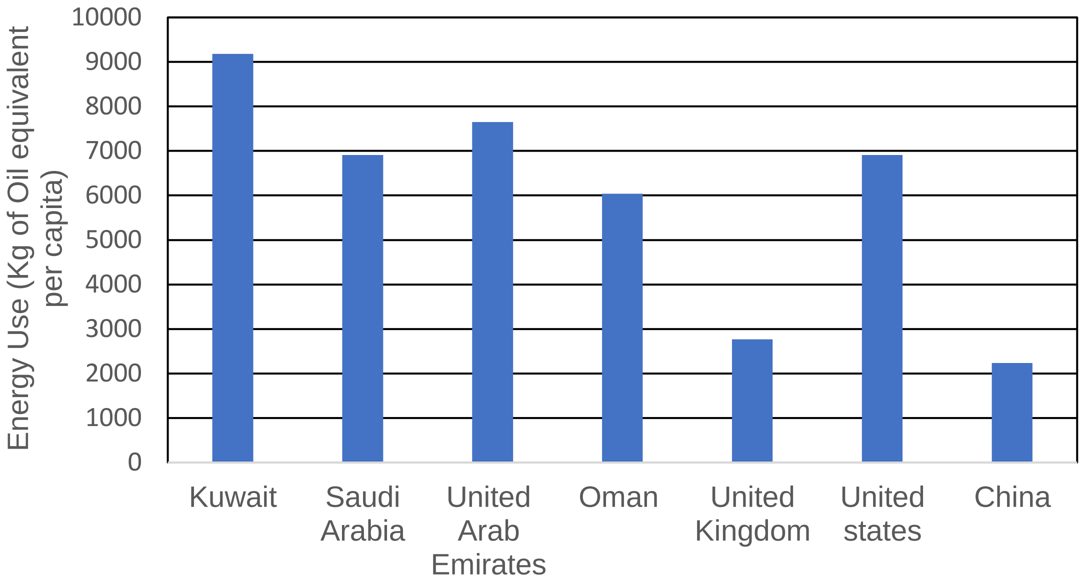


Figure 4 Per Capita Energy Consumption of Different Countries [11]

The end use energy consumption in the residential sector of countries around the world has varying distributions. Clearly, countries in the Middle East have much larger shares for air conditioning. Figure 5 shows a comparison of the end use consumption of the residential sector in the United States and Kuwait. The United States has multiple types of climate zones and all types of weather in different parts of the country. Overall, the cooling and heating requirements in the United States are similar with air conditioning taking 17% and space heating slightly lower at 15% [12]. By contrast, the air conditioning requirements in Kuwait are almost 70% of total consumption, with space heating occupying only 4.5% [6].

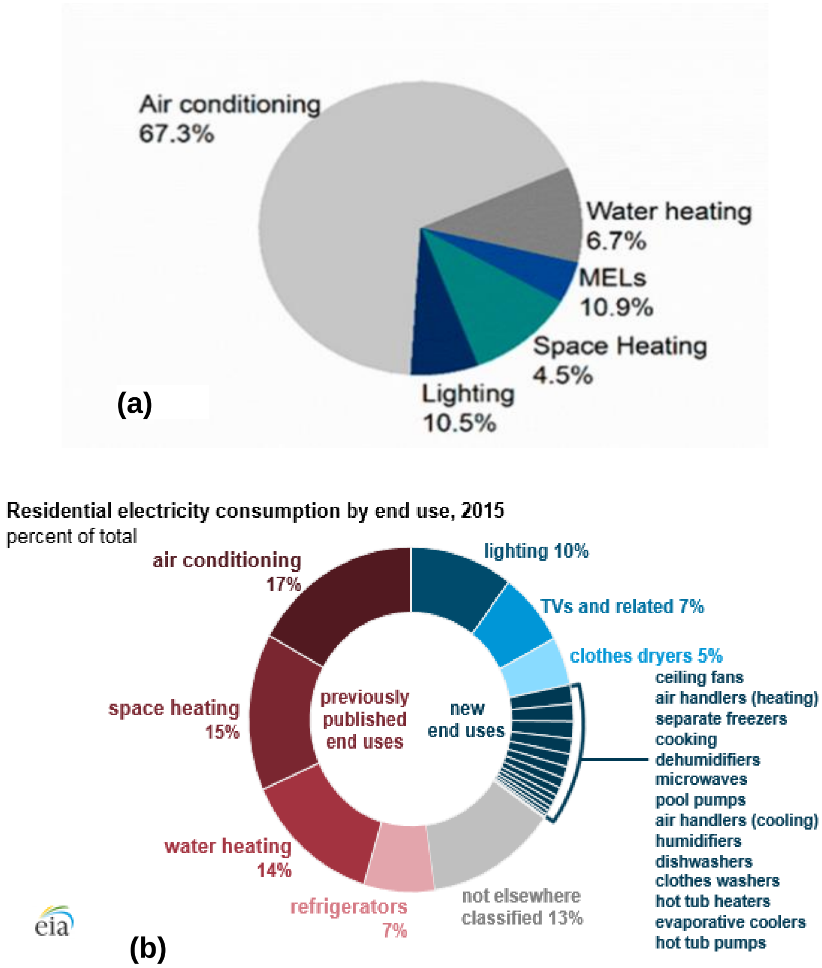


Figure 5 (a) End-use residential electricity in Kuwait (b) End-use residential electricity in the US [6]. [12]

It is evident that the electric load profile (Fig. 3) follows seasonal weather conditions and is greatly influenced by cooling energy use. Table 1 shows the date, dry-bulb temperature, and relative humidity of annual peak loads from 1999 to 2018 in Kuwait. All annual peak loads occurred during the period from June to September on hot summer days with temperatures ranging from 47-51 ^{0}C (117-124 ^{0}F) except for the peak load in 2002. On the peak load day of 2002, the temperature was relatively low (43 ^{0}C), however, the humidity was high at 38%. Overall, it can be concluded that extreme weather conditions contribute to peak loads due to building cooling requirements.

Table 1 Peak Loads and Weather Conditions in Kuwait for different years with corresponding dates [13]

Year	**Peak Load (MW)**	**Date**	**Max Temperature (^{0} C)**	**Max Relative Humidity (%)**
1999	6,160	4-Sep	49	10
2000	6,450	28-Aug	48	8
2001	6,750	13-Aug	50	5
2002	7,250	22-Jul	43	38
2003	7,480	6-Jul	50	7
2004	7,750	26-Jul	49	2
2005	8,400	3-Sep	50	16
2006	8,900	26-Jul	51	7
2007	9,070	3-Sep	49	6
2008	9,710	28-Jul	47	6
2009	9,960	28-Jul	50	5
2010	10,890	15-Jun	48	4
2011	11,220	27-Jul	50	3
2012	11,850	1-Aug	50	5
2013	12,060	17-Jul	50	5
2014	12,410	11-Jun	49	6
2015	12,810	30-Aug	49	6
2016	13,390	15-Aug	48	9
2018	13,800	26-Jul	49	8
2018	13,910	10-Jul	48	10

2.2 Drivers of Residential Energy Use in Kuwait

To understand residential energy use in Kuwait, statistical energy data was studied in conjunction with the respective policies that drive energy use trends. The data from the Ministry of Electricity and Water’s (MEW) electricity books showed a drop in residential electricity consumption in 2014 shown in Figure 6. However, it is evident that the data does not resemble actual values. Table 2 shows that the energy shares were disaggregated into other sectors with industry taking a lot of the energy share from 2014 onwards, making the MEW’s statistical books an unreliable source to obtain an exact share for the residential sector. Therefore, 55% of total generation with 15% losses was assumed for this analysis, shown in Figure 7, using the average value of two studies [6] and [14]. Alajmi and Phelan used a value of 50% based on information provided from the MEW. Jaffar et al. used a value of 60% based on an energy flow analysis that was developed using local energy consumption by sector data from the Ministry of Oil.

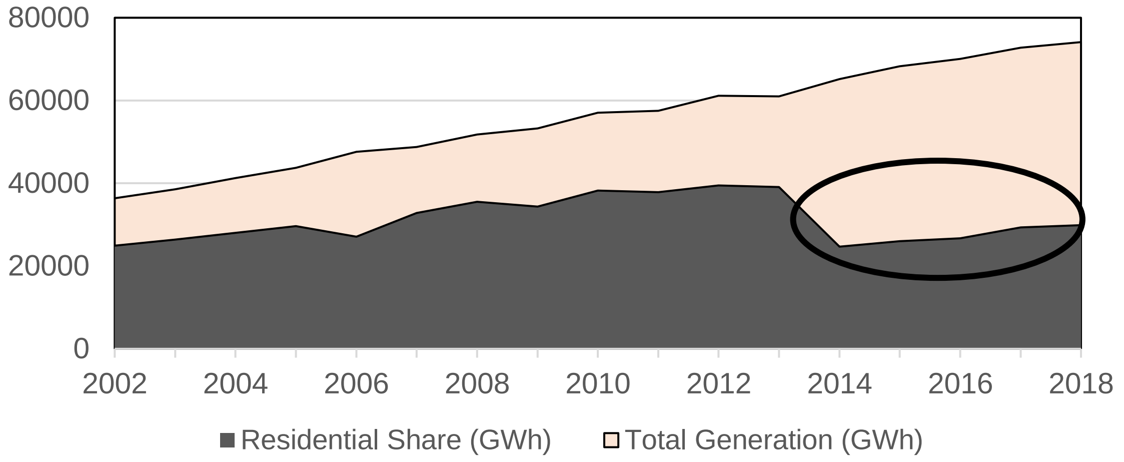


Figure 6 Total generation and residential share in Kuwait showing unrealistic data as seen by the drop in 2014 [13]

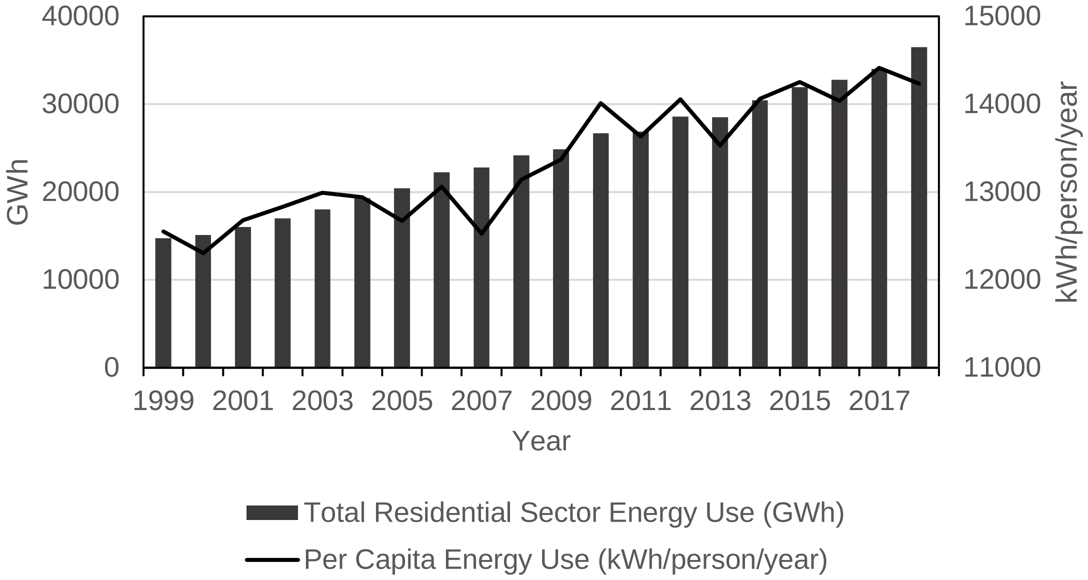


Figure 7 Total residential energy use and per capita energy use from 1999 to 2018 for Kuwait [13]

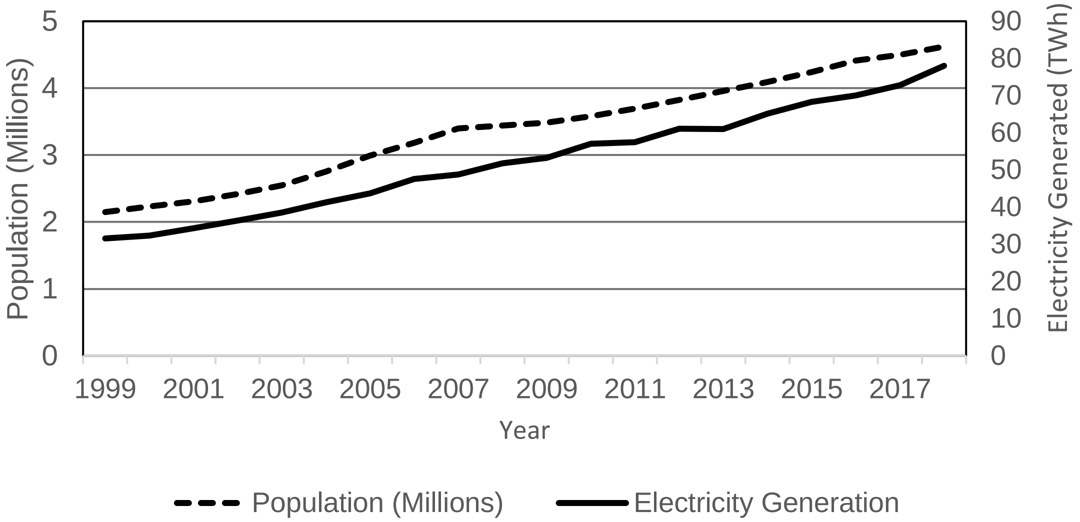


Figure 8 Time Series Plot of Kuwait's Electricity Generation and Population from 1999-2018 [13]

Electricity and population growths in Kuwait follow similar trends; shown in Figure 6 from 1999 to 2018. The per capita energy consumption has been increasing for the same period, as shown in Figure 7.

Table 2 Fractional share of each sector out of total electrical energy consumption showing drastic changes after 2014 for Kuwait [13]

Year	Residential	Commercial	Industrial	Agriculture	Governmental	Services
2000	0.8345	0.1254	0.0227	0.0041	0.0000	0.0132
2001	0.8271	0.1373	0.0233	0.0042	0.0000	0.0081
2002	0.8055	0.1545	0.0274	0.0047	0.0000	0.0080
2003	0.8055	0.1545	0.0274	0.0047	0.0000	0.0080
2004	0.7980	0.1631	0.0187	0.0067	0.0000	0.0134
2005	0.7980	0.1631	0.0187	0.0067	0.0000	0.0134
2006	0.6695	0.1455	0.1699	0.0064	0.0000	0.0087
2007	0.7911	0.1700	0.0205	0.0056	0.0000	0.0128
2008	0.8069	0.1465	0.0212	0.0054	0.0000	0.0199
2009	0.7593	0.1646	0.0547	0.0076	0.0000	0.0138
2010	0.7874	0.1649	0.0256	0.0075	0.0000	0.0147
2011	0.7739	0.1763	0.0271	0.0075	0.0000	0.0153
2012	0.7594	0.1871	0.0258	0.0086	0.0000	0.0191
2013	0.7542	0.1950	0.0272	0.0080	0.0000	0.0156
2014	0.4457	0.1107	0.31681	0.01574	0.10123	0.00982
2015	0.4479	0.1342	0.27415	0.0224	0.1100	0.01135
2016	0.4479	0.1342	0.27415	0.0224	0.1100	0.01135
2018	0.4479	0.1342	0.27415	0.0224	0.1100	0.01135

Kuwait's increasingly high residential consumption is attributed to the relatively high average villa floor area, which is 550 m^2 [15]. The average floor area of a single-family villa in Kuwait is more than twice the size of an average home in the United States, which is 250 m^2 [10]. The following list shows the average floor areas of neighboring countries in the GCC:

Kuwait: 550 m^2 [15]
Oman: 240 m^2 [16]
Saudi Arabia: 525 m^2 [17]
Iraq: 200 m^2 [18]

Another parameter to consider when identifying drivers of high residential energy use is by comparing the total floor area to the number of occupants in an average villa. Apartments in Kuwait generally have much lower area/occupant. By contrast, a Kuwaiti villa has an average of 8 occupants and an average floor area of 550 m^2 [15] This give a ratio 69 m^2/occupant (743 ft^2/occupant). According to the engineering toolbox, which provides recommended areas for calculating climate loads, residential units should ideally range from 200 ft^2/occupant to 600 ft^2/occupant [19].

Looking at the residential energy consumption of villas to apartments in Kuwait further explains the influence they have on total energy consumption. Although the total number of apartments is more than the total number of villas, their contribution to total energy use is considerably less. The number of apartments in 2013 was almost 1.7 times the number of villas, however, villas consumed 88% of total residential energy use as shown in table 3 [15]. Table 4 shows 2018 statistics on the number of units distributed over the six governorates in Kuwait taken from the Kuwait Authority for Civil Information (PACI) [20].

Table 3 Statistics for villas and flats in 2013 [15]

Dwelling type	Number of dwellings	Percentage of total residential energy use	Average kWh/dwelling/year	Average kWh/m^2/dwelling/year
Villas	105,764	88%	145,444	264
Apartments	170,815	12%	20,278	127

Table 4 Statistics for villas and apartments in 2018 [20]

Governorate	Villa	Apartments
Capitol	21,806	14,443
Hawalli	25,285	138,676
Al Ahmadi	27,796	85,946
Al Jahra	16,995	7,682
Al Farwaniya	22,353	80,123
Mubarak Al Kabeer	20,088	5,019
Total	134,323	331,889

Although non-Kuwaiti residents can own villas, villa occupants are mostly Kuwaiti residents mainly due to the housing program that provided generous opportunities for Kuwaiti families to own housing property since its establishment. However, the program has experienced a growing backlog of applicants since 1980 due to difficulties in meeting demand [21]. There are no statistics on the number of Kuwaitis and non-Kuwaitis living in villas or apartments. However, it has been argued that the Kuwaiti per capita consumption is higher than the non-Kuwaiti per capita consumption [6].

The non-Kuwaiti population mostly consists of labor workers in different industries (construction, oil, services, etc.) and domestic workers. However, there exists a population of non-Kuwaiti business owners and private company employees that generate sufficient income to sustain a luxurious lifestyle similar to the one Kuwaiti citizens are accustomed to [22]. Therefore, the assumption of generalizing energy usage pattern based on the citizen-foreigner approach has its limitations. Indeed, most of the foreign population reside in apartment units in commercial high-rise buildings, however, there also exists a large fraction that live in the standard 400m^2 lot sized 3-story villa. Figure 11 shows the Kuwaiti and non-Kuwaiti population over time.

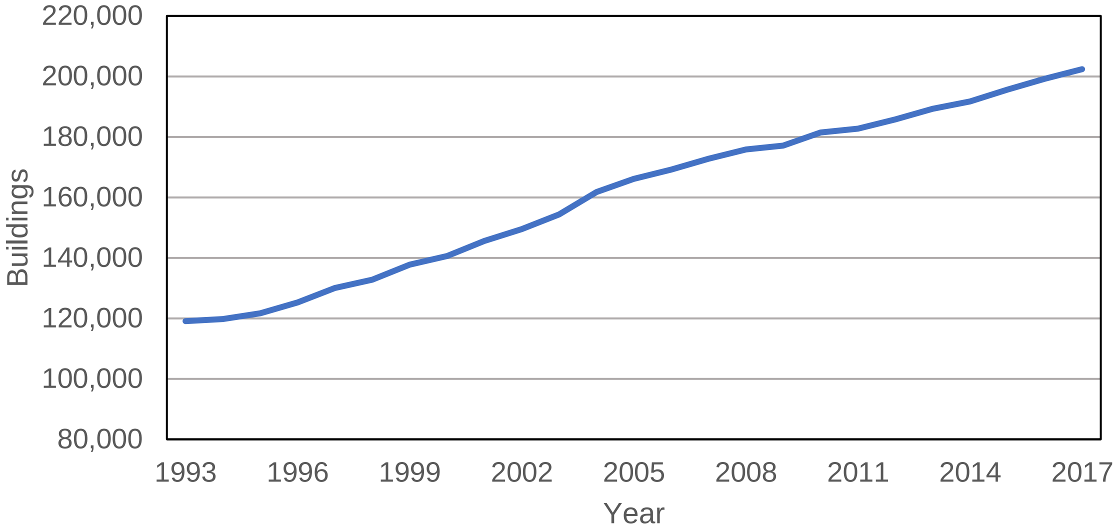


Figure 6 Plot of increase in total number of buildings in Kuwait from 1993-2018 [20]

Figure 7 Typical villas in Kuwait

In addition to the generous distribution of oversized housing properties, the low price of electricity is among the main drivers of energy use. Kuwait has the highest subsidized energy prices in the world at 0.002 KWD/kWh (0.0065 $/kWh), where the cost of generation, distribution, and transmission is 0.047 KWD/kWh (0.15 $/kWh) [9]. The financial support from the government allows Kuwaiti consumers to afford more appliances and end uses. A Kuwaiti citizen gets an additional government paid salary that is another form of wealth distribution among citizens. The Public Institute for Social Security operates the Employment Support program which offers employed Kuwaiti's additional salaries based on credentials ranging from 400 K.D. to 900 K.D. ($1,400 - $2,926) [23]. It has been proven that reliance on the welfare state approach has become an increasing burden on the government throughout the years since the establishment of these policies after the rise of the oil industry [21]. Evidently, price reforms are required to balance the large gap between income and energy prices.

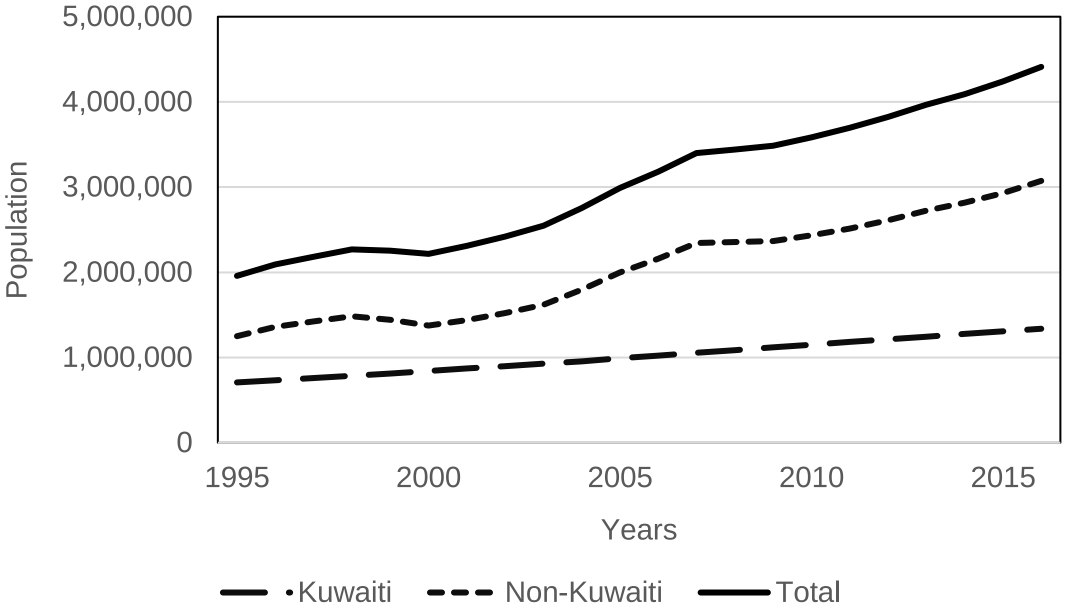


Figure 8 Time series plot of Kuwaiti, Non-Kuwaiti, and total population in Kuwait

For the scope of this study, and based on all the above information, it can be concluded that residential villas, which are mostly occupied by Kuwaiti residences, have the highest share of residential electricity consumption.

2.3 National GHG mitigation strategies

Multiple studies have proved that local residential energy consumption has a direct impact on oil export and revenue levels [6][8][9][1]. In [1], Jaffar et al. generated an energy flow diagram to show the significance of residential energy use and its influence on export of oil and gas products shown in Figure 12. The same study established a framework to guide energy analysts when developing residential energy models for Kuwait. Similarly, the Kuwait Energy Outlook (KEO) emphasized the development of more stringent code requirements and implementation to drive down residential energy consumption [8].

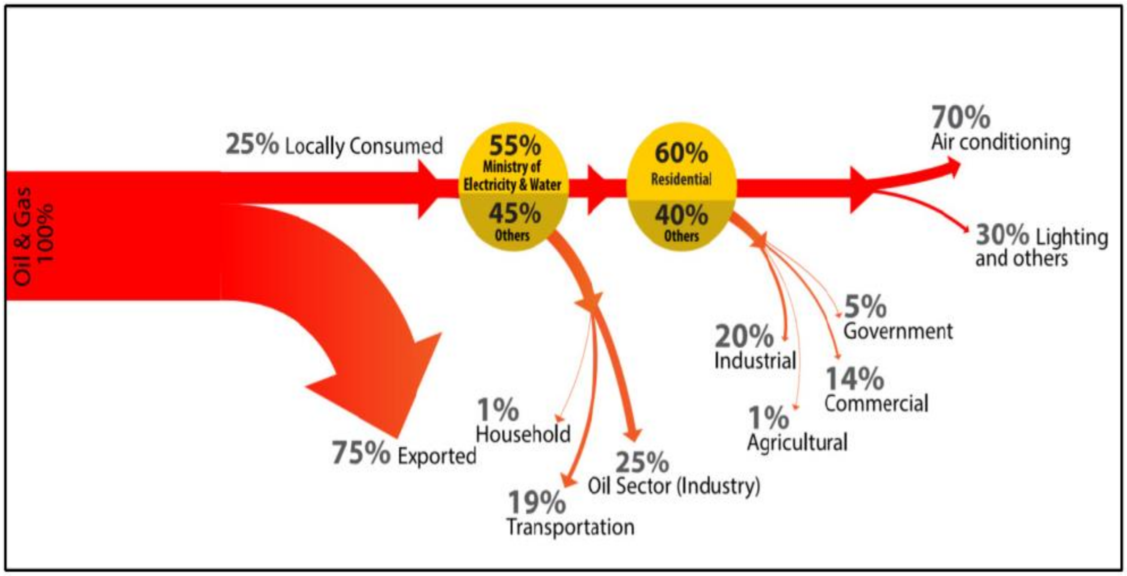


Figure 9 Energy flow diagram taken from [1] showing high residential energy consumption

Reducing residential energy use is aligned with broader national goals of meeting 15% of total energy usage through renewable energy generation which was announced by the Amir of Kuwait in 2012 at the United Nation’s 18th conference for climate change [24]. The Amir’s decision has led to the development of large scale solar and wind power plants, most notably the Shagaya pilot plant. Such plants provided valuable information for local Wind and Solar generation. In comparison to renewable energy, improving energy efficiency would have a lower cost in reducing CO2 emissions and could potentially reshape energy consumption trends [25]. For this reason, most GHG emission mitigation reports include the effect of added energy efficiency with respect to baseline CO2 levels. Progress is seen as the ability to either maintain or reduce emissions and simultaneously advance the transition of the energy generation system to renewable technology.

At the time of this writing, there were no reports that included energy efficiency in the context of CO2 mitigation strategies. The First Biennial Update Report of The State of Kuwait submitted to the United Nations Framework Convention on Climate Change (UNFCC) in September of 2019 included a GHG mitigation scenario that only included reductions from added renewable energy capacity and added efficiency specifically to the distribution system, not towards energy use [26]. The report estimated combined reductions up until 2035 of 60,000 Gg of CO2e when the GHG mitigation scenario was compared to the baseline. Overall, estimates showed that GHG emissions will continue to rise, and that GHG reductions are minor relative to the length of the planning period and baseline values.

There is a growing need to address the stock of inefficient buildings that lack appropriate energy saving measures, the most significant of them all are the standard residential villas. Existing energy policies provide little incentive for consumers to lower energy use, especially with highly subsidized energy prices and no limits on consumption. Energy efficiency measures could be used as a strategy to lower local oil consumption levels, especially since 50% to 60% of electric generation is consumed by residential buildings.

Energy saving policy reforms provide a practical low-cost approach in contrast to renewable energy capacity expansion, especially for the case of Kuwait where little attention is given to the benefits of energy efficiency. Ideally, both renewable integration and efficient consumption strategies should be used simultaneously to reduce GHG emission rates. Moreover, the integration of energy efficiency scenarios in GHG mitigation plans provides more opportunity to reduce CO2 emissions enabling strategies that either hold total annual emissions constant or potentially decrease emissions over the long run.

2.4 Residential Energy Policies

Kuwait has the second highest energy subsidies per capita in the world falling behind UAE, which is also an oil producing country in the middle east [2]. The Kuwaiti government has been committed to the subsidized electricity prices for more than 50 years now, which means increasing the price even slightly would be a huge challenge given the lifestyle that Kuwaitis are now accustomed to. Tackling the issue of high per capita consumption could start with the integration of two concepts: Energy Conservation Measures (ECMs) and Energy Efficiency Measures (EEMs).

ECMs refers to the practices that reduce energy consumption through behavioral changes such as lowering thermostat when a building is unoccupied. EEM refers to the practices that reduce energy consumption through the utilization of less energy consuming end-use devices such as installing a more efficient AC system. A wide variety of policy tools have been implemented in the international community that drive such behavior. The current approach taken by the state has been mainly focused on EEMs through code compliance. The benefits of ECMs have not been captured as no programs currently exist that promote such behavior (since energy prices are low).

The Ministry of Electricity and Water (MEW) uses the Energy Conservation Code of Practice R-6 to mostly emphasize EEMs. Although the code includes conservation in its title, it mainly focuses on technical limits of equipment and material and not on behavioral shifts to push for energy conservation.

The building code has been updated several times with most of the updates occurring in recent years. The Kuwait Energy Conservation Code of Practice, hereinafter referred to as building code, was first developed in 1983, and updated in 2010, 2014, and 2018, and are only applied to certify new buildings. The responsibilities of the institution/government authority are represented in table 5.

Table 5 Responsibilities of institution/government authority [8]

Institution/Government Authority	Responsibilities
Ministry of Electricity and Water	Approval of W/ m^2 calculations for A/C and lighting. Approval of all electrical drawings before obtaining building permit from Kuwait Municipality. Approval of all energy conservation measures. Approval of kW/t for A/C system and requirement.
Kuwait Municipality	Approval relating to compliance with zoning regulations. Inspection during construction of insulation materials and glazing application.
Ministry of Public Works	Testing and certification of building materials, including all insulation materials and systems.

Table 6 assembles the villa requirements of the building codes released from 1983 to 2018. The code covers other types of buildings including apartments, clinics, schools, Mosques, offices, restaurants, shopping malls, and supermarkets. However, due to the scope of this study, and the high share of total energy consumption from villas emphasized in section 1.2, only villas are investigated in this study. Table 7 shows the maximum solar heat gain coefficient (SHGC) and the maximum U-value allowed for different types of windows.

Table 6 Building codes for villas in Kuwait

Building Code for Villas	**1983**	**2010**	**2014**	**2018**
DX units (kW/RT)	2	1.7	1.6	1.1
Lighting (W/m^2)	15	10	7	5
U-values BTU/h·f^2·°F				
Walls	0.1	0.1	0.1	0.085
Roofs	0.07	0.07	0.07	0.045

Table 7 Glazing requirements for villas in Kuwait

Glazing Type	**Maximum SHGC**			**Maximum U-value (BTU/h·f^2·°F)**		
Building Code	**2010**	**2014**	**2018**	**2010**	**2014**	**2018**
6-mm single-clear	0.72	NA	NA	1.3	NA	NA
6-mm single-reflective	0.32	NA	NA	1	NA	NA
6-mm double-tinted	0.4	0.4	0.4	0.64	0.64	0.64
6-mm double-reflective	0.25	0.25	0.25	0.59	0.59	0.59
6-mm double-spectrally selective	0.23	0.23	0.22	0.35	0.35	0.35

CHAPTER 3

LITERATURE REVIEW

3.1 Residential Energy Modeling

There are increasing initiatives to model residential sector energy use mainly driven by climate change concerns, high energy prices, and energy supply/demand constraints [28]. Using building modeling techniques, a modeler can gain better understanding of the factors that drive energy consumption and demand in existing or planned buildings. Furthermore, a modeler can identify better practices that reduce energy requirements for a specific type of building. Modeling the entire residential sector energy consumption, however, is a challenge due to the sector's diversity in building sizes, geometries, materials, occupant behavior, and limited data. Using regression analysis, a top-down approach could capture energy consumption by utilizing macroeconomic indicators, energy prices, and climate conditions. A bottom-up approach on the other hand, extrapolates energy consumption estimates of individual dwellings to regional and national levels. Bottom-up models consist of two approaches: the statistical approach which relies on large historical data sets and the engineering approach where detailed modeling of a house is performed using a building simulation tool [28].

Both approaches are based on measured energy consumption of end-uses. The statistical method utilizes energy data from a sample of houses and applies regressions analysis to determine the contribution of end-uses towards total consumption. Just like the top-down approach, statistical methods can also utilize macroeconomic data to determine energy consumption of end-uses. The second bottom-up approach is the engineering method which relies more on the details of the building characteristics and power ratings of the technological equipment. The engineering method makes use of thermodynamics and heat transfer principles to determine the energy consumption of end-uses as well as total consumption. It is a much better approach to determine the effects of new technologies on residential energy consumption. In both methods, the two bottom-up approaches can yield insights into the contribution of different end-uses in total energy consumption aggregated to the total stock of buildings.

Swan and Ugursal identified three bottom-up engineering methods in their review paper [28]: Distributions, Archetypes, and Sample. Distributions technique utilizes the distributions of appliance ownership and usage patterns as well as the energy ratings of these appliances to calculate the total end use energy consumption of the residential sector. In this technique, no interactions among the appliances are considered since they are usually modeled separately. The Archetypes technique classifies the stock of residential buildings according to the vintage, size, location, etc. to determine total energy consumption from the sector by simulating sample archetypes and aggregating results. Finally, the Sample method utilizes a large database of representative units and accounts for the wide variety of consumption among the stock of houses. Like the Archetypes approach, results can be aggregated by applying weights to match the representative sample to the total stock. This approach requires a large database with enough units to represent the entire stock of houses.

Most engineering methods require the use of a building simulation tool such as eQuest and EnergyPlus to determine energy consumptions of end-uses. The ratings of appliances and building characteristics are used as inputs to the model along with weather data. The software utilizes mathematical formulations and thermodynamic equations to calculate energy intensity and usage patterns. Typically, a software includes a set of assumptions made to simplify calculations thereby reducing the required computing power. For example, in some simulation software such as eQuest, only one-dimensional heat transfer is considered, and adjustments are made to account for thermal bridges and ground heat

3.2 Residential Studies in Hot Climates

There are multiple studies on conservation and efficiency measures and the increased energy consumption from the residential sector in hot climates. Some studies investigate a single residential unit since more data can be acquired providing accurate inputs to the model and allowing calibration of results with actual values. Taleb collected data for a single residential unit in Dubai, UAE to assess the energy reductions and thermal improvements achieved using passive cooling strategies [29]. Some of the energy reducing strategies implemented in the model include harnessing of natural ventilation, shading devices to minimize heat gain, using double-glazed windows, and the addition of a green roof. It was found that the passive cooling strategies were able to reduce the energy consumption of a residential building in Dubai by up to 23.6%.

A similar analysis was performed for a typical villa in Saudi Arabia [30]. In Saudi Arabia, almost 40% of the residential building stock is classified as villa, implying that energy reductions from these units could have major impact on overall building energy use in KSA. The characteristics of the typical villa obtained through surveys and previous studies was modeled using EnergyPlus. An economic assessment was included for the retrofit measures which comprises a brute force optimization approach to find the most cost-effective retrofit measures for subsidized and unsubsidized energy prices. The main outcomes of the study showed that for the five different cities investigated, the building achieved savings that ranged from 23% to 40% for subsidized energy prices and 26% to 47% for unsubsidized energy prices.

Most residential energy studies that estimate energy savings for the entire sector by utilizing bottom-up or top-down approaches. A residential building stock model for Saudi Arabia was developed using the bottom-up engineering approach to evaluate energy efficiency and demand-side management [17]. The model utilized the Archetype approach where 54 prototypes representing the housing stock in Saudi Arabia were identified by vintage, type, and location. The 54 building prototypes were each modeled using the US Department of Energy's building simulation software DOE-2.2 and results were aggregated to generate the residential sector's total energy consumption. Large-scale implementation of retrofit programs was then applied to the model to evaluate energy saving potentials. It was clear that the retrofit programs were cost-effective and had economic, environmental, and social benefits. Most notably, 50% energy reductions were achieved by implementing a full scale optimal retrofit program.

Energy saving potential in the residential sector in Oman was examined by utilizing energy forecasts and building simulation software [16]. The country's residential energy consumption was studied through historical data and forecasted using growth rates. A base case was developed using eQuest to simulate the energy consumption of a typical residential building under eight different climate zones that represent the diverse climate conditions of Omani cities. Since the country does not have a building code, building codes of other Gulf Cooperation Council (GCC) countries were applied to the model to assess the energy saving potential achieved by enforcing different building code. It was found that the Saudi building code was able to achieve the most savings in the hot dry climate regions of Oman while the Abu Dhabi building code achieved better savings in hot humid and warm tropical climates of the country. The analysis ended with an economic assessment of the retrofit measures necessary to comply with each of the codes and used life cycle costs and simple payback as indicators.

Table 8 Summary of literature review for residential studies in hot climates

Authors	Title (Year)	Description
H. Taleb [29]	Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E. buildings (2014)	Assesses the energy reductions and thermal improvements achieved using passive cooling strategies: harnessing of natural ventilation, shading devices to minimize heat gain, using double-glazed windows, and the addition of a green roof. Up to 23.6% energy reductions were achieved.
A. Alaidroos, M. Krarti [30]	Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia (2015)	Models typical villa in Saudi Arabia using EnergyPlus software and develops optimization approach to select most cost-effective retrofit measures for subsidized and unsubsidized energy prices. Energy savings ranged from 23% to 40% for subsidized energy prices and 26% to 47% for unsubsidized energy prices.
M. Krarti, M. Aldubyan, E. Williams [17]	Residential building stock model for evaluating energy retrofit programs in Saudi Arabia (2020)	Performed bottom-up engineering approach utilizing the Archetype approach where 54 prototypes represented the housing stock in Saudi Arabia identified by vintage, type, and location. Model was used to evaluate large-scale implementation of retrofit programs. Energy savings up to 50% were

		achieved under the full scale optimal retrofit program.
C. Alalouch, S. Al-Saadi, H. Alwaer, K. Al-Khaled [16]	Energy saving potential for residential buildings in hot climates: The case of Oman (2019)	Performed energy simulations of a typical villa under eight climate conditions in Oman and utilizing four different building compliance codes of neighboring GCC countries. The Saudi building code was able to achieve the most savings in the hot dry climate regions of Oman while the Abu Dhabi building code achieved better savings in hot humid and warm tropical climates of the country.
M. Kharseh, M. Al-Khawaja [31]	Retrofitting measures for reducing building cooling requirements in cooling-dominated environment: Residential house (2016)	Models a common type of residential house in Qatar and considers five retrofitting measures: (1) U-value of the external shell, (2) indoor set-temperature, (3) light efficacy, (4) the color of external shell, (5) window's quality. Energy savings of up to 53% were achieved and payback times ranged from 0.5 to 4 years.
A. Abbood, K. Al-Obaidi, H. Awang, A. Abdul Rahman [32]	Achieving energy efficiency through industrialized building system for residential buildings in Iraq (2015)	Models house in Iraq using EnergyPlus and compares conventional energy use to the more efficient Industrial Building System (IBS). IBS reduced the annual energy consumption by 37.32% for heating and 65.36% for cooling.

S. Al-saadi, J. Al-Hajri, M. Sayari [33]	Energy-efficient retrofitting strategies for residential buildings in hot climate of Oman (2018)	Models an existing house in Badiyah city of Oman and calibrates results with actual data to perform energy efficiency analysis. Energy savings of up to 42.5% were achieved using optimum configurations.
H. Mohamed, J. Chang, M. Alshayeb [34]	Effectiveness of High Reflective Roofs in Minimizing Energy Consumption in Residential Buildings in Iraq (2015)	Models energy usage of an existing building in Iraq using EnergyPlus to determine the effectiveness of cool roof technology under four reflectivity scenarios.

3.3 Residential Studies in Kuwait

According to Cerezo et al., the building parameters of a studied area in Kuwait, which closely represented the entire stock of residential villas, could be characterized by the construction/renovation period of the villa [35]. The results indicate that the archetypes reflected the building codes that were enforced at the time the building was constructed. Cerezo et al. divided the villas into four archetypes; 60s-70s (Original), 60s-70s (Retrofitted), 80s-2000s, and 2010-present. The first two archetypes represent buildings built before any conservation codes were enforced. The retrofitted archetypes include more efficient building characteristics than the original buildings built in the 60s-70s period. The period from 80s-2000s represents buildings that implemented the 1983 building code. Finally, the last period represents buildings that implemented the new building codes of 2010. The average EUI of the villas was 220 KWh/m2.

Benefits of retrofitting existing residential buildings were examined on a large scale in 2002 [36]. Due to the highly subsidized energy prices, customer financial savings are difficult to obtain through retrofitting measures. Alragom suggests a different approach whereby the government would cover retrofitting costs allowing both customers and the government to greatly benefit from the reduced energy consumptions. Alajmi and Hanby in 2007 simulated energy consumption of residential buildings and put emphasis on a much-needed update to the 1983 codes that were still in force at the time [7]. In [37], Omar evaluated the effects of thermal bridging on the total energy consumption and peak load requirements of typical private residential villas in Kuwait. Results indicated that thermal bridging accounted for 1.8% and 2.3% of total energy consumption and peak load requirements, respectively.

When modeling residential building energy, definitions of building parameters are required to accurately simulate the effects of efficiency measures. These parameters can have a range of values characterizing different buildings. One important parameter that was investigated in 2001 was occupant's behavior and activity patterns that influence energy consumption [38]. It was found that most residential occupants tend to leave all lights on even when the rooms are vacant. Another outcome of the study was that substantial energy savings can be realized when lowering the AC thermostat to 24 ^{o}C as opposed to the more favorable 22C occupants' settings.

It was apparent from the outcomes of [14] that occupant behavior plays a major role in modeling the energy consumption of villas in Kuwait. Jaffar et al. proved that some of the more efficient villas still used more energy than older less efficient villas in part due to more occupants. Through routine interviews spanning over the entire year of energy data collection, occupant behavior was tracked qualitatively to model usage patterns. The power rating of appliances was also collected to use with the developed usage patterns. Two out of the four modeled villas yielded acceptable results based on ASHRAE’s guideline 14 statistical indices. The study concludes that uncertainties were mainly attributed to occupant behavior through (a) direct energy usage of appliances, (b) altering thermal set points of conditioned zones, and (c) tendency to resolve HVAC maintenance issues using quick fixes that could render the system inefficient in the long run.

Ameer and Krarti evaluated the impacts of the highly subsidized energy prices in Kuwait and investigated the benefits of energy price reforms, energy efficiency measures, and government rebate programs [2]. The study used an optimized life cycle cost approach to find the most effective efficiency measures suitable for Kuwaiti residential buildings and compared these measures to the building codes of 1983 and 2010. In another analysis, Krarti examined the potential energy saving opportunities for the existing stock of buildings using the 1983 and 2010 building energy codes [3]. Three different levels of building efficiency retrofit programs were evaluated to estimate CO2 emission, energy, and cost savings.

Alajmi and Phelan used a bottom-up approach to forecast residential energy demand [6]. The approach utilizes diffusion calculations for the stock of equipment and a retirement function to account for product end of life. The model was matched to annual data for residential energy use and forecasted to obtain further estimations into the future. The end-use energy was divided into the different components that make up residential energy use including AC, lighting, water heating etc. The model utilized the same archetypes developed by Cerezo et al. After calibrating, it was concluded that cooling loads in residential buildings account for 67% of total energy as shown in Figure 5.

In terms of energy generation, Hadi et al. analyzed the economic benefits of adding rooftop solar, where savings were calculated for the utility (MEW) not the customer [39]. The annual savings per house for new and previously built houses was estimated to be 744 and 635 KD/house respectively. Al-Mumin and Al-Mohaisen performed simulations for solar PV on Kuwaiti homes [40]. Building energy consumption was evaluated against simulated solar energy production from PV system covering all rooftop and wall areas of the building. The results concluded that surplus PV generation could be achieved if an entire building was covered with solar PV. The method for calculating available PV space was based on rough calculations without considering shading or rooftop obstacles. An average rooftop area of 300m^2 was used, which does not represent realistically the average available rooftop space. Al-Rashed et al. assumed a lower value of 150m^2 as the average available PV space on the rooftops of Kuwaiti residential buildings [41]. Based on this area and local weather data, PV production numbers were calculated. It is vital to mention that both studies mention the need to accurately measure available PV area on Kuwaiti building rooftops.

Bryan and Ben Salamah investigated the implementation of community scale solar in Kuwaiti residential areas [42]. This approach uses space available on government services building, which are usually grouped in a single area for each community. The results indicated that the combined generation of solar systems placed on the rooftops of community service buildings was enough to offset the energy use of 34 houses, approximately 10% of the houses in the community. The study uses an annual consumption rate of 128,000 KWh per residential unit.

Table 9 Summary of literature review for residential studies in Kuwait

Authors	Title (Year)	Description
C. Cerezoa, J. Sokola, S. AlKhaled, C. Reinhart, A. Al-Mumin, A. Hajiah [35]	Comparison of four building archetype characterization methods in urban building energy modeling (UBEM): A residential case study in Kuwait City (2018)	Uses four methods to calibrate archetype building characteristics to existing buildings in Kuwait based on vintage of villas. Calibration process involved the utilization of Energy Use Intensity data of 336 villas in a residential area in Kuwait.
F. Al-Ragom [36]	Retrofitting residential buildings in hot and arid climates (2003)	Models a base case villa in Kuwait using DOE-2.1 E simulation software and applies retrofit scenarios to reduce energy consumption. Economic benefits were estimated based on payback calculations for customer and government for large scale implementation of retrofits.
F. Alajmi, Hanby [7]	Simulation of energy consumption for Kuwaiti domestic buildings (2008)	Models energy consumption of typical Kuwaiti villa using TRNSYS simulation program.
A. Al-Mumin, O. Khattab, G. Sridhar [38]	Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences (2003)	Surveys 30 houses in Kuwait for occupancy patterns and operation schedules of electrical appliances used. The surveyed parameters were used as input data for the thermal simulation program to model energy usage. It was found that occupants prefer to leave AC setpoint at 22C.

B. Ameer, M. Krarti [2]	Impact of subsidization on high energy performance designs for Kuwaiti residential buildings (2016)	Uses building simulation tool to model typical villa in Kuwait and applies brute force optimization to select optimal low-cost design that benefits customer and government by utilizing higher energy prices and rebate programs.
M. Krarti [3]	Evaluation of large-scale building energy efficiency retrofit program in Kuwait (2015)	Models the annual consumption of a residential building in Kuwait under several scenarios including parameters that comply with the 1983 and 2010 building codes. Analysis includes an economic and energy savings assessment for the implementation of retrofit programs based on 3 design levels.
T. Alajmi, P. Phelan [6]	Modelling and forecasting end-use energy consumption for residential buildings in Kuwait using a bottom-up approach (2020)	Uses a bottom-up engineering approach to develop a residential end-use energy consumption model and matches results with actual residential sector total energy use.
M. Hadi, R. Abdel-Razek, W. Chakroun [39]	Economic assessment of the use of solar energy in Kuwait (2013)	An economic analysis of the installation of solar systems on Kuwaiti rooftops with rooftop area assumptions based on [40].
A. Al-Mumin, A. Al-Mohaisen [40]	Greening the Kuwaiti houses: studying the potential of photovoltaics for	An energy analysis of the use of solar PV systems on the surfaces of 25 sampled houses. The study does not

	reducing the electricity consumption (2006)	consider roof shading and assumes all surfaces are PV applicable.
A. Al-Rashed, T. Beyrouthy, A. Al-Rifaie [41]	Feasibility study of solar energy integration for electricity production in Kuwait (2016)	Shows the feasibility of integrating solar systems on houses and parking through an economic and environmental analysis.
H. Bryan, F. Ben Salamah [42]	Investigation of the possible implementation of community-scale solar systems in Kuwaiti neighborhood units: a study on their effect of offsetting energy demands in Kuwait (2019)	Uses rooftops of public service buildings to model energy production from solar systems and their ability to offset energy demand for a residential community.

CHAPTER 4

VILLA ENERGY EFFICIENCY ANALYSIS

4.1 Overview of Villa Characteristics

There are two types of residential villas that exist in Kuwait, government villas and private villas. A government villa is built completely by the Public Authority for Housing Welfare (PAHW) and is provided to qualified Kuwaiti applicants. A private villa is one where only the land is purchased at fixed nominal prices to qualified Kuwaiti applicants. The following represent the three options available for a Kuwaiti family seeking housing welfare for the first time (taken from [21]):

1. A government house built on a minimum 400 m^2 plot or a minimum 400 m^2 apartment provided by the PAHW at nominal value, plus a monthly rent allowance of KWD 150 ($490 during the waiting period.
2. A minimum 400 m^2 plot of land provided by the PAHW at nominal value and a KWD 70,000 long term, interest-free loan from the Savings and Credit Bank for construction, plus a monthly rent allowance of KWD 150 during the waiting period.
3. A KWD 70,000 long-term, interest-free loan from the Savings and Credit Bank, to buy or build a house with a minimum area of 360 m^2, or to buy an apartment with a minimum area of 360 m^2. (Public Authority for Housing Welfare 2011a)

The standard villa designs in Kuwait share similar features that include a rectangular floor area with two floors above (3 floors total) with the top two floors generally having less total floor area than the ground floor. The Kuwait Municipality requires that a maximum number of 3 floors be allowed for residential villas. Some exceptions do exist where building owners exceed those limits by building additional floors. The roofs of residential buildings are characterized as flat roofs typically surrounded with parapet.

These parapet walls create fixed shade that hinders energy generation from rooftop solar systems mounted on the ground of the roof. Avoiding parapet shade is the primary reason for limited available solar area on residential rooftops.

The structure of Kuwaiti villas consists of columns, beams, and slabs made from reinforced concrete and walls made from masonry blocks [37]. Previous studies have distinguished the effects of classical masonry blocks and autoclaved aerated concrete blocks AAC on the thermal resistance of the building envelope [7]. These two types of concrete blocks are used for most residential buildings in Kuwait with AAC being the current standard. The incorporation of sand as insulating material for the roof structure is a common practice and is found in most residential buildings.

Table 10 Typical building properties (generated by author from surveying numerous publications)

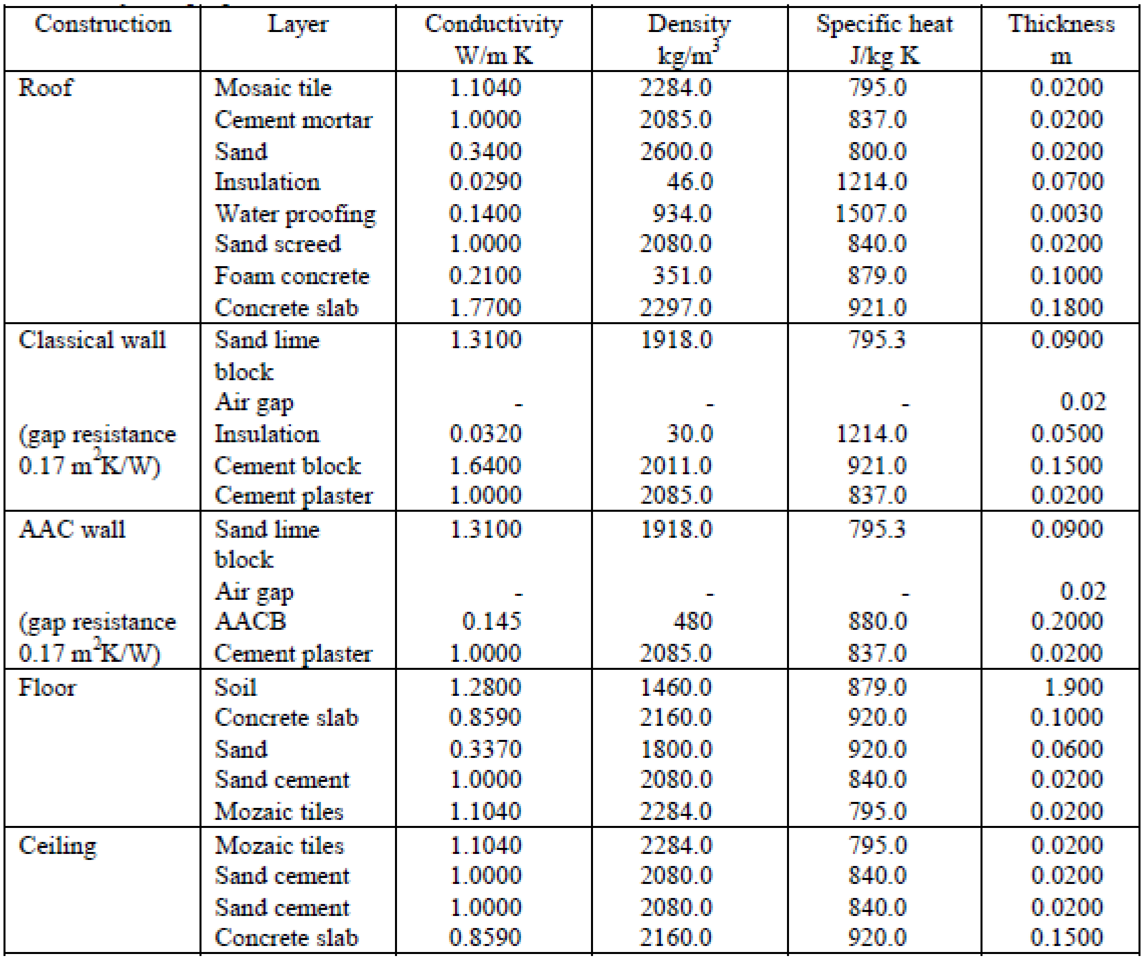
Building Type	2 to 3 Story Residential Building (Single Family)
Construction	Reinforced concrete beams, columns, and slabs with autoclaved aerated concrete (AAC) or classical concrete wall blocks
Walls	Sand lime block, air gap, insulation, concrete blocks, cement plaster
Roofs	Mosaic tiles, cement mortar, sand, insulation, water proofing, sand screed, foam concrete, concrete slab
Ground	Mosaic tiles, sand cement, sand, concrete slab, soil
Total floor area	550 m2

Conditioned Zones	2 Zones per floor and 1 zone for third floor - all zones conditioned
Door type	Solid wood with wood frame and clear glass with aluminum frame
Windows type	Single and double pane clear glazing with aluminum frame
WWR	10-20% each side
Occupancy	8 persons
Lighting	Incandescent, CFL, and LED
Miscellaneous equipment	Varies depending on zone type
HVAC system	Multiple DX heat pumps with average COP of 2.0 at the average external temperature (35C °)
Thermostat set-points	Cooling: 22C (72 F), Heating: 20C (68F)
DHW	Electric water heater with 80-120 gallon capacity

Building lots are arranged based on zero-lot-line distributions, meaning houses are constructed side-by-side. In many cases, no space exists between two properties when their exterior walls are attached. One benefit of such lot distribution is that buildings would experience more shade during the day, lowering cooling energy use in hot climates. Single family villas in Kuwait have larger than average floor areas with 99% of lots ranging from 400 m^2 to 1,200 m^2 [46]. It is common practice to construct residential villas using most of the given lot area. Furthermore, all residential villas are centrally cooled by several packaged direct expansion air conditioning (AC) units with air cooled condensers. Packaged units are located on the rooftop of villas and are assigned to different zones that are each controlled by a single thermostat. Some rooms are not centrally cooled and instead have smaller split units [14].

Figure 10 Google Maps image of villa distribution in a typical residential area

Table 11 Construction layer properties of a typical Kuwaiti villa [37]



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

4.2 BEM Background

In building energy models (BEM), it is important to distinguish between the different types of energy loads and their share of total consumption since some loads are more dominant depending on the design of the building and local weather conditions throughout the year. For example, in dry hot climates such as Kuwait, cooling loads are the predominant energy loads making up around 70% of total energy consumption [6]. Based on the same data, heating loads are around 5% of total energy consumption. It becomes evident then that the most effective approach to reduce building energy consumptions in hot arid climates is to Figure out ways to reduce cooling loads.

Reducing cooling energy use can be done through a variety of different approaches including (a) improving thermal envelope by using better insulation, (b) improving building air tightness to lower infiltration, (c) occupant related behavior such as lowering AC temperature setpoint when unoccupied, and (d) technological improvements which include using more efficient HVAC equipment. HVAC efficiency is typically quantified using measures such as coefficient of performance (COP) and energy efficiency ratio (EER).

Setting up a building model begins by defining the building geometry, giving the simulation tool as much information as needed about the architecture of the building and its directional orientation. This includes defining the types of material and respective thermodynamic properties of walls, roofs, ground, floors, and windows. Usually, subsequent steps then identify the air tightness of the modeled building shell by defining an infiltration value, which could vary by zone. Setting up the building geometry and material properties allows the model to make accurate calculations of cooling and heating load requirements by using heat transfer calculations. These calculations rely on exterior temperature conditions and indoor comfort air conditioning settings.

In Kuwaiti villas, lighting and plug loads have the second highest share of total energy consumption with similar shares at around 10% according to [6]. However, villas have unique patterns that are highly dependent on occupant behavior much more than cooling and heating loads. Both lighting and plug loads are usually quantified as input values using their power densities W/m^2 or W/ft^2 but can also be characterized using the combined power ratings of equipment.

In practice, most uncertainties related to building energy models lie in the fact that a significant share of energy consumption is attributed to occupant related activities, especially in residential applications. Occupant behavior is usually accounted for using surveyed data that identifies a usage pattern which is then combined with the corresponding power densities or ratings. In general, lighting power densities (LPD) are easier to obtain than plug loads, since plug loads have varying power densities depending on the appliances being used and the frequency of usage. In [43], Fuertes and Schiavon analyze the role of plug loads in energy models submitted for LEED certification where it was noted that varying plug loads were used based on different assumptions.

Domestic hot water DHW calculations require the following occupant related data: gallons of water used per person, the number of occupants, and the usage patterns which could vary depending on time of the year. Technical parameters required in the DHW calculation include: the volume of the heater’s storage tank, the inlet water temperature, the make-up water temperature, and the efficiency of the heater. For hot climates, a typical usage pattern is developed since DHW loads are negligible when compared to the more dominant cooling load. DHW usage patterns become more significant in cooler climates where Time-of-Use (TOU) pricing mechanism is applied influencing the behavior of occupants. Some DHW systems incorporate automatic switches that turn off the system during peak hours, altering the occupant’s usage patterns.

4.3 Modeling Procedure

The weather data used for the analyses combined data collected from two sources: the Kuwait Institute for Scientific Research (KISR) and the National Oceanic and Atmospheric Administration (NOAA) data bank. The KISR TMY file includes data collected from the period of 1994 to 2012 in Kabed, Kuwait. The TMY estimates were available as P90 and P50 estimates but only the P50 data was used since it resembled a middle estimate as opposed to the lower estimates of the P90 data. The hourly data collected from this file are only solar irradiation data including global horizontal GHI, direct normal DNI, and diffused DIF. The NOAA file was used for temperature data including dry bulb, wet bulb, dew point, pressure, and air speed. Since the energy consumption data for the villa was available from 01/16/2014 to 01/16/2015, the hourly temperature data collected from NOAA reflected these dates for better calibration.

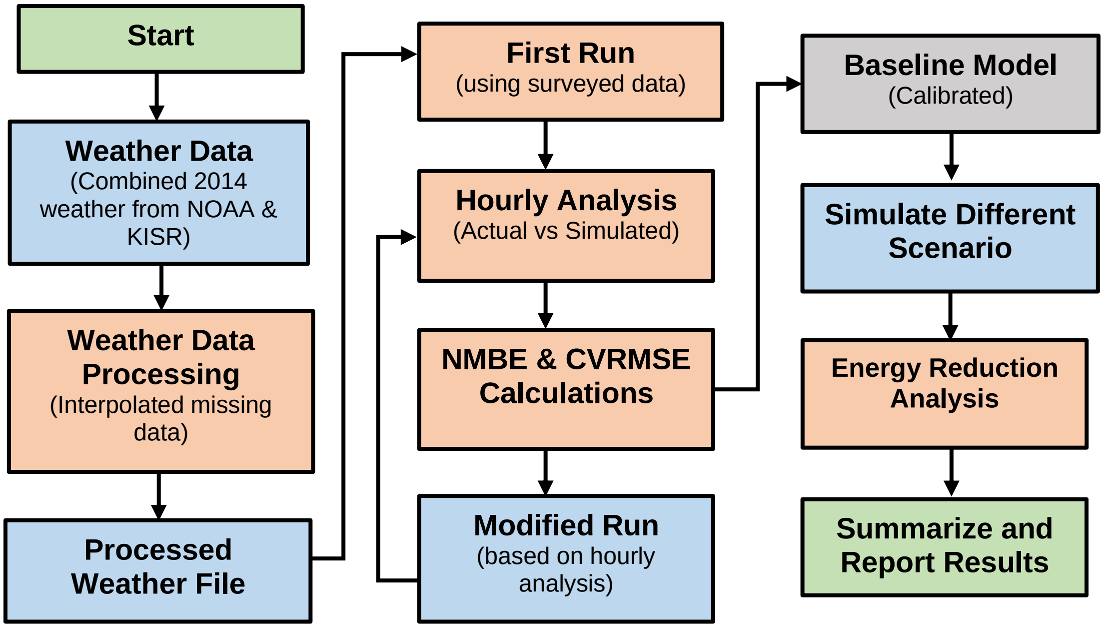


Figure 11 Flow chart illustrating the calibration of the detailed building simulation baseline model and subsequent scenario analysis

The eQUEST software is the latest version of the original DOE-2 building simulation software funded by the United States Department of Energy [44]. The tool has been used for various applications including utilizing the tool to qualify for government tax deductions in the United States under continually updated energy policy acts. It is also widely utilized for obtaining the U.S. Green Building Council's LEED certifications by modeling the energy performance of building projects under baseline and energy improvements scenarios. The advantage of using eQUEST over other tools is in its ease of use for basic calculations (Schematic Wizard) as well of its flexibility when performing detailed analysis (Detailed Mode). The tool's significance in this study was the ability to perform hourly analysis under short run times to predict hourly load distribution.

To model the villa, architectural drawings were used alongside building parameter data taken from the building owner through a short survey followed by multiple phone interviews. Calibration was performed using actual hourly energy consumption data of the building for the year 2014. Since the modeled villa was built in 2004, it falls under the 80s-00s range, which represents the period between the 1983 and 2010 building codes. The survey data completed by the owner for the modeled villa is shown in table 12.

Table 12 Building properties of modeled villa based on survey completed by building owner

Building Type	Single Family (2.5 Floors)
Construction	Reinforced Concrete Skeleton with Autoclaved Aerated Concrete AAC
Wall Type	Thermal insulator blocks with external concrete bricks
Roof type	Foam type insulation covered with concrete and sand screed

Ground floor	Marble Tiles
Total floor area	705 m2
Conditioned Zones	Floor 1: 13.5 cooling tons for first zone & 6 cooling tons for second zone Floor 2: 6 cooling tons for each of the three zones Floor 3 (1/2 floor): 6 cooling tons for one zone.
Door type	Both front and rear doors are solid wood.
Windows type	Front windows: Double pane clear glazing with Aluminum frame. Side and rear windows: Single pane clear glazing with Aluminum frame
WWR	North wall: about 30% East/West (side) walls: about 10% South wall: about 2%
Window overhang, fins, and shutters	Front windows: shutters Side and rear winds: curtains
Occupancy	7 persons
Lighting Power Density	Average per floor is about 5 W/m2
Miscellaneous equipment	Average of about 2 W/m2.
HVAC system	COP = 2.3
Thermostat set-points	Cooling: 22 C
Cooking load	Use LPG (propane) for cooking.
Domestic Hot Water	Electric boiler with capacity of 80 gallons.

Using the eQUEST energy modelling tool, simulations were performed for an entire year to report hourly energy consumption loads and assess the benefits of building code compliance as well as efficiency measures on an existing residential building in Kuwait. The simulated data was then used and compared with solar generation in section 5.2 to realize potential benefits of installing rooftop solar systems in reducing grid power demand. To assess the effectiveness of the existing building codes, modifications were made to the baseline model to simulate a version of the building that complies with the code's minimum requirements. Finally, to analyze the potential of using more stringent codes, an additional scenario was included that evaluates realistic efficiency retrofit measures beyond the most recent building codes.

4.4 Calibration

The first run of the model uses exact building geometry and orientation as well as survey data of the house parameters. A calibration step was necessary prior to any scenario runs to make sure the model was well representative of the villa under investigation. The Normalized Mean Biased Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CVRMSE) were calculated for each run to maintain acceptable error values. Based on ASHRAE Guideline 14P, NMBE should be at most +/- 5% and CVRMSE should not exceed 15% for monthly calibration [45]. Calibration was assisted by an hourly analysis which was performed for every month of the year and compared to the villa's energy data. Multiple runs were performed, each time changing parameters within an acceptable range, to match the simulated data to the actual data.

$$\boldsymbol{CVRMSE}\ (\%) = \frac{\sqrt{\sum(\boldsymbol{y_i}-\boldsymbol{\hat{y}_i})^2/(\boldsymbol{n}-\boldsymbol{1})}}{\boldsymbol{\bar{y}}} \qquad \textbf{(1)}$$

$$\boldsymbol{NMBE}\ (\%) = \frac{\sum(\boldsymbol{y_i}-\boldsymbol{\hat{y}_i})}{(\boldsymbol{n}-\boldsymbol{1})\times\boldsymbol{\bar{y}}} \qquad \textbf{(2)}$$

In equations (1) and (2), $\mathrm{y_i}$ is the metered data, $\hat{y}_\mathrm{i}$ is the simulated data, $\bar{\mathrm{y}}$ is the average of metered data, and n is the number of data points.

The U-Value of the walls and roofs of the villa were modelled based on the layers of material construction. Data for properties of construction layers of typical villas in Kuwait assisted in the selection of U-Values for different layers [46]. These values were also compared to building code requirements enforced at the time, namely, building code of 1983. Infiltration was not directly calculated for the specified house and thus a calibration-based air change value of 0.076 cfm/ft^2 was used. Although air infiltration is an important parameter in BEM, increasing air tightness was not specifically investigated since no measured infiltration data was available.

For the villa under investigation, a value of 20 gallons per person per day was utilized based on [2] with a storage tank of 80 gallons. The modeled inlet temperatures varied throughout the year ranging from 68°F to 85 °F. Water cooling energy use was found to be negligible and did not have a significant impact on daily profiles. The assumption, however, is only true when inlet water temperatures are consistent with the ranges mentioned above. In some cases, the inlet water temperature reaches higher temperatures if it has been stored for a long time in a water storage tank typically found on the rooftop of a residential building. In such cases, the energy used for cooling water would be much greater than that calculated for this analysis.

During calibration, it was observed that occupant behavior had a significant role on usage patterns. An example of occupant behavior that altered energy levels is the tendency to leave all exterior roller shutters on windows closed throughout the year. This is one of multiple modifications made after analyzing data of initial runs and additional information was obtained from the building owner. Modeling occupancy behavior usually requires making several assumptions. Although details were obtained from the building owner, some ambiguity remains in completely understanding hourly behavior of all occupants. Jaffar proved in [14] that even with detailed interviews, the unpredictable behavior of occupants gave uncertainty in the outcomes. As such, for this analysis, occupancy patterns were averaged for all months based on interpretation of survey data and interviews. To isolate and capture the cooling patterns on daily load profiles for all months, the calibration procedure depended on (a) building orientation, (b) surrounding building shade, (c) identical building geometry, (d) building envelope, and (e) appropriate power densities and schedules.

The model was altered slightly at each run during calibration. For example, a cooling temperature set-point of 70F was provided from the survey data, however, it was found that less cooling loads were needed during the day in the summer which was well matched when raising one or two of the six conditioned zones to 71F. Furthermore, lighting and plug loads were kept the same for all months of the year except for August which exhibited much lower power usage. It was assumed that fewer occupants were in the villa in the month of August and the lighting and plug loads were reduced by 20%. Based on the calibration procedure the two main drivers of uncertainty in occupant’s behavior are (a) thermostat set-point temperatures and (b) lighting and plug load densities and their usage patterns.

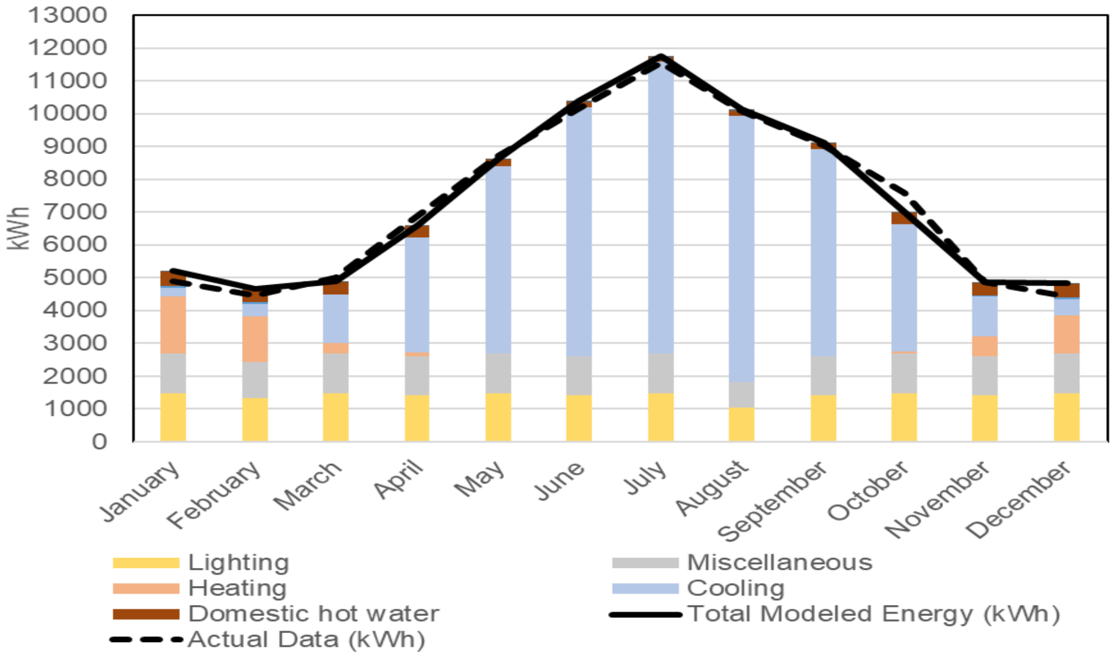


Figure 12 Comparison of the actual monthly energy use versus calibrated model results. Important end-use consumption generated by the model are also shown. Note the dominant effect of cooling loads

Examining the annual energy consumption density of the residential villa shows consumption levels quite different than typical villas in Kuwait. The villa exhibited relatively lower annual energy consumption mainly due to (a) the utilization of aerated autoclaved concrete as opposed to the classical concrete wall, (b) the direction of the house (north-facing), (c) shade caused by adjacent buildings to the east, west, and south of the building and (d) the overall efficient use of lighting and appliances as mentioned by the owner in the interviews.

Table 13. Monthly results compared to actual usage. [kWh]

Month	eQUEST Predictions	Actual Energy Use
Jan	5,315	4,885
Feb	4,732	4,454
Mar	4,895	5,019
Apr	6,646	6,879
May	8,750	8,717
Jun	10,575	10,176
Jul	11,988	11,558
Aug	10,366	10,087
Sep	9,251	9,025
Oct	7,051	7,584
Nov	4,849	4,878
Dec	4,901	4,430
SUM	89,320	87,689
AVG	7,443	7,307
NMBE	**-2.0%**	
CVRMSE	**4.7%**	

Table 14 Comparison of villa energy consumption with respective floor areas

Villa Construction Year	**Floor Area (m^2)**	**Annual Energy Consumption (kWh)**	**Energy Use Intensity EUI ($kWh/m^2/year$)**	**Source**
2004	705	87,689	124	Metered energy consumption of modeled villa
All	550	145,444	264	Average of national stock based on MEW data taken from [15]
1982	397	86,943	219	Metered villa energy consumption from [14]
1981	568	97,128	171	Metered villa energy consumption from [14]
2010	705	122,670	174	Metered villa energy consumption from [14]
1999	809	182,025	225	Metered villa energy consumption from [14]
N/A	500	106,579	213	Modeled villa energy consumption from [2]

The model was calibrated with acceptable statistical indices based on equations (1) and (2) for the energy consumption. However, the calibrated model tended to underpredict the peak power loads. This can be noted in Figure 17, where the daily peak-hour power was averaged for each month for both modeled and actual data. Figure 18 provides an explanation of why the model's underestimates peak power by showing hourly power profile of 4 consecutive days in January. Each day had a unique peak power and peak time which could be the result of the instantaneous power required by some appliances in conjunction with occupant usage of these appliances [47]. This variability in how occupants operate lights and equipment is what results in a poor power calibration.

The gap between actual and modeled data widens during increased demand for cooling. All refrigeration systems use compressors that generally cycle ON and OFF to keep the temperature of a space at a defined setting. The initial power these compressors need have been observed to be much higher in the first minute of the ON cycle. In general, the model focused primarily on capturing the overall cooling effect throughout the different seasons of the modeled year. Since these loads are the more dominant loads and contribute directly to peak loads in the summer, efficiency measures mainly focused on lowering cooling requirements. Once the baseline model was established, building code analysis and efficiency scenarios were simulated and energy savings were calculated with respect to baseline values.

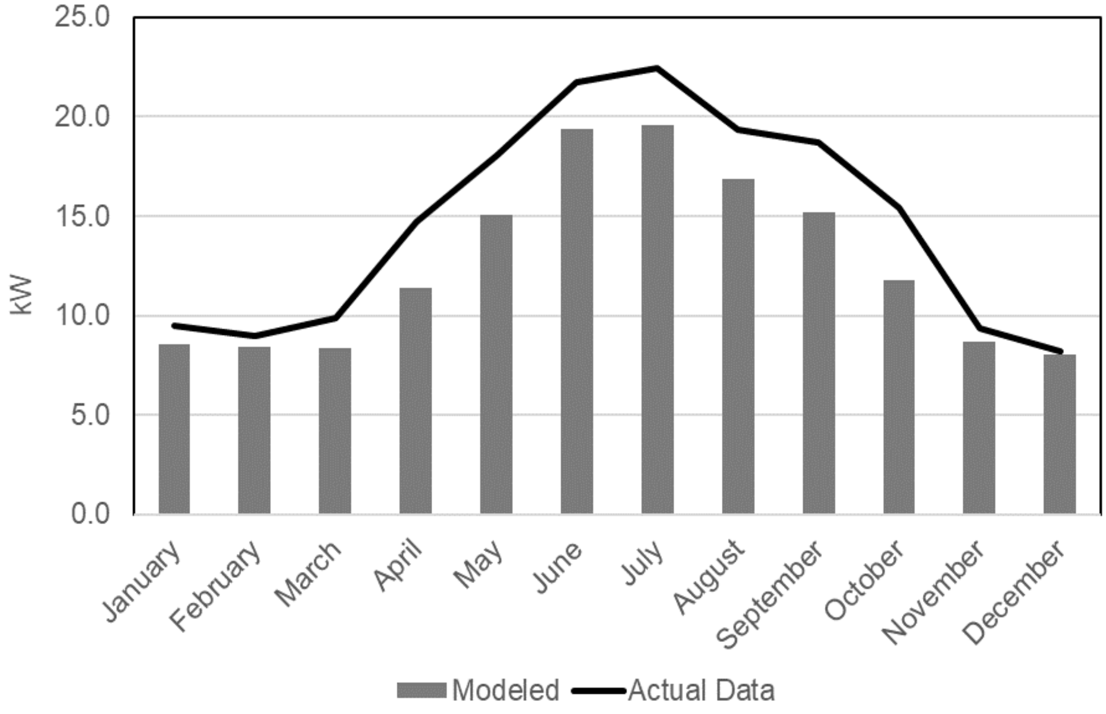


Figure 13 Peak hour kW demand averaged by day for each month of calibrated model

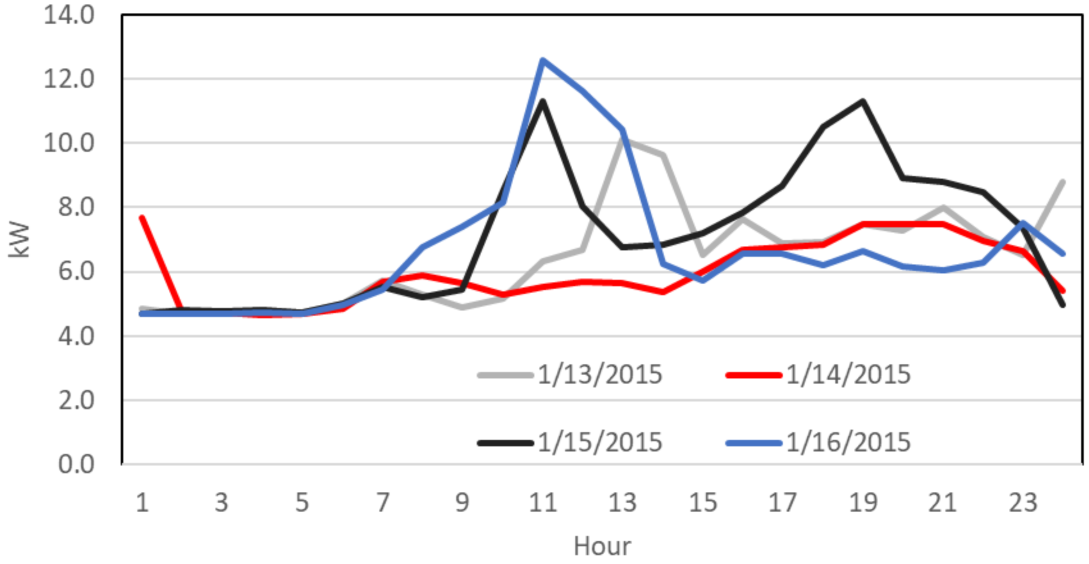


Figure 14 Actual data daily load profile for four consecutive days in January showing varying peak loads mainly due to occupant behavior. This erratic behavior results in poor model calibration of peak power

4.5 Code Compliance and Energy Efficiency

Retrofits were simulated by altering the baseline model parameters to comply with the minimum requirements of the building codes of each considered scenario. This provided a means to evaluate the extent to which compliance with previous and existing codes would yield energy reductions. Since the building was built in 2004, the 1983 codes were not considered for the energy saving analysis. Instead, all subsequent codes that followed were used, starting with the 2010 code. Minimum code requirements as well as an additional energy efficient scenario are shown in table 15. The Energy Efficient Design scenario included extra measures such as better window and wall/roof insulations and efficient lighting and HVAC system. Monthly graphs of each scenario are presented in Figures 23-30.

To further identify the modifications that yielded the most savings, two cases were considered for further analysis. The first case considered assessing the 2018 building codes to the baseline villa model. The second case assessed the benefits of the energy efficient design to the modeled villa under 2018 code compliance. In both cases, individual runs were made for each modification to calculate end-use and total savings. Additionally, cascaded runs were made where each EEM/ECM modification was added incrementally in each run to calculate end-use and total savings. Tables 17-20 show details of the modifications made in the independent and cascaded runs as well as energy and percentage saved. Figures 19-22 show the same results as pie charts of the percentage of energy saved in each run.

Table 15. Assumed Parameter Values for the Code compliance and energy efficiency scenarios

Parameters	**Baseline**	**2010 Building Code**	**2014 Building Code**	**2018 Building Code**	**Energy Efficient Design**
HVAC COP at DBT 95F° and WBT 75F°	2.3	2.1	2.2	3.2	3.4
LPD (W/ft^2)	0.6	0.93	0.65	0.46	0.27
Wall R-value $(h \cdot ft^2 \cdot °F/BTU)$	10	10	10	12	20
Roof R-value $(h \cdot ft^2 \cdot °F/BTU)$	14	14	14	22	26
Window U-value $(BTU/h \cdot ft^2 \cdot °F)$	0.47 – 1.02	0.35 - 1.3	0.35 - 0.64	0.35 – 0.64	0.30 – 0.50
Window SHGC	0.42 – 0.76	0.23 – 0.72	0.23 – 0.4	0.22 – 0.4	0.15 – 0.2

Table 16. Annual energy use predicted by the calibrated eQUEST model for different modeled scenarios

Scenario	**Annual Energy (kWh)**
Modeled Baseline	89,320
2010 Building Code	106,020
2014 Building Code	91,560
2018 Building Code	65,760
Energy Efficient Design	54,370

Table 17 Cascaded run results of energy savings from baseline to 2018 code compliance modifications

Cascaded Runs	**Energy Percentage Saved (%)**	**Energy Saved (kWh)**
1. COP 2.3 to 3.2	16.3%	14,584
2. Roof Insulation: R-14 to R-22	2.7%	2,441
3. Wall Insulation: R-10 to R-12	0.9%	762
4. Base Glass to 2018 Code Glass	1.4%	1,211
5. LPD 0.6 to 0.27 W/sf	5.1%	4,561
Savings from 2018 code	26.4%	23,559

- Baseline energy use was 89,320 kWh/year

Table 18 Individual run results of energy savings from baseline to 2018 code compliance modifications

Individual Runs	**Energy Percentage Saved (%)**	**Energy Saved (kWh)**	**Readjusted Savings (kWh)**
COP 2.3 to 3.2	16.3%	14,584	13,586
Roof Insulation: R-14 to R-22	3.7%	3,275	3,050
Wall Insulation: R-10 to R-12	1.1%	1,011	941
Base Glass to 2018 Code Glass	1.8%	1,607	1,497
LPD 0.6 to 0.27 W/sf	5.4%	4,813	4,484
Savings from 2018 code	28.3%	25,290	23,559

- Baseline energy use was 89,320 kWh/year

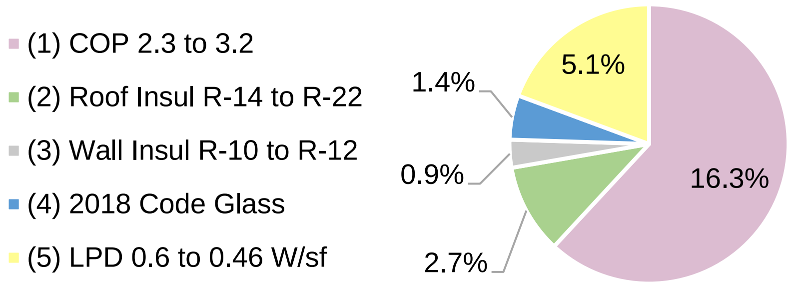


Figure 15 Pie chart of energy savings from Cascaded runs using 2018 code compared to the base case

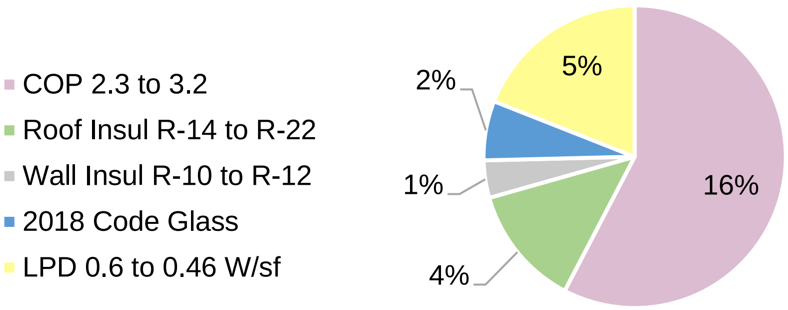


Figure 16 Pie chart of energy savings from Individual runs using 2018 code compared to the base case

Table 19 Cascaded run results of energy savings from 2018 code compliance to energy efficient modifications

Cascaded Runs	**Energy Percentage Saved (%)**	**Energy Saved (kWh)**
1. COP 3.2 to 3.4	3.3%	2,199
2. Roof Insulation: R-22 to R-26	1.0%	684
3. Wall Insulation: R-12 to R-20	2.4%	1,608
4. Base Glass to 2018 Code Glass	1.9%	1,232
5. LPD 0.6 to 0.27 W/sf	9.3%	6,137
Savings from energy efficiency	18.0%	11,860

Table 20 Individual run results of energy savings from 2018 code compliance to energy efficient modifications

Individual Runs	**Energy Percentage Saved (%)**	**Energy Saved (kWh)**	**Readjusted Savings (kWh)**
COP 3.2 to 3.4	3.3%	2,199	1,983
Roof Insulation: R-22 to R-26	1.5%	997	899
Wall Insulation: R-12 to R-20	3.0%	1,972	1,779
Base Glass to 2018 Code Glass	2.4%	1,573	1,419
LPD 0.6 to 0.27 W/sf	9.7%	6,410	5,781
Savings from energy efficiency	19.9%	13,150	11,860

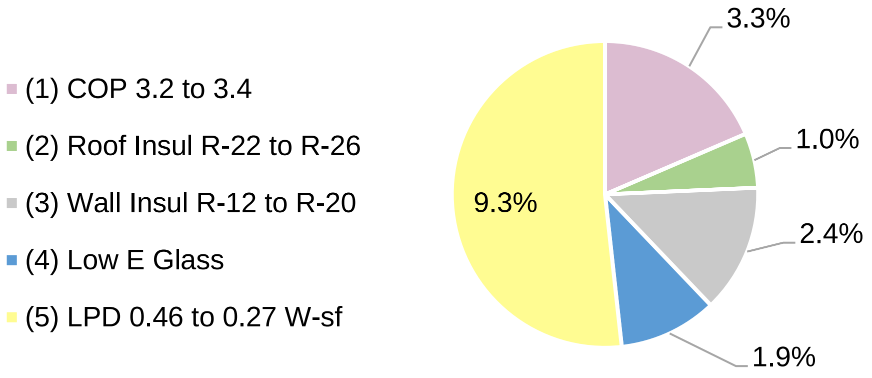


Figure 17 Pie chart of energy savings from Cascaded runs using energy efficiency compared to 2018 code compliance

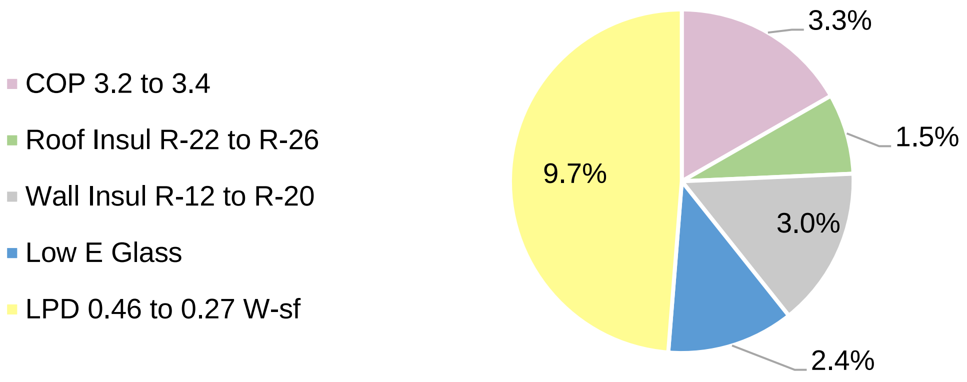


Figure 18 Pie chart of energy savings from Individual runs using energy efficiency compared to 2018 code compliance

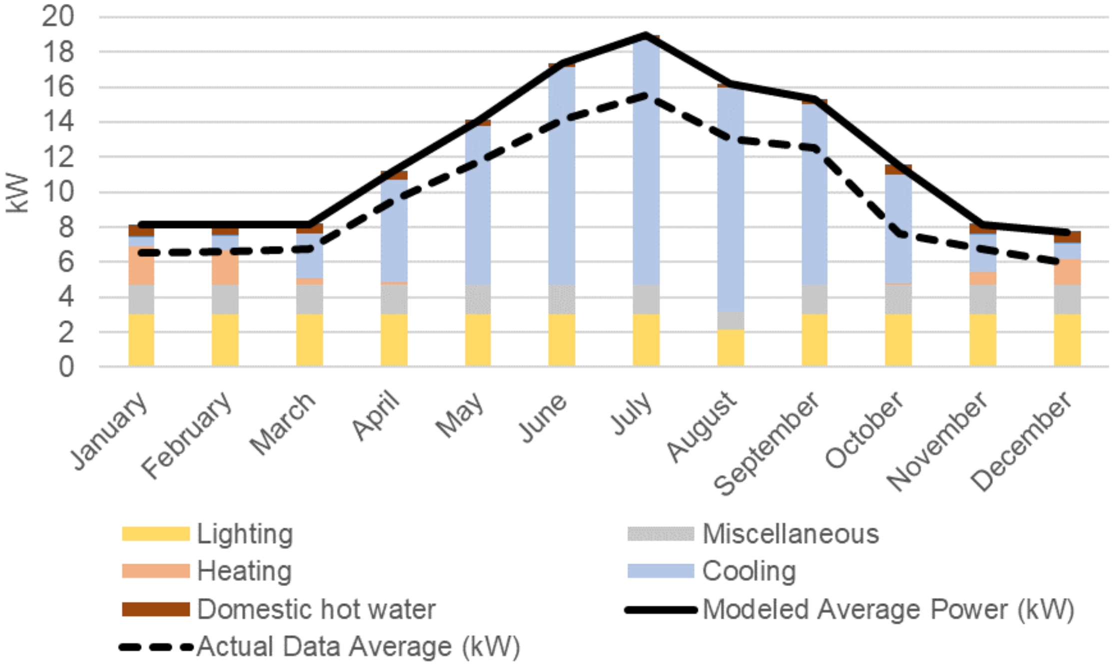


Figure 19 Comparison of monthly average power between actual and modeled for 2010 Code Compliance Scenario

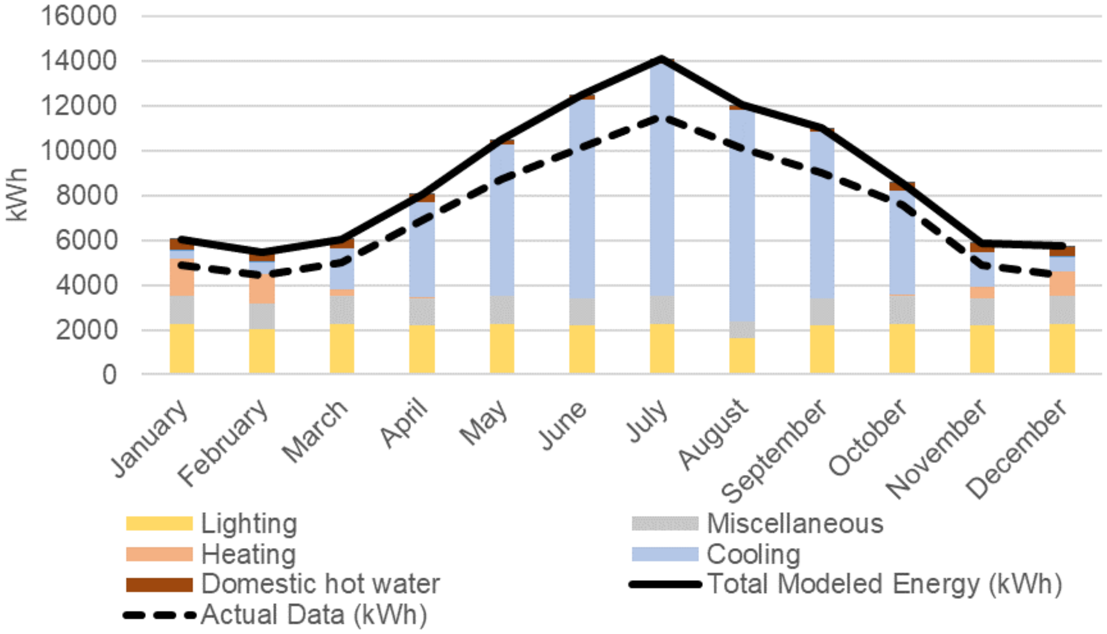


Figure 20 Comparison of monthly energy use between actual and modeled for 2010 Code Compliance Scenario

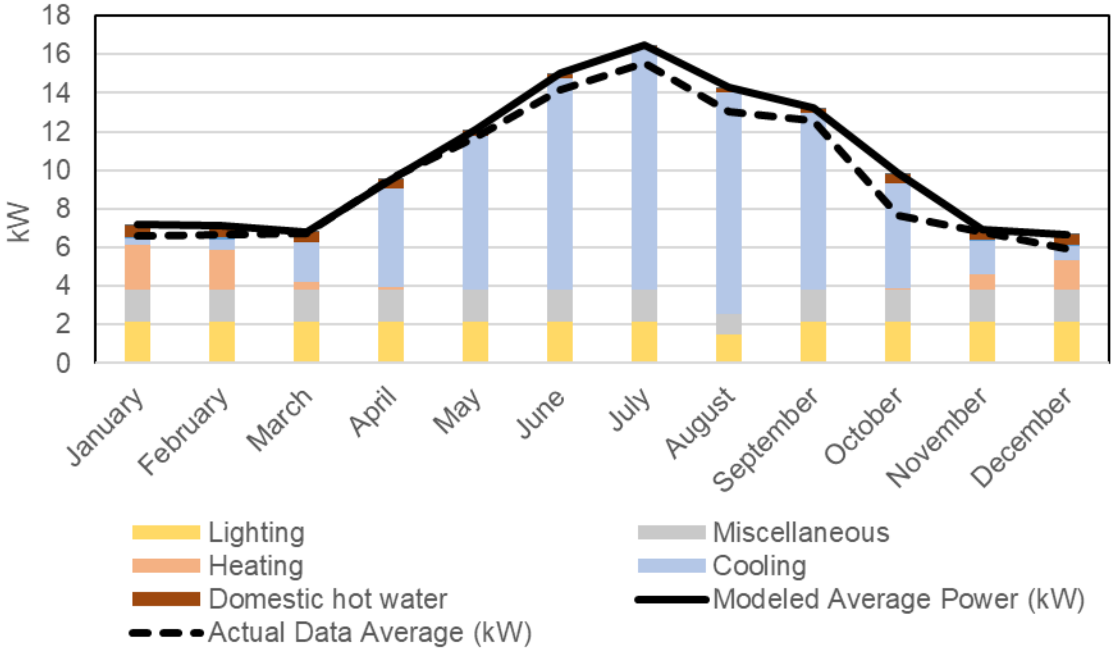


Figure 21 Comparison of monthly average power between actual and modeled for 2014 Code Compliance Scenario

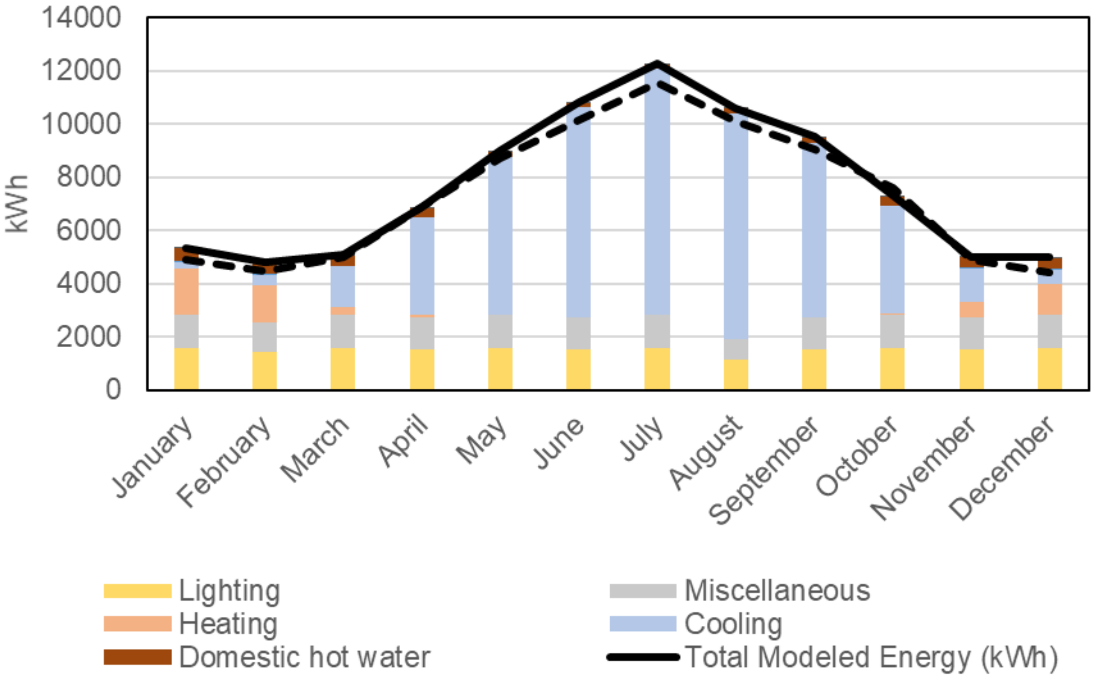


Figure 22 Comparison of monthly energy use between actual and modeled for 2014 Code Compliance Scenario

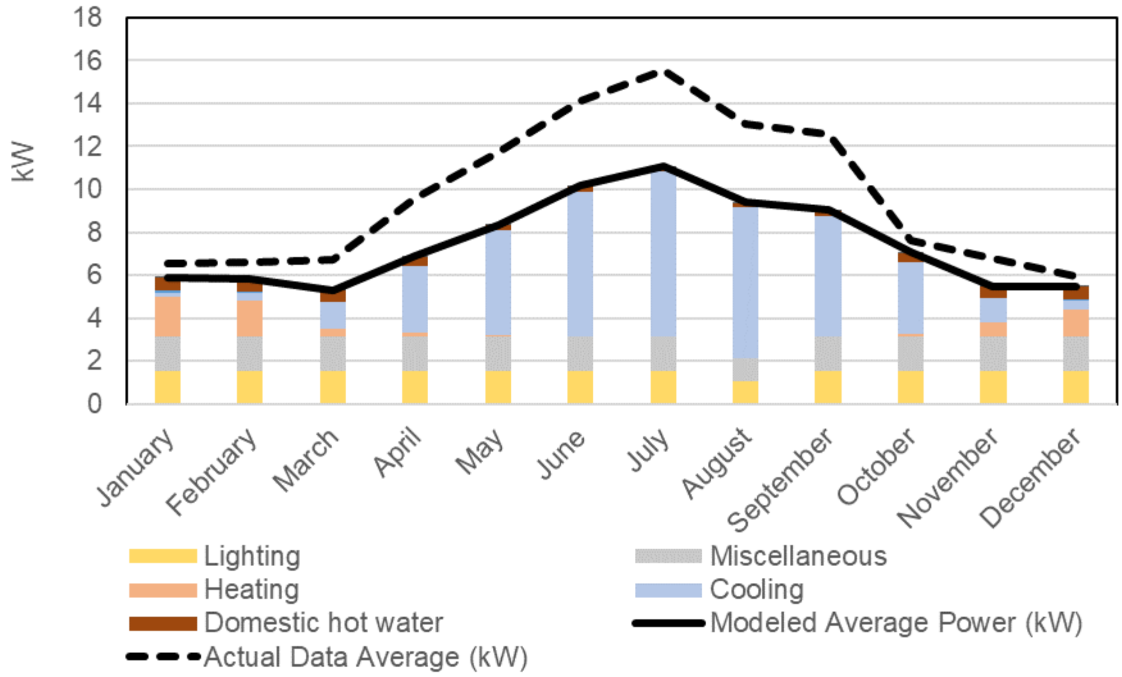


Figure 23 Comparison of monthly average power between actual and modeled for 2018 Code Compliance Scenario

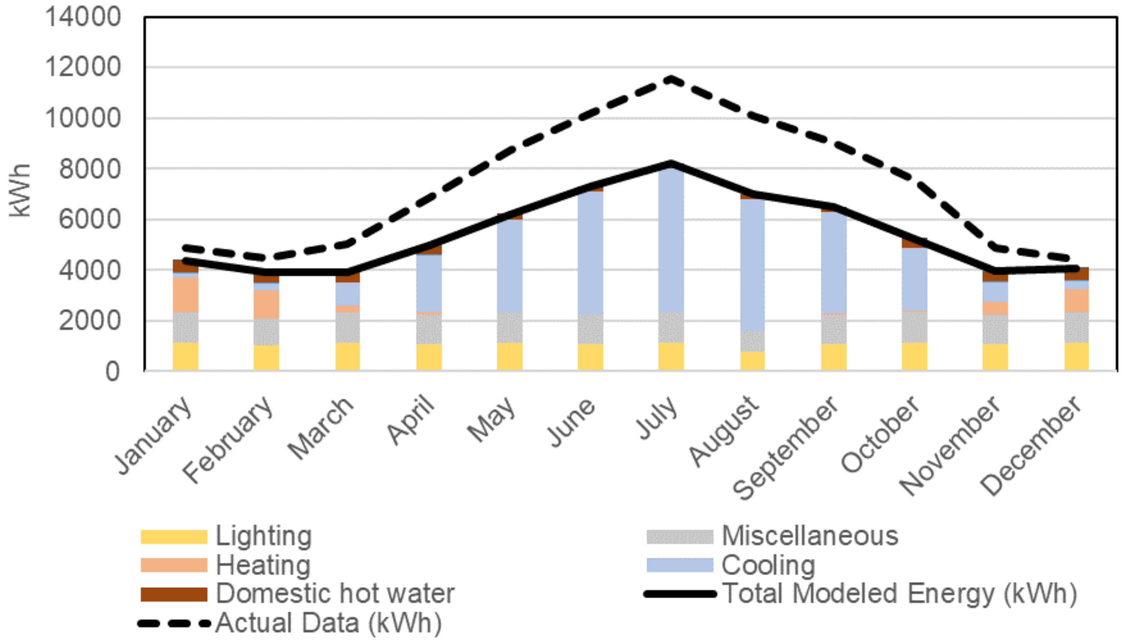


Figure 24 Comparison of monthly energy use between actual and modeled for 2018 Code Compliance Scenario

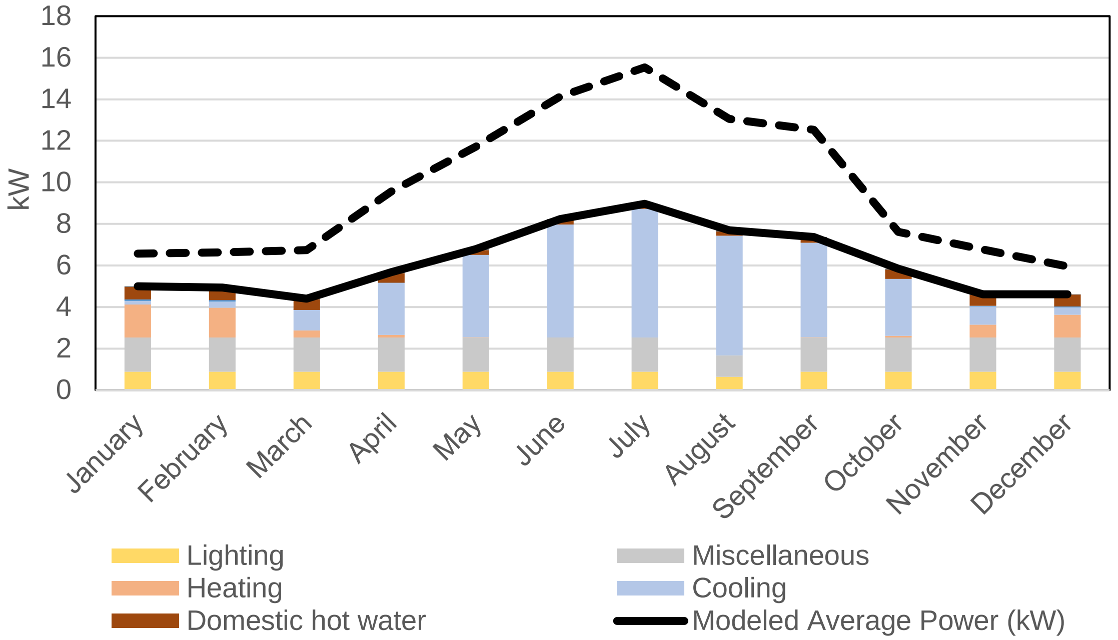


Figure 25 Comparison of monthly average power between actual and modeled for Energy Efficiency Scenario

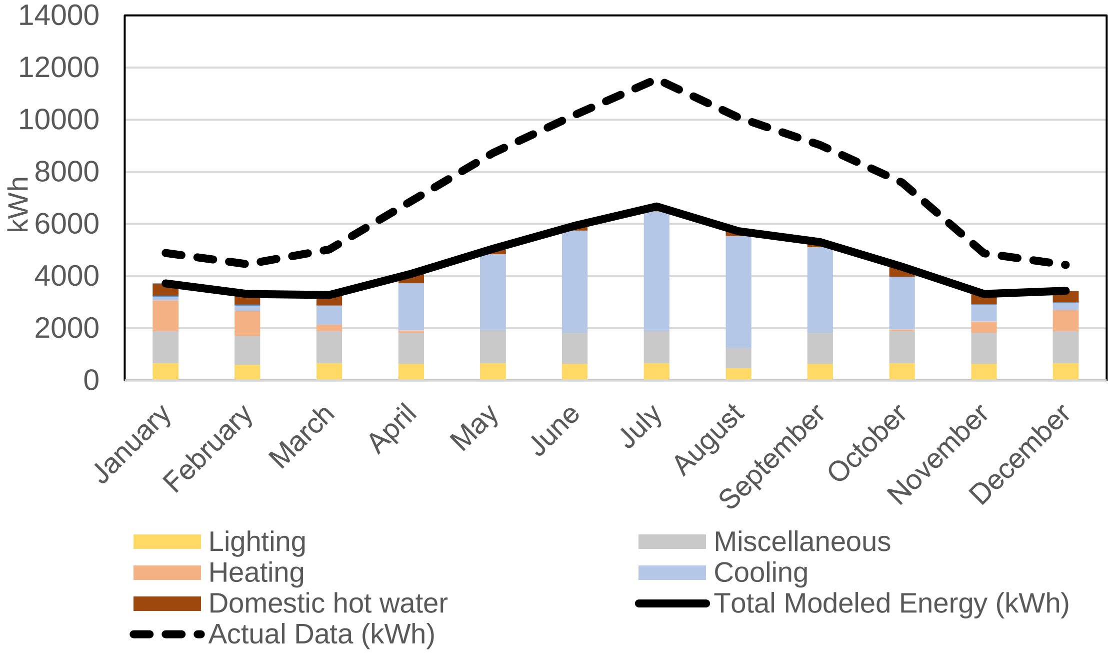


Figure 26 Comparison of monthly energy use between actual and modeled for Energy Efficiency Scenario

Results of the modeled scenarios further demonstrated the efficiency gain achievable in the baseline villa. Compliance with the minimum requirements of the 2010 building code increased the LPD and window U-Values, and decreased AC unit's COP relative to the baseline; all of which are factors greatly contributed to the increased energy use by 19%. Compliance with the minimum requirements of the 2014 building code gave results close to the baseline model, with a slight increase of 2,000 kWh, an increase of 2%. Compliance with the 2018 building code was the most effective at reducing the villa's energy use due to the much more stringent requirements compared to previous codes, reducing energy use by 26%. The energy efficiency model used wall and roof U-Values and an HVAC COP that resemble market available upgrade measures. These measures further decreased the villa's energy use by 39%. Moreover, the energy efficiency scenario had much lower summer average power levels compared to the other scenarios, which is evidence that peak loads can be managed at the demand side through relatively simple retrofits.

In general, it was noted that the shape of the demand profiles compared to baseline profiles were similar throughout the daytime hours. Overall energy demand drops with increased efficiency, however, the peak demand remains at similar times following the same pattern. To control peak demands, incentive-based policies or electric storage technology are required to shift consumer behavior from peak hours to non-peak hours.

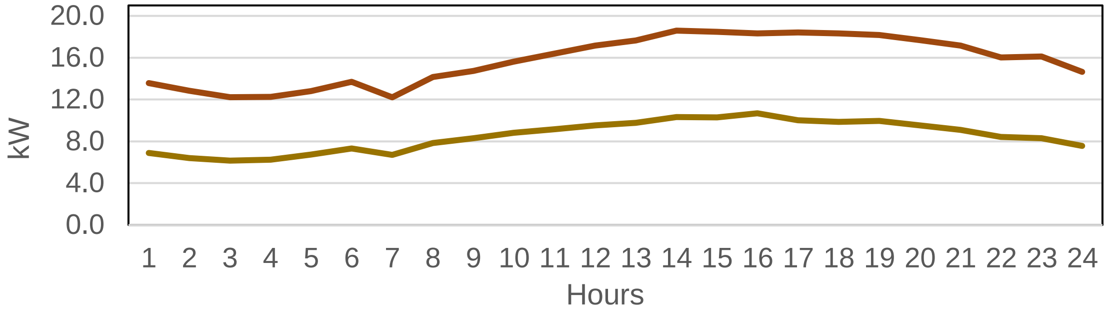


Figure 27 Demand profile of baseline vs energy efficient scenario averaged for the month of July

CHAPTER 5

ROOFTOP SOLAR SYSTEM ANALYSIS

5.1 Characteristics of Typical Flat Roof

Adding rooftop solar photovoltaic (PV) systems on a large scale could be one way to bring down peak loads of residential units in Kuwait, especially in the summer when the sun is shining, and AC demand is the highest. Deployment of Distributed Energy Resources (DER) would be beneficial in terms of lowering peak loads and energy requirements on the supply side, especially since peak loads are the most expensive energy loads to satisfy. Rooftop solar, however, is not popular in Kuwait due to highly subsidized energy prices, where it is difficult for customers to achieve any financial benefits from installing a rooftop PV system.

In 2018, KISR completed the installation of 150 rooftop solar PV systems on residential villas that met the rooftop area requirements. Although ambitious, it was a continuous struggle throughout the project implementation period to find villa rooftops that meet the minimum area and shading requirements. Eventually, the project team decided to decrease the system capacity sizes, thereby reducing the minimum area requirement. During the first phase of the project, a monocrystalline solar panel was used, however, a decision was later made to use thin-film technology instead due in part to their better performance under: (a) lower irradiance levels due to shade and (b) high temperature climate conditions. One of the most important outcomes of the pilot project was that adequate area for the installation of a solar system is extremely limited on villa rooftops because of the typical flat roof design. This became clear from the hundreds of surveyed houses.

As mentioned in the literature review, multiple studies expressed the need to accurately measure the available rooftop area for solar panels in Kuwait. As such, an analysis was performed on the availability of usable solar area on Kuwaiti rooftops using survey data from KISR's residential PV project. The factors that hinder solar area availability on Kuwaiti rooftops based on survey drawings of one hundred villa rooftops include: (a) multiple AC units that are laid out on the roof along with their ducting, electrical connections, and piping taking a relatively large area of the roof, (b) high parapet structure and other rooftop obstacles creating shade, and (c) building orientation and surrounding buildings minimizing irradiation. All solar panels have to be directed south and tilted at an angle of about 10° since Kuwait is in the northern hemisphere. Figure 32-35 show images of typical layouts of Kuwaiti villa rooftops.

Figure 28 Rooftop image showing typical flat roof and layout of obstacles

Figure 29 Image showing random placement of objects on roof occupying usable solar area

Figure 30 Two images showing the use of shading structures to provide shade for water tanks and AC units

Figure 31 Rooftop Seating area with shading structure on one of the surveyed villas

5.2 Modelling Procedure

The procedure for the rooftop solar system analysis involved multiple steps using simulation software and survey data. The analysis with the extrapolation of statistical averages for rooftop area availability. Once area estimates for Kuwaiti villas were established, a solar simulation tool, System Advisor Model (SAM), was used alongside Kuwait weather files [50]. The tool was used to simulate multiple scenarios relating to area availability and the use of battery storage options. Figure 36 shows a flow chart of the rooftop solar system analysis.

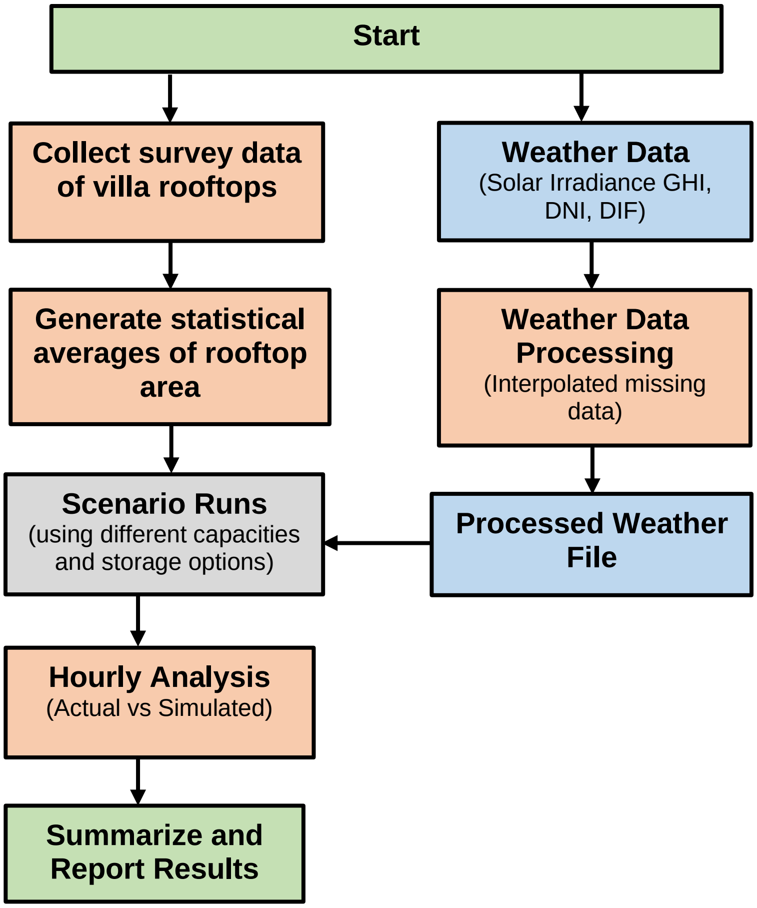


Figure 32 Flow chart of rooftop solar energy analysis adopted in this study

5.3 Rooftop Area Analysis

As seen in Figures 37-39 solar area is extremely limited. To quantify the limited availability, statistical calculations were made to obtain the average available rooftop area for buildings in Kuwait based on one hundred survey drawings. This provided an indication of the solar area availability for a typical villa with a flat roof and parapet walls. An additional statistical measure was considered, namely the total rooftop area averaged over the entire survey sample. This measure was assumed for a secondary solar analysis where simulations were performed for a hypothetical rooftop solar canopy system.

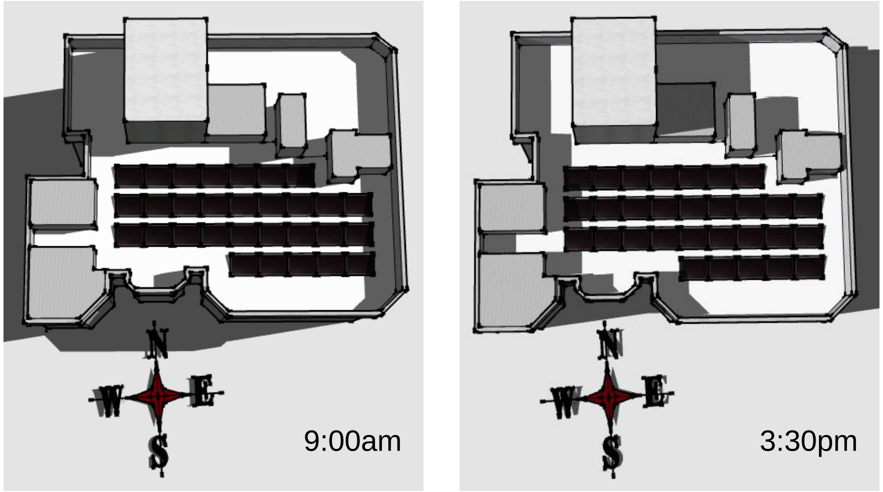


Figure 33 Solar rooftop drawing at two different times (9:00 am and 3:30 pm) of the same day showing shading effect

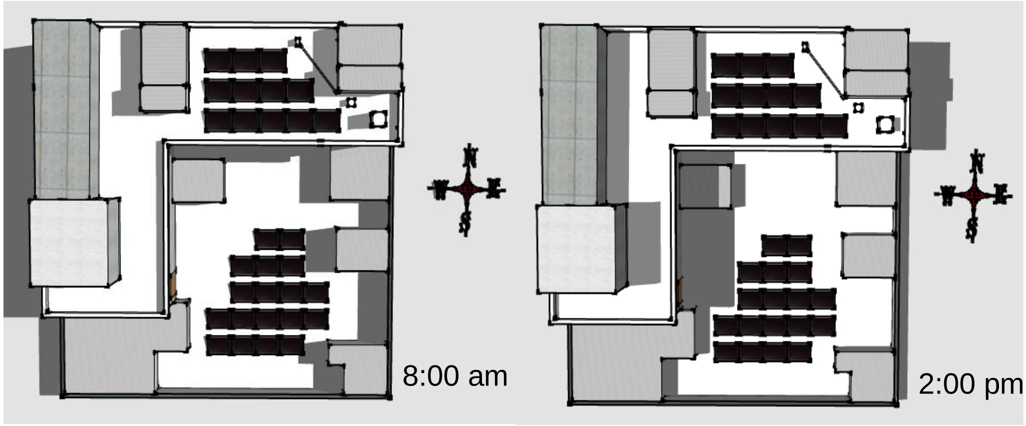


Figure 34 Solar rooftop drawing at two different times (8:00 am and 2:00 pm) of the same day showing shading effect

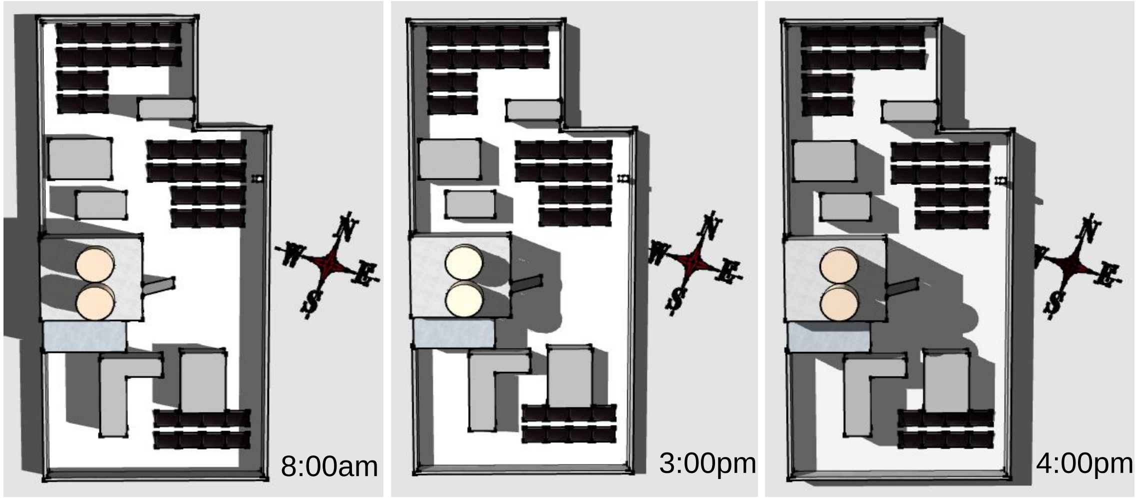


Figure 35 Solar rooftop drawing at three different times of the same day showing shading effect.

To measure the available solar area of a surveyed rooftop, a solar PV system was modeled with acceptable shading levels. In practice, the criteria for shading used in the KISR project varied due to the difficulty in finding rooftops with adequate area. Thus, there was no specific shading limit used to guide in the design of these systems, other than reducing shading levels as much as possible while utilizing the most open roof space. Each surveyed house was modeled using this approach. The area that the solar system covered in each modeled survey drawing was used as the available solar area. Results for averaged available area with mean, 90th and 10th percentile values are shown in table 21. The same analysis was repeated assuming that the solar PV system can be installed as a canopy covering the entire rooftop area. Results for the averaged total rooftop area with mean, 90th and 10th percentile values are also shown in table 21. Clearly, a rooftop canopy has the potential to provide much more space for solar utilization Can you give the values of the 10th, median and 90th percentiles here.

Due to the limited available area, a solar canopy would provide a much bigger area that would theoretically cover approximately the entire rooftop. In doing so, the solar system would be installed on the rooftop canopy avoiding all shading including ones created by parapet walls. The canopy would allow for the recovery of lost rooftop area that is usually occupied by AC units, satellite dishes, and other obstacles. Moreover, the canopy could act as a shading device making the area comfortable for outdoor activity. In many rooftops, it was observed that water tanks were covered to protect them from the sun’s radiation avoiding overheating. Some rooftops include canopies that cover central AC units, however, there are no studies that prove significant energy reductions from such protection. Structurally, the reinforced concrete skeleton of most residential villas is capable of handling additional loads from a rooftop solar canopy as the one mentioned. Figures 40 and 41 show two villa rooftops that were modified to include a theoretical solar canopy with a solar system directed south.

Table 21 Distribution of available solar areas for the 150 villas surveyed. These values are assumed for a typical villa rooftop

Area Type	**90th percentile**	**10th percentile**	**Median**	**Mean**
Rooftop Area Usable for Solar	97	45	66	70
Total Rooftop Area	465	195	290	312

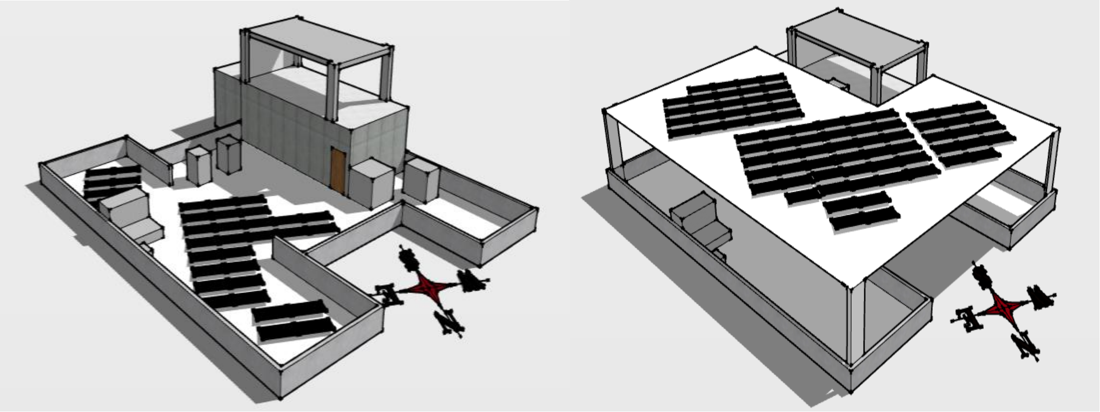


Figure 36 Before and after design of solar canopy on rooftop of surveyed villa

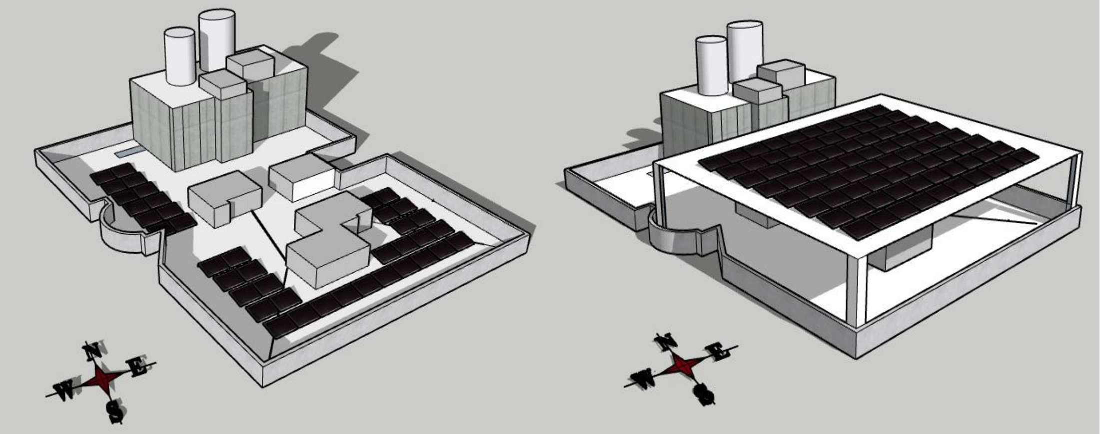


Figure 37 Before and after design of solar canopy on rooftop of surveyed villa

5.4 Solar Scenario Models

Once the design of villa rooftops was ascertained, average area availability was determined, and annual energy simulations were performed to obtain hourly results using SAM. These hourly results were compared to the building simulation results from the previous sections. The simulations considered 5 scenarios of grid-integrated rooftop solar systems. Each scenario represented a combination of either efficiency or renewable measures. A second analysis was performed for each scenario where batteries were added to the system to minimize peak requirements when there is no sunshine and the solar panels are idle. All panels were tilted 20 degrees and directed south. Assumptions were made to account for losses due to soiling.

Energy losses due to soiling significantly reduces performance. In arid desert climates, the effects of soiling are much more significant where the accumulation of dust particles requires continuous cleaning strategies. The soiling effect is an ongoing challenge in arid climates. Losses have been reported to reach 24% from the accumulation of dust over a period of three months without cleaning [48]. Several cleaning methods have been analyzed using lifecycle assessments to compare their costs and benefits [49]. In [49], Alzubi et al. used a value of 0.44% as the soiling loss rate per day where cleaning was performed when the system reached soiling losses of 10% or after 23 days. In some cases, it has been observed that homeowners prefer a cleaning cycle of once a month. For this analysis, a soling loss of 7% was used based on the above information and a cleaning cycle of 30 days. Furthermore, a light-induced degradation value of 1.5% was taken. Shading was assumed to be 3% to account for nearby obstacles.

It is important to distinguish between the different solar technologies that exist and the pros and cons of each. In general, thin-film technologies perform better than monocrystalline under low irradiances due to its ability to generate power from diffused irradiance. Additionally, thin-film technologies perform better under extreme hot conditions due to their lower temperature coefficients. By contrast, monocrystalline panels usually have higher nominal power per unit area; however, the temperature degradation coefficient is lower and the panels have low efficiency under diffused irradiance. The simulations performed do not resemble the differences between technologies since it was beyond the scope of the study. Rather, energy generation was simulated using SAM's PVWatts tool to perform hourly analysis. Since the area needed to install a certain nameplate capacity of a solar system is highly dependent on the technology, some assumptions had to be made. To get an initial estimate of the area requirement, the average nameplate capacity per unit area was averaged for the two technologies used in KISR's solar residential project.

Table 22. Nameplate capacity per unit area of two solar technologies and their average power per area based on STC conditions

Technology	**Watt per square meter**
Recom Black Panther RCM 280 (Monocrystalline)	172
Solar Frontier SF 155 (Thin-Film)	126
Average	149

As seen from table 23, the average power per unit area was 149 W/m^2, which means an area of approximately 67m^2 is needed for a 10-kW system. This matches the requirements initially set for the residential PV project where an area of 70m^2 was required to fit a 10-kW system. However, since this assumption does not consider pitch area and walk-access area, a 10% increase was added to the calculation to account for additional area needed for spacing out the panels. Thus, for a 10-kW system an area of 74m^2 is required. With this assumption, an estimate was made for the potential increase in solar capacity that can be obtained from incorporating a solar canopy. Overall, the analysis mainly focused on (a) the generation profile of solar systems under Kuwait weather and how they relate to energy use patterns of residential buildings, and (b) the potential for integrating more capacity on villas with a flat roof.

The total rooftop area average determined from the survey sample was 312m^2. Using the calculations mentioned above, if the entire area is adequate for the utilization of a solar system, it would be sufficient to accommodate a system with up to 42-kW of nameplate capacity. The modelled villa had a total rooftop area of 230 m^2, which is capable of handling 31-kW of nameplate capacity if a hypothetical canopy were to cover the entire roof. However, only 50 m^2 is available if the floor of the rooftop area were to be used. This area would be able to accommodate a system with 6.7-kW nameplate capacity. As such, solar simulations were performed for five scenarios to realize the benefits of integrating solar energy and including a solar canopy on villas. Table 24 presents details of each modeled scenario. In scenarios 3, 4, and 5, incremental solar capacities on a rooftop canopy structure were modeled until a limit of 31-kW was reached.

Table 23. Solar scenarios combined with different demand profiles

Solar Scenario	**Mounting Type**	**Nameplate Capacity (kW)**	**Demand Profile**	**Annual Energy Use (kWh/year)**	**Annual Solar Output (kW/year)**
Scenario (1)	Flat roof	6.7	Baseline	89,320	9,468
Scenario (2)	Flat roof	6.7	Energy Efficient	54,368	9,468
Scenario (3)	Solar canopy	10	Baseline	89,320	14,130
Scenario (4)	Solar canopy	20	2018 Building Code	65,757	28,255
Scenario (5)	Solar canopy	31	Energy Efficient	54,368	43,793

Figures 42-46 show results of the modeled scenarios. Since the model represents grid-integrated solar systems, electric energy can be sent back to the grid in some scenarios when there was excess generation. For all solar scenarios, it was evident that the net load, which is the electricity supply to the house from the grid (net load = energy consumption - solar generation), starts to decrease as soon as the sun rises and increases rapidly when the sun sets, a profile known as the duck curve. The hypothetical duck curve created in this simulation provides a good idea of the villa’s grid demand when a grid tied system is deployed without the use of batteries.

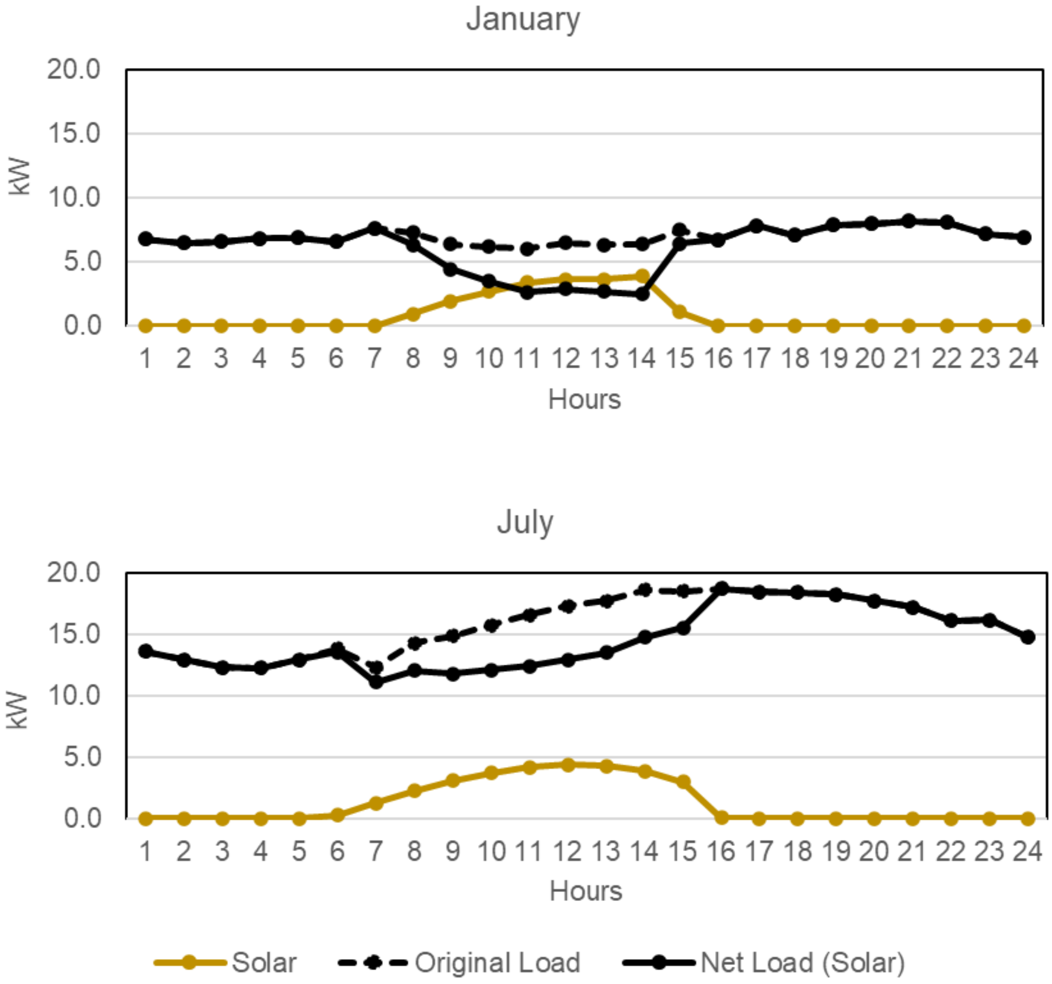


Figure 38 Baseline + 6.7 kW results for an average day in January and July

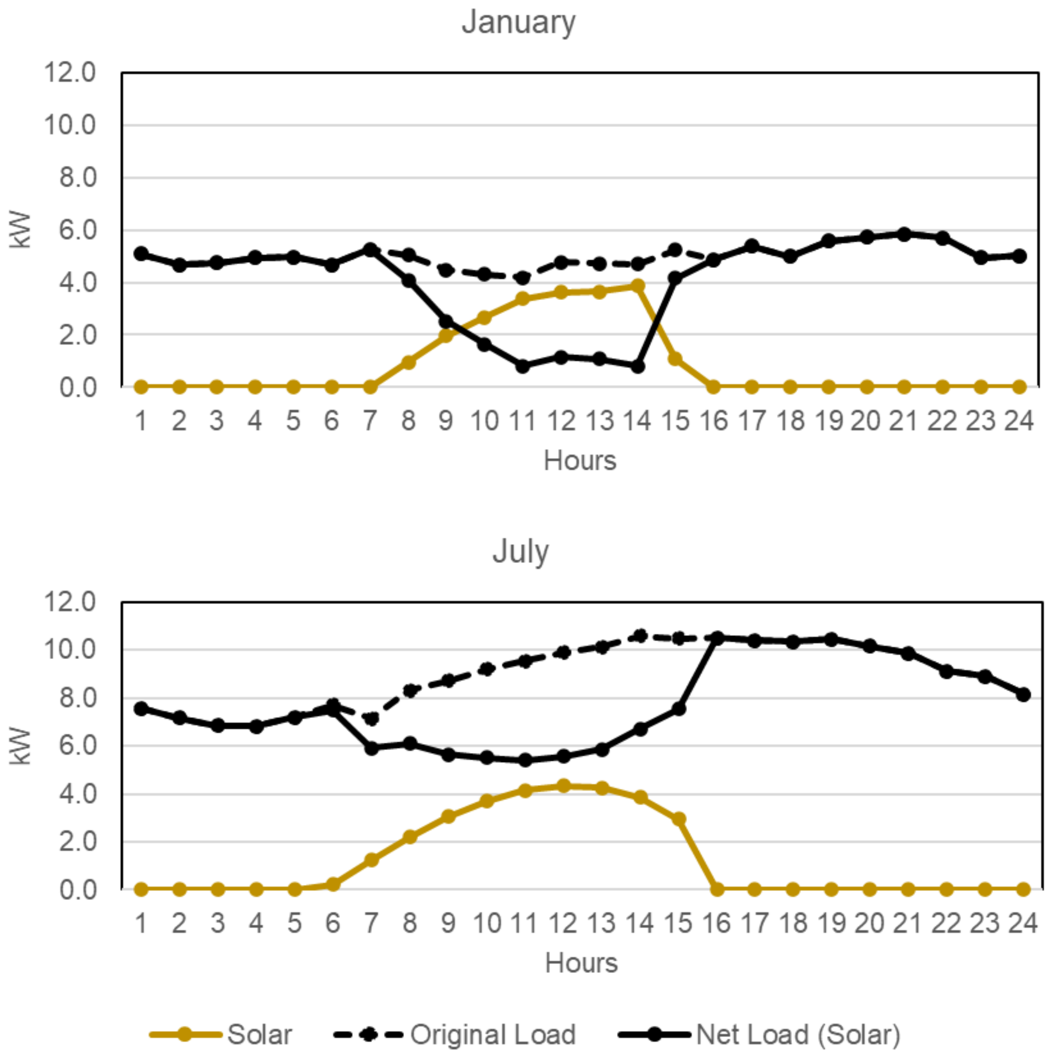


Figure 39 Energy Efficiency + 6.7 kW results for an average day in January and July

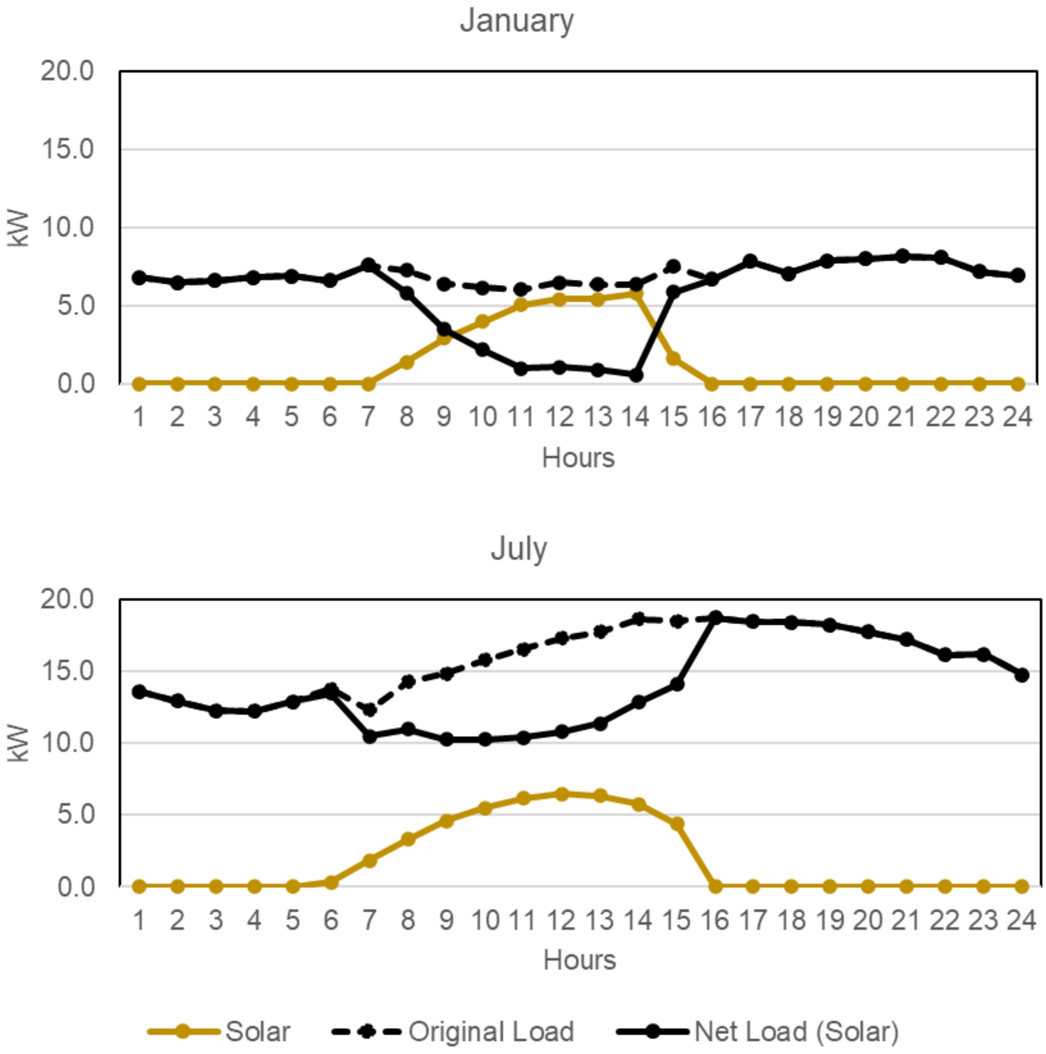


Figure 40 Baseline + 10 kW results for an average day in January and July

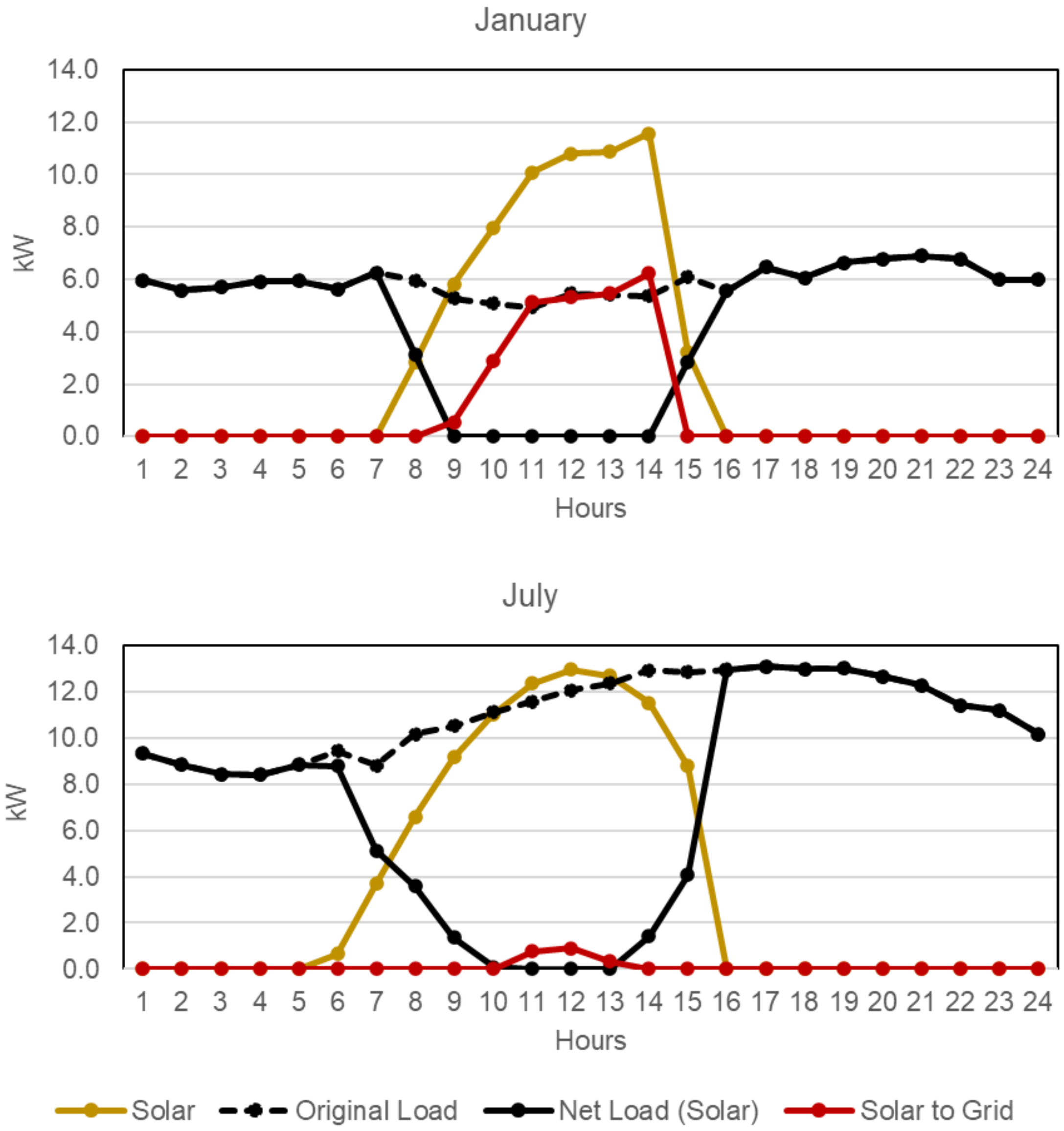


Figure 41 2018 Building Code + 20 kW results for an average day in January and July

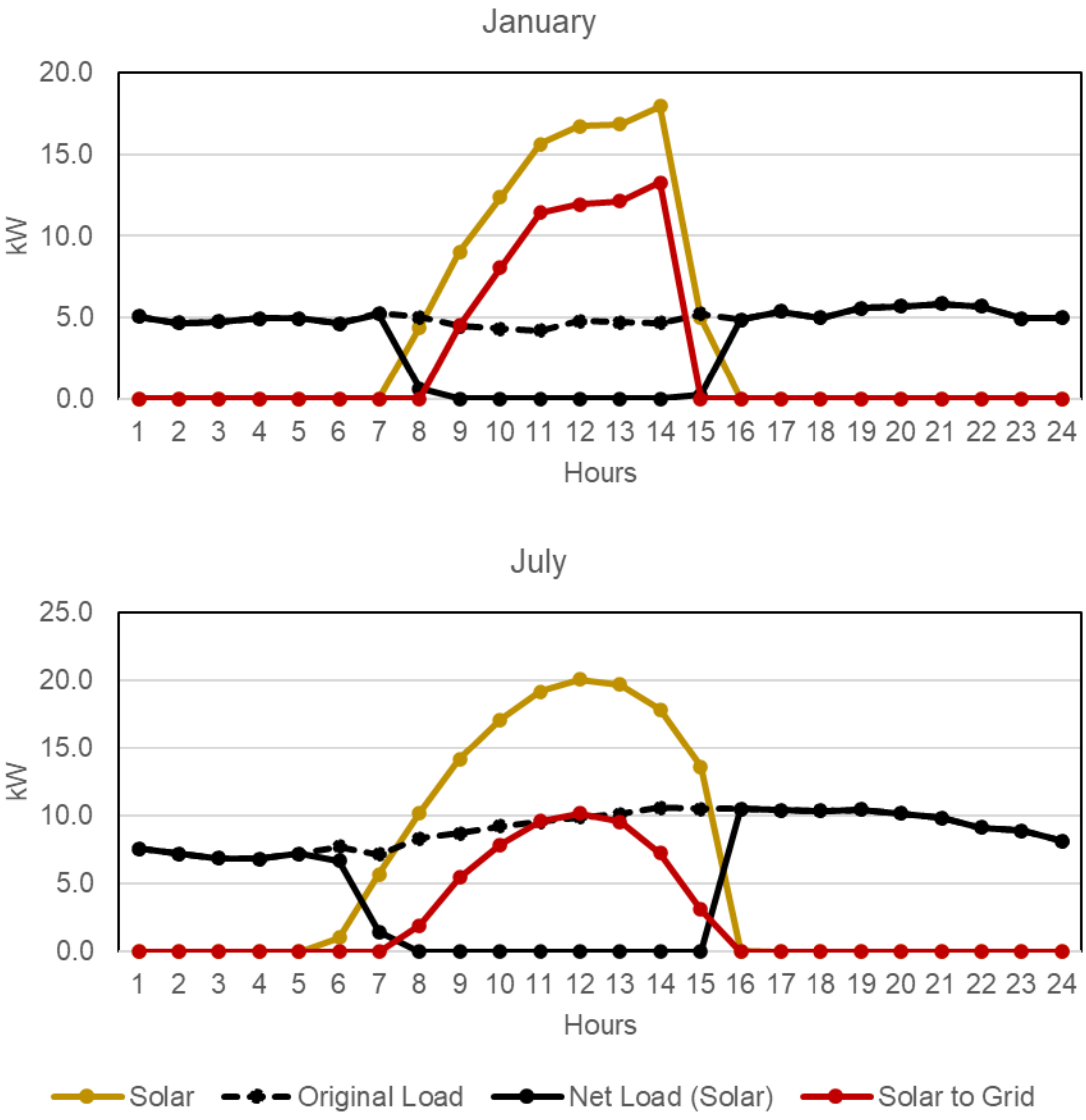


Figure 42 Energy Efficient + 31 kW results for an average day in January and July

A second analysis included the use of batteries for the same scenarios. Figures 47-51 show results from the month of July, the hottest month of the year when energy requirements are the highest. The Tesla Powerwall 2 battery was modeled to reflect the current market available options for consumers. In scenario (5), a hypothetical storage size was developed to estimate the battery capacity size required for effective peak reductions. The batteries charging and discharging schedule was modeled using the built-in near-horizon forecasting “Peak Shaving (look ahead)” function in SAM.

Table 24. Battery capacity and power for each scenario

Solar Scenario	**Battery Capacity (kWh)**	**Battery Peak Power (kW)**
Scenario (1)	13.5	7
Scenario (2)	13.5	7
Scenario (3)	27	14
Scenario (4)	27	14
Scenario (5)	100	20

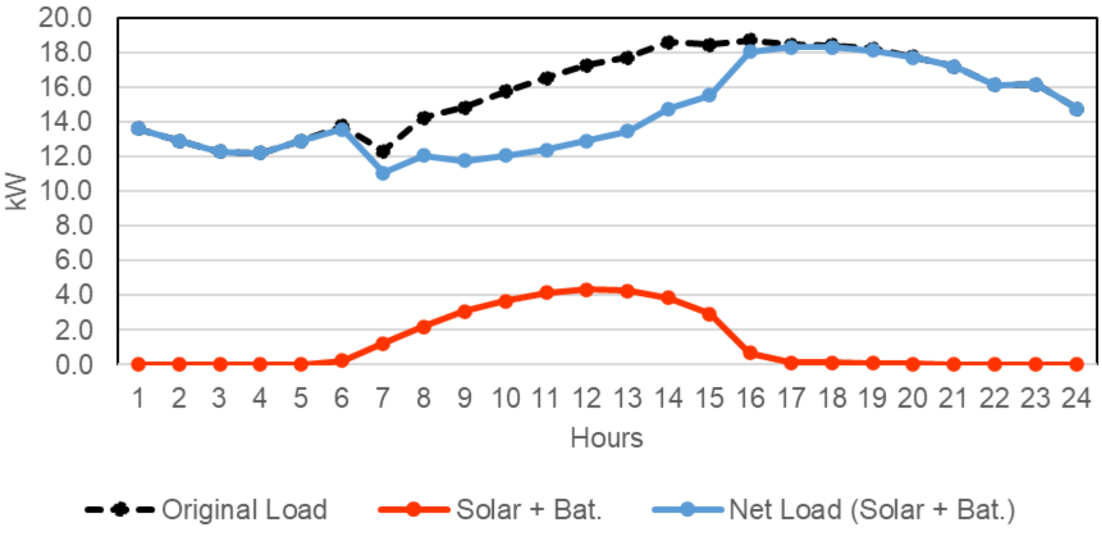


Figure 43 Solar Scenario (1) results for an average day in the month of July

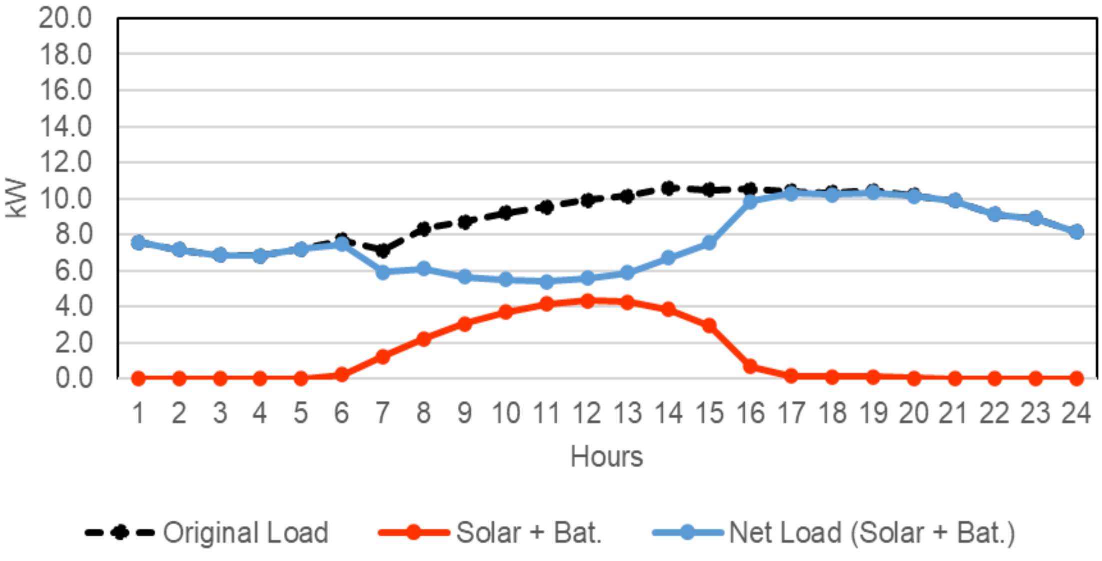


Figure 44 Solar Scenario (2) results for an average day in the month of July

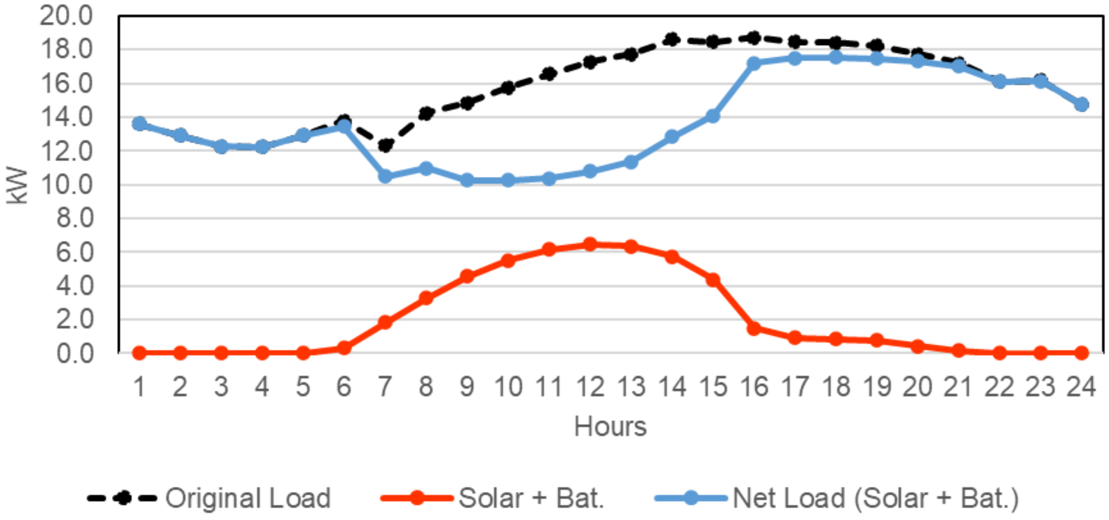


Figure 45 Solar Scenario (3) results for an average day in the month of July

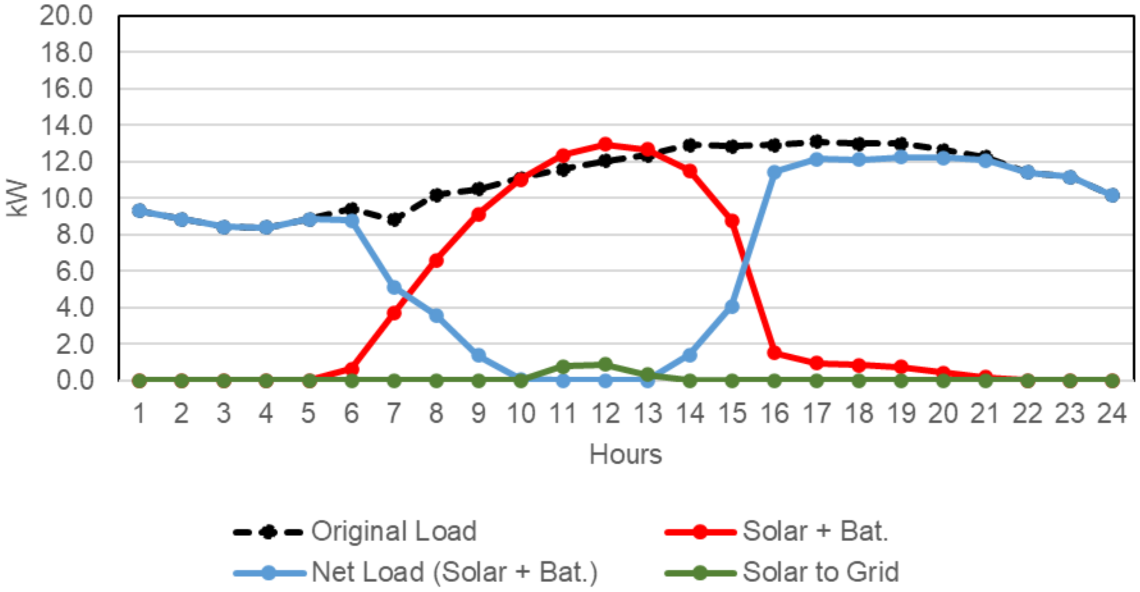


Figure 46 Solar Scenario (4) results for an average day in the month of July

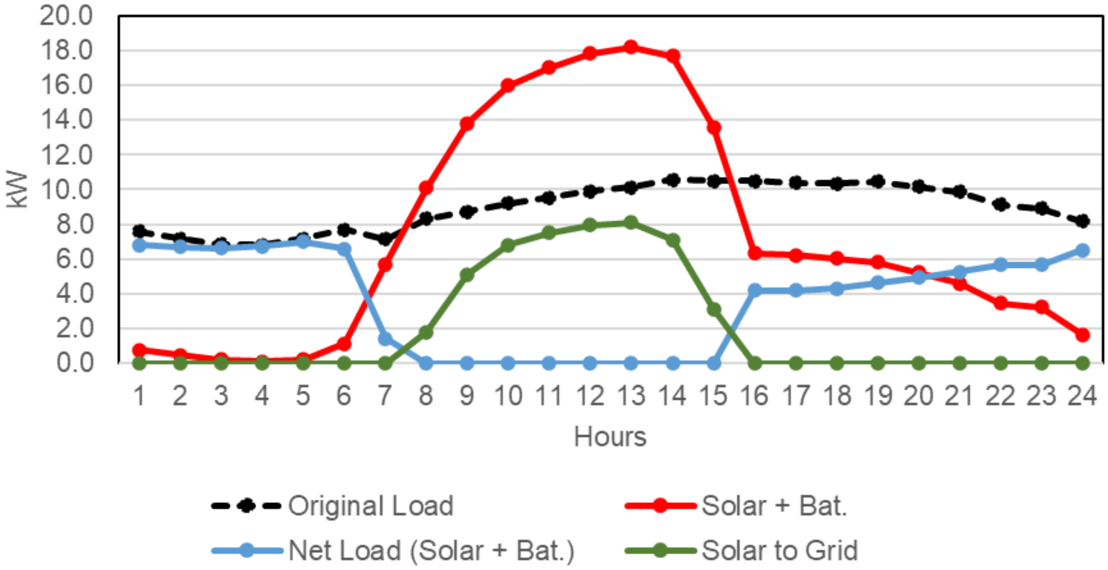


Figure 47 Solar Scenario (5) results for an average day in the month of July

Results shown in Figures 47-51 are for an average day in the month of July. Peak load reductions achieved from the inclusion of battery storage varies depending on the solar system capacity, the battery size, and the battery dispatch method. Using the “Peak Shaving (look ahead)” function in SAM, evening peak reductions were observed. In Figures 47 and 48, the peak load reductions were negligible, indicating that a larger sized battery is needed than a single Tesla Powerwall 2. When two Tesla Powerwall 2 were used, evening reductions start to appear as shown in Figures 49 and 50. In the final scenario, a bigger battery storage was modeled, and peak reductions are much more noticeable.

CHAPTER 6

CONCLUSIONS AND FUTURE EXTENSIONS

6.1 Comparison of EEM and RE measures

The modeled scenarios were compared to determine which measures are effective in reducing energy consumption and peak demands.

The bar graph in Figure 52 shows the differences between the modeled EEM scenarios. Most of the end-use savings from baseline values were attributed to cooling. Notable savings came from improved lighting; however, cooling energy reductions were much greater. In Figure 53, the load profile of EEM scenarios and net load of RE scenarios are plotted together to illustrate when and by how much reductions are being achieved. EEM scenarios lowered the demand profile completely. The RE scenarios managed to greatly increase mid-day demand; however, evening demand still remains high. Thus, EEM scenarios are more effective in reducing peak demand since market available battery systems are not big enough in size to significantly reduce peak demands.

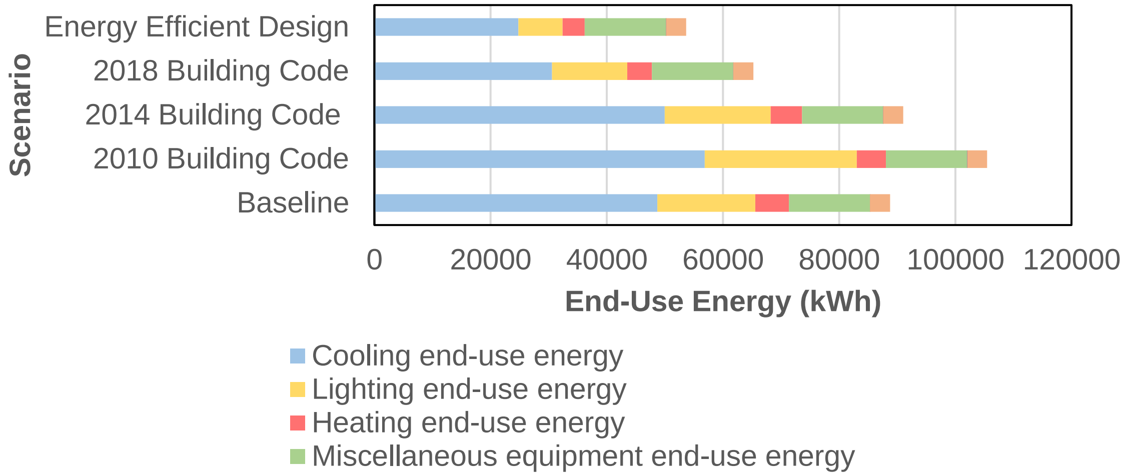


Figure 48 Bar graph of energy savings from different BEM scenarios disaggregated by end-use

Table 25 Comparison of Energy Savings from EEM and RE measures

	Annual Energy Saved (kWh)	Percent Reduction from Baseline (%)
EEM		
2018 Code Compliance	23,570	26
Energy Efficient Scenario	34,950	39
RE		
Solar Rooftop 10-kW	14,130	16
Solar Canopy 31-kW	43,790	49

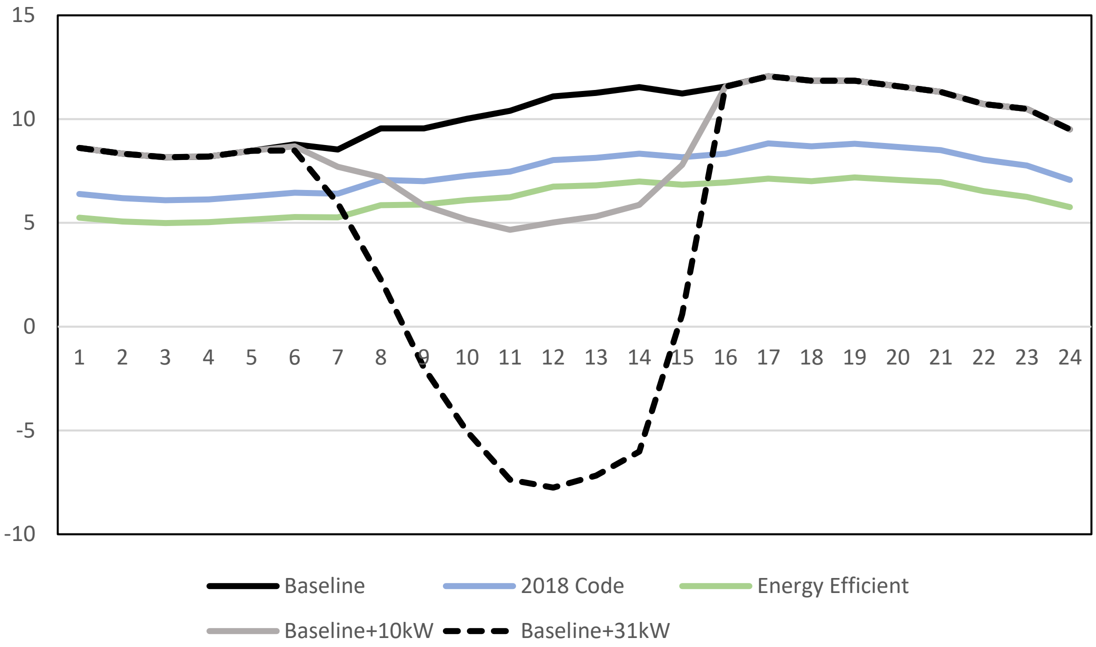


Figure 49 Averaged annual electricity demand profiles of the baseline, and with different EEM and RE scenarios

6.2 Rooftop Solar Potential

The Kuwaiti national hourly electric load profile for the year 2014 was assumed to study the effect of renewable penetration on the grid net load should the high rooftop solar capacity scenario is assumed. The analysis was performed using surveyed data to represent the average rooftop area of the national stock of villas. On this basis, two scenarios were considered. The first scenario modeled the country’s power system average daily net load for the year 2014 with 10-kW rooftop solar installations on every villa. This case reflects the average rooftop area availability in a typical villa. The second scenario looked at the utilization of a 42-kW rooftop solar canopy system based average total rooftop area estimates.

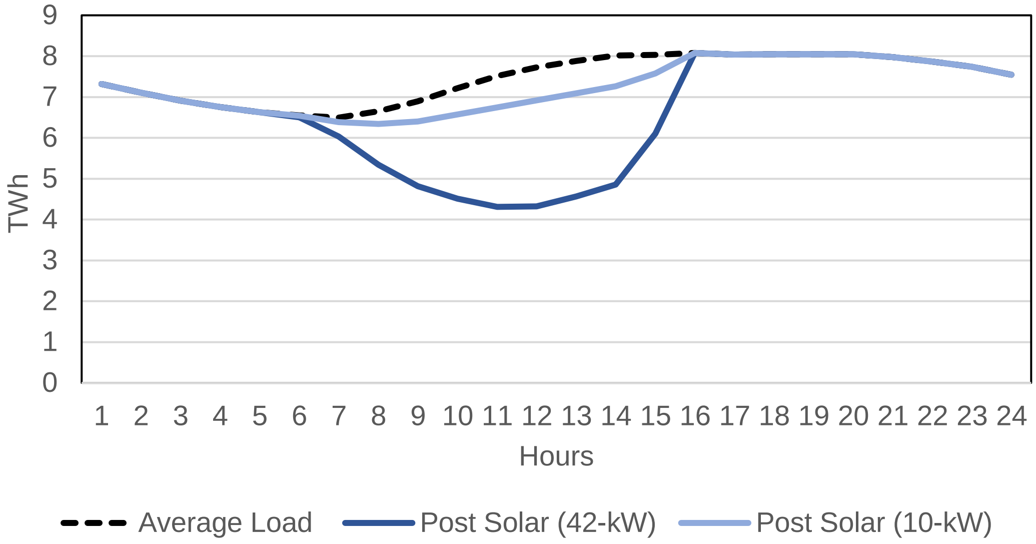


Figure 50 Rooftop solar influence on average net Kuwaiti electric load when all residential rooftops are utilized

As seen from Figure 52, when all existing villas incorporate a 10-kW rooftop solar, the effect on net load is minor. However, when a bigger system was used, net load experiences a significant mid-day drop, taking the shape of the duck curve. Battery storage and efficiency measures are therefore the best approach to reduce peak loads as proven in the rooftop solar system analysis. EEMs are initially more effective since the entire demand profile is shifted. RE measures become useful once EEMs have already been considered.

As a step forward, a concept design for new construction villas was developed to emphasize the benefits of a built-in solar canopy as part of the building's construction. The concept design is built on a 400m^2 lot size, the typical lot size in Kuwait. The intent is to provide shade for all rooftop end-use devices (AC units and water tanks) and create more space for the integration of rooftop solar. In the concept design, multiple outdoor areas were considered under the canopy to emphasize functionality. Furthermore, a solar glass panel was installed in the center of the canopy for daylight into the house if desired. The concept design provides a visual representation of a sustainable villa under current lot sizing and distribution. However, it is recommended that lot sizes and distribution policy be reevaluated to lower floor area and promote efficiency.

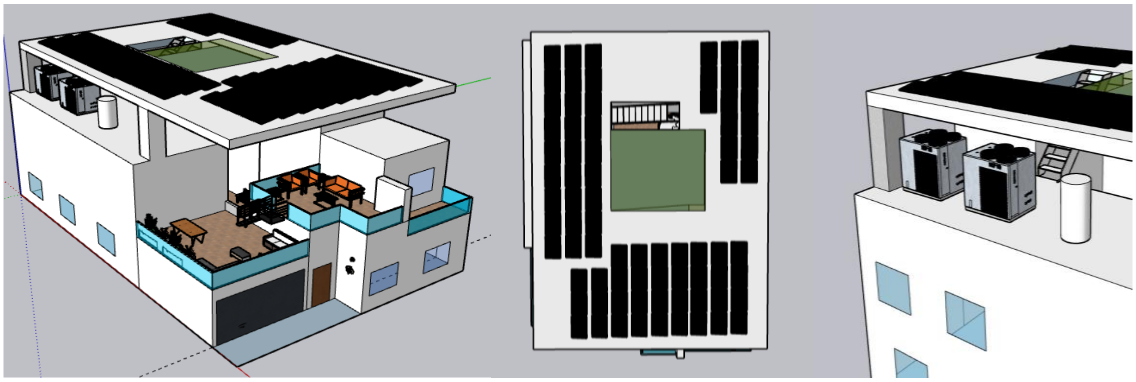


Figure 51 Concept design of villa built on 400m^2 lot size

6.2 Limitations and Lessons Learned

The motivation behind this analysis was an initial intent to use a bottom-up engineering approach to model the entire stock of residential buildings. This, however, proved to be a challenging task with the lack of residential electricity data that currently exists. Existing studies have proposed archetype parameters for different building age categories. However, a large-scale analysis of the entire residential building stock would require high resolution data sets with hourly information on each end use. Although occupancy related behavior has been investigated in previous studies, it remains difficult to undertake a bottom-up modeling study without detailed data sets.

The Ministry of Electricity and Water (MEW) oversee all operations from generation to distribution. The MEW produces a statistical yearbook annually with electrical energy data. However, the residential electricity data is not accurately documented due to issues with consumer data collection. Through interviews conducted in past studies, the MEW claims that this issue is due of the lack of consistent utility payments from consumers, especially since (a) there is no limit on when payments should be made and (b) the utility will rarely disconnect a customer. Some consumers pay their bills monthly, and some yearly. Since there is no precise data that measures the share of residential electric energy, the numbers are usually estimated. To resolve such issues, digital meters should be installed by the MEW for remote data collection. The current analogue meters provide little value for energy modeling purposes and restricts the use of financial incentive programs for the application of EEM and RE measures.

In future studies, more attention should be focused on building data collection through surveys. Moreover, some parameters require accurate measurements and are not necessarily defined. These include occupancy behavior related to energy use patterns, and air tightness measurements using commercially available techniques such as a blower door. The availability of such data would be extremely helpful for this type of analysis allowing further investigations of the potential in reducing villa energy consumption.

6.3 Discussion and Recommendations

Both Jaffar and Alajmi mention growing concerns of meeting the electricity demand of future residential projects, let alone meeting the demand of existing residential buildings [1][6]. At the time of this writing, blackouts/brownouts continue to occur in peak summer days when supply cannot meet demand. The grid operator through the National Control Center (NCC) usually cuts power from outer vacation homes or chalets since they are occupied less. There exists great potential in implementing energy efficiency measures (EEMs) to reduce peak loads and avoid blackouts. More importantly, reducing consumption lowers the amount of emissions which in return benefits the environment. The lowered emissions should be accounted for and aligned with broader state clean energy initiatives.

Land-use related constraint limit the ability of the PAHW to build new homes in outer areas because there is no sufficient power that can be provided. Furthermore, the grid's capacity increasingly faces difficulties in meeting demand as more detached villas are being built with the same lot sizing and distribution. Thus, a major rehaul to the existing housing program is needed to provide energy affordable housing solutions for the government and living spaces for all applicants in the backlog.

Analyzing the behavior of an existing building proved that major energy savings are achievable through retrofits. By enforcing mandatory compliance of old buildings to new codes, significant energy reductions are possible. One way to approach mandatory compliance is by the development of a program where villas are surveyed, and a score is calculated representing the villas compliance levels. When non-compliance is observed, the utility could use such results to provide villas with appropriate EEM measures or increase the villa's electricity rates.

For new buildings, additional energy savings can be obtained through behavioral incentives. Currently, no energy conservation program exists that allows for demand side management. Such programs, which are enforced by the utility, could greatly alter consumer energy use patterns. Furthermore, new buildings should be based on updated lot sizing and distribution focusing on reducing floor area per occupant. Lot distributions could promote the use of walkways and bike lanes for less vehicle transportation requirements, however, this was not the focus of the study. From the perspective of energy, these updates should redefine the standard lot sizes and floor areas taking into consideration energy use in the process.

There are no demand response programs, feed-in-tariff, net-metering, rebates, or any other incentives for customers to reduce grid power demand levels. These are effective ways in reducing building energy consumption through behavioral shift. A demand response program could associate higher energy prices during peak hours of the day making customers consider using less energy in the day or shift their appliance usage patterns to later times [27]. Feed-in-tariff and net-metering are examples of policies that incentivize cleaner generation from rooftop solar installations on buildings by providing credit-based incentives. Additionally, rebates could be offered for consumer retrofit measures based on their cost and potential in reducing energy consumption.

Due to the subsidized energy prices it is currently difficult for building owners to invest in rooftop solar generation. Furthermore, a rooftop system on a Kuwaiti villa will not cover the building's total energy consumption due to limited available roof area, relatively high floor to area ratio (FAR), and high building energy needs. Even when there is large enough roof area, solar systems are not feasible for building owners as payback periods are long and unappealing due to the low price of electricity.

Establishing a program that provides economic benefits for the application of rooftop solar PV requires establishing an incentive for both homeowners and the utility. With low solar PV prices, the utility could benefit from programs that reduce the price of rooftop solar systems for consumers. Additionally, an increase in electricity rates could provide shorter payback periods, making solar systems an attractive option to lower consumption. However, the utility currently does not have strong incentives other than meeting demand through traditional oil and gas electricity generation. This is partly due to subsidization, leaving no real source of revenue, other than government backed budgets and investments.

To transition towards sustainable energy systems, a separate regulatory agency is necessary. The regulatory agency would mandate that the utility produces annual reports submitted with detailed updates of the current progress of the energy system and its long and short-term goals serving the interest of the public. Targets must be clearly stated, and visions aligned with broader national goals of diversifying the economy and promoting sustainable development. Meeting national targets through policy reforms opens the possibility to create new incentives that could be cost based or performance based. Both could potentially provide profit for the utility and its energy saving participants.

Evidently, the low price of electricity has created undesirable complexities that involve interdependent components. For example, building designs have become interlocked with the existing pricing mechanism creating a standard that building occupants have become accustomed to. These standards incorporate energy consuming levels that would only be affordable with the current electricity prices. Hence, increasing electricity prices even slightly could create major disruption to all energy consuming sectors in the country. Ultimately, the price of electricity must change either completely or periodically using pricing mechanisms such as Time-of-Use (TOU), where the price of electricity varies with time. Many buildings are left unoccupied during the day but their AC thermostats for example are left unchanged. This is a result of little incentive from the consumer to reduce energy consumption. Thus, reducing peak demand has the potential of saving generation costs attributed to peak loads, which are much higher than base load costs as peak supply is built to handle varying demand levels and, in most cases, only operate during these hours. Energy policies and regulations are the key to incentivize the efficient use of energy.

6.4 Conclusion

From the literature review, it was evident that the average building floor area is oversized creating difficulties in meeting future cooling driven energy demand. These difficulties are mainly due to limitation on the grid's capacity. As part of wealth distribution, housing property ownership has become a right for all Kuwaiti families that do not own any property. However, due to limited infrastructure, increased land-use, and the continued distribution of large lot areas, the current status of the housing program consists of major shortages where the backlog has reached 100,000 units [1]. Such path dependencies has resulted in (a) the inability to provide housing for a large share of the population, (b) oversized residential units that are interlocked within the building stock, (c) high energy consuming residential units that give little consideration to efficiency, (d) much more occupied land than is necessary, (d) the need to transport long distances creating more traffic congestion since units are spatially spread out, and (e) the tendency to remodel upper levels to accommodate family members who were not provided housing.

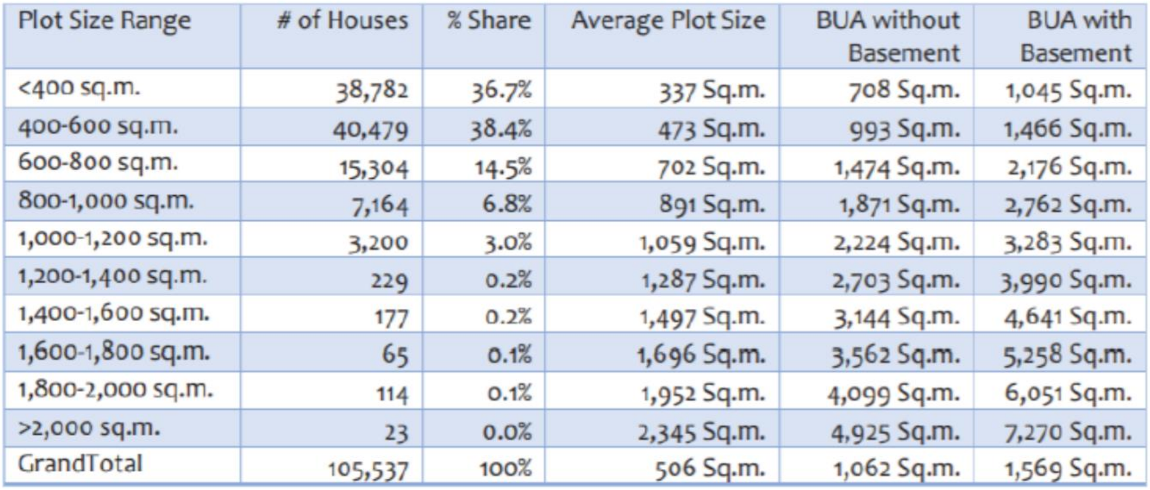
The utilization of actual hourly data combined with hourly generated simulation results provided valuable insights on the demand profile of a typical Kuwaiti villa. Similar studies have only been performed for weekly data. A higher frequency of data points provided more precise energy use patterns. Additionally, it was observed that the modeled villa exhibited less energy consumption than typical villas of the same size. This was due to the villas orientation, use of daylighting, and general energy conservation behavior. It was also evident that peak loads followed similar trends as the national demand profile. Energy use is mainly driven by cooling and lighting energy use. Peak energy use occurs in the evening when both cooling and lighting are required.

The most recent updates of building energy conservation code of practice are effective at reducing the energy use of new construction. Although there is significant potential to reduce energy use of existing buildings, there are no incentives or retrofit programs currently in place. Furthermore, modelling code compliance using a calibrated BEM showed that only the 2018 code was effective in reducing the modeled villa's energy use. The low savings were mainly due to the relatively efficient energy use of the villa under investigation.

Upon analysis of savings from each retrofit or modification, efficient cooling and efficient lighting yielded the most savings for the villa. However, since thermostat settings are mostly kept unchanged, a vastly untapped territory of saving potential exists through the utilization of smart thermostat operations. End-use analysis indicated that some modifications altered end-use demand by interaction. For example, lowering lighting power density (LPD) also lowered energy used for cooling in the summer, however, increased energy used for heating in the winter. The influence that one EEM had on the rest of the end-uses provided an idea of the interactions among end-use devices that drive cooling demands.

Rooftop solar energy is underutilized, and government progress has been hindered due to difficulty in finding applicable rooftop areas. The analysis presents a unique approach to advance the application of DERs tailored for the typical design of Kuwaiti rooftops. It has been observed from multiple surveys that some homeowners tend to cover their AC units and water tanks with a shading canopy. Furthermore, some villas utilized the rooftop for outdoor seating and gathering area. As such, a solar canopy has the potential to accommodate all these issues as well as recover most of the lost rooftop solar area. Due to the existing power system's high energy capacity, the integration of rooftop solar systems will not hinder grid operations. The current share of renewable is less than 1%, meaning that extreme ramping events due to high intermittency from renewable generation will not be an issue until a much higher share of renewable energy is integrated to the system.

Table 26 Plot Sizes and Floor Areas [BAU] taken from [46]



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.

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APPENDIX A

MONTHLY RESULTS OF CALIBRATED DIURNAL ENERGY USE FOR BASELINE VILLA MODEL

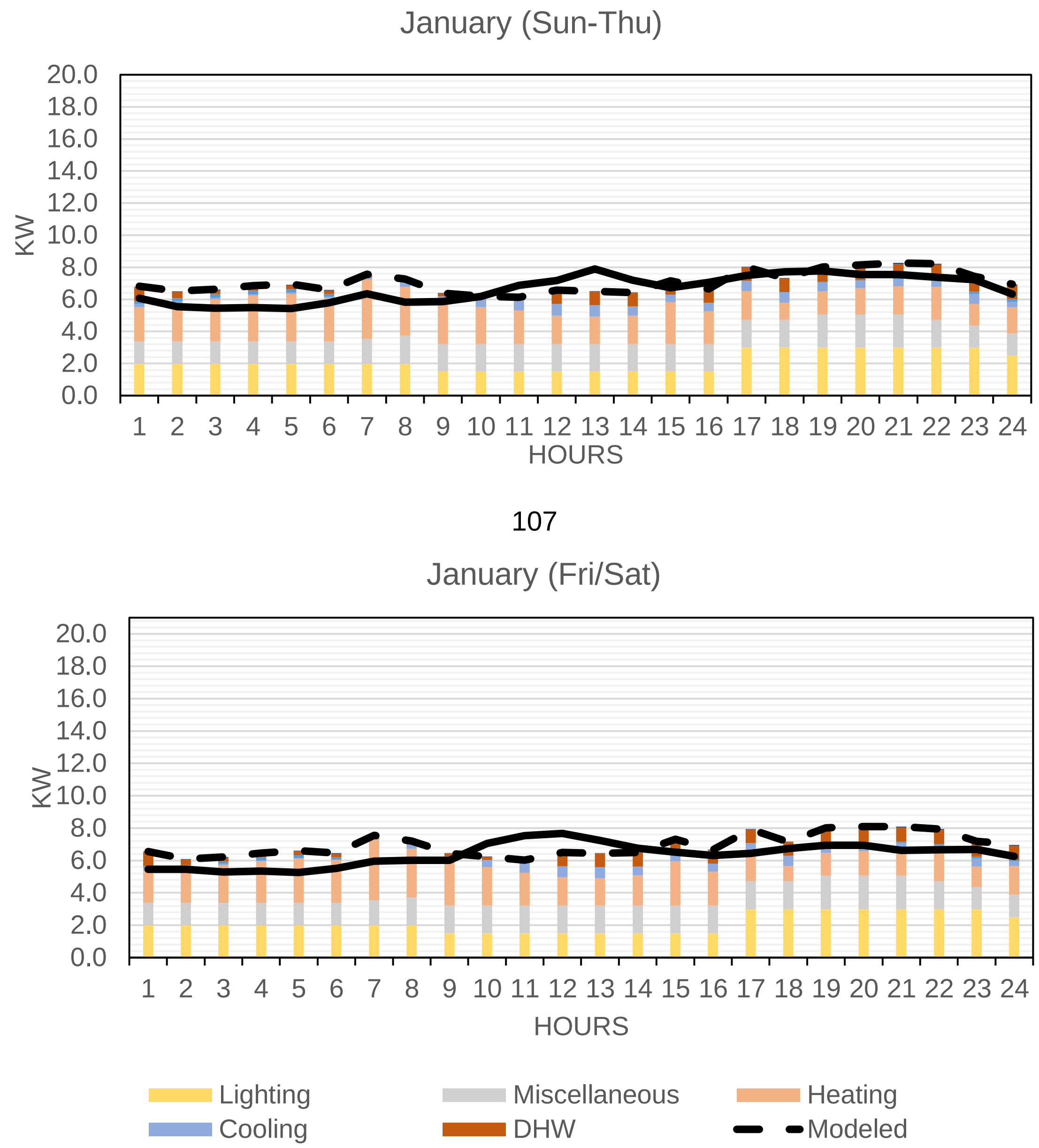


Figure 52 Hourly results of an average weekday and weekend in January

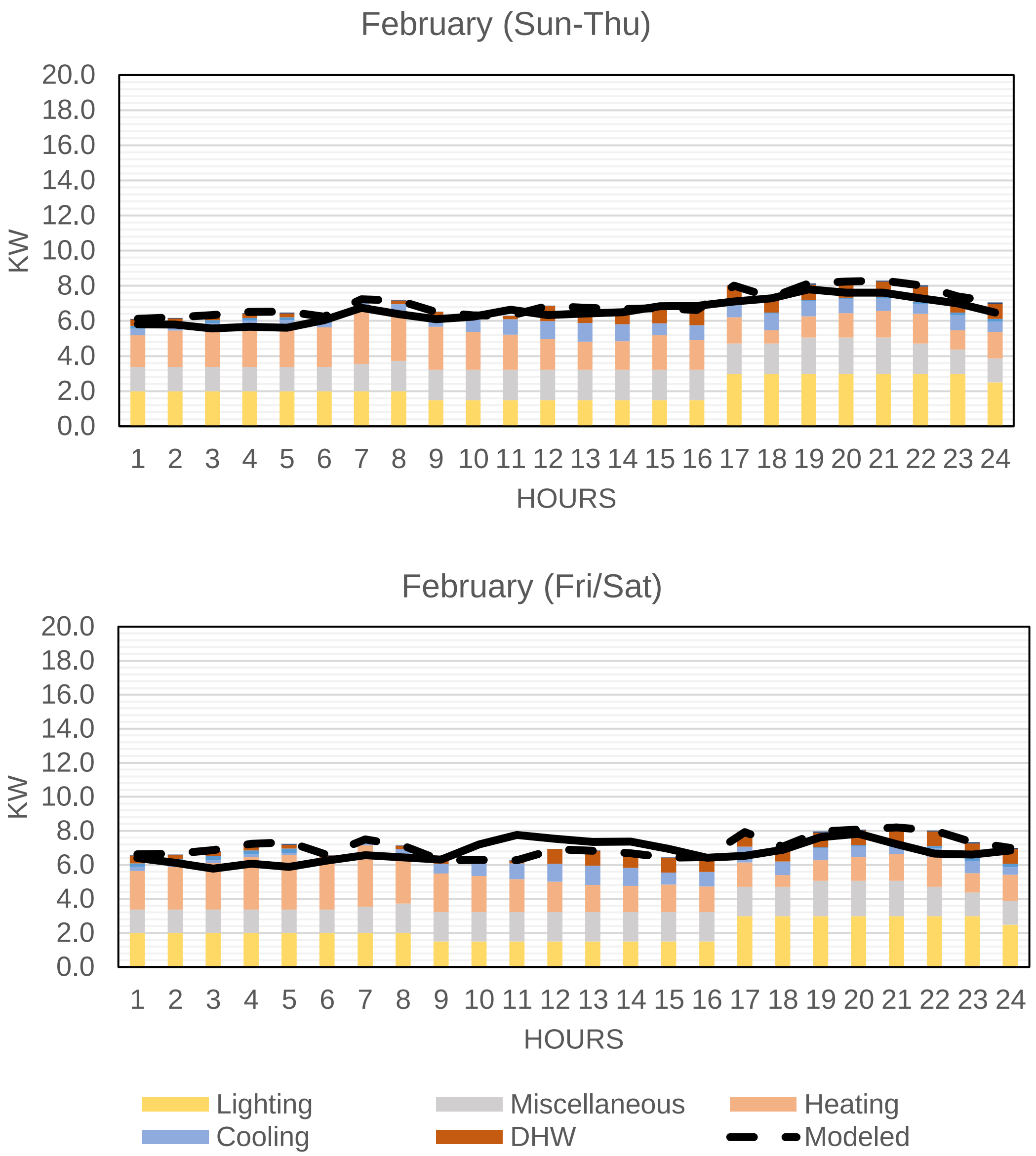
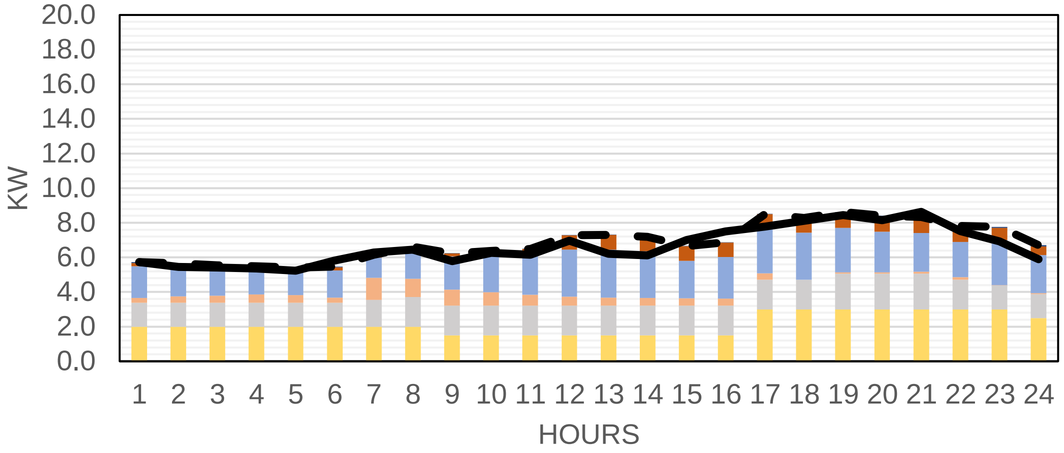


Figure 53 Hourly results of an average weekday and weekend in February

March (Sun-Thu)



March (Fri/Sat)

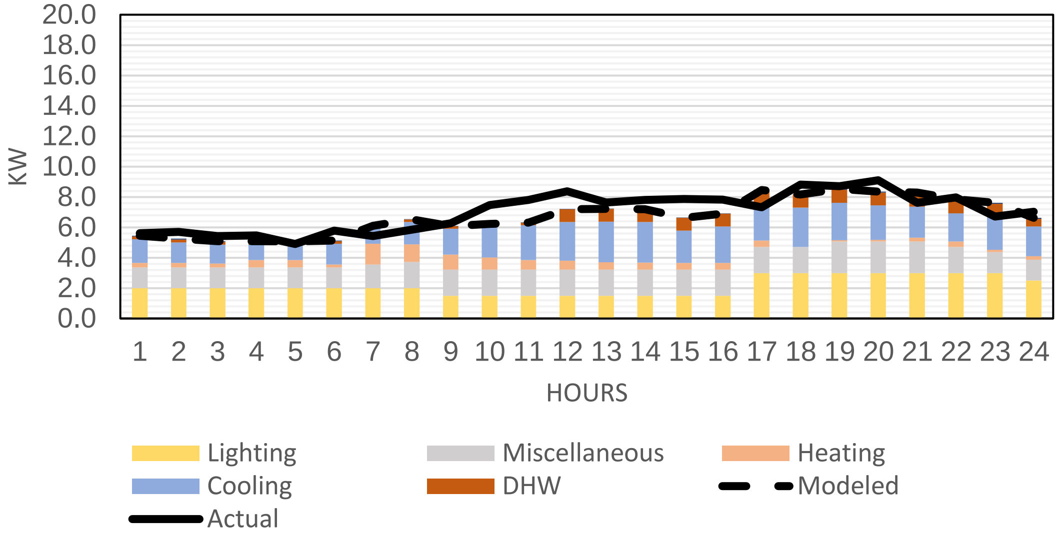


Figure 54 Hourly results of an average weekday and weekend in March

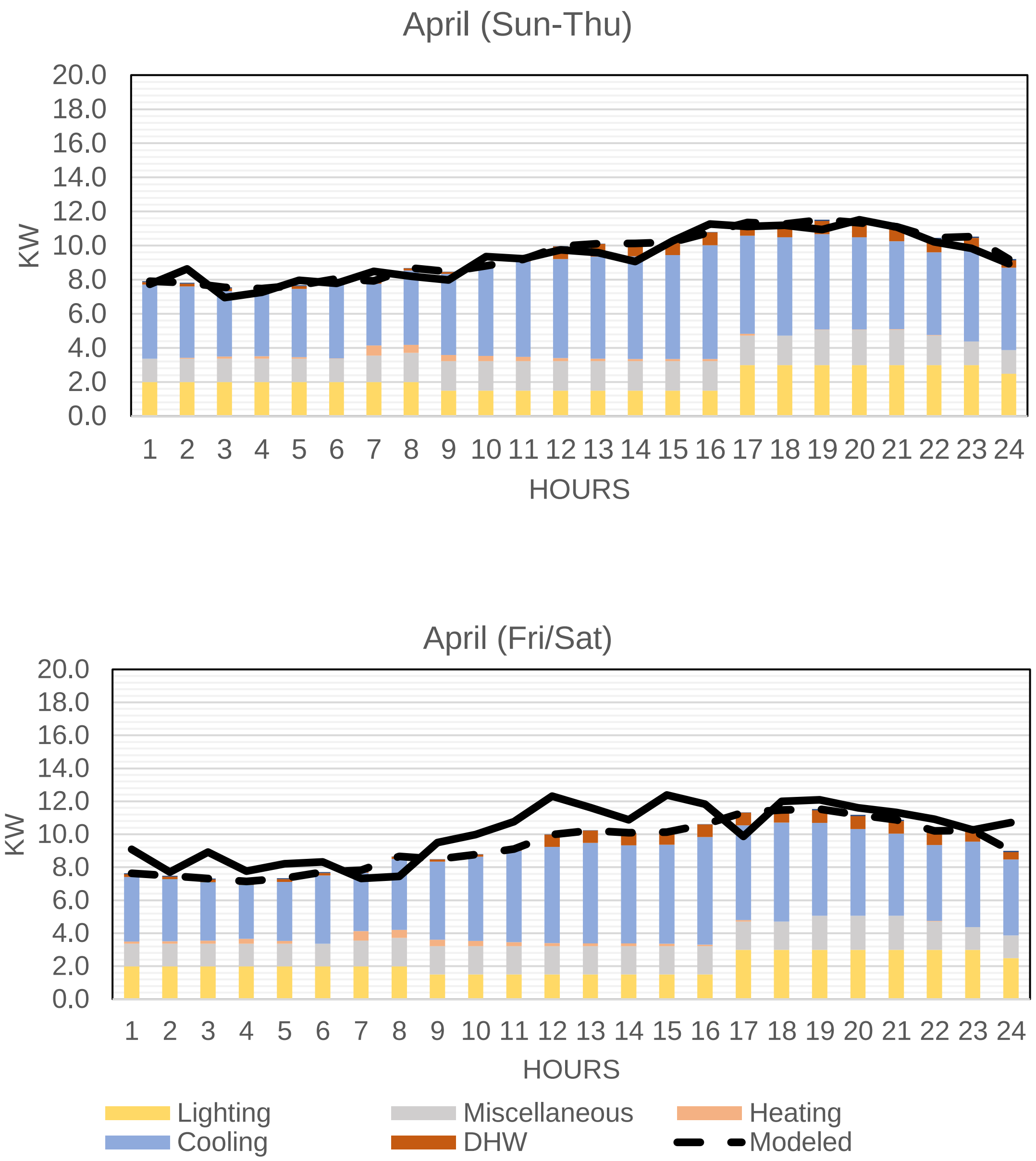


Figure 55 Hourly results of an average weekday and weekend in April

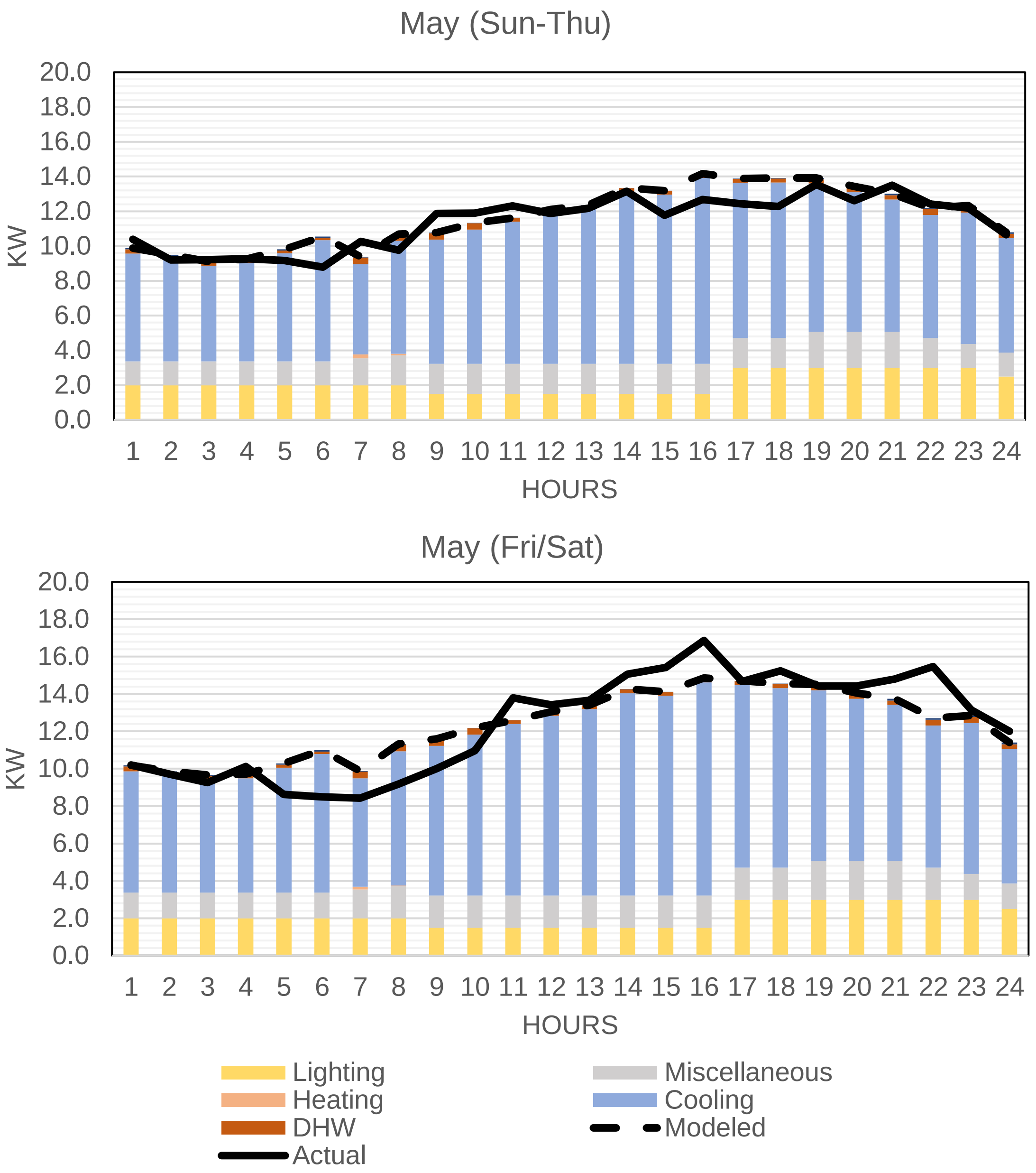


Figure 56 Hourly results of an average weekday and weekend in May

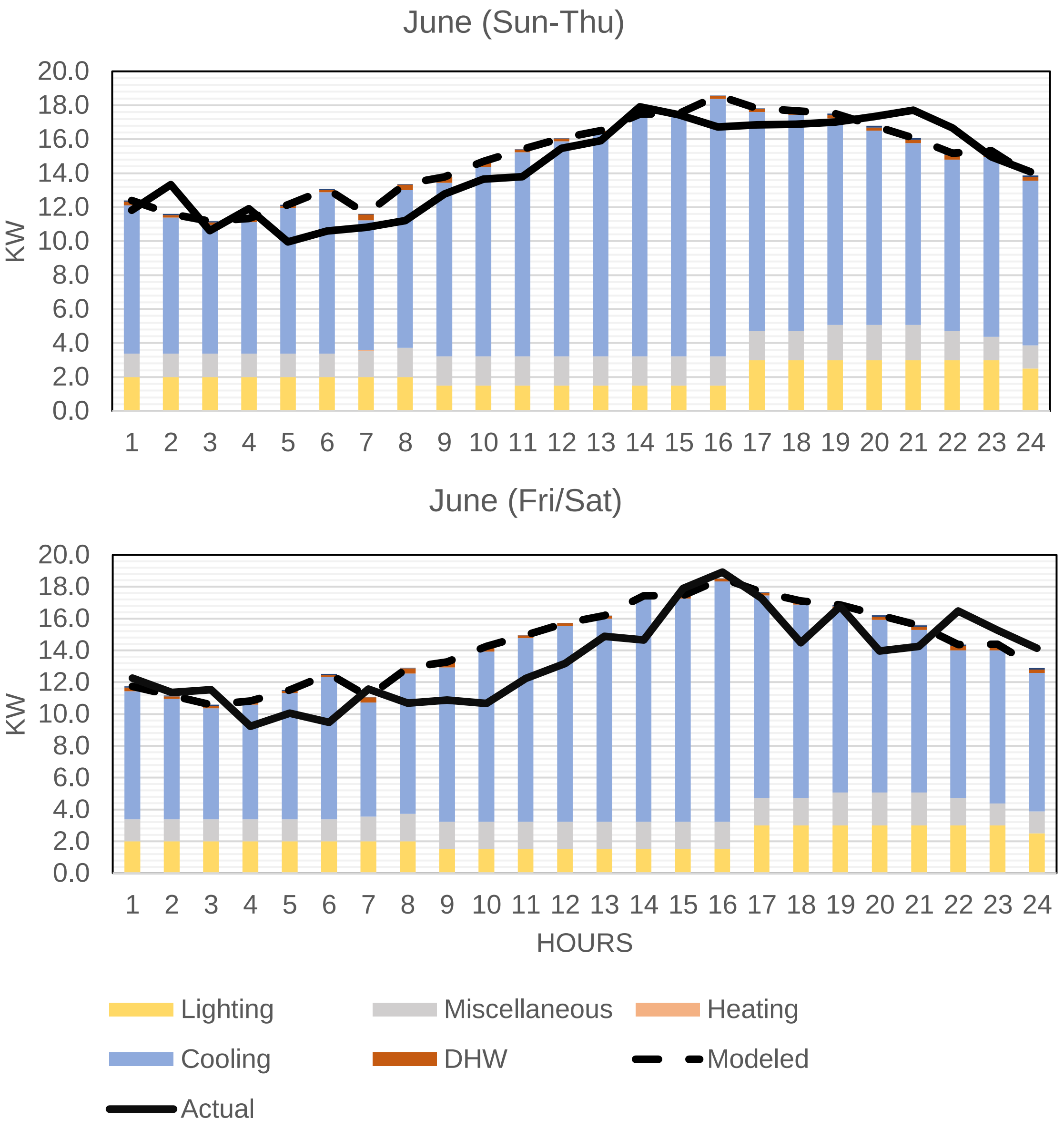


Figure 57 Hourly results of an average weekday and weekend in June

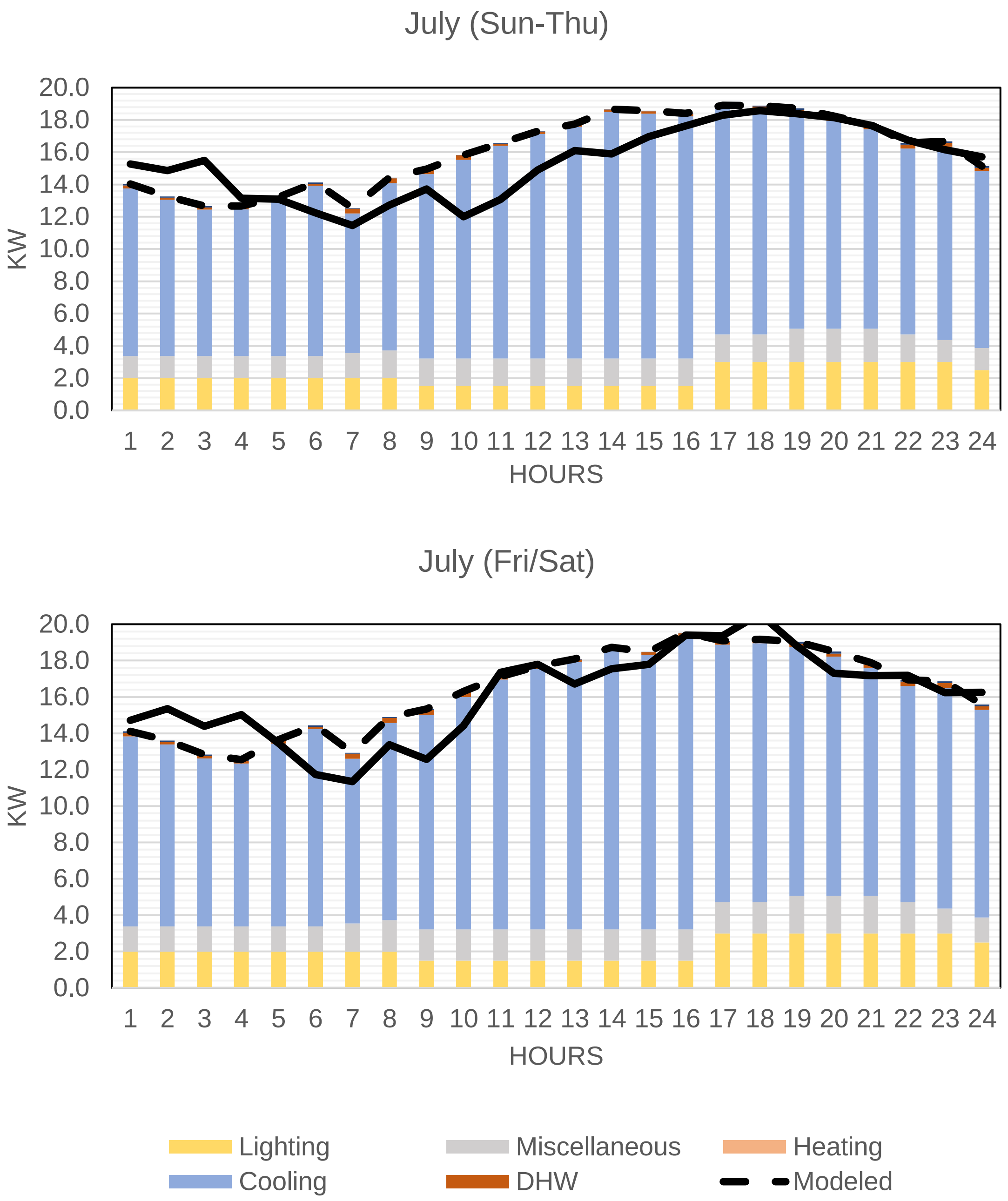


Figure 58 Hourly results of an average weekday and weekend in July

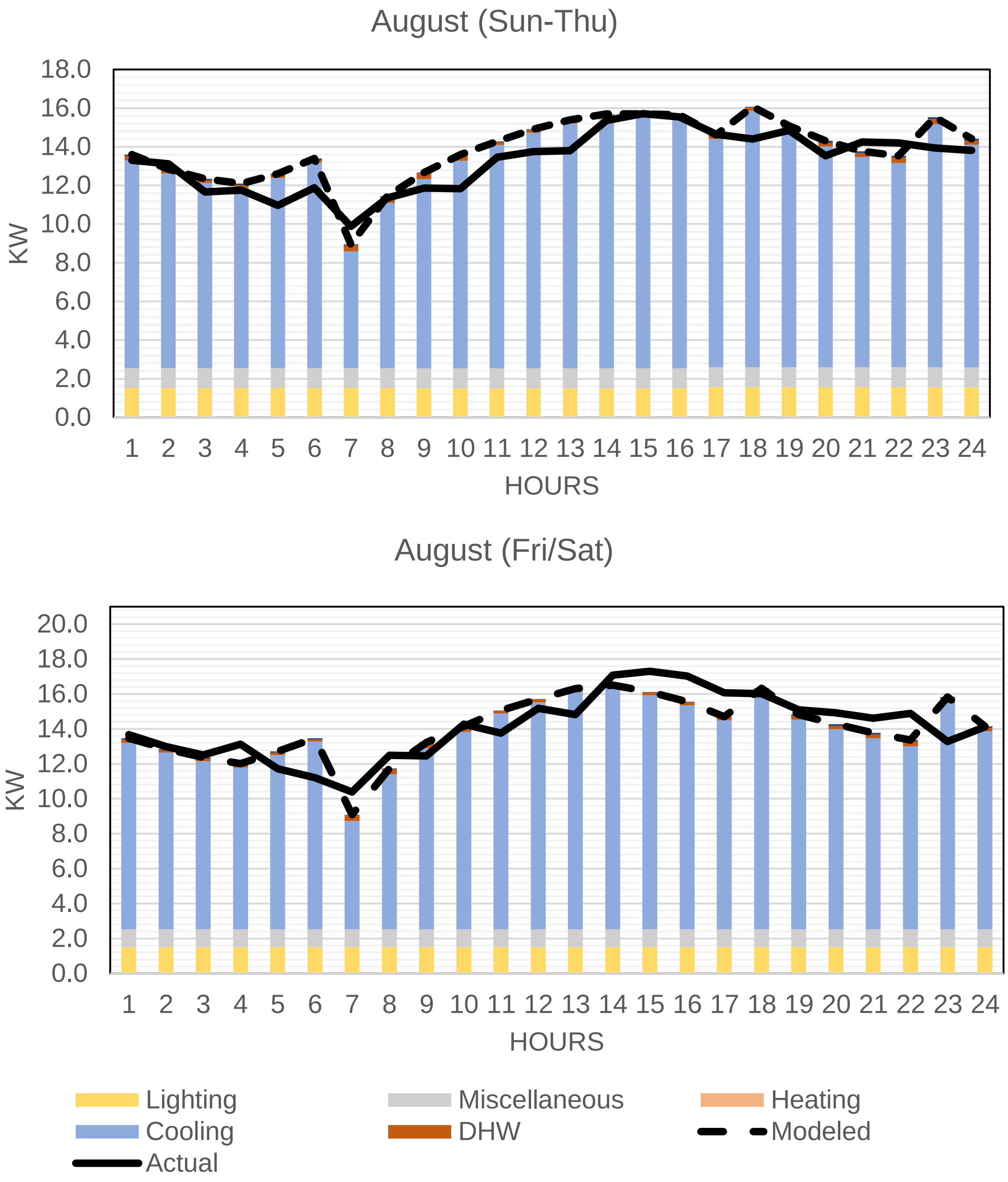


Figure 59 Hourly results of an average weekday and weekend in August

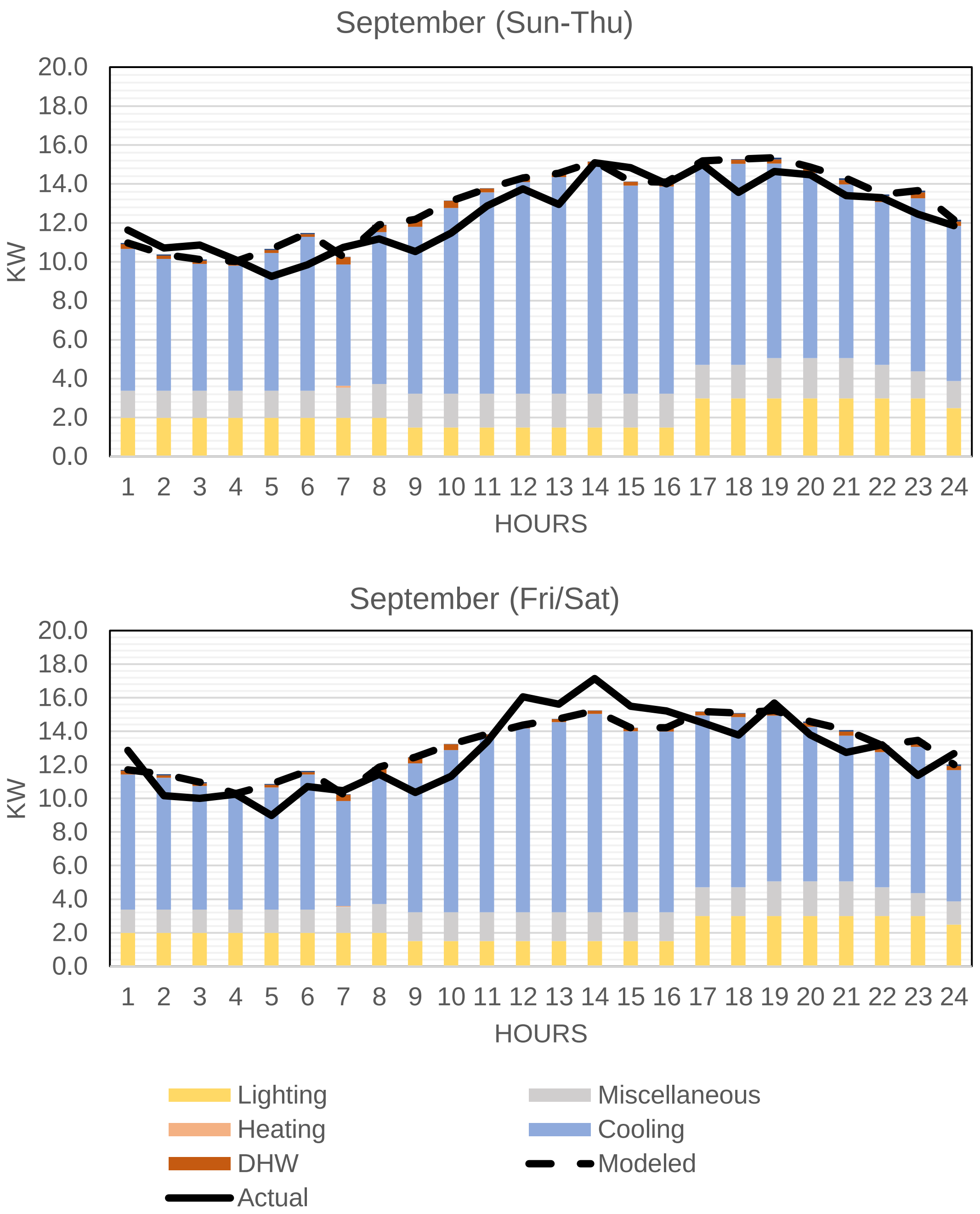


Figure 60 Hourly results of an average weekday and weekend in September

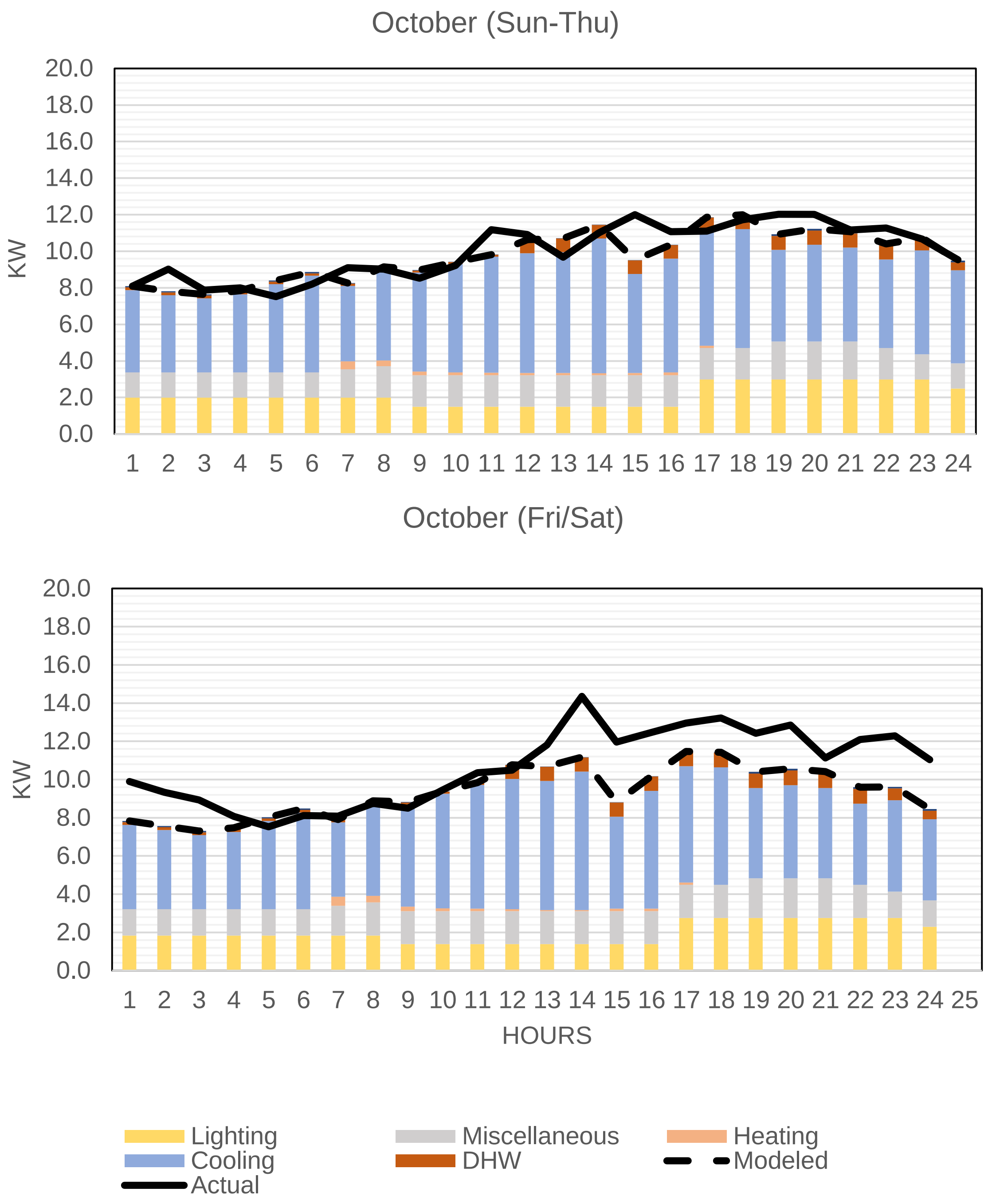


Figure 61 Hourly results of an average weekday and weekend in October

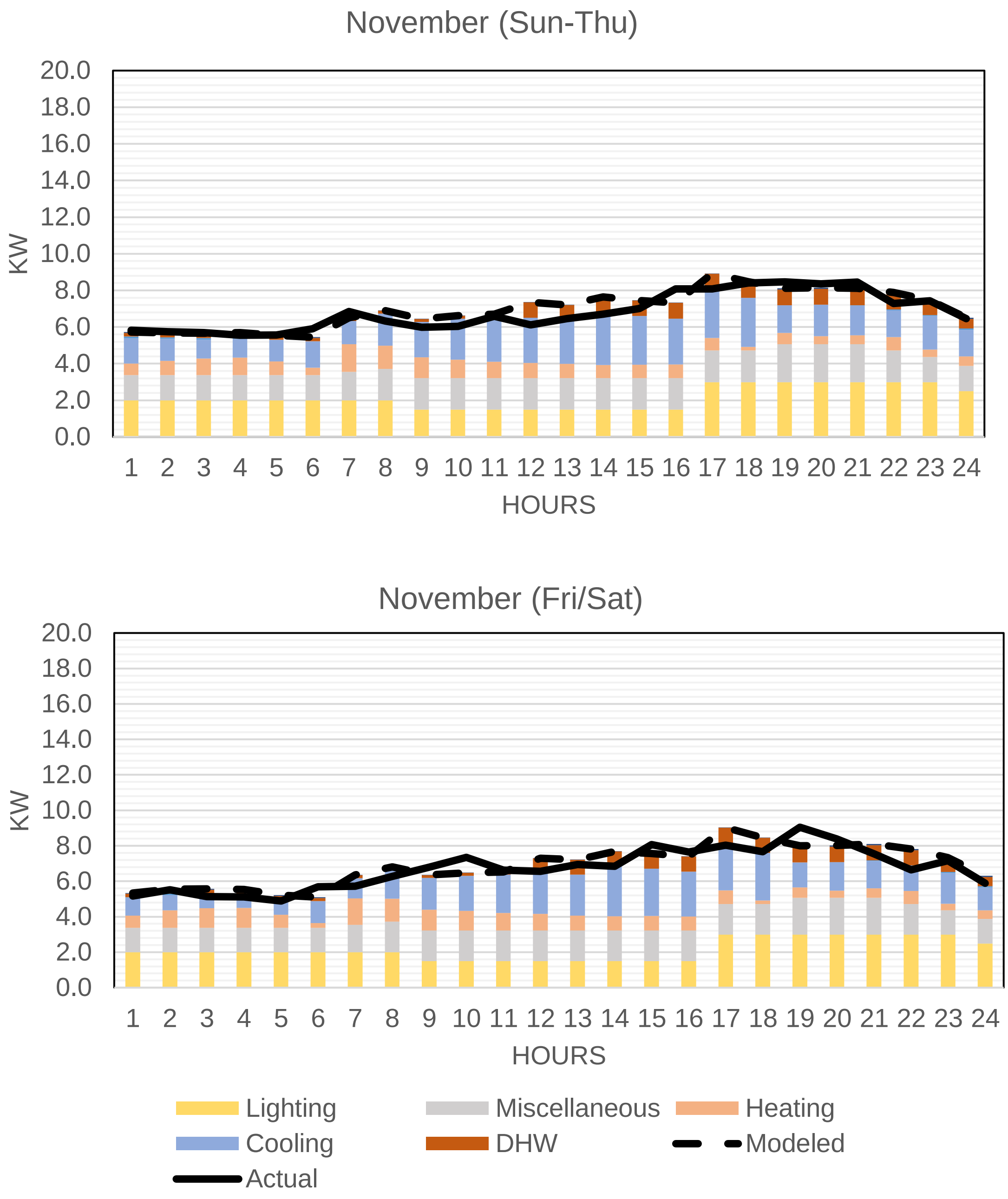


Figure 62 Hourly results of an average weekday and weekend in November

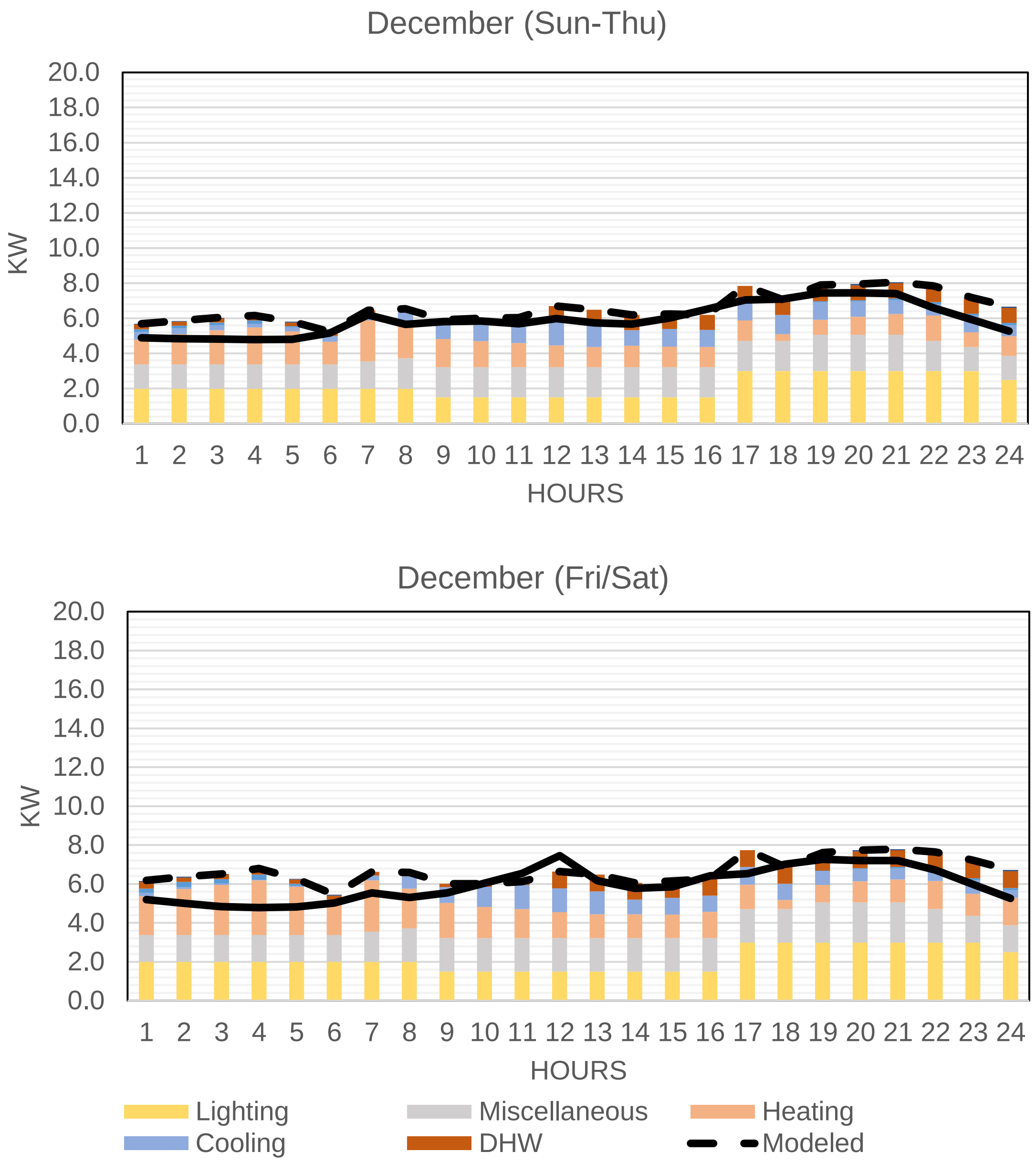


Figure 63 Hourly results of an average weekday and weekend in December