407: Modelling cooling loads and impact of PV deployment in middle income domestic buildings in Saudi Arabia

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Energy efficiency and conservation are important areas of consideration in many developed and developing countries. Over the last 5 years, electricity consumption in Saudi Arabia has grown at a compound annual growth rate of 6%; due to population growth and industrial activities. Such growth is predicted to be sustained at a similar rate over the next decade. The residential sector alone is responsible for over 50% of the total national electricity consumption. Recently, electricity prices rose by 35% to 253% depending on consumption levels. Around 65% of Saudi residents, mainly of middle-income families, live in either modern villas or traditional houses. This type of housing is the target of the research presented here, which aims to understand the effect of residents' behaviour and its impact on internal temperatures and electricity use. A selection of residences in the Khobar city in Saudi Arabia is used as a case study. TRNSYS modelling estimated the annual cooling loads in the case study based on detailed characteristics of the buildings including architectural form, envelope, occupancy profile and local weather data. The results indicate 20,350 kWh annual electrical loads are expected of which 52% are associated with cooling. Deploying solar photovoltaic (PV) systems to displace some of such loads is considered effective due to the 6 kWh/m^2 average daily solar irradiance in Khobar city. A 4-kWp solar PV system, which could be deployed in such homes, was also modelled. These results show that such a system would generate around 7000 kWh/year which could displace approximately 34% of such a load. The estimated payback period for the solar system is 21 years for the 0.048 $/kWh tariff rate without any additional subsidies. Further technical and economic assessment are also included in the paper.

Keywords: Electricity consumption, Domestic building, Middle-income, PV, Saudi Arabia.

1. INTRODUCTION

The Kingdom of Saudi Arabia (KSA), occupies the larger part of the Arabian Peninsula and has a population of around 27 million (Global Alliance of SMEs, 2016). Saudi Arabia has the world's second largest oil reserves which are concentrated mostly in the Eastern Province (BP, 2017). The economy is petroleum-based; around 75% of budget revenues and 90% of export incomes come from the oil industry, the oil industry accounts for around 45% of Saudi Arabia's nominal gross domestic product (Global Alliance of SMEs, 2016).

KSA is characterised by its hot climate and geographical location in a global region renowned for its high energy consumption and carbon emission rates. The Kingdom of Saudi Arabia is now committed to effectively implementing a programme of sustainable growth within its national development plan (Saudi Vision 2030, 2016). KSA's vision for 2030 is to increase national income from non-oil-based energy resources. Today, more than 80% of global energy consumption is attributable to fossil fuels, and the global population is currently dealing with a significant issue in terms of the environment and the energy we use (Alrashed, 2015)). One of the countries most associated with this issue is Saudi Arabia, where the lack of energy conservation regulations coupled with the speed of economic development has led to the rise of electricity consumption, which has increased by around 50% over the last 10 years (Al-Ajlan et al., 2006; KAPSARC, 2018). In 2001, KSA's had a peak electrical load of approximately 24 GW; which is 25 times higher than that of 1975. This electrical load is projected to grow to 60 GW by 2023. Over the last 5 years, the electricity consumption in Saudi Arabia has grown at a compound annual growth rate of 6% and this is predicted to continue at a similar pace over the next few years (Jones, 2012). Taleb and Sharples (2011) explain that one of the main reasons for the KSA's rising electricity consumption is the widespread use of air conditioning to cope with the country's high ambient temperatures especially in the summer. Saudi Arabia also has corresponding high levels of CO_2 emission and is amongst the world's largest producers and exporters of oil. In 2016, the Kingdom spent a total of $29.6 billion on fossil fuel consumption subsidies, making it the third highest in the world after China and Iran (IEA, 2018). Recently Saudi Arabia announce plans to cut energy subsidies and to this end the government increased energy prices in early 2018, so that residential and commercial electricity prices will increase gradually between 2018 and 2025 to reach 100 percent of international levels (Nereim, 2017).

As indicated earlier, cooling is a major contributor to the electrical consumption in Saudi Arabia, especially for residential buildings. To reduce energy consumption, buildings will need to be more efficient, this may require retrofits including improvements of insulation, the use of shading devices, and the installation of solar photovoltaic systems to shave off some of the electrical cooling loads. There is a paucity of information and understanding of how people use and interact with their homes, resulting in poor predictions of energy use at the building level. This research is part of a wider study which aims to increase our understanding of the electrical consumption in buildings including the role of residents' behaviour, building design and the needed interventions to provide clear energy use reductions. In KSA, the residential sector alone is responsible for over 50% of the total national electricity consumption where most of the residents prefer European house designs and architecture. Some of the utilised architectural features such as high glass facades, pitched roofs and the shape of the building or its orientation are however, not suitable for the Saudi hot climate environment. This leads to the following research questions:

- What are the determinants of electricity consumption in typical existing homes in Saudi Arabia?
- Can we understand occupants' behaviour from their electricity consumption data?
- Under what energy cost development scenarios will low energy building concepts become adopted as the standard approach in the KSA context?

1.1. Saudi Arabia climate

Saudi Arabia is primarily characterised by its desert climate, which follows a pattern of low rainfall annually, high temperatures during the day and quickly descending temperatures at nightfall. It is typical for summer temperatures to reach 45°C when the sun is at its peak, they can reach a high of 54°C; the winters are warm and rarely fall below freezing (0°C). Spring and autumn both have an average temperature of 29°C, which is temperature in comparison (Weather Online, 2016).

Electricity consumption is split between a host of different sectors and for a number of different purposes: the major contributors are industrial, agricultural, desalination plants, commercial, governmental, and residential. The latter sector consumes the overwhelming majority of electricity produced by fossil fuel based generation in Saudi Arabia (in the form of gas and oil) (Sankey IEA, 2015). Jeg and Sa (2016) note that industrial consumption (18.76 percent), commercial consumption (15.37 percent), governmental consumption (thirteen percent) agricultural consumption (1.75 percent), and desalination efforts (1.01 percent) follow as the highest-use sectors after residential. Figure 1 below represents power consumption levels between 2005 and 2016 (expressed as annual consumption in TWh) by sector:

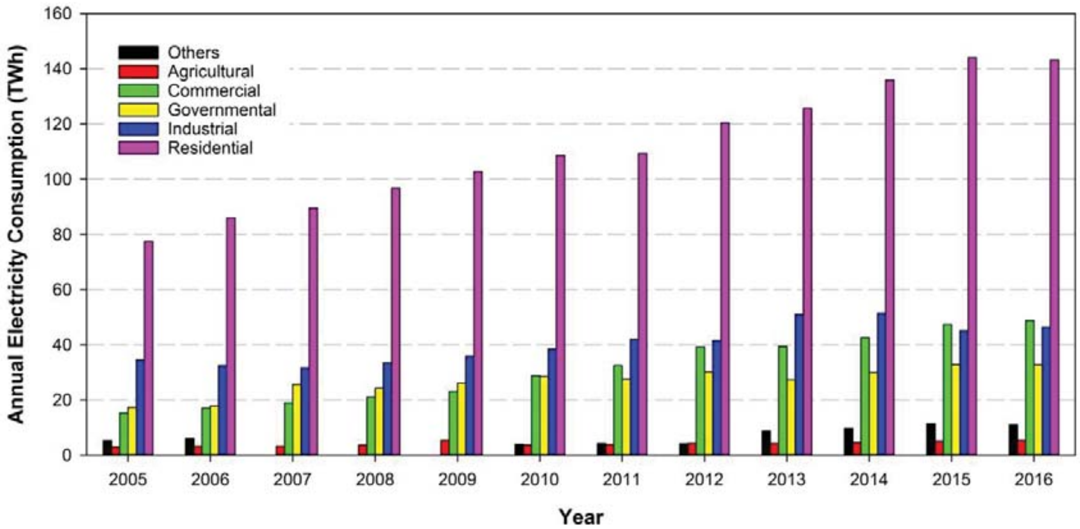

Figure 1: Annual electricity consumption in Saudi Arabia by sector (TWh). Source : http://www.sama.gov.sa/ar-sa/EconomicReports/Pages/YearlyStatistics.aspx

The Saudi Arabian governmental report outlines updated price points for electricity, which has resulted from the Council of Ministers proclamation that they would implement a national conservation programme for water and energy resources (ECRA, 2016). According to Jeg and Sa (2016), this would involve auditing prices for diesel kerosene, sewage, electricity, and water, and then amending prices to make their usage more sustainable. The New Tariff started from January 2018 and electricity prices rose 35% to 253% depending on the consumption level. Table 1 shows a comparison of a monthly household electricity bill before and after the introduction of the new tariff. It is interesting to note that the significant burden falls on low electricity consumers, there is no change in tariff for usage above 6000 kWh per month.

Table 1: Comparison between the monthly household Bill before and after the New Tariff for The Residential Sector. Source: www.se.com.sa.

Consumption (kWh)	Old Tariff		New Tariff	
	Unit rate ($/kWh)	Total bill ($)	Unit rate ($/kWh)	Total bill ($)
1000	0.01	13.33	0.048	48.00
2000	0.01	26.67	0.048	96.00
3000	0.03	80.00	0.048	144.00
4000	0.03	106.67	0.048	192.00
5000	0.048	240.00	0.048	240.00
6000	0.048	288.00	0.048	288.00
7000	0.08	560.00	0.08	560.00
8000	0.08	640.00	0.08	640.00
9000	0.08	720.00	0.08	720.00
10000	0.08	800.00	0.08	800.00

1.2. Overview of housing in Saudi Arabia

Saudi Arabian families live in different types of housing, including villas, duplex villas, penthouses, apartments, etc. These housing types are differentiated according to the influence of many factors, such as family income, resident's needs, and Saudi community traditions and customs (Alhubashi & Roca Cladera, 2016).

Table 2: General Authority for Statistics, Kingdom of Saudi Arabia 2010 (last statistics).

Type of housing	Percentage
Apartments	34.3%
Traditional House	26.9%
Villa (modern house)	25.5%
Floor in a Villa	10.9%
Floor in a Traditional House	1.2%
Other	1.3%

Table 2 illustrates the different types of housing available in Saudi Arabia and the percentage of how many of each type is present. Around sixty-five percent of Saudi residents live in either a modern villa or traditional house, which represents the majority of Saudi citizens, who are mainly middle-income families. This type of housing should thus be considered as a key factor in studies relating to low energy and sustainable housing in Saudi Arabia.

2. SUSTAINABLE DOMESTIC AND LOW ENERGY DESIGN IN HOT CLIMATIC REGIONS

There are a number of studies relating to the subject of domestic sustainable and low energy design in hot climatic regions especially in Saudi Arabia. The following section briefly summarises these and findings in provides an insights into gaps in knowledge.

Taleb (2011) said that houses in Saudi Arabia are heavily reliant on cooling, most of the families target a luxurious style and the principles of low energy buildings are rarely considered. She argues that the application of sustainable architectural practices is important to improve the efficiency of electricity use and water consumption in Saudi buildings. Taleb (2011) demonstrated through simulation of case study buildings located in Jeddah City, that the per capita electricity consumption for the apartment complex was around 8,047 kWh, while for villa it was 14,377 kWh per year. Taleb (2011) showed a significant reduction in the total electricity consumption for two case studies after adopting the suggested energy conservation measures and applying changes to the DesignBuilder (a building simulation software) models. It was shown that the calculated annual electricity use and resulting CO_2 emissions for the apartment complex which contains six apartments was estimated to have been reduced to around 76,446 kWh and 52.36 tonnes (from 144,850 kWh and 99.22 tonnes as a base case). With regard to the second case study the villa, the consumption was estimated to be around 122,785 kWh and 84.11 tonnes of CO_2 per year (compared to 186,901 kWh and 128.03 tonnes as a base case).

Another study focused on establishing a low carbon domestic design framework for Saudi Arabia (Aldossary, 2015). The research methods used in this study are: site visit, modelling and simulations of existing homes in different locations across Saudi Arabia (Riyadh city, Jeddah city, Abha city). 3 different houses and 3 apartments in each city were selected as case studies. The suggested solutions for the existing homes were retrofitting, remodelling and simulation the investigated homes in the three climatic regions. In addition, expert interviews were conducted to assist establishing a low carbon domestic design framework for sustainable homes in Saudi Arabia. Finally, the results suggest that an energy reduction of up to 71.6 % is achievable.

Alshaikh (2016) has reviewed and reported on different aspects to improve residents' thermal comfort in homes in a Saudi Arabia context. The approach used in this study was by measuring and analysing the thermal performance of the buildings, the thermal satisfaction and comfort responses of the residents and the electricity consumption during the summer period and the winter period. The comfort of residents was evaluated using the adaptive thermal comfort method. Alshaikh (2016) found that indoor air temperatures for several homes were high. In addition, most of the studied houses were not considered to be thermally comfortable as described within either by Predicted Mean Vote or Adaptive comfort limits. The study reviewed numerous influencing actors that included the houses properties, resident behaviour towards high electricity use, loads and charges. The result of the study found that lifestyle, attitudes and other socio-cultural factors have a strong influence on the comfort and energy use in individual houses.

Although (Aldossary, 2015; Taleb, 2011) studies show a significant reduction in electricity consumption there are some limitations in both of the studies. The building sample used for the case study in Taleb (2011) research may not be representative of the majority of housing or the residents lifestyle in Saudi Arabia. While, (Aldossary, 2015) research studied a larger sample size that may overcome this limitation his case studies are categorised under different types of houses in terms of house area, resident income, lifestyle. In addition, middle income families and residents behaviours in energy use were not explicitly considered in (Aldossary, 2015; Taleb, 2011) research . Alshaikh (2016) focused on improving residents' thermal comfort in Saudi homes, the study did not measure electricity use and household modelling through simulation programs was not conducted. It is clear that middle-income level of citizens is an important grouping to study as they represent the majority of families.

3. STUDY APPROACH

The approach in this study is to understand the effect of residents' behaviour on internal temperatures and electricity use. The following sub-sections provide an overview of the case study, initial research including thermal/electrical modelling. A model was created for the case study using the TRNSYS simulation tool to predict the electricity consumption and calculate the annual cooling loads.

3.1. Case study

The case study is the AlShablan development in AL Khobar city in the eastern region in Saudi Arabia. It contains 19 typical villas and 30 typical apartments that are newly built (2015) from precast concrete, residents are middle-income families. Khobar is a large city located in the Eastern Province of the Kingdom of Saudi Arabia on the coast of the Arabian Gulf. Khobar experiences clear weather consistently, and temperatures generally fall between 11°C and 42°C. It doesn't exceed 45°C or fall below 8°C (Weathersparks, 2018). Figure 2 below shows the psychrometric chart analysis from ClimateConsultant for the nearest city to Khobar city. Thermal comfort without additional strategies will only be achieved for 11.6% of the hours of the year. Air conditioning with dehumidification is seen as the dominant intervention strategy in this climate, being required for 35.1% of the hours.

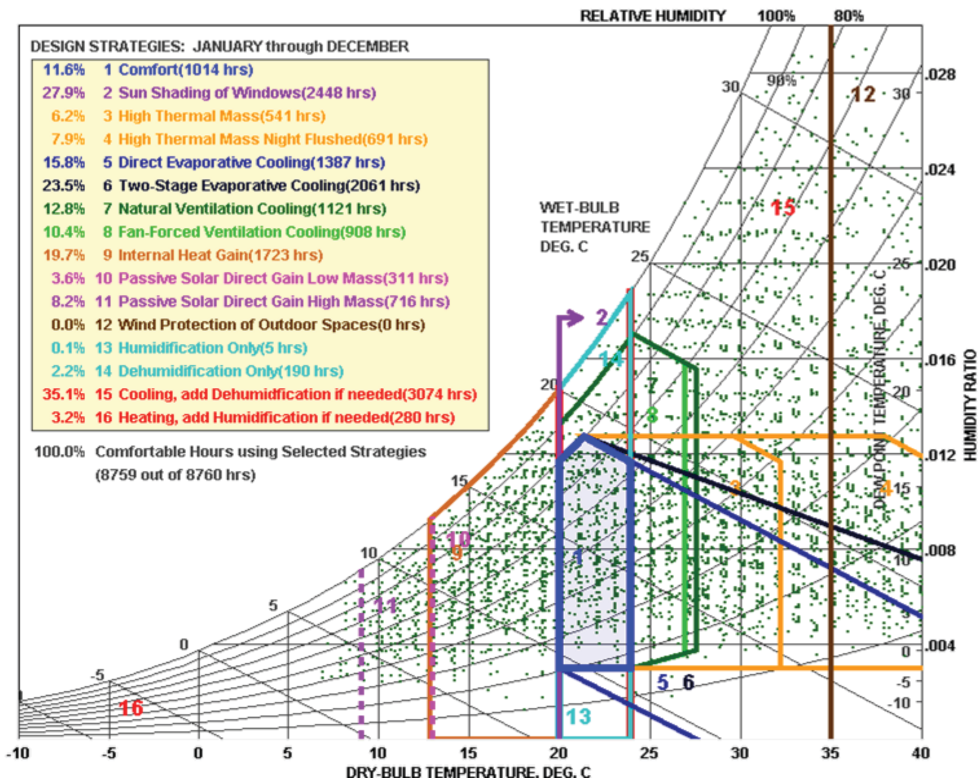

Figure 2: PSYCHROMETRIC chart for the nearest city to Khobar city (lat 26.27 deg N, long 50.17 deg East). Solid blue region (1) = comfort region without additional strategies applied, 11.6% of all hours. Source: ClimateConsultant.

3.2. Building simulation using (TRNSYS)

The case study (villa) was modelled, simulated and analysed using TRNSYS to estimate the annual cooling loads. The following elements were taken into consideration in this process of analysis: Building architectural form, building envelope, occupancy profile and local weather data (see Figure 3). The base reference case was created as a model using TRNSYS, based on building dimensions, the construction materials used, occupants' profile and energy consumption per appliance to calculate the internal gains of the weekday and the weekend. The area of each window, and the overall orientation of the building were considered.

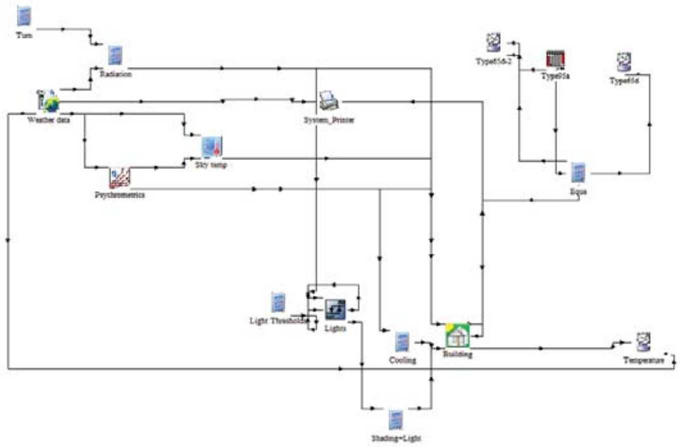

Figure 3: TRNSYS component model for KSA villa complex. Source: researcher.

The modelled building has a living area of 200m^2 across two storeys. The key parameters of the building model simulation are given in Table 3. The residence is assumed to have a combined infiltration and ventilation rate of 1 air change per hour.

Table 3: TRNSYS model parameters of residence.

Parameter	U-value (W/m^{2}K)	Area (m^2)
External wall	0.36	240
Roof	0.23	100
Ground floor	0.31	100
Glazing	1.40	23.8

The electrical appliance loads and lighting loads are estimated to have a consumption of 24 and 34 kWh per day for a weekday and weekend day respectively. The annual electrical appliance and lighting loads is 9800 kWh, the majority of which becomes additional cooling load for the air conditioning (AC) system. The AC system is assumed to maintain an upper limit of 21 deg C at all times in the dwelling and provide dehumidification above 80% RH. The temperature in the house drops below 21 deg C at the start and end of the year due to low ambient temperatures during this period.

The TRNSYS model estimates the annual cooling load to be 31,691 kWh thermal, which for a split unit AC system with a Coefficient of Performance (CoP) of 3.0 (Fujitsu General, 2017), corresponds to an annual electrical load of 10,564 kWh. Air conditioning is therefore estimated to represent 52% of the annual electricity consumption of the dwelling (20,350 kWh). Figure 4 below shows the ambient temperature and modelled dwelling temperature over the year alongside the thermal cooling load.

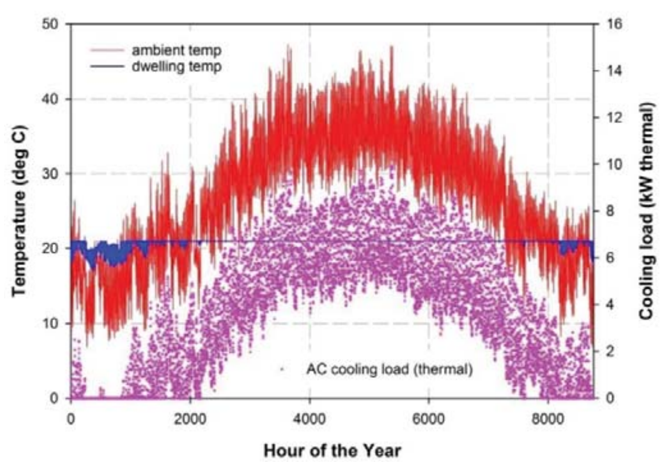

Figure 4: Ambient temperature and modelled dwelling temperature over the year alongside the thermal cooling load.

The TRNSYS model also considers 1 kWp of PV roof mounted at a slope of 20 degrees. For a typical inverter efficiency of 93% the annual AC generation is estimated to be 1750 kWh/kWp or 8% of the household electricity use. NOTE: This estimate does not consider the cumulative effects of dust or module mismatch (~1%) or dc cable losses (~1%) in the system yield. PV-GIS estimates 1 kWp at a slope of 20 degrees to generate 1720 kWh/kWp per annum (European Commission, 2018). 1 kWp of PV requires approximately 7m^2 of roof area, a 4kWp system is therefore a realistic deployable system which would meet around 32% of electrical demand of the dwelling. Khan et al (2017) have assessed the rooftop potential of PV in KSA considering the available roof areas due to building form self-shading etc. Their work suggests 30% of the nominal roof area is useable for PV deployment, which equates to our 4kWp estimate. As would be expected there is a very good seasonal and daily match between PV generation and cooling demand. Figure 5 shows the hourly PV generation (kW/kWp) across the year in comparison to the modelled cooling load.

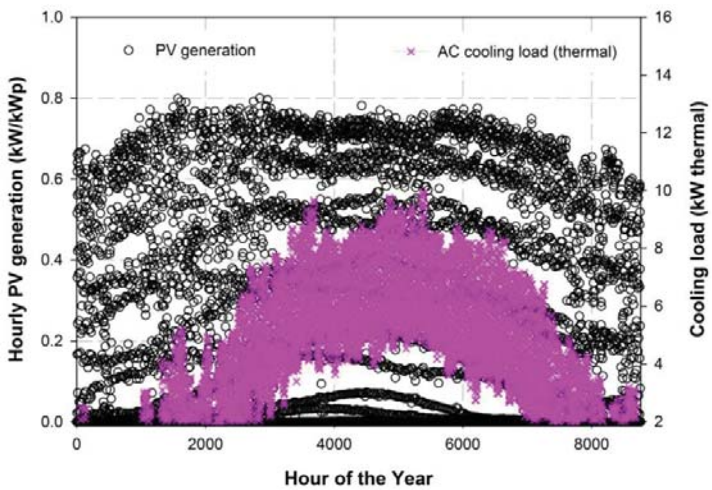

Figure 5: Hourly PV generation (kW/kWp) across the year in comparison to the modelled cooling load (kW thermal).

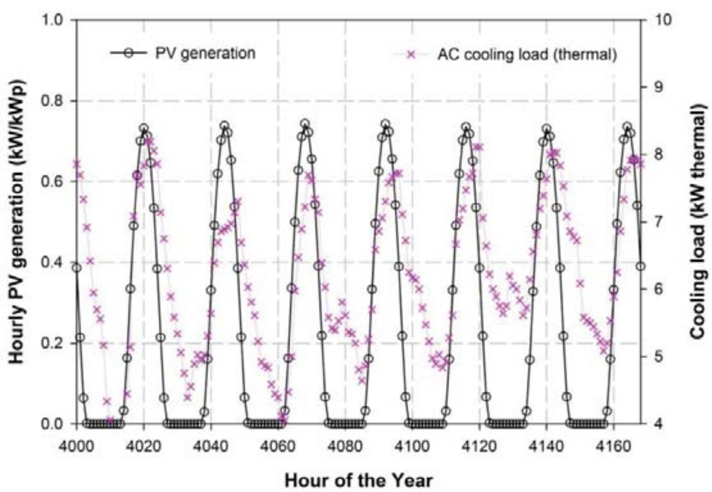

Figure 6: Hourly PV generation (kW/kWp) across a summer week in comparison to the modelled cooling load (kW thermal)

The summer cooling loads (Figure 6: 1-week example hours of the year 4000-4168) vary between 4 and 8kW thermal. For a CoP of 3.0, this corresponds to an electrical load of 1.3-2.7 kW. 4kWp of PV is estimated to have a peak electrical output of 3.2 kW, which when the additional electrical loads of the dwelling are considered means that export to the utility grid from the dwelling will be minimal.

4. RESULTS

4kWp of PV is a good sizing match to the electrical load of the dwelling if avoidance of export is considered important. The dramatic increases in electricity prices in KSA mean there is an opportunity for PV to be economically deployed. Here, by calculating the electricity bill for a year we compare the old tariff with the new tariff (see table 4), the new cost of the bill is raised by around 365%.

Table 4: Annual electricity bill by comparing the old tariff with the new tariff. Source: researcher.

Electricity Consumption (kWh/year)	Old tariff		New tariff	
	Unit rate (US$/kWh)	Annual bill (US$)	Unit rate (US$/kWh)	Annual bill (US$)
20,350	0.013	264.5	0.048	976.8

Table 5 represents the case study annual electricity consumption if 4 kWp of PV system is used, the system will generate annually 7000 kWh. The residential rooftop PV market is still relatively new in KSA and so we have considered turnkey CAPEX costs between 1000 and 1600 US$/kWp. We assume the annual maintenance cost is 2% of CAPEX. At a CAPEX cost of 1200 US$/kWp and a discount rate of 0% on the financing a system would have a payback time of 21 years, just less than the typical 25 year PV lifetime for the 0.048 $/kWh tariff rate.

The payback period is reduced to 11 years if the annual electricity consumption of the dwelling reaches 72,000 kWh, because at this consumption level, the tariff rate is 0.08 $/kWh. There are likely to be further increases in the electricity price as KSA tries to eliminate electricity subsidies. Figure 7 shows the payback time for PV CAPEX between 1000 and 1600 US$/kWp as a function of electricity tariff increase to up to 2X the new tariff. Payback times of as little as 7 years are predicted (Figure 7).

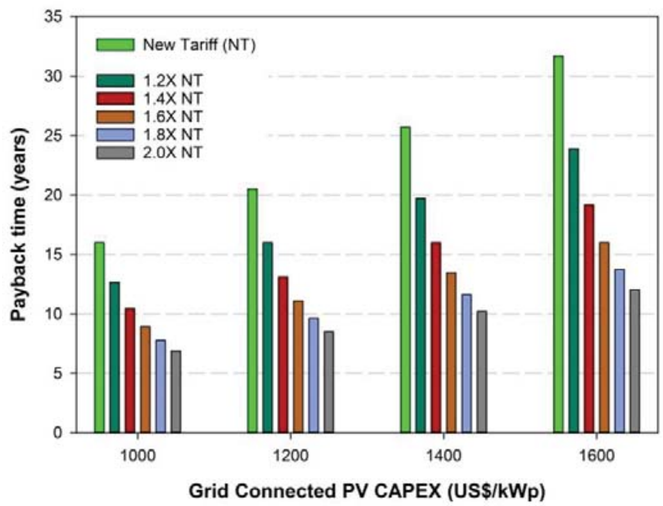

Figure 7: Estimated payback time for rooftop PV in KSA as a function of CAPEX and multiplier of the New Tariff KSA. Maintenance cost is 2% of CAPEX per annum, 0% discount rate on CAPEX.

Table 5: Case study annual electricity consumption before and after reduction and payback period in years. Source: researcher.

consumption (kWh/year)	consumption (kWh/year) after reduction	Tariff (US$/kWh)	annual bill before reduction (US$)	annual bill after reduction (US$)	Reduction per year (US$)	Payback period in years
20,350	13,350	0.048	976.8	640.8	336	21

5. CONCLUSIONS AND FUTURE WORK

This study focused on the residential buildings of middle-income Saudi's families and their electricity consumption. A case study development of villas and flats in Khobar city was adopted. This was achieved by modelling the existing case study through TRNSYS simulation tool and calculating the annual cooling loads, the model estimated a 20,350 kWh annual electricity consumption. Using solar photovoltaic system was considered as an effective solution to reduce electricity import and avoid grid export as results showed, a 4-kWp solar PV system would generate around 7000 kWh/year which could cover around 34% of such a load. The estimate payback period for the solar system is 21 years, but because residential rooftop PV market is still quite new in KSA and there are possible further increases in the electricity price. The payback time for PV CAPEX between 1000 and 1600 US$/kWp as a function of electricity tariff increase to up to 2X the new tariff. Payback times of as little as 7 years are expected.

Future work will use a mixed methods approach of environmental and energy usage monitoring combined with surveys of participants in the case study development. The participant study will determine patterns in behaviour, actual electricity demand profiles through analysing collected data and relate these to internal environmental conditions and energy use in middle income domestic buildings. This approach will provide model validation and enable the exploration of the real world impact of a range of building form changes such as shading and alternative cooling strategies.

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