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Building energy performance simulation: a case study of modelling an existing residential building in Saudi Arabia

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Keywords: energy consumption, efficiency, residential building, sustainable design, performance, simulation

Abstract

Saudi Arabia, like many other developing countries, has had extensive experience with rapid urbanisation and infrastructure expansion, especially in the area of buildings. Buildings play an even bigger part, accounting for roughly 80% of total national electricity consumption. Forecasts indicate that domestic energy consumption will rise at a rate of 4% to 5% annually by 2030, based on current local energy consumption patterns. A significant portion of this energy consumption growth results from the inefficient use of energy, and absence of coordinated enforcement and stakeholder engagement. This paper presents results of a study performed to propose potential energy-saving and CO_2 reduction techniques for residential buildings in hot climates, by critically examining an existing and recent building types. A model was designed using computer-based simulation software, DesignBuilder (DB), and the energy performance was then validated against the actual collected data. Building related parameters that make the construction systems behave differently in terms of energy efficiency were analysed. Additional simulations were run with the chosen building's shape, fabric, and user behaviour. Thermal insulation in the walls and roof can save about 45% in overall energy consumption, and when combined with other energy efficiency measures, a substantial reduction of 67% can be achieved, according to the findings. In the residential sector, improvements in building energy efficiency were obtained from the perspectives of both technological capacity and initiative energy conservation consciousness.

1. Introduction

The building industry has experienced a considerable number of developments following economic growth causing exploitation of natural resources. These developments are due to the activities in the extraction of a substantial number of raw materials as well as consumption of large quantities of energy. Therefore, this situation has been one of the key contributing factors for the increased interest in buildings sustainability, which is even more significant for developing countries and hot climate regions. Electricity consumption in the Kingdom of Saudi Arabia (KSA) consumes more than one-third of the country's total daily oil production, as seen in figures 1 and 2 [1]. Total electricity usage is increasing at a rate of about 5%–8% per year, which means that oil production and consumption will be equal in 2035 [1]. Therefore, residential buildings must be evaluated further in terms of their actual energy usage.

Buildings currently consume approximately 80% of total generated electricity [2, 3]. Owing to numerous defects, residential buildings currently consume about half of the overall energy consumption of the building stock [3]. All housing units in Saudi Arabia is powered by electricity [4]. According to [4], detached buildings represent about 38% of total residential units in Saudi Arabia. Because of its effect on overall energy use, building energy consumption is the first area of concern. The government has made it a priority to reduce current energy usage and re-evaluated its future economy and is investing in sustainability measures. It is now putting money into renewable energy plants. The Saudi government announced in 2018 a $200 billion investment with Soft Bank in 2018 to generate 200 GW of energy by 2030 using concentrated photovoltaics (PV) solar plants,

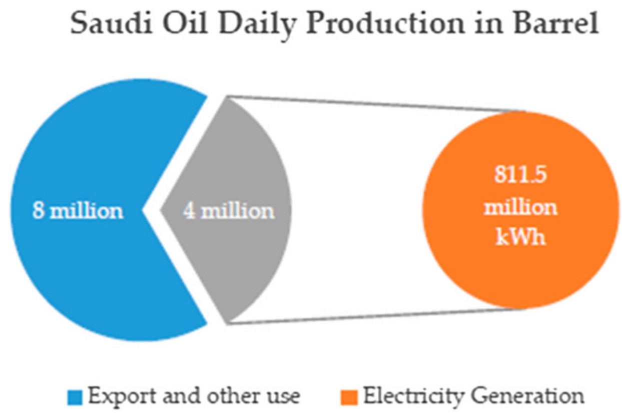

Figure 1. Generated electricity share from daily oil production [1, 2]. Reproduced from [1]. CC BY 4.0.

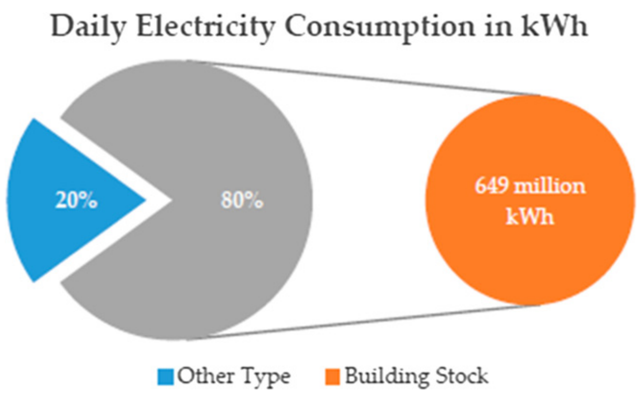

Figure 2. Building sector electricity consumption [3]. Reproduced from [1]. CC BY 4.0.

which should cover the country's projected energy demand by 2035 [5]. The Saudi government recently implemented a set of standards and regulations (known as the Saudi Building Code SBC) to curb energy usage in the building industry. It, in particular, has implemented thermal standards to improve the energy efficiency of new residential buildings since 2014 [5]. Furthermore, in 2018, a new building code was adopted. By 2020, 2.32 million new residential units had to be built, which 33 percent was completed by January 2019 (buildings constructed under the previous building code) [2, 6, 7]. Without redevelopment, this problem of high energy consumption would persist.

The development of current Saudi buildings still lacks application of sustainability in which buildings remain heavily dependent on air conditioning, a factor that results in high energy consumption [8]. Building performance generally in Saudi Arabia lacks the application of energy efficient and sustainable technologies. 70% of residential buildings were erected without thermal insulation [2]. The major issue of energy efficiency is still not given serious consideration by public with regard to Saudi building designs [9]. Building sector alone was responsible for about 80% of the total energy consumption in 2009 in Saudi Arabia, 70% of this rate is a result of the operation of HVAC systems [10]. Reference [11] mentions that this example of unsustainable practice poses a high pressure on the energy consumption in Saudi Arabia as the future projections of energy consumption depict an alarming image of the country. However, this code that requires the incorporation of sustainable and energy efficiency applications into the design of buildings which has not yet being fully enforced and its implementation has been divided into stages of different building types [12, 13].

According to some recent surveys, the energy efficiency level of KSA buildings remains poor, owing in part to difficulties in the implementation of standards and regulations [14–16]. Recent energy price reforms can provide enough motivation for the private sector and households to implement and invest in energy efficiency systems in order to lower energy consumption and thus energy costs for both existing and new buildings [17]. Therefore, this study will focus on an existing building with the aid of simulation software and seek techniques to improve its performance in term of energy use. The fact that residential buildings are considered one of the biggest energy consumers and are negatively impacting the sustainable development in the country drives the purpose of this study.

2. Methods

2.1. Building simulation

Internationally, a broad range of scientifically validated building performance simulation (BPS) tools are accessible. Computer simulation software tools have made major strides forward in recent years and will continue that trend since they make the evaluation of the whole process of design, operation, maintenance, and lifecycle processes of any building possible from concept to design [18]. Furthermore, these tools can be utilised to assess the energy performance of an existing or new building. Furthermore, BPS can integrate human activity and thermal and visual comfort simulations into the computer modelling and simulation process of buildings [19, 20]. Previous literature [18, 21, 22] have mentioned some of the noticeable advantages of the application of computer based simulation and modelling. A study done by [23] that outlines major criteria for BPS tools evaluation and selection based on analysing user's needs for tools capabilities and requirement specifications concludes that DesignBuilder (DB) is almost the only tool that was appreciated by architects and engineers and was ranked in the top. DB is a building simulation software that was created specifically for running EnergyPlus simulations on virtual building models [24]. Other studies [24–26] have emphasised the validity and suitability of DB software, especially in the context of building performance studies. As for this reason, this study will employ DB as the main BPS tool.

2.2. Case study selection

The case study analysis method can be used to elucidate minute facts and in-depth details about real phenomena [27]. The most dominant dwelling types according to the public survey were flats and detached two-storey villas. However, flat buildings are mainly constructed for investment purposes and therefore they may be difficult for in-depth study. Hence, the building type that has been selected to be analysed in this study is the detached house type. The building has to be existing and occupied to allow for data gathering including building specification, users profiling, and energy used. This study will focus on the prevailing climatic zone in Saudi Arabia (zone 1) as according to the SBC classification. It contains regions characterised by the hot dry climate which comprise almost 65% of the area in the KSA. The city of Riyadh was selected to be the representative study area.

2.3. Riyadh profile

Riyadh, capital city of the KSA, is located in Riyadh region at latitude 24.7°N and longitude 46.8°E and at about 600 m above the sea level sloping eastward. Since the past five decades, the city of Riyadh began to change from a small-enclosed town to a modern city covering an area of 3115 square kilometres, including 15 municipalities and home to more than 6.5 million people in 2017 [28]. Because of its economic growth and availability of job opportunities, Riyadh has become a magnet for people from other regions. As a result, population growth has risen, as has the need for more housing. According to the Saudi housing statistics 2019, the number of houses occupied by Saudi citizens in Riyadh was 865.4 thousand, a share of 23.5% of the total houses number in the KSA [29]. Also, the average family size in the KSA is 5.86. Most dominant housing unit in Riyadh is villa type contributing to about 46% of the total houses in Riyadh.

It is usual for Saudi Arabian summer ambient temperatures to go higher than 46.1 °C with mean monthly temperatures range between 27.3 °C and 37.1 °C, see figure 3. The extremely high summer ambient temperatures require suitable cooling systems to maintain thermal comfort for building occupants [30].

2.4. Base case simulation

The model parameters must be specified before the DesignBuilder software can simulate a house's thermal performance. Physical characteristics such as geometry and plan, installed appliances or equipment, building function and occupancy profile, site location and climate, and the nature of the surrounding environment, among other things, are defined by model parameters [18]. This definition is required in order for the DB tool to select the appropriate material for modelling. Models in DB are arranged in a basic hierarchy. This arrangement allows to create settings at the building level that become active in the entire building [31]. Default data is inherited from the level above in the hierarchy.

2.5. Building characteristics

The case study building used for this thesis is a two-storey detached villa, a conventional building representing the typical Saudi dwellings. Table 1 represents the main characteristics of the selected house.

The ground floor of this building consists of separate guest room for each gender, guest dining room, common lounge, kitchen, and two toilets. This design style is very popular in the KSA which reflects Saudi Muslim culture, that is mainly involving gender separation. Furthermore, main bedrooms are located in the upper floor, figure 4. The household of the building used in this study indicated that there are some rooms on

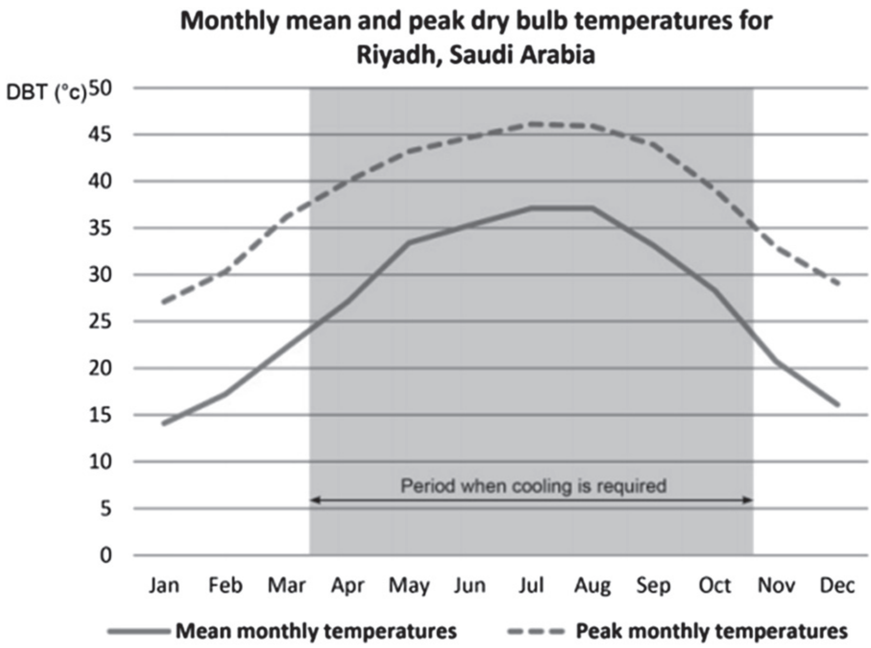

Figure 3. Annual temperature profile for Riyadh. Reproduced with permission from [30].

Table 1. Selected building characteristics.

Location	Riyadh
Façade and orientation	Front elevation eastern face
Number of floors	2
Floor dimensions	15.8 m × 15 m
Plan shape	Rectangular
Total height	7.0 m
Total built area	237 m^2
Total building area	403 m^2
Gross wall area	470.5 m^2
Total area of windows	41.9 (m^2)
Surface area to volume *S*/*V*	0.46 (m^{-1})
Glazing area for each cardinal orientation	N (12.6 m^2), E (6.0 m^2), S (14.3 m^2), W (9.0 m^2)
Windows	Single pane windows (SHGC 0.62), *U*-value (5.78 W m^{-2} K^{-1})
External walls	*U*-value (2.15 W m^{-2} K^{-1})
Roof	*U*-value (2.13 W m^{-2} K^{-1})
Number of occupants	6
Age of the building	4

the ground floor that are occasionally occupied such as guest rooms and guest dining room. The upper floor, on the other hand, seems to consume most of the end-use energy due its continuous occupancy.

As stated earlier, the residential building sector consumes a substantial amount of energy relative to other major energy consumers, and this is expected to increase in the future if the public remains unaware of the country's current energy situation and sustainable building energy alternatives. Energy bills are important to this study because they specify the rate of energy usage in buildings and the amount of money spent on energy by householders on a monthly or annual basis. Hence, the monthly electricity bills for year 2019 were gathered from the household and the Saudi Electricity Company. The total annual energy consumption of the selected building was 46 143 kW h (114.5 kW h m^{-2}).

Typically, houses in Saudi Arabia are masonry structure made from reinforced concrete and concrete blocks. The construction of the envelope of the examined building is without insulation, according to the household. The construction details of the building's envelope are given in appendix A. This practice seemingly still common in residential buildings construction in Saudi Arabia. The modelling drawings and simulation inputs are shown in figure 5 and table 2, respectively.

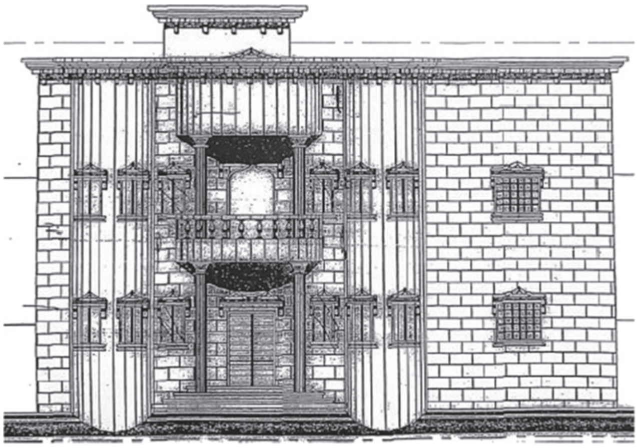

Figure 4. Reference building front elevation.

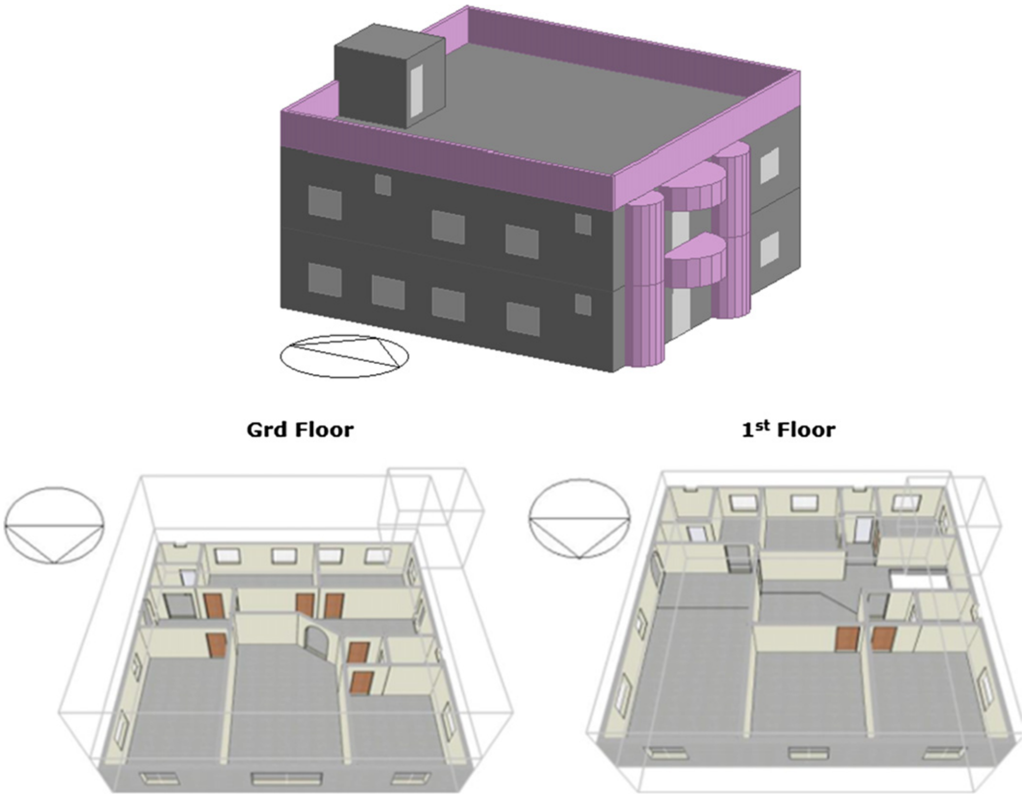

Figure 5. DesignBuilder model drawing.

3. Simulation results and discussion

3.1. Base case energy consumption

Having the parameters defined using input data given in table 2 and the building elements construction details, the simulation output reflects the total annual energy consumption in kW h. A breakdown of the monthly energy use in kW h (i.e., electricity by rooms, lighting, heating, cooling, and domestic hot water) is displayed in figure 6. The demand for water heaters across the region to satisfy rising domestic applications of warm water such as cooking, cleaning, and bathing has also contributed to the increasing energy consumption in residential buildings. It is worth noting that the computer simulation was able to capture the considerable rise in energy consumption from May to October, owing to the use of air conditioning during this period. The annual energy consumption of the modelled base case is 47 389 kW h (117.6 kW h m^{-2}). It is obvious from figure 7 that most of the total annual energy consumed (82%) was attributed to cooling loads, 38 836 kW h (96.4 kW h m^{-2}). This is justified by the local harsh climatic condition. The total energy consumption for

Table 2. Summary of DesignBuilder model input data.

Openings	HVAC	Lighting	DHW	Occupancy
Single glazing windows (blue 6 mm) U value = 5.778 W m^{-2} K Position: inside	Packaged DX AC CoP = 2.5 *AC no fresh air (in specific zones) Cool setpoint temp = 20 °C Electricity from grid	Surface mount LED lighting Power density = 2.5 (W m^{-2} −100 lux) Radiation fraction = 0.72 Visible fraction = 0.18	Instantaneous hot water with default CoP = 0.85 Electricity from grid	Density = 0.16 people m^{-2} Metabolic activity = light manual work Metabolic factor = 0.9

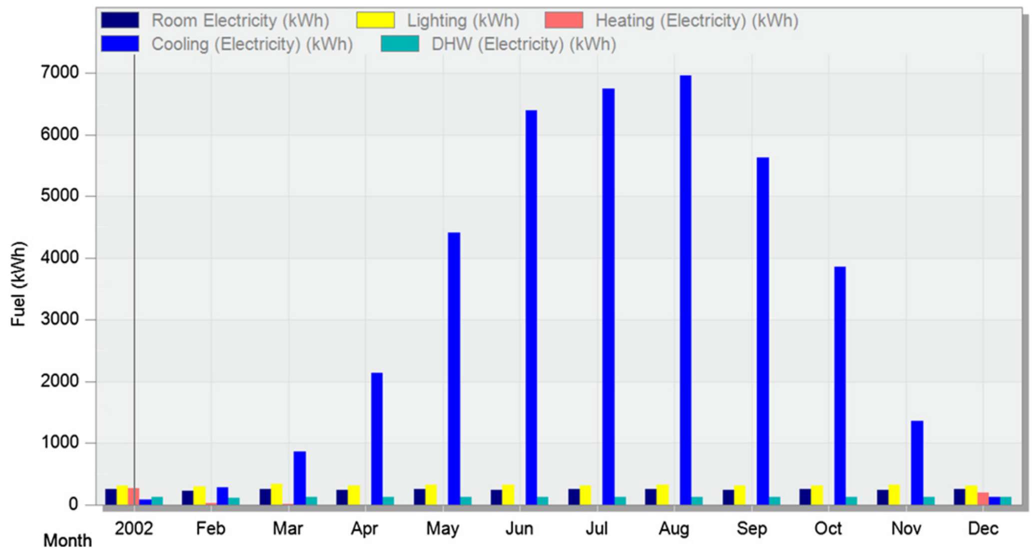

Figure 6. Breakdown of monthly energy consumption.

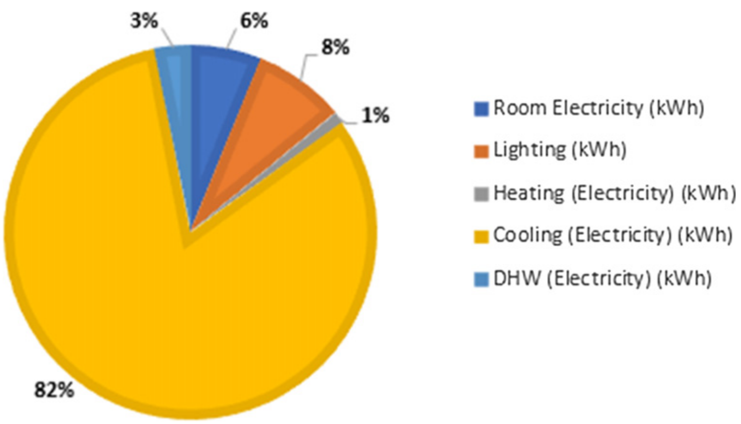

Figure 7. Breakdown of the total annual energy consumption—base case.

space cooling in kW h m^{-2} per year is 96.2. The European Standard recommended 20–30 kW h m^{-2} per year space cooling [32].

In addition, the total CO_2 emissions in kg for the whole year is 28 718. The emissions increased in summer months due to the operation of cooling systems to maintain occupants' thermal comfort at desired level from an environmental perspective. As there are six occupants in this house which agrees with the size of the average family in [33, 34], the CO_2 emission per capita is about 4786 kg (4.8 tonnes), which is almost twice the average CO_2 emission per capita of the 25 EU member states (about 2.5 tonnes) [35]. High energy consumption results in high CO_2 emissions, and vice versa. Environmental protection can be obtained if more sustainable domestic buildings are designed.

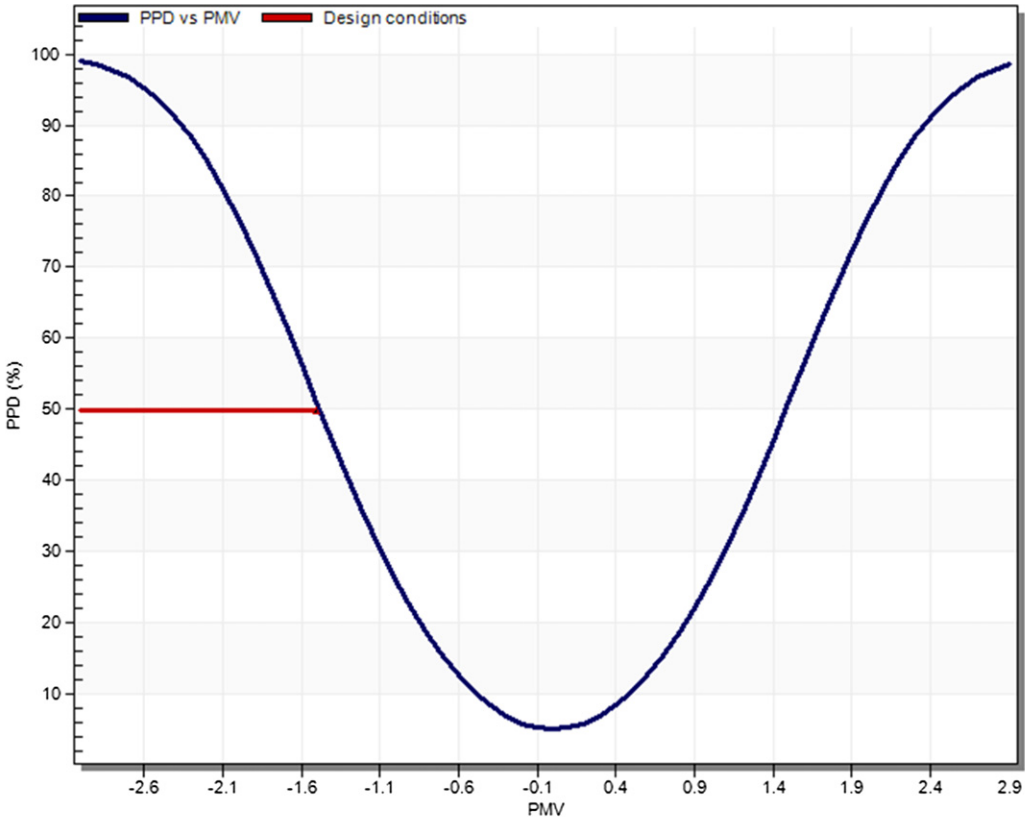

Figure 8. DesignBuilder thermal comfort graph.

3.2. Base case thermal comfort analysis

The thermal comfort of occupants is difficult to analyse because it is as much psychological as it is physiological. The term 'comfort' is a state of mind or a personal feeling—not a quantifiable metric [36]. However, Fanger has established a model to evaluate occupants' comfort with account to specific parameters. He extended the usefulness of his work by proposing a method by which the actual thermal sensation could be predicted by producing values for the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD) [36].

Acceptable PMV and PPD ranges:

- ASHRAE 55 standard states that the recommended thermal limit on the seven-point scale of PMV is between −0.5 and 0.5 with a corresponding PPD falling below 10%.
- ISO 7730 expands on this limit, giving different indoor environments ranges. ISO defines the acceptable comfort limits range between −0.7 and +0.7 for old buildings, and between −0.5 and +0.5 for new buildings.

EnergyPlus provides a sophisticated building thermal analysis tool that allows to determine if the environmental control strategy would be sufficient to maintain occupants thermal comfort [31]. This tool is the DesignBuilder thermal comfort calculator. The outcome of thermal comfort calculator is reflected by Fanger comfort model shown in figure 8.

Figure 8 indicates that the comfort analysis in the existing building falls outside the comfort limits with a PMV value of −1.48 and a PDD of 49.9% which implies the fact the indoor condition is cool. This can be justified with the lack of thermal insulation and hence the continuous operation of air conditioning to level the discomfort caused due to hot outer weather of Riyadh city. This is in line with [36] where it states that hot climatic region in summer season have a trend of −1 and −2 actual thermal sensation vote which shows that occupants are overcooled.

3.3. Validation

Validation ensures that research is conducted in an objective and unbiased way [37]. Accordingly, and to prove that the study is close to reality and representative of the actual building, a comparison of values between gathered real life energy consumption and DB simulated cases was made as shown in figure 9.

Due to increased levels of automation, lower costs, and other factors, the whole-building approach of building energy models (BEMs) is now more popular than the single-measure approach [38–41]. Since the BEM

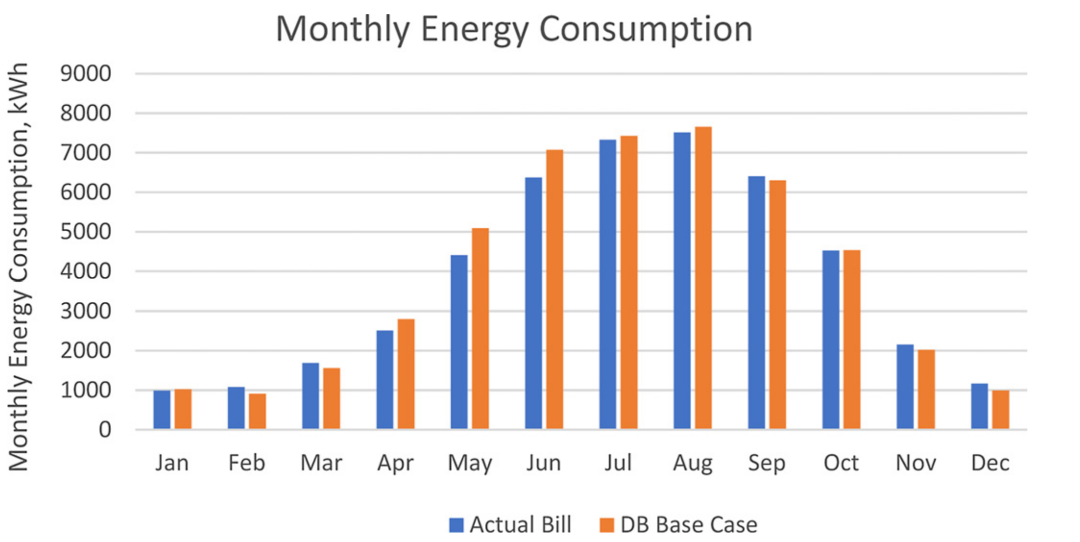

Figure 9. Comparison between actual and simulated monthly energy consumption.

Table 3. Three main criteria to validate a calibrated model. Reproduced from [38]. CC BY 4.0.

Data type	Index	FEMP criteria	ASHRAE guideline 14	IPMVP
Calibration criteria				
Monthly criteria %	NMBE	±5	±5	±20
	CV (RMSE)	15	15	—
Hourly criteria %	NMBE	±10	±10	±5
	CV (RMSE)	30	30	20
Model recommendation				
	R^2	—	>0.75	>0.75

accuracy is a deciding factor in all applications, calibrated models are needed. The task of determining the accuracy of BEMs is critical since once the model has been validated through a calibration process, it can be used to test and implement various strategies for reducing energy use while preserving human comfort. Calibration is defined according to ASHRAE 14-2014 guidelines as the: 'process of reducing the uncertainty of a model by comparing the predicted output of the model under a specific set of conditions to the actual measured data for the same set of conditions...' [42]. The three principal guidelines that clarify how to determine this 'degree' of confidence, its uncertainty, are FEMP [43–46], ASHRAE guideline 14, and IPVMP [47–50], summarised in table 3.

The principal uncertainty indices used are: normalized mean bias error (NMBE) found by equation (1), coefficient of variation of the root mean square error (CV(RMSE)) which measures the variability of the errors between measured and simulated values as in equation (2), and coefficient of determination (R^2).

$$\mathrm{NMBE} = \frac{1}{\overline{m}} \cdot \frac{\sum_{i=1}^{n} (m_i - s_i)}{n - p} \times 100\,(\%) \rightarrow \overline{m} = \frac{\sum_{i=1}^{n} (m_i)}{n}. \tag{1}$$

Where: m_i refers to measured value, s_i refers to simulated value, n is the number of measured data points (in this study $n = 12$ months), $(\bar{m})$ is the mean of measured values, p is the number of adjustable model parameters, which is suggested to be zero, for calibration purposes.

It is worth noticing that positive values mean that the model under-predicts measured data, and a negative one means over-prediction. ASHRAE guidelines [42] subtract measured values (m_i) from simulated ones (s_i) instead of FEMP [44, 45] and IPMVP [49], which do the opposite. For this reason, the explanation of the under- or over-prediction is inverted. In equation (2), the value of p is suggested to be one [50, 51]. Table 4 shows the final calculations for validating the model using both equations.

$$\mathrm{CV(RMSE)} = \frac{1}{\overline{m}} \sqrt{\frac{\sum_{i=1}^{n} (m_i - s_i)^2}{n - p}} \times 100\,(\%)\,. \tag{2}$$

Table 4. Validation of the model.

Month	Monthly consumption (kW h)		Difference (kW h)	Difference
	Measured (m_i)	Simulated (s_i)	($m_i - s_i$)	%
Jan	995	1024	−28.8	3%
Feb	1080	915	165.4	−15%
Mar	1689	1557	131.9	−8%
Apr	2509	2800	−290.9	12%
May	4410	5090	−679.6	15%
Jun	6374	7073	−698.9	11%
Jul	7329	7426	−96.9	1%
Aug	7510	7656	−145.2	2%
Sep	6403	6296	106.8	−2%
Oct	4522	4532	−10.0	0%
Nov	2156	2024	132.2	−6%
Dec	1165	998	167.0	−14%
Total	**46 143**	**47 389**		
Mean (measured values $\tilde{m}$)			2990.91	
(NMBE)			−3.47%	
(CV(RMSE))			12.57%	

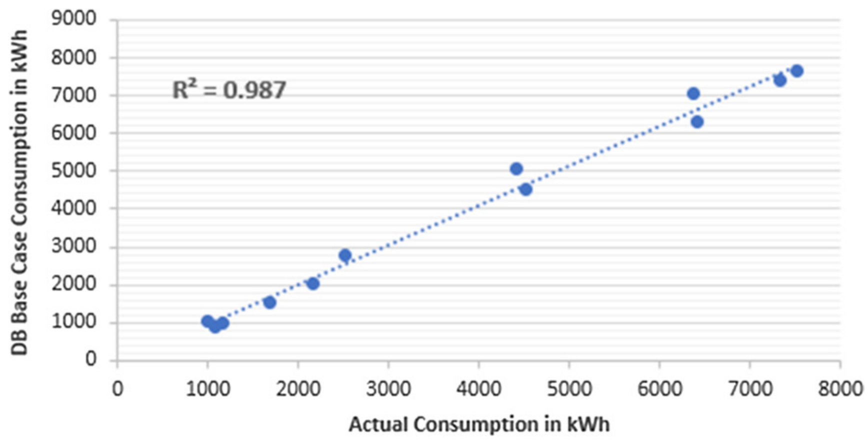

Figure 10. A plot of coefficient of determination between actual and simulated values.

Coefficient of determination (R^2) indicates the proximity of simulated values to the regression line of the measured values. It is a statistical index that is widely used to calculate the uncertainty of a model. It is limited to a range of 0.00 to 1.00, with the upper limit indicating perfect match of simulated and measured values while the lower limit indicating the opposite. Both the ASHRAE Handbook [52] and the IPVMP [49] suggest that it should never fall below 0.75. In this study, R^2 value was equal to 0.987 as depicted in figure 10.

It is obvious, according to the above validation criteria in table 3, that this model has met these guidelines and proven to be valid and indicates that the predictions from monthly simulation highly fit the data from the actual measurements.

3.4. Improvement on reference case based on individual parameters

Since most Saudi buildings heavily rely on mechanical cooling systems to ensure thermal comfort, a proper strategy for reducing the energy consumption is required. This included: (1) improvement of thermal resistance in building envelopes (walls and roof); (2) application of advanced window systems (window to wall ratio WWR, glazing type, and shading devices); (3) airtightness expressed by infiltration rate (i.e. air changes per hour ac/h); (4) the use of energy efficient mechanical systems (cooling setpoint temperature, and AC coefficient of performance CoP). The DB parametric analysis tool enables to see the effect of different parameters on the building's annual energy performance (in kW h). This process allows for comparing different inputs for each individual parameter in term of total annual energy consumption. For the purpose of this study, simulation parameters (also called variables) were categorised into: design-related and behaviour-related parameters described in table 5. These parameters, individually and as a whole set, were analysed in order to find their impact on the total energy consumption.

Table 5. Parameters considered for building improvement simulation.

Parameters		Description	
		Base case	Improved case
Design related	Ext. wall construction	No insulation (U value = 2.15 W m^{-2} K)	100 mm XPS (extruded) insulation (U value = 0.294 W m^{-2} K)
	Flat roof construction	No insulation (U value = 2.123 W m^{-2} K)	200 mm polyurethane foam insulation (U value = 0.131 W m^{-2} K)
	Glazing type	6 mm single glass (U value = 5.78 W m^{-2} K, SHGC = 0.62)	Double blue glass (6 mm/13 mm air) U value = 2.665 W m^{-2} K, SHGC = 0.497
	WWR	9%	9%
	Local shading	No external shading	Overhang + sidefins (0.5 m projection)
	Airtightness	Infiltration 1 ac/h	0.25 ac/h
Behaviour related	Cooling setpoint temp	20 C°	25 C°
	AC CoP	2.5	4
Total annual energy (kW h)		**47 389**	**15 467**
CO_2 emissions (kg)		**28 718**	**9373**
Total energy consumption change (%)			**67.4**

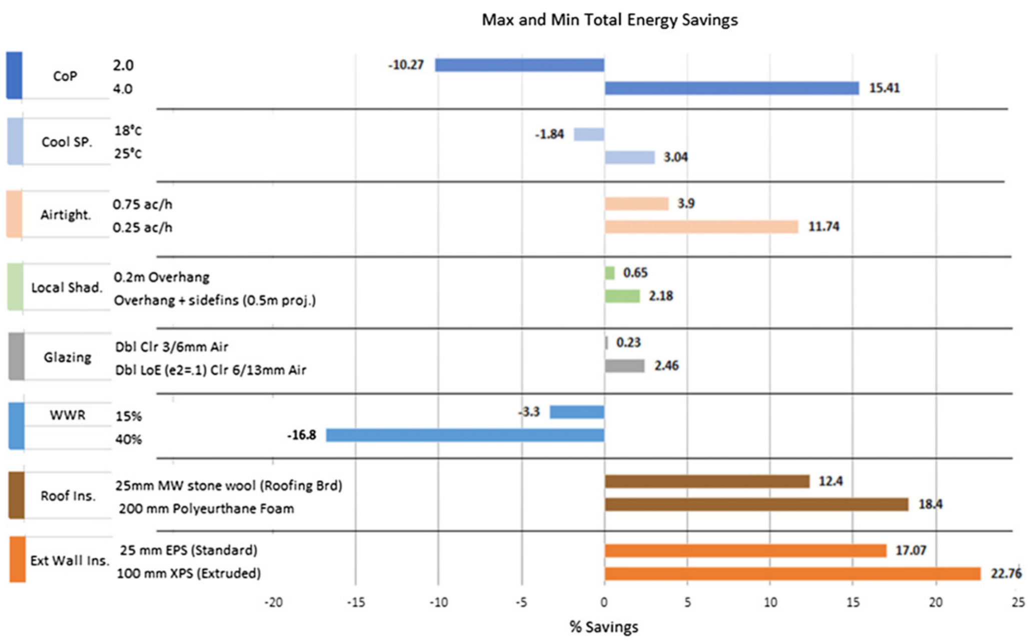

Figure 11. Impact of considered parameters on the total energy saving.

A detailed parametric analysis of the prototypical model can be used to determine the effect of many design and operating measures on the total annual energy consumption. Figure 11 depicts the total energy saving percentage through the complete simulation associated with all individual parameters (stated in table 5) where it can be seen that the improved case impact increases the energy savings.

As expected, figure 11 indicates that adding insulation has the most significant impact, reducing annual consumption by 22.8% and 18.4%, for walls and roof, respectively. It is worth noticing that the lower the U value of the insulation composition the better thermally the insulation will be leading to greater energy saving. This is mainly by the effect that thermal insulation materials pose on the heat gain through envelope elements which subsequently affects the dominant cooling load in a positive way. The combined addition of thermal insulation in building's walls and roof can achieve 31% to 45% savings in total energy consumption. This is consistent with other studies, which suggested energy reductions of 15% to 35% when complying with exterior walls and roofs thermal insulation requirements [53–56].

The measure with the second highest impact is installing an energy efficient air conditioning (i.e., CoP) which can result in 15% reduction of the annual energy consumption. According to SEEC, most common AC types used in dwellings are windows systems, and/or windows combined with split systems. Old versions of window AC (CoP = 2.0 to 2.5) are considered inefficient with respect to energy consumption [57].

Table 6. Requirements for thermal insulation.

Specification	Climatic zone	U values (W m^{-2} K)			
		Wall	Roof	Windows	Doors
	Z1	0.34	0.20	2.67	2.84
	Z2	0.40	0.24	2.67	2.84
SBC-602	Z3	0.45	0.27	2.67	2.84
SEC	All zones in SA	1.75	0.6	2.9	5
Base case	Z1-Riyadh	2.15	2.12	5.78	2.38
Improved case	Z1-Riyadh	0.29	0.13	2.67	2.38

Increasing the WWR negatively affects the energy consumption and leads to no saving as shown in figure 11. This falls in line with [14] where adopting a WWR of 40% led to 32% increase in the total energy use. However, a study done by [33], reported that only a 2% difference in the annual energy use was observed between the WWR of 25% and 50% which reflects the minimum overall effect on energy consumption.

The greater the airtightness at a given pressure difference across the envelope, the lower the infiltration [31]. The Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) suggests that there are a growing number of studies indicating that there is considerable impact on energy use in buildings in mild and hot climates [12]. For the purpose of this study, the reference building is assumed to have an infiltration rate of 1.0 ac/h. Reducing this rate to 0.25 ac/h will lead to 12% saving. Therefore, it is highly recommended to design and construct the building fabric to be reasonably airtight and to seal air leakage sources around building envelope as this positively contribute at maintaining good indoor air quality and minimising energy use [12].

Finally, minimum impact on energy saving was noticed when considering other energy efficiency measure (EEM) such as increasing the cooling set temperature, installing double glazing windows, and utilising local shading. Interestingly, the effect of two behaviour related parameters, cooling setpoint temperature and CoP, contributed to an annual energy saving of 18%. This is to quantify the overall effect of occupants' behaviour related variables on total energy consumption. The Saudi Energy Efficiency Centre (SEEC) recommends the set thermostat point of air conditioning be between 23 °C and 25 °C [57] although in most cases occupants still tend to set their internal cooling temperature at 18 °C [58].

3.5. Impact of residential buildings regulations based on the new Saudi energy conservation code (SBC-602) and Saudi Electricity Company (SEC)

Many countries around the world are using regulation for new buildings to produce minimum values of thermal insulation, with an analysis of the economic and environmental impact on the country [59–62]. As previously mentioned, the 2030 vision aims to control the high load demand in several ways, like making all buildings efficient. Hence, the SBC-602 is being eventually reinforced by the Saudi government. The main goal of SBC-602 is to decrease the cooling and heating load with optimum thermal insulation. In the past, the SEC has initiated a set of minimum requirements of thermal insulation to achieve efficiency in new and existing buildings as well. Table 6 represents the requirements for thermal insulation in local authority codes (SBC-602 and SEC) which only consider the thermal characteristics of building envelope members (wall, roofs, and glazing's (W m^{-2} K). It also stated those characteristics for both base and improved case.

This section will only evaluate the impact of applying thermal insulation requirements in zone 1 considering the vast area covered by climate zone 1 which is the most significant hot zone in Saudi Arabia [63]. To draw conclusion, the residential building will be studied in the following four scenarios:

- Not insulated (existing and relatively old buildings i.e., base case).
- It complies with the SEC construction specifications.
- It fulfils the SBC-602 thermal insulation requirements.
- It applies those parameters with the highest effect on energy demand (as in figure 11)

This section will only focus on the impact of improving the envelope insulation in reducing energy consumption in the residential sector. Hence, only the parameters mentioned in table 6 will be considered in the following analysis. Note that the basic case for comparison is at a setpoint temperature of 20 °C. The outputs of the studied four scenarios are summarised in table 7. By comparison between the base case energy used intensity (EUI) value and the results presented in the work of [64] for Riyadh, where the value ranged from 100 to 162 kW h/(m^2 year), it was found that the result obtained falls within the range that was obtained previously [33, 64, 65].

By comparison between these values and the results presented in table 7, it is found that the annual electrical energy when applying the minimum requirement of thermal insulation by SEC is still considered high when

Table 7. Summary output of the four scenarios.

Month	Base case	SEC		SBC-602		Improved case	
	Energy cons (kW h)	Energy cons (kW h)	Reduction (%)	Energy cons (kW h)	Reduction (%)	Energy cons (kW h)	Reduction (%)
Jan	1023.8	946.0	7.6%	812.4	20.7%	801.5	21.7%
Feb	914.6	857.4	6.2%	736.8	19.4%	729.5	20.2%
Mar	1557.1	1351.8	13.2%	1081.9	30.5%	1061.2	31.8%
Apr	2799.9	2309.3	17.5%	1689.1	39.7%	1639.1	41.5%
May	5089.6	3951.9	22.4%	2605.2	48.8%	2507.7	50.7%
Jun	7072.9	5417.9	23.4%	3488.3	50.7%	3342.6	52.7%
Jul	7425.9	5698.8	23.3%	3643.7	50.9%	3492.0	53.0%
Aug	7655.6	5868.3	23.3%	3739.1	51.2%	3580.1	53.2%
Sep	6296.2	4878.6	22.5%	3161.6	49.8%	3031.6	51.8%
Oct	4532.1	3599.8	20.6%	2418.6	46.6%	2329.9	48.6%
Nov	2023.8	1760.2	13.0%	1328.2	34.4%	1299.2	35.8%
Dec	998.0	928.2	7.0%	796.8	20.2%	787.7	21.1%
Total annual (kW h)	**47389.5**	**37568.1**		**25501.6**		**24602.2**	
Savings (kW h)		**9821.4**		**21887.9**		**22787.3**	
Savings (%)		**20.7%**		**46.2%**		**48.1%**	
EUI (kW h/m^2/Yr)	**117.4**	**93.1**		**63.2**		**61.0**	

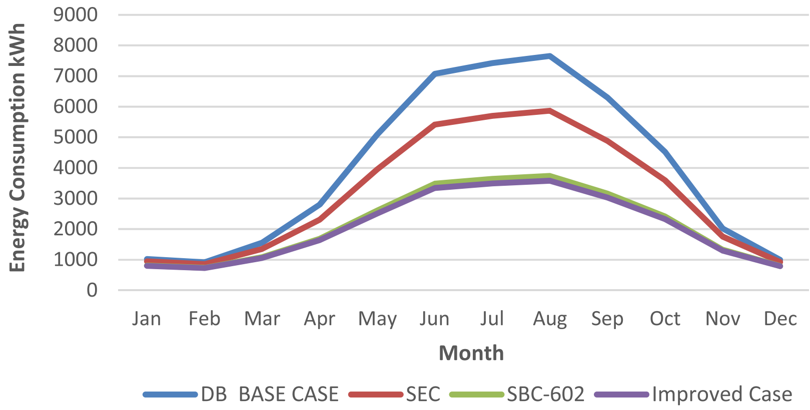

Figure 12. Comparison of the four simulation scenarios.

compared with SBC-602 and best improved scenarios. An annual energy reduction of 46.2% and 48.1% was observed when applying SBC-602 and improved case thermal insulation, respectively. SBC-602 and improved scenarios seem to be identical in terms of building energy performance where the annual saving of electricity consumption will be about 21 888 kW h and 22 787 kW h, respectively. The comparison of the total monthly electrical energy consumption at 20 °C can be seen in figure 12.

Figure 13 benchmarks the annual energy consumption per unit area of the existing case with different standards and results obtained by other researchers. The energy consumption value investigated in this study for the improved case is lower than the benchmark value for energy-efficient residential buildings in Norway, France, and Germany, which is, for instance, less than 70 kW h m^{-2} [66]. These standards reflect the importance and significance of efficiency requirement in domestic houses. It is worth mentioning that the analysis in section 3.5 only considered the application of proper insulation only and not the whole performance parameters which is discussed in section 3.6.

3.6. Benefit analysis for improvement of building energy performance

This work was inspired by [67] where they used the computational efforts required using the full combination options of efficiency measures to seek the optimum design strategy for a prototypical single-family house. In this study, optimal design values for 18 EEMs were evaluated through DB. In comparison to the current building, the simulation results of the enhanced building based on the various parameters examined showed a noticeable difference. Having investigated the effect of each parameter as described previously, this section will analyse the overall effect of the combination of all measures listed in table 5.

The combination of variables yielded a significant total energy reduction of 67% with only 15 467 kW h being used annually. Generally, the simulation tends to follow same trend as the base case where the peak energy consumption falls in July–August months (hottest months in the KSA). Hence, largest reductions also

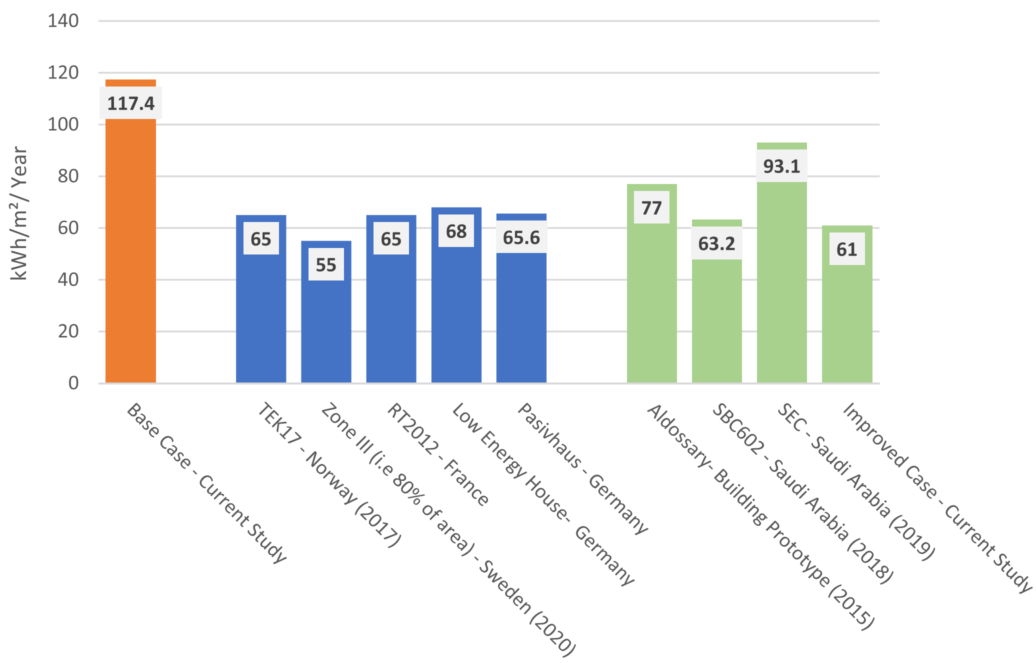

Figure 13. Comparison of annual energy consumption of different standards for residential buildings.

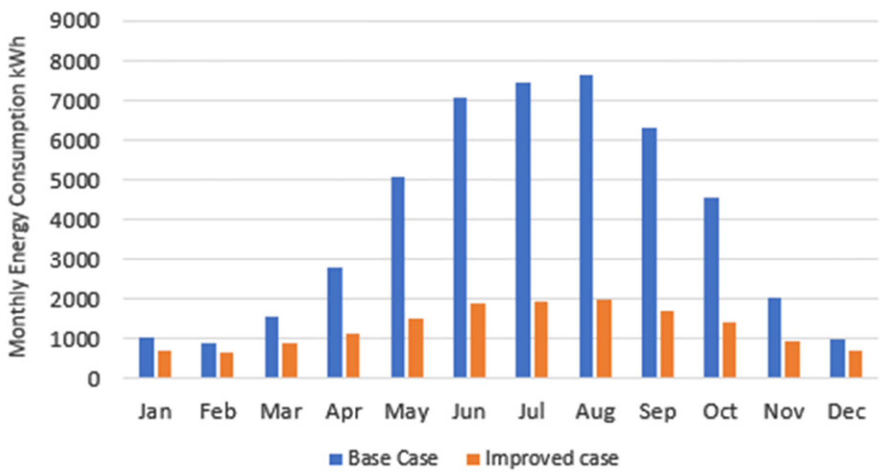

Figure 14. Comparison of monthly energy consumption of base and improved case.

happened during summer months (May–Oct), shown in figure 14. The cooling load of the existing building was responsible for 82% of the whole energy consumption. The significance of cooling is obvious since it was responsible to nearly 97% of total energy savings obtained in the improved design.

The price of 1 kW h of electricity is 0.18 Saudi Riyal (equivalent to $0.0479) according to the current stated cost of power production in the KSA [68]. This energy reduction leads to 5746 SR being saved of the energy operation cost. Moreover, 19.35 ton of CO_2 emission would also be reduced when adopting the changes in the improved case as mentioned in table 5. Environmentally, the avoided GHG emissions can be expressed in the annual number of cars not used. To clarify, when the annual amount of CO_2 avoided is divided by the typical passenger vehicle emission which is about 4.6 metric tons of per year, 4.2 vehicles will not be used. This GHG analysis was conducted according to the United States Environmental Protection Agency [69].

4. Conclusions

This paper presented an investigation of energy consumption parameters of a two-floor residential villa using DesignBuilder software, and this is based on the deriving method that will further provide a benchmark of whole-building energy management. Among the advantages examined in this analysis are reducing electricity demand and subsequently lowering peak demand pressures, reducing carbon emissions and improving the environment, as well as contributing to economic saving opportunities in term of energy operational costs at individual and national levels. It is found that energy efficiency measures implementation for domestic buildings has a great potential to reduce electricity demand and subsequent carbon emissions by 67%. The result indicates that application of thermal insulation only can achieve savings of 21 325 kW h/year in total energy consumption, that is 45%, as highlighted in the villa case study. The study draws some broad suggestions for enhancing residential building sustainability.

- Assuring that the existing code of building energy efficiency is followed and applied in all new construction. At least once every five years, the code should be revised and updated to reflect advancements in energy efficiency strategies.
- Implementing gradually a mandatory programme for energy efficiency retrofit of domestic buildings, especially applied in new buildings in zone 1 since most regions in Saudi Arabia fall in this zone.
- Providing government support and financial incentives for house owners to carry out efficient retrofitting and tackle the implementation costs of EEMs.
- Using efficient insulation in the housing envelope.
- Raising public consciousness about how to reduce energy use by educating building users and occupants.
- Local authorities should update some of their building regulations to include some of the parametric improvement included in this study in their guidelines and specification for buildings. For example, they may recommend efficient materials to be used in the construction process and thermal insulation.
- Building designers should include performance simulation as part of design process as this step could lead to potential future savings. Designers are mainly architects and they hardly pay attention to the operational aspect of the building. Therefore, it is suggested to involve engineers at the design stage to assess their building performance and ensure if that building is in accordance with the SBC or other relevant standards.
- Researchers are suggested to do a little bit further to introduce new sustainable technologies such as renewable materials or to provide some evidence to the authorities to improve the regulations and enhance the building performance. They can assist to set up a new benchmark for the building to meet the target of the sustainable development or search for some sustainable materials and test its functionality in the local climate; for example, aerogel materials which is a new material that can be used as an insulation. In addition, cost-benefit analysis should be covered in further studies to provide sufficient data about building improvement investment cost, feasibility, and the overall impact of saving energy on the country development.
- To have an efficient residential building, it is recommended that the building energy consumption for detached houses not to exceed 63 kW h m^{-2}.

This paper reflects that when broader system advantages are factored into the analysis of energy efficiency investment options, their attractiveness to government is dramatically increased. This can lead to a huge step forward for a sustainable economy and a healthy environment of Saudi Arabia.

Conflict of interest

The authors have declared no conflict of interests exists.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix A. Building elements construction details

Building element	Number of layers	Description of layers	Total thickness (mm)	*U* value (W m^{-2} K)
External walls	3	25 mm stucco + 200 mm concrete hollow block + 20 mm cement plaster	245	2.146
Internal walls (partitions)	3	20 mm cement plaster + 200 concrete hollow block + 20 mm cement plaster	240	1.728
Roof	6	25 mm terrazzo + 25 mm cement sand render + 50 mm sand + 5 mm bitumen + 220 mm cast concrete + 200 mm air gap+ 15 mm gypsum plasterboard	540	2.123
Internal floor (ceiling)	5	12 mm ceramic + 25 mm cement sand render + 50 mm sand + 220 cast concrete + 150 mm air gap+ 15 mm gypsum plaster	322	2.047
Ground floor	4	12 mm ceramic + 25 mm cement sand render + 50 mm sand + 100 mm cast concrete	187	2.767
Windows	1	6 mm single pane blue glass	6	5.778
External doors	3	3 mm steel + 40 mm air gap + 3 mm steel	46	2.856
Internal doors (rooms)	1	40 mm woods	40	2.381
Internal doors (toilets)	3	3 mm aluminium + 25 mm EPS + 3 mm aluminium	31	1.258

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