Analysis of Optimal Energy Performance for Commercial Buildings in the GCC Region

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1 Introduction

Bahrain, Kuwait, Kingdom of Saudi Arabia, Oman, Qatar, and the United Arab Emirates are countries located in the Middle East and form an alliance known as the Gulf Cooperation Council (GCC) based on economic and political agreements. The economy of these six countries depends heavily on oil and gas for domestic energy consumption and export revenues [1]. The GCC region holds almost 40% and 20% of the world's known oil and gas reserves, respectively [2]. The national GCC energy consumption has significantly increased in the last decade due to a rapid growth in population size and economic development. By 2020, the population is expected to increase by 30% from the year 2000 and reach 53.5 million, with a projected 56% increase in gross domestic product (GDP) [3]. Furthermore, international companies have established significant base operation in most GCC countries due to their relatively low prices in energy, labor, and taxes [4]. As a result, between 2000 and 2010, energy consumption attributed to buildings has doubled as outlined in Fig. 1 and is expected to increase annually by 10–15% rate until the year 2020 [2]. As clearly indicated in Fig. 1, buildings in the GCC region consume almost exclusively electricity to operate.

Table 1 shows the electrical power capacity, average electricity price, electricity annual consumption per person, and the per-capita annual carbon emission for all GCC countries obtained from various sources [1–3]. In particular, Table 1 indicates that the GCC region has 115,287 MW of available electric power generating capacity with 69% from natural gas and 31% from oil products. The GCC region is considered to be one of the world's largest per-capita contributors to greenhouse gas

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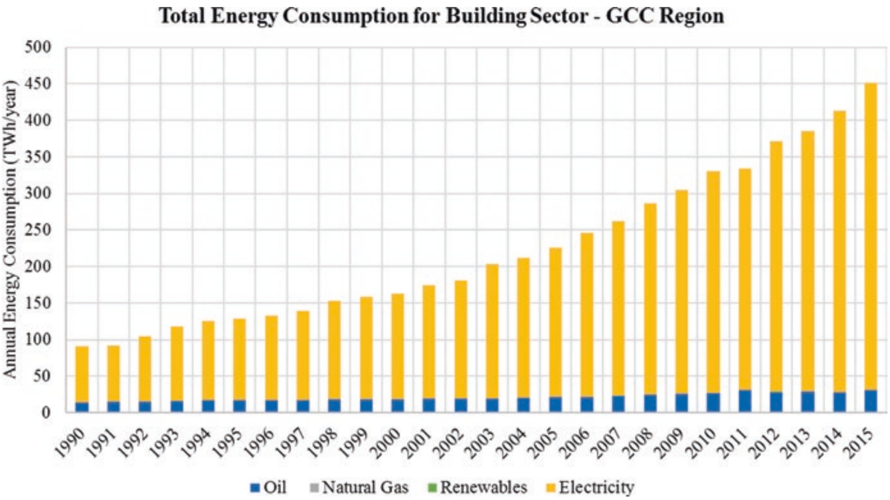

Fig. 1 Total annual energy use of the building sector in the GCC region between 1990 and 2015

Table 1 Electricity prices, energy use, and carbon emission indicators for GCC countries

Country	Cost of electricity ($/kWh)[a]	Electricity generation capacity (MW)[b]	Electricity consumption per capita (kWh/person)[c]	Total final energy consumption per capita (TOE/person)[c]	CO_2 emissions per capita (tons/person)[d]
Bahrain	0.008	3889	20,190	4.568	23.450
Kuwait	0.007	18,000	14,951	4.523	25.224
Oman	0.026	8750	6588	4.548	15.443
Qatar	0.022	8900	17,460	8.769	45.423
Saudi Arabia	0.013	46,400	9926	4.6	19.529
UAE	0.080	29,348	12,916	5.805	23.202
GCC	0.041	115,287	147	0.095	0.865

[a] Average prices in 2014 for residential buildings estimated based on 500 kWh of consumption [28]
[b] Data for 2015 obtained from IRENA [29]
[c] Data for 2015 obtained from IEA [1]
[d] Data for 2014 obtained from the World Bank [5]

emissions with all six countries accounting for the top 25 highest carbon dioxide emissions per capita [2].

The average building energy consumption per capita for the GCC region has been increasing significantly over the last two decades as illustrated in Fig. 2 especially when compared to the same metrics in the world. However, the GCC region per-capita building total energy use remains lower compared to the values reported for the EU and especially the USA as illustrated in Fig. 2a [1]. It should be noted that the building energy consumption per capita for EU and the USA has started to decline since 2009 even though they remain significantly higher than the global

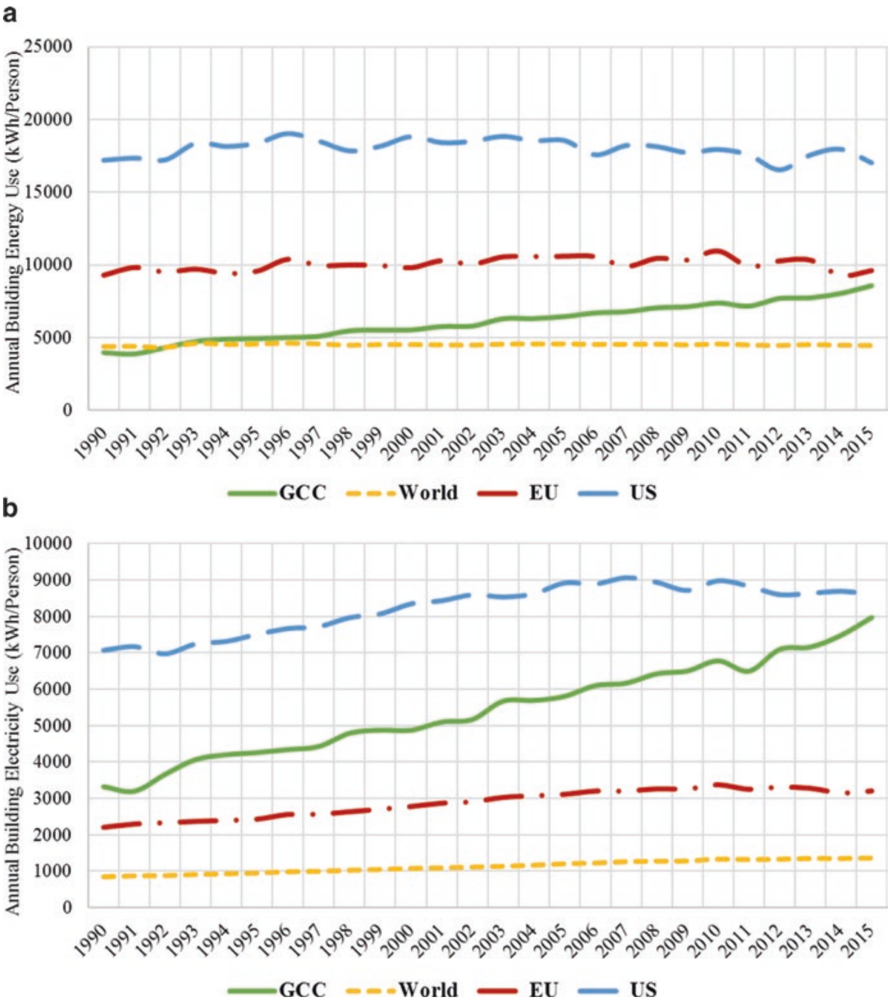

Fig. 2 Annual per-capita building (**a**) total final energy consumption and (**b**) total electricity consumption of the GCC region compared to those of the USA, EU, and world

average. The rate of increase in the GCC region is even more pronounced for the per-capita building electricity consumption compared to that observed for the world, EU, and the USA as outlined in Fig. 2b. Currently, buildings consume almost the same electricity per capita in the GCC region than that reported for the USA.

Using a commonly used building energy performance indicator, building energy use per floor area or energy use intensity (EUI) data are compiled for the GCC region and compared to those in other regions in the world as listed in Table 2 [32]. Specifically, Table 2 clearly indicated that the EUI values for the GCC have been increased significantly between 2000 and 2012 while and EUI values estimated for

Table 2 Energy use intensity (expressed in kWh/m^2) for the building sector for the Arab region, world, USA, EU, China, and India estimated for 2000, 2006, and 2012

Country region	2000	2006	2012
World	200	175	165
EU	223	215	187
USA	212	207	197
China	131	108	102
India	195	180	165
Arab region[a]	196	238	273

[a] Estimated using the average building floor area estimations discussed in Sect. 3.3

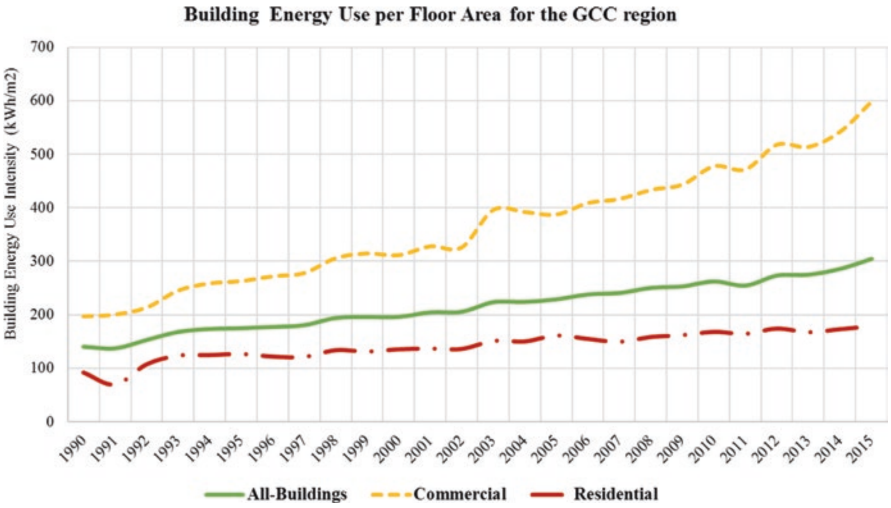

Fig. 3 Energy use intensity variations for commercial, residential, and all building types for the GCC region during the 1990–2015 period

the world, EU, USA, China, and India are generally decreasing over the same period [32]. The increase of standards of living and the lack in any substantial energy efficiency programs have been suggested as the main reasons for this decrease in energy efficiency levels of the building sector in the GCC region [32].

Figure 3 shows the EUI variations for the 1990–2015 period for the GCC region by building type. It is clear that the EUI values for the commercial buildings are significantly higher than those for the residential buildings with the difference gaps widening especially since 2000. The GCC region has seen its commercial buildings' EUI doubled from 311 kWh/m^2 in 2000 to 598 kWh/m^2 in 2015. Meanwhile, the residential building sector EUI has slightly increased by 31% from 136 kWh/m^2 in 2000 in 2015. This trend is most likely attributed to the prevalent use of energy-intensive equipment in the commercial building sector including AC systems within all the GCC countries.

In this paper, potential benefits of reducing energy consumption for commercial buildings are evaluated for all the countries in the GCC region. In particular, optimized designs and energy retrofit measures are analyzed to assess their impacts for new and existing buildings in each GCC country.

First, a review of the literature is summarized to identify the various reported design and retrofit options suggested to improve the energy performance of buildings within the GCC region. Then, a detailed evaluation is described to assess the benefits for implementing energy efficiency measures for prototypical commercial buildings located in representative locations within the GCC region. A bottom-up approach is then used to estimate the impacts of scaling-up energy efficiency programs for the commercial building sector in all the GCC countries.

2 Literature Review

This section provides a brief summary of the reported studies specific to the building energy performance and potential benefits of implementing energy efficiency programs and policies for each country within the GCC region.

2.1 United Arab Emirates

United Arab Emirates (UAE) has experienced over the last two decades a rapid urban growth leading to significant increase in carbon dioxide emissions per capita, as well as in energy consumption. In order to maintain comfortable indoor environment, UAE requires regular air-conditioning that represents over 60% of the electrical peak demand during the summer season and 40% of the average annual energy consumption. The high space cooling demands are due to the high design temperatures (45 °C dry bulb, 30.6 °C wet bulb), humidity (70% summer, 80% winter), and solar irradiance (20 MJ/m^2/day average annual global horizontal irradiance) [6]. Furthermore, the increase in the country's building energy consumption has intensified by delayed implementation and enforcement of adopted energy efficiency codes and by the relatively low energy prices [6]. Therefore, energy efficiency measures need to be applied to both new and existing buildings in order to reduce the country's energy consumption. The impacts on energy performance of UAE buildings of some design and retrofit options have been outlined by several studies reported in the literature as summarized in the following sections.

Geometric characteristics such as shape, layout, orientation, and window size can significantly affect the energy consumption of a building since they dictate exposure to climatic factors such as thermal, wind, and solar energy [6]. A study by Aboulnaga et al. [9] compared four residential buildings that had different building orientations in the city of Al-Ain. The study concluded that by limiting the window to wall ratio (WWR) to 1:6, and by constraining the windows to two orientations, building energy savings can reach up to 55%.

The addition of thermal insulation and/or a reduction in the absorbed solar radiation on the building's exterior surfaces can significantly reduce cooling loads. In the last decade, UAE has established prescriptive requirements for the thermal performance of building envelopes. In Dubai, U-values are restricted to a maximum of 0.30 W/m^2-K for roofs and 0.57 W/m^2-K for walls as required by the Dubai Green Building Regulations [6]. As for Abu Dhabi, U-values have to be lower than 0.14 W/m^2-K for roofs and 0.32 W/m^2-K for walls [10]. Friess et al. [11], Radhi [12], and Al-Masri et al. [13] conducted experimental analyses for residential villas located in Dubai, Al-Ain, and Abu Dhabi, respectively. They tested the effects of thermal insulation and thermal mass on the building's energy consumption. Specifically, Friess et al. [11] indicated that a villa in Dubai achieved 23% in electrical energy savings when only 50-mm EPS insulation was added to 54% of the building's enclosures, which helped reduce the wall's U-value from 2.40 W/m^2-K to 0.60 W/m^2-K. However, when the entire villa's perimeter was insulated with additional insulation using 160-mm EPS insulation to further reduce the wall's U-Value to 0.23 W/m^2-K, only additional 11% of electrical savings were achieved. Radhi [12] conducted a similar experimental analysis on a villa located in Al-Ain. He concluded that a total of 19% of savings can be achieved in cooling energy use if wall and roof U-values decrease from 2.32 W/m^2-K and 0.60 W/m^2-K to 0.30 W/m^2-K and 0.23 W/m^2-K, respectively. Radhi [12] also achieved a 13% reduction in cooling energy use when the concrete thickness was increased from 150 mm to 250 mm. Another study conducted by Al-Masri [13] tested the effect of adding both insulation and thermal mass on a villa located in Abu Dhabi. A total energy reduction of 3% was achieved when insulation thickness was increased from 50 mm to 100 mm. However, only 1% energy reduction was achieved when the building's thermal mass increased by changing the wall concrete layer thickness from 250 mm to 400 mm. Therefore, only adding the appropriate levels of thermal insulation and thermal mass to the building's envelope can effectively decrease the building's total energy consumption.

Solar heat gains can significantly increase the building's cooling thermal loads in UAE. Currently, Dubai Green Building Regulations requires all new buildings to have 75% of their exposed walls coated with paintings that have a minimum reflectance value of 45% and for all low and flat roofs to have a minimum Solar Reflective Index of 78 [10]. Radhi [14] tested the effect of solar heat gains on a three-story university building's wall cladding system in Dubai. Al-Sallal [15] investigated the effect of solar absorption using various landscaping options for a villa located in Abu Dhabi. He concluded that adding trees to reduce direct and reflected solar heat gains can reduce the wall and window thermal loads by 18% and 31%, respectively, and reduce the total villa's cooling energy by 6%. M. Haggag [16] studied the effect of a green wall system on energy performance of an institutional building in Al-Ain. The analysis found that the green wall helped reduce the temperature of the building's external wall by a range of 5–13 °C and hence reduced the building's cooling thermal loads.

Since UAE has high solar irradiance and sky illuminance levels, Dubai Green Building Regulations requires all new buildings to have 50% of their glazed walls and be located in the northern facades. Furthermore, buildings with facades that are more than 60% glazed require a maximum U-Value and shading coefficient of 1.9 W/m^2-K and 0.25, respectively, and a minimum of 0.1 light transmittance [10]. Aboulnaga [9] conducted a study on a two-story residential building in Al-Ain to test the thermal performance of various window glazing designs. A total of 55% of total energy savings were achieved when the building's windows were restricted to the northern and eastern elevations using 10–20% window to wall ratios. Al-Masri [13] evaluated the effect of window glazing type for a 14% glazed residential building in Dubai. The study indicated that 12% and 15% of energy savings were achieved when single glazed windows were modified to double and triple low-e glazed windows, respectively. Friess et al. [11] investigated the effect of changing double glazed windows to triple glazed windows with low-e and high reflectivity properties on a 21% glazed villa in Dubai. It is found that the villa's annual energy consumption decreased by 5%. Hammad et al. [17] tested the effect of adding lighting controls and external dynamic louvres on a 60% glazed small office building in Abu Dhabi. The building experienced a decrease of 28–34% in its annual energy consumption. Al-Sallal [15] also tested the effect of external shading techniques by adding vegetation outside a villa located in Abu Dhabi. He demonstrated a total of 7% reduction in total energy consumption.

Some studies analyzed the effects of introducing natural ventilation into UAE low-rise buildings. Using computational fluid dynamics (CFD) models, it is found that cooling energy can be reduced by 30% when outdoor conditions were suitable and occupants relied on natural ventilation by opening windows than turning on their air-conditioners [6]. The use of courtyards, wind towers, and solar chimneys into the building's layout can further reduce the energy consumption by 35–73%, depending on the mixed mode of ventilation strategy used [6].

2.2 *Oman*

Buildings in Oman account for more than 75% of Oman's total electricity consumption. It is estimated that without any energy efficiency program, Oman will experience significant increase in energy consumption and electrical peak demand to reach 55,288 GWh and 11,240 MW, respectively, by 2030 [18]. Currently, Oman has no enforceable energy efficiency programs for the building sector. Moreover, only limited reported studies have evaluated options and impacts to improve the energy performance of new and existing buildings in Oman. Krarti and Dubey [18] studied the impact of a wide range of energy efficiency measures and their effect on various residential and commercial buildings located in Oman. They found that optimal set of energy efficiency measures applied to all building types can reduce energy use and electrical peak demand by over 50% compared to current design practices [18]. Moreover, they found that a basic energy retrofit of the existing residential building stock in Oman can achieve savings of 957 GWh in annual energy consumption and 214 MW in electrical peak demand [18]. Mallela et al. [19] found that through simulation analysis 26% in annual energy savings can be achieved for a building located in Oman when the cooling set point was increased from 20 °C to 24 °C and when lighting consumption was decreased by 25%. Malik [20] examined the impact of retrofitting lighting and air-conditioning measures on commercial and governmental building stocks in Oman. He found that reductions can reach 596 MW in electrical peak demand and 44 TWh in annual energy consumption generating up to 597 millions of dollars in savings.

2.3 Qatar

Limited analyses have reported to assess impacts of energy efficiency measures on building thermal performance in Qatar. Kharseha et al. [22] indicated that 46% reduction in total cooling thermal load can result for a building located in Qatar when (1) thermal insulation was added to the building's walls and roof, (2) the cooling set point was increased from 22 °C to 24 °C, and (3) more energy-efficient lighting fixtures were installed. Krarti et al. [21] evaluated the benefits of multiple energy efficiency measures for both new and existing buildings. The investigated energy efficiency measures include addition of thermal insulation, implementation of improved glazing, use of shading devices, installation of better efficacy lighting fixtures, increase of cooling temperature set points, and specification of high energy performance HVAC systems. As a result of optimal designs and retrofits, residential buildings can achieve savings of 58–65% in annual energy consumption and 66–70% in electrical peak demand of 7–66%. Similarly, savings obtained for commercial/governmental found to range between 56% and 60% for annual energy consumption and 61% and 65% for electrical peak demand. Krarti et al. [21] estimated that the combined impacts of improvement energy performance of new building construction and existing building stock can reduce the annual energy consumption and electrical peak demand by 11,000 GWh and 2500 MW, respectively.

2.4 Kingdom of Saudi Arabia

The building sector accounts for the majority of the total electricity consumed in the Kingdom of Saudi Arabia (KSA). Several studies and analyses have been carried out to assess the impacts of adopting renewable energy and energy efficiency programs for various KSA sectors including buildings [23]. In particular, Abd-ur-Rehman et al. [24] investigated the impact of applying the International Energy Conservation Code (IECC) as a standard residential building in Saudi Arabia. The results indicated that significant energy use savings could be achieved including 56% for space cooling, 37% for space heating, 46% for lighting, and 27% for appliances against current design practices. Furthermore, Krarti et al. [23] used a detailed simulation analysis to determine optimal sets of measures to improve the energy performance for both new and existing buildings. Implementing and enforcing these optimal set of measures for new KSA buildings can reduce the annual energy consumption and peak demand by 1751 GWh and 468 MW, respectively. Moreover, retrofitting the existing building stock was found to be highly cost-effective and provide significant economic, environmental, and social benefits. For instance, a level 3 retrofit of residential building stock can results in an annual decrease of 1.3 million tons in carbon emissions [23]. However, level 2 and level 3 retrofit programs require significant investments to be implemented with estimated costs of \$104 billion and \$207 billion, compared to level 1's \$10 billion. Therefore, implementing level 1 retrofits on the country's entire building stock can be highly cost-effective. Finally, utilizing energy efficiency programs on KSA's residential and commercial building can save 27% and 30% on energy consumption and electrical peak demand, respectively [23].

2.5 Kuwait

Buildings in Kuwait consume 70–80% of the country's generated electrical power. Air-conditioning systems account for the majority of the consumed energy, since Kuwait is situated in a desert climate with an average ambient air temperature of 45 °C and intense solar radiation that can reach up to 940 W/m^2 on horizontal surfaces during the summer [8]. Krarti [7] investigated the impact of implementing and retrofitting new and existing buildings with energy efficiency measures. A base case model for a villa was used, and the building operations and schedules were collected from surveys in order to establish an analysis of the impact of retrofitting residential buildings on the country's energy consumption, peak demand, and carbon dioxide emissions. The building characteristics of the base case model were modified to match the Ministry of Electricity and Water's (MEW) energy code for buildings established in 1983 against the energy code for buildings established in 2010 [25]. Energy-efficient measures included adding wall and roof thermal insulations, modifying window types, implementing shading devices and techniques, reducing lighting wattage per square feet, adding 8.2 ft. of fence walls around the building, and utilizing HVAC equipment with a higher coefficient of performance (COP). As a result, the 2010 energy code for buildings achieved 23% of energy savings compared to the 1983 energy code since it had more stringent requirements. Implementing and enforcing optimal design and operating strategies from the 2010 energy code on new construction can reduce the annual energy consumption and peak demand by 164 GWh and 94 MW as well as decrease the annual emissions of carbon dioxide by 143×10^3 tons. Furthermore, an additional study conducted by Ameer and Krarti [26] confirmed that implementing the current Energy Conservation Code of Practice in comparison with MEW's 1983 energy code can yield a total of 22% in energy savings annually, as well as decrease the electrical peak demand by 24%, and decrease the carbon dioxide emissions by 17 tons per year for each individual residential building in Kuwait.

However, Krarti [7] recommended that in order to further improve the energy efficiency of the building sector in Kuwait, the Ministry of Electricity and Water should update the energy code every five years to incorporate more stringent requirements and to perform energy efficiency retrofits for the residential buildings and then for the entire building sector in Kuwait. As a result, significant economic and environmental benefits can be achieved in Kuwait if both residential and commercial buildings adopt the stringent requirements.

2.6 Bahrain

The building sector in Bahrain consumes the majority of the total annual energy, with residential and commercial buildings accounting for 54% and 29% of the total energy consumed, respectively [27, 28]. However, only limited energy efficiency standards have been adopted in Bahrain to reduce energy consumption in the building sector especially for the existing building stock. Radhi [27] investigated the benefits of retrofitting a governmental building in Bahrain and found that 30% of monthly energy savings can be achieved by adding insulation to the roof and walls and installation of high efficiency lights and equipment. Furthermore, retrofitting the building's operation measures such as raising the set point temperature yielded 15–40% of savings in heating and cooling loads [28].

2.7 Review Summary

Countries in the Gulf Cooperation Council (GCC) have been witnessing a major development in their urban and socioeconomic growths which result in a significant increase in their energy demand. The building sector is responsible for a significant fraction of the increased energy consumption. Based on the reported analyses for the building sector, Table 3 summarizes the range of energy savings for each GCC country when energy efficiency measures are implemented mostly in residential buildings.

Table 3 Range of reported energy savings for improved buildings in the GCC region

Country	Range of energy savings	Sources/references
Bahrain	28–71%	[27, 28]
Kingdom of Saudi Arabia (KSA)	27–56%	[23, 24]
Kuwait	22–42%	[7–26]
Oman	57–66%	[18]
Qatar	58–65%	[21]
United Arab Emirates (UAE)	46–59%	[6]

As noted throughout the literature review, the reported analyses are mostly limited to improving the energy performance of residential buildings within the GCC region. It is the aim of the study presented in this paper to evaluate and assess the impact of providing optimal design and retrofit energy efficiency alternatives for new and existing commercial buildings in the GCC region. The results of the analysis can be suitable to investigate the effect of scaling-up energy efficiency programs to promote high performance residential and commercial buildings on the energy consumption for the entire GCC's building stock.

3 Analysis Methodology

A prototypical commercial building model developed by the US Department of Energy (DOE) was used to represent a medium-sized office building located in a hot and dry climate zone similar to that of the GCC region [29]. Specifically, the building model complied with ASHRAE standard 90.1 as well as American National Standards Institute (ANSI) and Illuminating Engineering Society (IES) codes [29]. In this study, the DOE prototypical commercial building model established for KSA conditions was adjusted in order to be suitable as a baseline model for all six GCC countries and assess the building's energy performance using detailed simulation analysis [30]. A series of parametric analyses were performed on the building in each individual country to test the effect of providing design and retrofit alternatives on the building's energy consumption, electrical peak demand, and carbon dioxide emissions. Finally, the building energy performance was optimized based on a life-cycle cost (LCC) analysis to select the energy efficiency measures that can minimize LCC value while minimizing the annual building energy consumption.

3.1 Commercial Building's Baseline Features

The commercial building model considered for the various analyses consists of a 16-story, 26,572 m^2 medium office building, comprised of four perimeter zones and a core zone that make up 40% and 60% of the total floor area, respectively, as shown in Fig. 4.

Each story is 50 m long and 33 m wide and has a floor to floor height of 4 m, as specified in the AECOM Middle East Property and Construction Handbook [31]. Table 4 lists the percent area each space type occupies in the commercial building. As indicated in Table 3, 70% of the building is composed of open and private offices, while the remaining 30% is distributed between conference rooms, restrooms, equipment rooms, and a lobby.

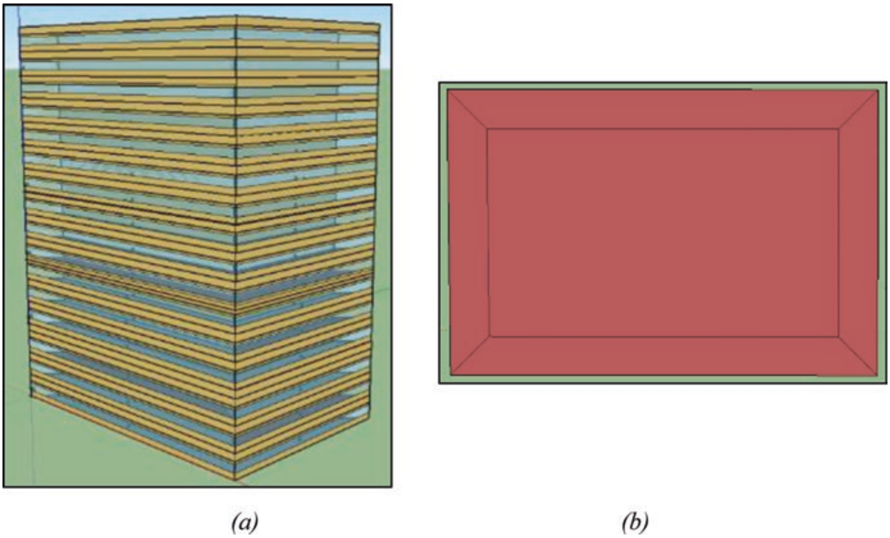

Fig. 4 Office building energy model. (**a**) 3D rendering and (**b**) thermal zones

Table 4 Percent area of building's space types

Space type	Percent area
Open plan office	40%
Executive office	30%
Corridor	10%
Lobby	5%
Restrooms	5%
Conference room	4%
Mechanical/electrical room	4%
Copy room	2%

3.1.1 Construction

Details and specifications of the building's constructions for walls, roofs, and floors were determined from the construction practices in the GCC region [7, 18, 23, 26, 28] as well as the US Department of Energy's Analysis of Building Envelope Construction specific to KSA [32, 33]. The construction layers in the baseline model did not include any insulation in order to mimic practices for the existing buildings in the GCC region, as well as to test the effect of adding insulation on the building's energy performance. Table 5 displays the materials and properties of the exterior wall's construction layers. The construction layers of the exterior walls yielded a total U-Value of 2.6 W/m^2-K. Furthermore, Table 6 displays the materials and properties of the roof's construction layers. The construction layers of the roof yielded a total U-Value of 4.6 W/m^2-K. Finally, the building's foundation was constructed using an unheated 203 mm concrete slab.

Table 5 Thermal properties of the exterior wall constructions

(38 × 89) mm steel frame walls at 0.41 m O.C.	Thickness (m)	Conductivity (W/m-K)	Resistance (m^2-K/W)	Density (kg/m^3)	Specific heat (J/kg-K)
Outdoor air film coefficient	–	–	0.030	–	–
25 mm Stucco	0.025	0.72	0.035	1856	840
16 mm Gypsum Board	0.016	0.16	0.099	800	1090
Air gap	0.016	4.80	0.003	–	–
16 mm Gypsum Board	0.016	0.16	0.099	800	1090
Indoor air film coefficient	–	–	0.122	–	–

Table 6 Thermal properties for the exterior roof constructions

Roof construction	Thickness (m)	Conductivity (W/m-K)	Resistance (m^2-K/W)	Density (kg/m^3)	Specific heat (J/kg-K)
Outdoor air film coefficient	–	–	0.031	–	–
Built-up roofing	0.009	0.16	0.059	1120	1460
Air gap	0.016	4.80	0.003	–	–
Metal decking	0.001	45.28	0.000	7824	500
Indoor air film coefficient	–	–	0.122	–	–

3.1.2 Fenestration

Despite the high temperatures and solar irradiance in the GCC region, some existing buildings still have low performance windows that contribute to buildings' high solar loads. Therefore, the baseline model incorporated single-pane, 3-mm clear glass windows that had a total U-value of 7.1 W/m^2-K, a solar heat gain coefficient (SHGC) of 0.82, and a visible transmittance (VT) of 0.76 [29]. Furthermore, the building had 33% of evenly distributed window to wall ratio (WWR) throughout the northern, southern, eastern, and western orientations. Finally, no shading techniques or fins were implemented on the baseline design.

3.1.3 Internal Loads

Based on the prototypical building model that followed ANSI/ASHRAE/IES Standard 90.1, the number of occupants was estimated at 18.6 m^2/person. Furthermore, the equipment power density was rated at 8 W/m^2, complying with the Ministry of Electricity and Water's Energy Conservation Program in Kuwait [25]. According to AECOM's Middle East Property and Construction Handbook [31], some countries in the GCC region are still using a range of 12–15 W/m^2 of lighting power density based on their local specifications. Therefore, in order to test the effect of lighting power density on the building's energy performance, the baseline model incorporated 2214 luminaires, with three fluorescent lamps per luminaire, and yielded a total of 15 W/m^2 of lighting power density.

3.1.4 HVAC System

The commercial building's summer and winter set points are set at 24 °C and 21 °C, respectively, as defined in the local specifications of the GCC countries in AECOM's Middle East Property and Construction Handbook [31]. The infiltration rate is set at 0.25 ACH as defined by the Kuwaiti Ministry of Electricity and Water's Energy Conservation Program [25]. Furthermore, the Energy Conservation Program specifies a maximum infiltration flow rate of 1.5 L/s/m^2 for all fenestrations. Based on the prototypical building model that followed ANSI/ASHRAE/IES Standard 90.1, and the Ministry of Electricity and Water in Kuwait, medium office buildings are eligible to utilize air-cooled HVAC systems [25]. Therefore, the building's cooling and heating loads are met by packaged rooftop air-conditioning units with VAV boxes that include electric reheat coils and dampers. The packaged rooftop units accommodate DX cooling coils, fans, filters, dampers, and control systems that help route air to the designated zones around the building through a series of ductwork. The VAV boxes with the reheat coils help adjust the airflow rate and temperature in order to cool or heat the zone and meet the desired set point. A coefficient of performance (COP) of 2.3 is used for the DX cooling coils in order to investigate the COP's impact on the building's energy performance and consumption. Finally, electricity is used as a primary source of energy in order to cool and heat the building, and natural gas is used for domestic hot water.

3.2 Parametric and Sensitivity Analyses

A series of parametric and sensitivity analyses were performed on the prototypical commercial building in order to assess the impact of each individual energy efficiency measure on the building's total energy consumption, electrical peak demand, and carbon dioxide emissions. Energy efficiency measures include improving the building's envelope construction, glazing, WWR, shading techniques, HVAC efficiency, and internal loads. Table 7 displays the options used to improve the building's performance for each category of energy efficiency measures as well as their implementation costs and the references considered to estimate these costs.

The first and second energy efficiency measures included adding insulation to the building's exterior wall and roof insulation to improve the building envelope's resistance to heat flow. The range of R-values implemented in the analysis was derived from ASHRAE 90.1 [29] and based on the availability of insulation materials in the GCC region. Furthermore, the Ministry of Electricity and Water's Energy

Table 7 List of energy efficiency measures and their cost of implementation

Energy efficiency measure		Initial cost	References
Exterior wall insulation (m^2-k/W)	R1.9	\$11.79/m^2	[26, 34]
	R2.3	\$15.31/m^2	
	R3.3	\$22.02/m^2	
	R4.4	\$29.45/m^2	
Roof insulation (m^2-k/W)	R1.9	\$11.79/m^2	[26, 34]
	R2.3	\$15.31/m^2	
	R3.3	\$22.02/m^2	
	R4.4	\$29.45/m^2	
Window glazing	Double tinted	\$203/m^2	[26, 34]
	Double reflective	\$210/m^2	
	Double tinted, low E, spectrally selective	\$294/m^2	
WWR	10%	Depends on glazing type	[26, 34]
	20%	Based on glazing	
	50%	Based on glazing	
	10% E-W, 20% S, 33% N	Based on glazing	
Shading projection	0.2 m	\$0/m^2	[26, 34]
	0.5 m	\$16.94/m^2	
	0.7 m	\$40.84/m^2	
Cooling COP	3	\$2122/RTU	[26, 35]
	4	\$2759/RTU	
	5	\$3862/RTU	
Infiltration rate	% reduction	\$0.54/LM	[35]*
Lighting power density	10 W/m^2	\$6.95/LED lamp	[35]*
	8 W/m^2	\$4.99/LED lamp	
	5 W/m^2	\$9.98/LED lamp	
Set point	25 °C (C)/20 °C (H)	\$0	[26]
	26 °C (C)/19 °C (H)	\$0	
Pump's motor efficiency	50%	\$211.66	[35]
	70%	\$291.66	
	90%	\$312.62	

Note: References with [*] do not include the labor rate but are accounted for in the optimization analysis

Conservation Program specifies a maximum wall U-value of 0.48 W/m^2-K and a maximum roof U-value of 0.34 W/m^2-K, in which both U-value requirements can be satisfied by adding R1.9 and R2.3 insulation, respectively.

The third energy efficiency measure assessed the effect of upgrading the window's glazing by improving the window's U-value and reducing the SHGC. The types of window constructions implemented in the analysis were derived from the Ministry of Electricity and Water's Energy Conservation Program and based on the availability of these window construction types in the GCC region [25]. Table 8 lists

Table 8 List of improved window glazing types

EEM 3: window glazing		
Window construction	U-value (W/m²-K)	SHGC
Single glazing, 3 mm clear glass, metal without thermal break	7.10	0.82
Double tinted (Blue) glazing, with 6 mm air gap	3.52	0.40
Double reflected glazing, with 13 mm air gap	2.44	0.25
Double tinted, low E, spectrally selective glazing, with 13 mm argon gap	1.36	0.23

the four glazing types considered for both the parametric and optimization analyses carried out for this study.

The fourth energy efficiency measure assessed the effect of providing design alternatives such as increasing, decreasing, or altering the window to wall ratio on several building orientations. The baseline design's WWR was set at 33%, and the building's performance is evaluated based on WWRs ranging from 10% to 50%. Furthermore, design considerations had to also be balanced between introducing more daylight into the building and considering heat gain during the summer and heat loss during the winter. Therefore, the building's performance is also evaluated based on WWR design modifications across various building orientations. The northern wall witnessed a WWR of 33% to provide diffused illumination and to maximize the amount of daylighting introduced into the building. Furthermore, a 20% WWR was applied to the southern wall, and a 10% WWR was applied to the eastern/western walls. Therefore, the building's energy performance is being evaluated based on higher WWR on the northern/southern exposures and limited WWR on the eastern/western exposures.

The fifth energy efficiency measure included adding overhangs to help reduce the solar load and to help diffuse daylighting prior to entering the building. To block the path of the sun coming from direct high solar angles, overhangs were added on the southern exposure. Furthermore, tilted overhangs were also added to the eastern and western exposures to block the path of the sun coming from direct low solar angles. The building's energy performance is being evaluated based on the effect of increasing the projection factor of the overhangs.

It is crucial to test the effect of improving the HVAC system's cooling COP since all six countries in the GCC region are dominated by air-conditioning systems. Therefore, the building's energy and HVAC performance is being evaluated based on the effect of improving the system's COP. However, since the medium office building is using a DX air-cooled system, a COP of 3, 4, and 5 does not necessarily mean the HVAC system will perform at its full rated COP capacity due to the harsh climate in the GCC region characterized by high outdoor temperatures during the summer.

The Ministry of Electricity and Water's Energy Conservation Program specified a maximum fenestration infiltration flow rate of 1.5 L/s/m² [25]. However, the prototypical commercial building model assigned a fenestration infiltration flow rate of

0.3 5 L/s/m^2. Therefore, the seventh energy efficiency measure investigates the effect of reducing the infiltration flow rate from the baseline design, as specified by the Ministry's Energy Conservation Program, to the infiltration flow rate assigned in the prototypical building model, in increments of 25%.

As noted earlier, all countries in the GCC region are still using a range of 12–15 W/m^2 of lighting power density based on their local specifications, according to AECOM's Middle East Property and Construction Handbook [31]. Therefore, EEM 8 tests the effect of reducing the lighting power density from 15 W/m^2 to 5 W/m^2. The baseline model incorporated 2214 luminaires, with (3) - 4 ft. fluorescent lamps per luminaire, and yielded a total of 15 W/m^2 of lighting power density. In order to reduce the lighting power density and maximize energy savings, all fluorescent lamps were upgraded to 4-ft LED lamps that can fit in the existing luminaires. Furthermore, installing the LED lamps does not require any rewiring and can work off of the existing ballast voltage.

The ninth energy efficiency measure investigates the effect of widening the deadband and decreasing the zone airflow rate by increasing the cooling set point and decreasing the heating set point by 1 °C on the building's performance and energy savings. Although some people might not accept a temperature set point of 26 °C for cooling and 19 °C for heating, it is important for people in the GCC region to implement a cultural shift by increasing awareness and proposing policy changes in order to improve the energy performance of commercial buildings.

The prototypical medium office building model specified a pump-motor efficiency of 30% for the building's water distribution system. Therefore the tenth, and final, energy efficiency measure investigates the effect of improving the pump's motor efficiency from 30% to 90% on the building's consumption and energy savings.

3.3 *Building Optimization Analysis*

An optimization analysis is performed to select all feasible and implementable energy efficiency measures using both life-cycle cost (LCC) analysis and total building energy use savings. Equations (1) and (2) display the formulas used to calculate the LCC for the baseline model and energy efficiency measures [36]. Equation (3) displays the formula used to calculate the simple payback period (SPP) of implementing the energy efficiency measures.

$$\text{Life Cycle Cost}(\$) = \text{Initial Cost}(\$) + \text{Energy Cost}(\$) \times \text{USPW} \tag{1}$$

$$\text{USPW} = \frac{1-\left(1+r_{\mathrm{d}}\right)^{-n}}{r_{\mathrm{d}}} \tag{2}$$

$$\mathrm{SPP} = \frac{\text{Initial Costs}}{\text{First Year Savings}} \tag{3}$$

where USPW = uniform series present worth, r_d = discount rate, n = period (years).

The life-cycle cost analysis was performed using a discount rate of $r_\mathrm{d} = 5\%$ and a life cycle of $n = 35$ years for the baseline design and all the energy efficiency measures, resulting in USPW = 16.4 [36]. A sensitivity analysis was also performed to assess the impact of the life-cycle period and discount rate, as discussed in the Optimization Analyses Results section. The building's energy cost is calculated using the energy usage (kWh) obtained from simulating the model in EnergyPlus [30] and multiplying the usage by the energy cost ($/kWh) for each country, as provided in Table 1. The implementation cost of each measure was calculated based on values provided by reference materials, manufacturers, and RS means [7, 18, 23, 26, 28, 34, 35]. Costs were typically given in terms of dollars per square meter or calculated per piece of equipment as noted in Table 6.

4 Selected Results

4.1 Baseline Design's Results

The baseline design model was simulated in EnergyPlus [30] using six different weather files that represent the countries of Bahrain (Manama), Kingdom of Saudi Arabia (Riyadh), Kuwait (Kuwait City), Oman (Muscat), Qatar (Doha), and the United Arab Emirates (Dubai). The total energy consumption, electrical peak demand, and carbon dioxide emissions were the three main results considered in the analysis. However, additional simulation results are considered including thermal loads, thermal comfort levels, and energy end-use distributions. Figures 5 and 6 display the total site and source energy consumed by the prototypical office building located in each GCC country.

Specifically, Fig. 5 displays the net site energy of the 16-story medium office building for each individual country in the GCC region. The total annual energy consumed by each country range from 251 to 268 kWh/m^2/year, with an average annual consumption rate of 265 kWh/m^2/year. Thus, the building yielded an average electricity consumption rate of 263 kWh/m^2/year for all six countries, which is significantly higher than 182 kWh/m^2/year, the average annual electricity consumed by US commercial buildings with comparable building floor space [37]. Bahrain and the Kingdom of Saudi Arabia have the highest and lowest energy consumption, respectively, while the remaining countries follow a similar pattern of electricity and gas consumption.

Figure 6 displays the net source energy of the 16-story medium office building for each individual country in the GCC region. The source energy includes the total kWh used to generate, distribute, and consume electrical power. The net source

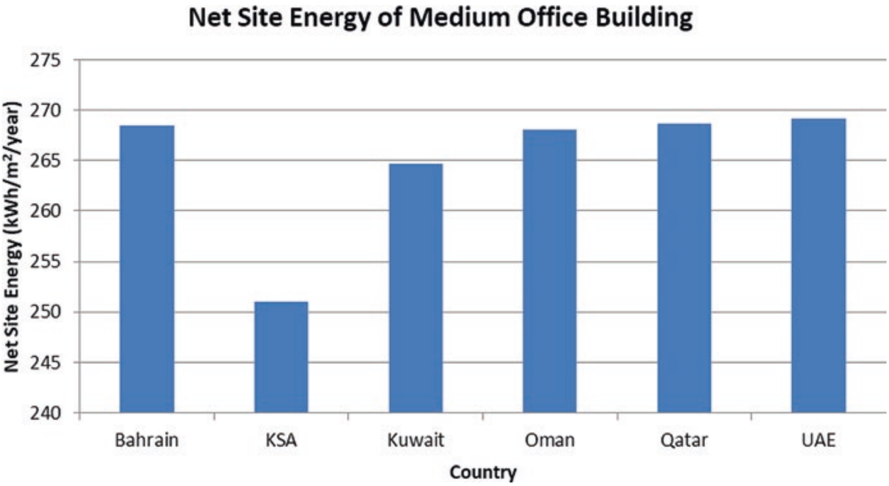

Fig. 5 Net site energy of medium office building in the GCC region

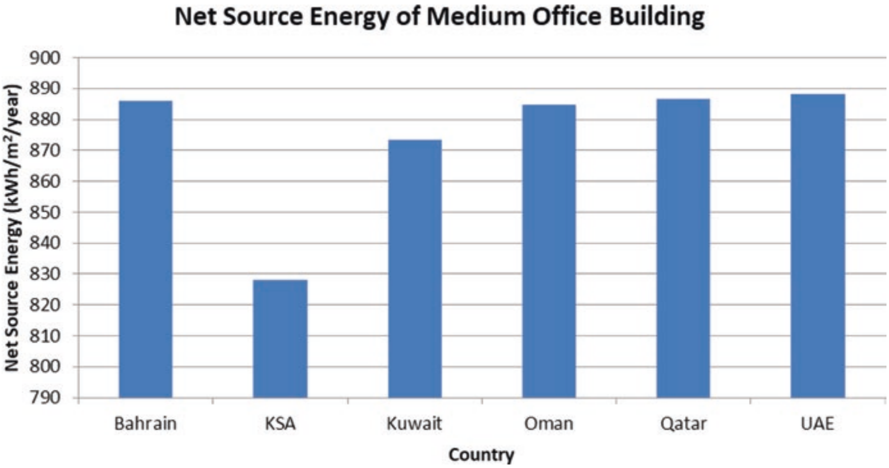

Fig. 6 Net source energy of medium office building in the GCC region

energy was calculated using a fuel source energy factor of 3.3 [7, 23, 26]. Therefore, for every unit of energy consumed on site, 3.3 units of energy are consumed in generation and distribution, and the process hence develops a site to source ratio of 3.3.

Figure 7 shows the end-use electricity distribution specific to the prototypical office building for all the GCC countries. As predicted, cooling energy consumes the majority of electricity, ranging from 44 to 49% of the total electricity consumed. Although the office building energy consumption is dominated by space cooling, the results indicate that a range of 15–18% of the total electricity consumed goes

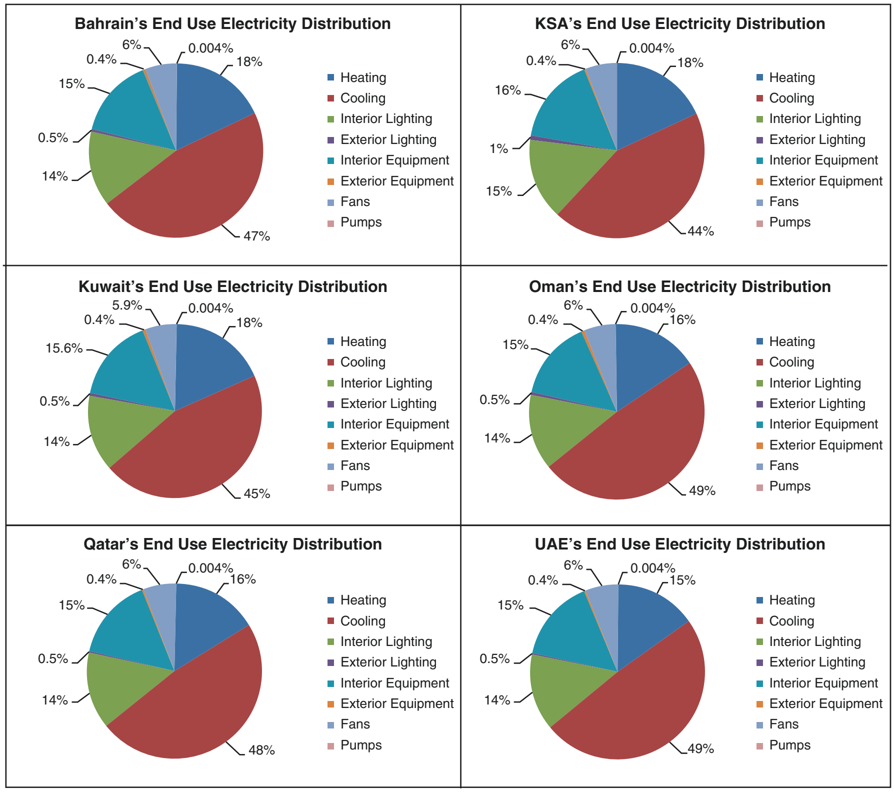

Fig. 7 End-use electricity distribution of GCC countries

toward space heating. Since countries in the GCC region typically tend to overcool their buildings (i.e., have cooling set point temperatures of less than 24 °C), the VAV reheat coils warm up the air in order to meet the set point and ensure the occupant's thermal comfort. Furthermore, interior lighting and equipment consume an average of 14% and 15% of the total electricity consumed, respectively, and the rest of the electricity goes toward fans, pumps, exterior lighting, and exterior equipment.

Building zones maintain 24 °C cooling and 21 °C heating set points during the building's occupied periods, which are scheduled from Sunday to Thursday, 7 am to 10 pm [38]. The building's HVAC system is scheduled to meet a set point of 27 °C for cooling and 16 °C for heating during unoccupied periods, including weekends and holidays.

One of the three main objectives of the analysis is to assess the building's electrical peak demand in order to reduce and/or eliminate power outages in some areas around the GCC region and to reduce the number of power plants operating throughout the region. The electrical peak demand is calculated based on the maximum wattage acquired during a billing cycle that is made up of 15-min intervals. Figure 8 displays the annual electrical peak demand for each of the individual countries. The

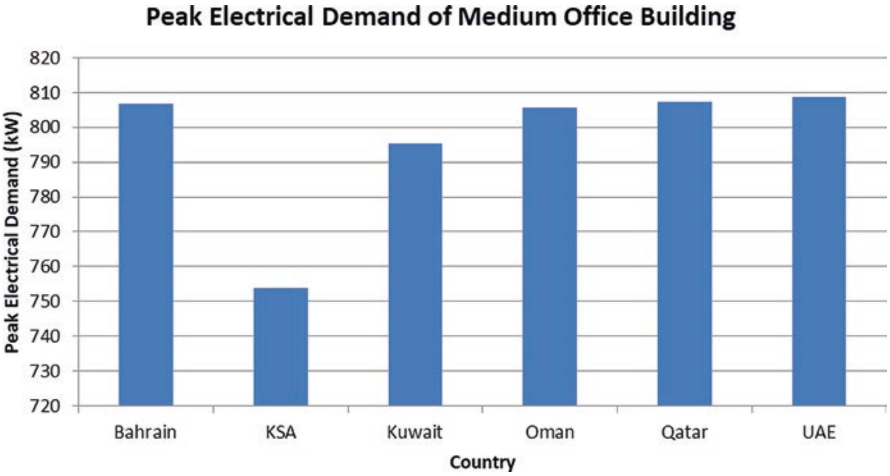

Fig. 8 Electrical peak demand of medium office building in the GCC region

annual electrical peak demand for each country ranges from 753 to 806 kW, with an average annual rate of 796 kW. Similar to the trend found in energy consumption, Bahrain and the Kingdom of Saudi Arabia exhibit the highest and lowest electrical peak demand, respectively, while the remaining countries have similar levels of electrical peak demand.

Figure 9 indicates the amount of carbon dioxide emissions released into the atmosphere, annually. The annual carbon dioxide emissions released into the atmosphere for each country range from 4,205,364 to 4,500,139 kg, with an average annual rate of 4,441,955 kg. Bahrain and the Kingdom of Saudi Arabia experience the highest and lowest carbon dioxide emissions, respectively, while the remaining countries follow similar patterns of released emissions.

4.2 Parametric Analyses Results

A series of parametric analyses were performed on the office building in order to study the impact of each individual energy efficiency measure on the building's total energy consumption, electrical peak demand, and carbon dioxide emissions [39]. Energy efficiency measures include improving the building's envelope construction, glazing, WWR, shading techniques, HVAC efficiency, and internal loads. The results obtained for the six GCC countries show very similar patterns on the impacts of all the measures considered in the analysis on the office building annual energy consumption, electrical peak demand, and carbon dioxide emission savings as those shown in, respectively, Figs. 10, 11, and 12 for Bahrain.

In particular, Fig. 10 presents the total energy consumption savings when each individual energy efficiency measure listed in Table 7 is implemented separately.

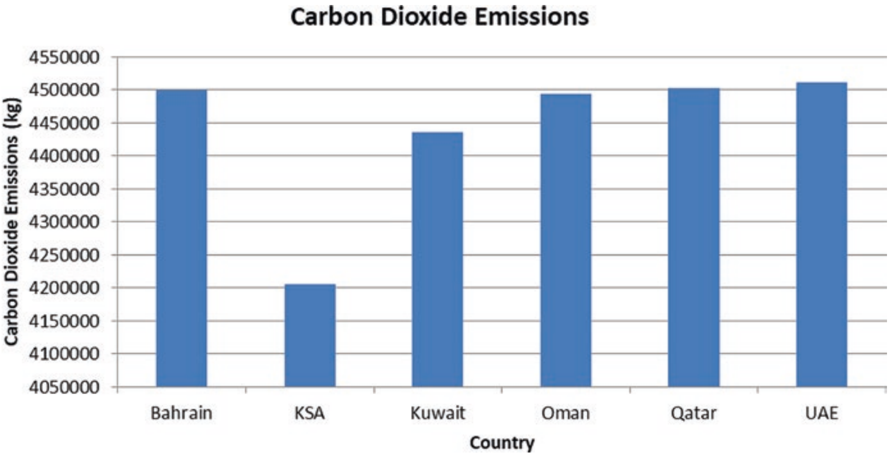

Fig. 9 Carbon dioxide emissions released into the atmosphere

Upgrading the HVAC's cooling COP had the highest impact on the total annual energy savings, saving up to 27% in the total energy consumed by the office building. Changing the temperature set point provides savings range of 17–25% in annual energy consumption, while installing double reflective glazing or double tinted, low-e, spectrally selective glazing leads to energy savings range of 17–25%. Adding exterior wall insulation, overhangs, and reducing the WWR and the lighting power density also had a noticeable impact on the building's performance, providing a range of 6–15% in energy use savings. Measures that had the least amount of energy savings for the office building included adding roof insulation, reducing the infiltration rate, and upgrading the pump's motor efficiency.

Figures 11 and 12 display the impact of individual energy efficiency measures on the electrical peak demand and carbon dioxide emissions released. Both figures follow the same trend as Fig. 10 and provide similar percent savings for the same energy efficiency measures.

4.3 Optimization Analyses Results

An optimization analysis for each GCC country was developed for the office building by selecting and combining energy efficiency measures into the building's baseline design using an LCC analysis and total energy use savings. Equations (1) and (2) were used to calculate the LCC for the baseline model and energy efficiency measures. Equation (3) was used to calculate the simple payback period (SPP) using the initial costs and first-year savings. All initial costs were utilized using the values found in Table 7.

The LCC values and simple payback periods for each individual measure for the countries of Bahrain, Kingdom of Saudi Arabia, Kuwait, Oman, Qatar, and the

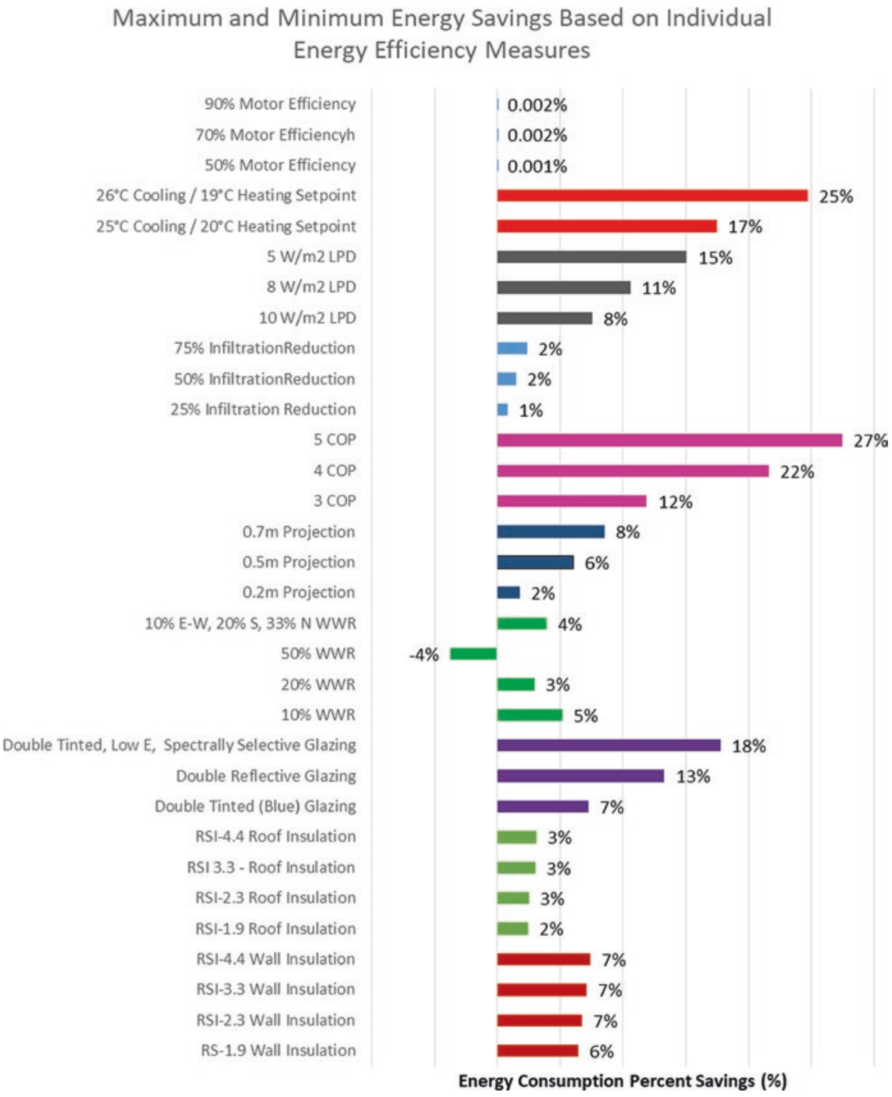

Fig. 10 Savings of annual energy consumption based on individual efficiency measures

United Arab Emirates are displayed in Table 18. Cost-effective and high impact energy efficiency measures are identified and considered in the optimization analysis based on the sequential search technique [18]. The optimization results are presented in the form of Pareto graphs showing the LCC values and the percent source energy savings for all the combinations of energy efficiency measures. These results are briefly discussed for each GCC country in the following sections. Furthermore, the results of a sensitivity analysis performed to evaluate the impact of the life-cycle period and discount rate indicate slight changes in the selection of the optimal sets of energy efficiency measures for all GCC countries.

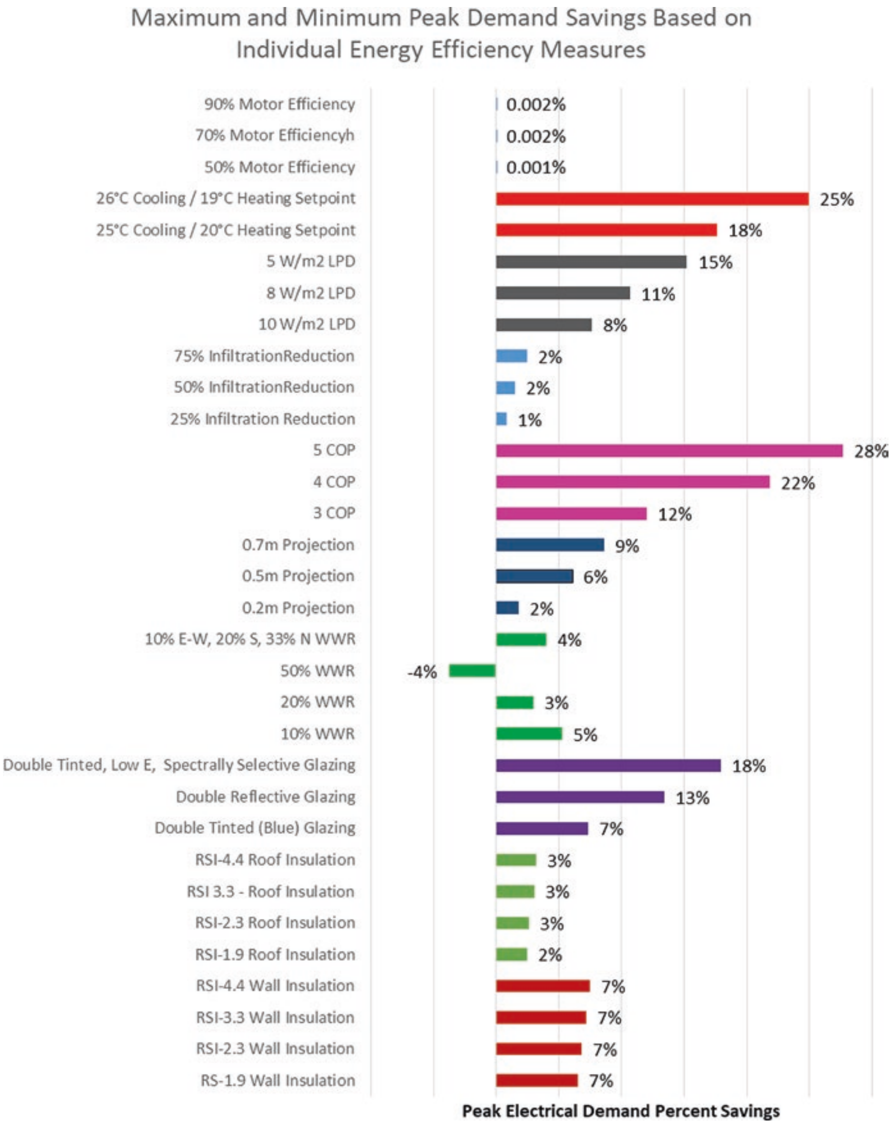

Fig. 11 Savings in electrical peak demand based on individual energy efficiency measures

4.3.1 Bahrain

Figure 13 displays the results of the office building optimization analysis for Bahrain. Implementing the cost-effective measures from Table 9 yielded an optimal point, as shown by the red dot in Fig. 13. Increasing the exterior wall and roof insulation and improving the window glazing type resulted in high energy savings, but high life-cycle costs, respectively. Table 10 displays the optimal point's imple-

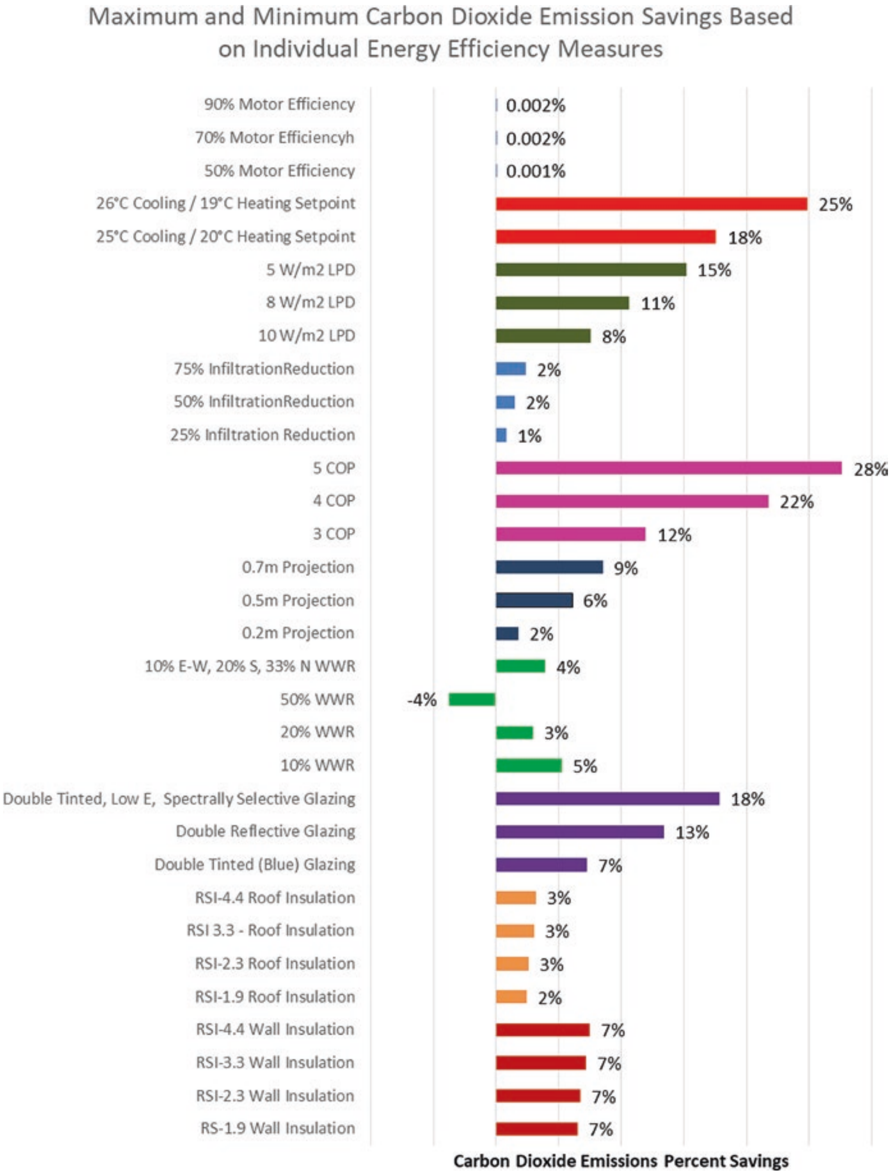

Fig. 12 Savings in carbon dioxide emissions based on individual energy efficiency measures

mented energy efficiency measures, along with the total LCC and SPP for the combined measures. The optimized office building design configuration yielded total savings of 63% in energy consumption, electrical peak demand, and carbon dioxide emissions. The comparative performance of the optimized building's energy performance against the baseline model is displayed in Table 11.

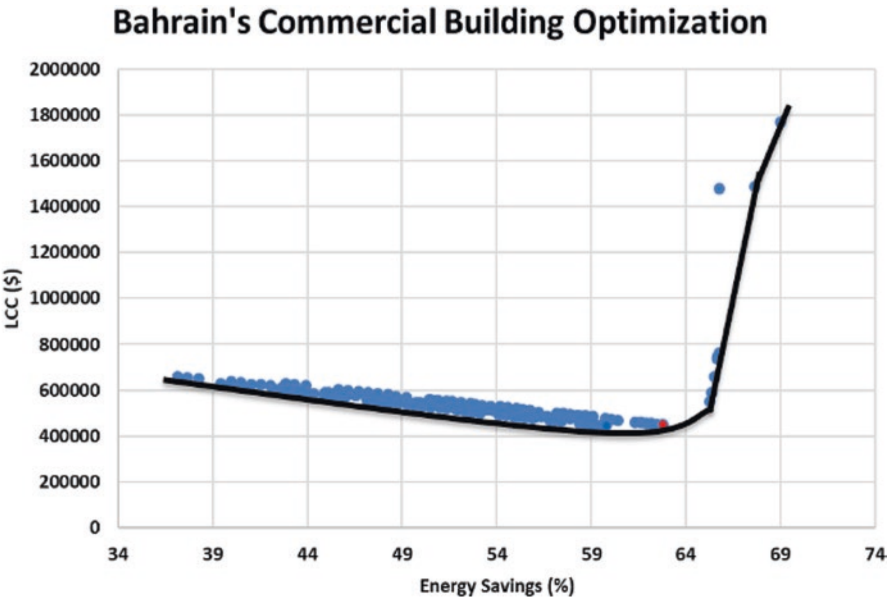

Fig. 13 Bahrain's office building optimization Pareto path

4.3.2 Kingdom of Saudi Arabia

Figure 14 displays the results of the optimization analysis for the office building located in Riyadh, KSA. The optimal set of energy efficiency measures yielded an optimal design as shown in red dot in Fig. 14. Increasing the exterior wall insulation, improving the window glazing type, and reducing the window to wall ratio resulted in high energy savings, but high life-cycle costs, respectively. Table 12 lists the optimal point's implemented energy efficiency measures, along with the total LCC and SPP for the combined measures. The optimized building yielded a total of 62% in savings regarding energy consumption and carbon dioxide emissions and 63% in savings toward the electrical peak demand. The indicators for the optimized building's performance against the baseline model are displayed in Table 13.

4.3.3 Kuwait

Figure 15 illustrates the optimization analysis results for the office building located in Kuwait City with the optimal set of energy efficiency measures shown in red. Increasing the exterior wall and roof insulation, improving the window glazing type, and reducing the window to wall ratio resulted in high energy savings, but high life-cycle costs, respectively. The optimal point's implemented energy efficiency measures, along with the total LCC and SPP for the combined measures, are dis-

Table 9 Bahrain's life-cycle cost analysis and simple payback period

EEM type	EEM	LCC($)	ΔLCC($)	Simple payback period (years)
Baseline	Baseline design model	934,417	–	–
Exterior wall insulation	R1.9 m^2-K/W	999,593	65,176	34
	R2.3 m^2-K/W	10345B0	100,163	42
	R3.3 m^2-K/W	1,102,220	167,302	53
	R4.4 m^2-K/W	1,173,342	244,424	74
Exterior roof insulation	R1.9 m^2-K/W	931,370	−3047	14
	R2.3 m^2-K/W	935,933	1566	17
	R3.3 m^2-K/W	942,523	3106	21
	R4.4 m^2-K/W	953,957	19,540	27
Glazing type	Double tinted (blue) glazing, with 6 mm air gap	1,530,022	645,605	172
	Double reflected glazing, with 13 mm air gap	1,543,141	613,724	97
	Double tinted, Low E, spectrally selective glazing, with 13 mm Argon gap	1,301,671	367,254	102
WWR	10%	1,011,460	77,043	42
	20%	1,153,315	223,397	150
	50%	1,597,745	663,327	−293
	10% E-W, 20% S, 33% N	1,147,704	213,236	111
Shading techniques	0.2 m	913,036	−16,331	0
	0.5 m	373,352	−55,565	0
	0.7 m	353,412	−76,005	1
COP	3.0	329,367	−104,550	1
	4.0	740,663	−193,750	1
	5.0	639,312	−245,105	1
Infiltration rate	25% reduction	927,952	−6466	2
	50% reduction	921,502	−12,916	1
	75% reduction	913,179	−21,239	1
Lighting power density	10 W/m^2	910,432	−23,936	11
	8 W/m^2	363,999	−65,413	6
	5 W/m^2	359,991	−74,426	3
Setpoint change	25 °C (C)/20 °C (H)	771,221	−163,196	0
	26 °C(C)/19 °C(H)	703,429	−230,939	0
Pump's motor efficiency	50%	934,617	200	293
	70%	934,693	275	239
	90%	934,711	293	267

played in Table 14. The optimized building yielded a total of 62% in energy savings and 63% in electrical peak demand and carbon dioxide emission savings as summarized in Table 15.

Table 10 Bahrain's optimal set of energy efficiency measures for the office building

EEM type	Energy efficiency measures	LCC ($)	ΔLCC ($)	SPP (years)
Exterior wall insulation	No insulation	449,626	−484,791	2.8
Exterior roof insulation	R1.9 m^2-K/W			
Glazing type	Single glazing, 3 mm clear glass			
WWR	33%			
Shading techniques	0.7 m			
COP	5			
Infiltration rate	75% reduction			
Lighting power density	5 W/m^2			
Setpoint change	26 °C (C)/19 °C (H)			
Pump's motor efficiency	30%			

Table 11 Bahrain's optimal design benefits vs. baseline office building

Bahrain	Baseline	Optimized	% Savings
Annual energy consumption (kWh/m^2/year)	268	100	63%
Annual electrical peak demand (kW)	807	295	63%
Annual carbon dioxide emissions (kg)	4,500,139	1,653,941	63%

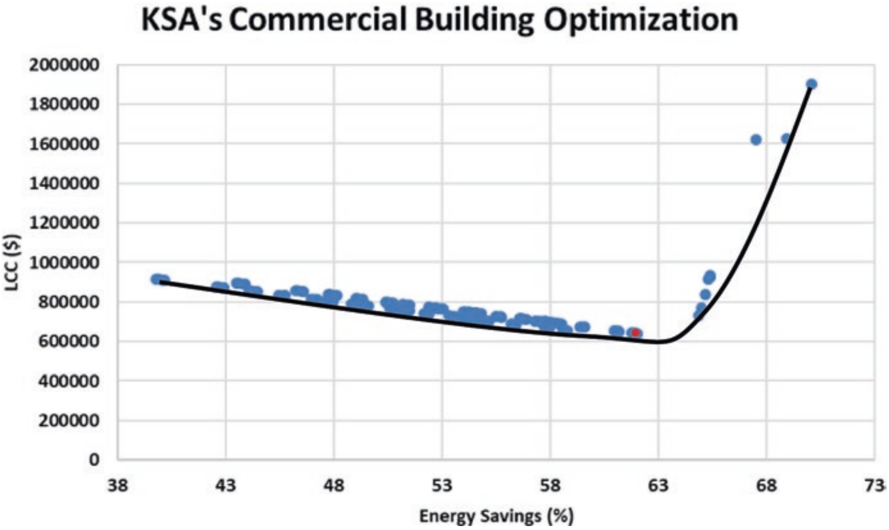

Fig. 14 KSA's office building optimization Pareto path

Table 12 KSA's optimal set of energy efficiency measures for the office building

EEM type	Energy efficiency measures	LCC ($)	ΔLCC ($)	SPP (years)
Exterior wall insulation	No insulation	641,928	−777,691	1.9
Exterior roof insulation	R1.9 m^2-K/W			
Glazing type	Single glazing, 3 mm clear glass			
WWR	33%			
Shading techniques	0.7 m			
COP	5			
Infiltration rate	75% reduction			
Lighting power density	5 W/m^2			
Setpoint change	26 °C (C)/19 °C(H)			
Pump's motor efficiency	30%			

Table 13 KSA's optimal design benefits vs. baseline office building

KSA	Baseline	Optimized	% Savings
Annual energy consumption (kWh/m^2/year)	251	95	62%
Annual electrical peak demand (kW)	754	282	63%
Annual carbon dioxide emissions (kg)	4,205,364	1,579,589	62%

4.3.4 Oman

The optimization analysis results for the office building located in Oman are displayed in Fig. 16 with the optimal design configuration specified in red. Increasing the exterior wall insulation and improving the window glazing type yielded high energy savings, but high life-cycle costs, respectively. The optimal point's implemented energy efficiency measures, along with the total LCC and SPP for the combined measures, are displayed in Table 16. The optimized building yielded a total of 67% in savings regarding energy consumption, electrical peak demand, and carbon dioxide emissions. The performance metrics of the optimized building's performance against the baseline model is displayed in Table 17.

4.3.5 Qatar

Figure 17 summarizes the Pareto graph associated with the optimization analysis results for the office building located in Doha, Qatar. The optimal design is identified in red in Fig. 16. Increasing the exterior wall insulation and improving the window glazing type yielded high energy savings, but high life-cycle costs, respectively. The optimal point's implemented energy efficiency measures, along with the total LCC and SPP for the combined measures, are displayed in Table 18. The optimized building yielded a total of 67% in savings regarding energy consumption and carbon dioxide emissions and 68% in savings regarding electrical peak demand. The comparative results of the optimized building's performance against the baseline model are displayed in Table 19.

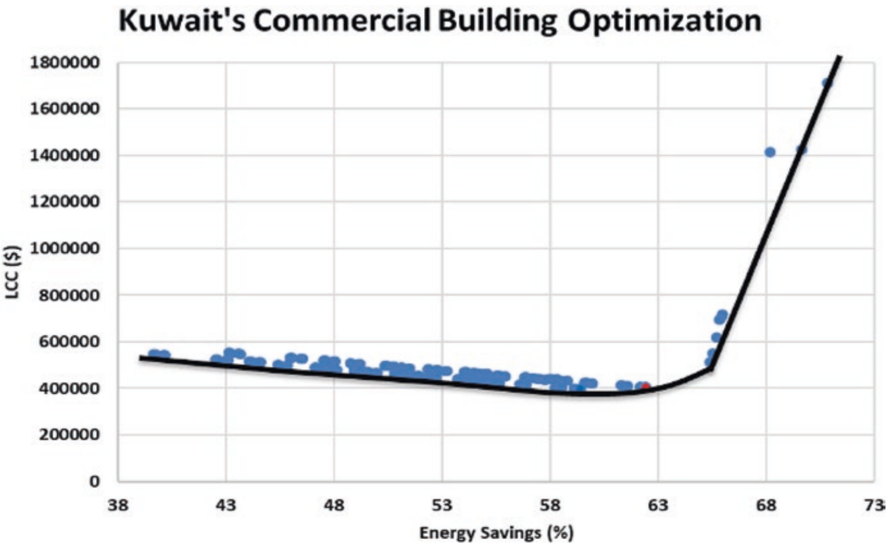

Fig. 15 Kuwait's building optimization Pareto path

Table 14 Kuwait's optimal set of energy efficiency measures for the office building

EEM type	Energy efficiency measures	LCC ($)	ΔLCC ($)	SPP (years)
Exterior wall insulation	No insulation	404,687	−401,495	3.3
Exterior roof insulation	R2.3 m^2-K/W			
Glazing type	Single glazing, 3 mm clear glass			
WWR	33%			
Shading techniques	0.7 m			
COP	5			
Infiltration rate	75% reduction			
Lighting power density	5 W/m^2			
Setpoint change	26 °C (C)/19 °C (H)			
Pump's motor efficiency	30%			

Table 15 Kuwait's optimal design benefits vs. baseline office building

Kuwait	Baseline	Optimized	% Savings
Annual energy consumption (kWh/m^2/year)	265	99	62%
Annual electrical peak demand (kW)	795	294	63%
Annual carbon dioxide emissions (kg)	4,436,798	1,645,681	63%

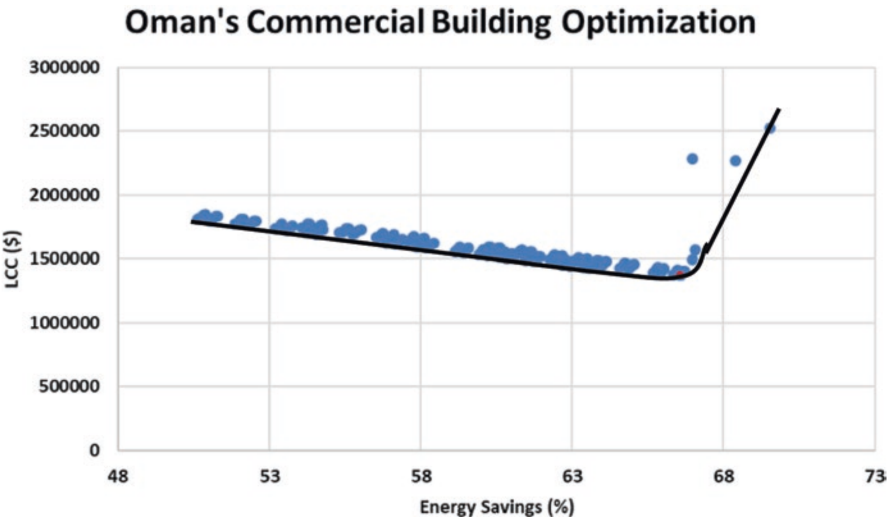

Fig. 16 Oman's building optimization Pareto path

Table 16 Oman's optimal set of energy efficiency measures for the office building

EEM type	Energy efficiency measures	LCC ($)	ΔLCC ($)	SPP (years)
Exterior wall insulation	R1.9 m^2-K/W	1,372,236	−1,660,561	2.9
Exterior roof insulation	R2.3 m^2-K/W			
Glazing type	Single glazing, 3 mm clear glass			
WWR	10%			
Shading techniques	0.7 m			
COP	5			
Infiltration rate	75% reduction			
Lighting power density	5 W/m^2			
Setpoint change	26 °C (C)/19 °C (H)			
Pump's motor efficiency	30%			

Table 17 Oman's optimal design benefits vs. baseline office building

Oman	Baseline	Optimized	% Savings
Annual energy consumption (kWh/m^2/year)	268	90	67%
Annual electrical peak demand (kW)	806	264	67%
Annual carbon dioxide emissions (kg)	4,494,087	1,480,313	67%

Table 18 Qatar's optimal set of energy efficiency measures for the office building

EEM type	Energy efficiency measures	LCC ($)	ΔLCC ($)	SPP (years)
Exterior wall insulation	R1.9 m^2-K/W	1,204,564	−1,367,012	3.4
Exterior roof insulation	R1.9 m^2-K/W			
Glazing type	Single glazing, 3 mm clear glass			
WWR	10%			
Shading techniques	0.7 m			
COP	S			
Infiltration rate	75% reduction			
Lighting power density	5 W/m^2			
Setpoint change	26 °C (C)/19 °C (H)			
Pump's motor efficiency	30%			

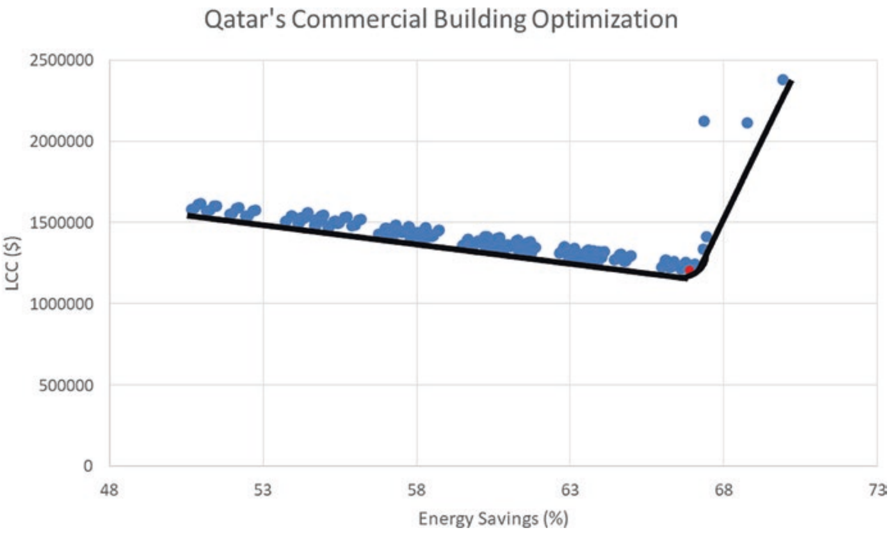

Fig. 17 Qatar's building optimization Pareto path

Table 19 Qatar's optimal design benefits vs. baseline office building

Qatar	Baseline	Optimized	% Savings
Annual energy consumption (kWh/m^2/year)	269	89	67%
Annual electrical peak demand (kW)	807	262	68%
Annual carbon dioxide emissions (kg)	4,503,541	1,469,814	67%

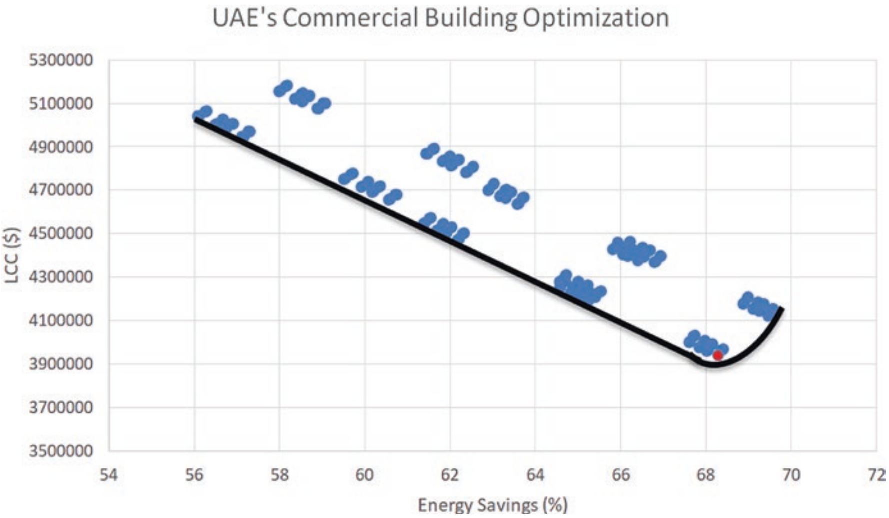

Fig. 18 UAE's building optimization Pareto path

Table 20 UAE's optimal set of energy efficiency measures for the office building

EEM type	Energy efficiency measures	LCC ($)	ΔLCC ($)	SPP (years)
Exterior wall insulation	R1.9 m^2-K/W	3,937,311	−5,430,910	2.5
Exterior roof insulation	R1.9 m^2-K/W			
Glazing type	Double reflective glazing			
WWR	10%			
Shading techniques	0.7 m			
COP	5			
Infiltration rate	75% reduction			
Lighting power density	5 W/m^2			
Setpoint change	26 °C (C)/19 °C (H)			
Pump's motor efficiency	30%			

4.3.6 United Arab Emirates

Figure 18 summarizes the optimization analysis results obtained for the office building located in Dubai, UAE. The optimal set of energy efficiency measures, along with the total LCC and SPP for the combined measures, are displayed in Table 20. The optimized building yielded a total of 68% in energy savings and 69% in savings regarding electrical peak demand and carbon dioxide emissions. The performance indicators of the optimized building's performance against the baseline model are displayed in Table 21.

Table 21 UAE's optimal design benefits vs. baseline office building

UAE	Baseline	Optimized	% Savings
Annual energy consumption (kWh/m^2/year)	269	85	68%
Annual electrical peak demand (kW)	809	251	69%
Annual carbon dioxide emissions (kg)	4,511,799	1,409,765	69%

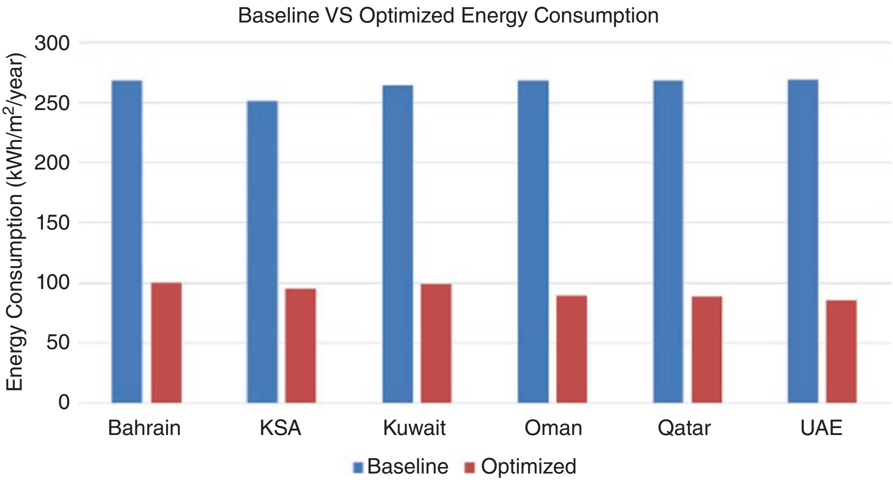

Fig. 19 Annual energy consumption savings for optimized office building in GCC countries

4.3.7 Summary of Optimization Analysis

The optimization analysis results for all the GCC countries indicate that the energy performance of office buildings can be significantly improved through the implementation of common and proven energy efficiency measures into the building's baseline model. The improved office building designs can yield a range of 62–69% savings in annual energy consumption, electrical peak demand, and carbon dioxide emissions with payback periods of 1.9–3.4 years. Figure 19 displays a graphical representation of the difference between the baseline and the optimized office building annual energy consumption per floor area. The energy consumption in all six countries is reduced significantly after applying feasible energy efficiency measures and can hence result in lower production, distribution, and consumption of energy.

Figures 20 and 21 illustrate the difference between the baseline and optimized office building's electrical peak demand and carbon dioxide emissions for all six GCC countries. Optimizing the building energy performance helped to reduce significantly electrical peak demand and carbon dioxide emissions for all GCC countries. Therefore, the improved designs will not only result in a significant decrease in the office building's energy bills, but the electric utilities will also experience less pressure to meet the peak demand, and GCC region will reduce their contribution to the world's environmental footprint.

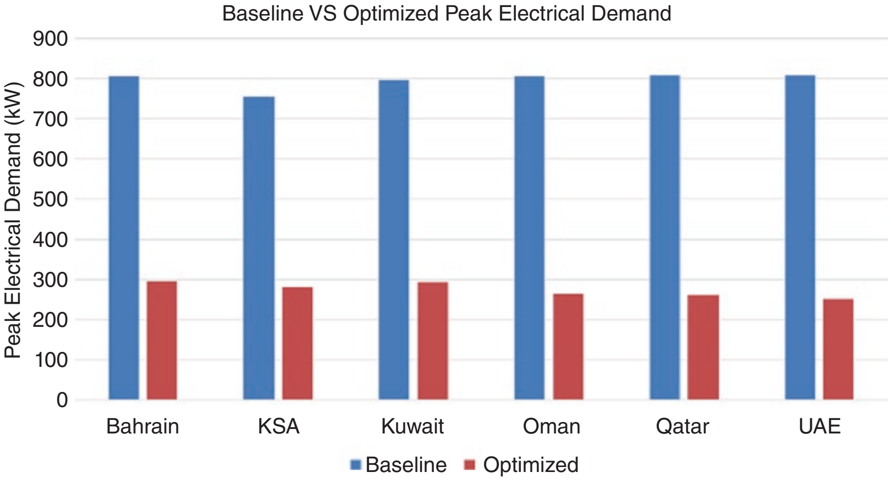

Fig. 20 Electrical peak demand savings for optimized office building in GCC countries

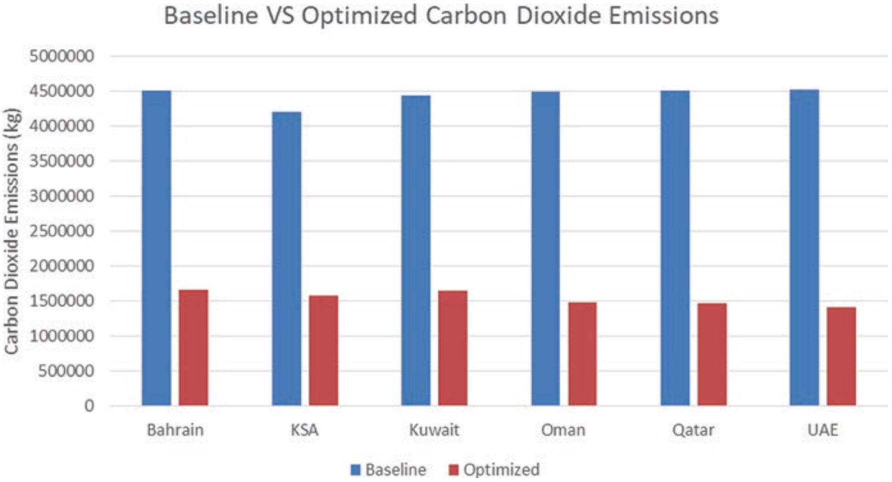

Fig. 21 Carbon dioxide emission savings for optimized office building in GCC countries

5 Summary and Conclusions

Countries in the Gulf Cooperation Council (GCC) region have been witnessing a major development in their urban and socioeconomic growth leading to significant increase in energy consumption and electricity demand especially for the building sector. Since commercial buildings contribute significantly to the building stock's energy consumption and carbon dioxide emissions, a series of parametric and sensitivity analyses were performed on a prototypical commercial building in order to assess the impact of individual energy efficiency measures on the building's total

Table 22 Potential savings from the optimization analysis of commercial buildings

Country	Energy savings	Electrical peak demand savings	Carbon dioxide emissions savings
Bahrain	63%	63%	63%
KSA	62%	63%	62%
Kuwait	62%	63%	63%
Oman	67%	67%	67%
Qatar	67%	68%	67%
UAE	68%	69%	69%

energy consumption, electrical peak demand, and carbon dioxide emissions. An LCC analysis helped develop a list of feasible energy efficiency measures in order to optimize the energy performance of the office building. The optimized building designs resulted in savings ranging between 62% and 69% in annual energy consumption, electrical peak demand, and carbon dioxide emissions as summarized in Table 22 for all GCC countries.

Improving the building's envelope constructions, glazing, WWR, shading techniques, HVAC efficiency, and internal loads can significantly improve the building's energy performance.

Future work concerns implementing a water-cooled HVAC system instead of a DX air-cooled HVAC system and implementing renewable energy sources to help decrease the GCC's heavy reliance on fossil fuels and address a post-oil future. Not only does the shift in energy sources benefit the economic aspect of the region, but also improve their high contribution to the world's environmental footprint. The GCC region has significant solar and wind resources to be suitable for integrating renewable energy technologies with buildings to achieve net or even positive energy designs and retrofits. As an initial step to improve the energy performance of buildings, it is crucial for GCC countries to update their local energy efficiency codes regularly and to impose more stringent specifications and requirements in terms of building constructions and systems in order to reduce energy consumed in both residential and commercial buildings.

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