Techno-Economic Analysis of Solar Energy Use in Cooling and Air Conditioning of Large Buildings Versus Small Houses

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***Abstract*—Energy efficiency and renewable energy sources can be employed as a solution to meet growing energy requirements and minimise carbon footprint. With the great amount of solar irradiance in the Kingdom of Saudi Arabia, solar energy is a perfect solution for simultaneously reducing electricity bills and carbon emissions. Solar air conditioning is air conditioning that is powered by solar energy. The benefit of solar air conditioners is that they can supply their own energy and have no emissions, allowing users to reduce their carbon footprint and electricity costs simultaneously. Air conditioning systems that uses renewable energy as a substitute for conventional fossil fuels need to be retrofitted. A techno-economic analysis was carried out to examine the potential of installing solar photovoltaic (PV) technology for HVAC systems. Villas are the most viable structure for installing solar PV because they have the lowest levelised electricity cost. Solar PV for traditional houses is the least feasible among the three residential buildings due to its high initial investment cost.**

***Index Terms*—Techno-economic, solar energy, air conditioning, buildings**

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I. INTRODUCTION

GLOBALLY, approximately 80% of energy consumption is sourced from conventional fossil fuels, which release significant amounts of carbon dioxide into the atmosphere [1]. In response, many countries, including the Kingdom of Saudi Arabia (KSA), are shifting towards energy efficiency and renewable sources to meet increasing energy demands while reducing carbon footprints. The KSA has embarked on several ambitious initiatives, such as the Saudi Vision 2030 and the National Renewable Energy Program (NREP), aiming to diversify the energy mix by significantly increasing the proportion of renewable energy, particularly solar power, to address both environmental challenges and economic sustainability.

In this transition, heating, ventilation and air conditioning (HVAC) systems play a crucial role in energy consumption, especially in harsh climate regions such as the Middle East. In Saudi Arabia, air conditioning systems consume a large amount of energy, contributing to high electricity demand and substantial carbon emissions. In line with Saudi Vision 2030's focus on energy reform and efficiency, optimising HVAC systems through renewable energy integration is a strategic priority. This integration can greatly reduce electricity consumption and support the national objectives of lowering greenhouse gas emissions and fostering sustainable energy practices.

The integration of solar energy solutions into HVAC operations in the KSA aims to enhance energy efficiency and capitalise on the region's abundant solar irradiance. Understanding the potential of solar energy to power HVAC systems can identify sustainable and cost-effective solutions vital for the energy needs of both residential and commercial buildings.

The demand for electricity in residential and commercial buildings continues to rise annually due to severe climatic conditions [2], recent rapid development and increasing housing requirements [3]. However, the design and construction of modern buildings rely heavily on air conditioning systems, leading to increased electricity usage [4], particularly in inadequately insulated buildings [5]. Research has shown that improvements in building hardware and insulation provide better control over energy performance in residential buildings [6]. Influencing factors include building characteristics, weather conditions, the quality and maintenance of equipment, and occupant behaviour [7, 8].

Air conditioning accounts for approximately 40%–70% of electricity consumption in buildings, contributing an estimated 117 million metric tons of carbon dioxide emissions annually [9]. In the Middle East, where outdoor temperatures can soar to 47 °C during the day, the energy demand for cooling is particularly high. Transforming energy production for cooling and heating is urgently needed.

Given the high solar irradiance in KSA, solar energy is a viable solution to reduce electricity costs and carbon emissions [10]. Solar air conditioning, which utilises solar power, offers the advantage of providing its own energy without emissions, thereby helping users lower their carbon footprint and energy expenses simultaneously. Furthermore, air conditioning systems need to be retrofitted to incorporate renewable energy, replacing conventional fossil fuels.

The objective of this research is to explore and evaluate the integration of solar energy into HVAC systems in Saudi Arabia, aiming to enhance energy efficiency and reduce carbon emissions. This study will investigate the technical and economic feasibility of solar-powered air conditioning solutions and their potential impact on reducing energy consumption in residential and commercial buildings. The research will also assess various factors that influence energy usage and identify opportunities for retrofitting existing systems to support sustainable energy practices as part of Saudi Vision 2030.

II. Energy Situation in Residential and Large Buildings

The building sector in the KSA is rapidly expanding, driven by modernisation, rising populations and extensive construction across the nation. This growth is characterised by significant energy consumption and carbon emissions, particularly from residential and commercial buildings, which rely heavily on air conditioning systems to cope with the harsh climate conditions [11]. Traditionally, the KSA has depended on its vast oil reserves to meet energy needs, resulting in considerable carbon dioxide emissions. However, in response to global environmental concerns and economic diversification needs, the KSA is now transitioning towards renewable energy sources.

Initiatives such as the Saudi Vision 2030 and the NREP are pioneering efforts to shift the Kingdom's energy dependency from fossil fuels to more sustainable resources such as solar and wind energy. These programs aim to reduce greenhouse gas emissions and enhance sustainability standards in building practices by promoting renewable energy solutions.

Recent housing data reveal that the KSA's total number of housing units reached more than 3.68 million in 2019 [12]. Apartments make up the largest portion (43.79%), followed by villas (29.42%). Notably, these housing units tend to be large structures, with many of them more than a decade old. The adoption of new building codes and standards is encouraging the integration of renewable energy systems and energy-efficient practices. Improved building elements such as enhanced insulation and energy-efficient glazing, along with the use of smart building technologies, are essential measures being implemented to decrease reliance on conventional energy sources.

A critical aspect of the KSA's energy consumption lies in the usage of HVAC systems, which account for a significant portion of building energy needs. According to housing surveys, window-type air conditioners (ACs) dominate with a 71.3% usage rate, followed by split ACs (25.8%), evaporative (1.8%) and central systems (1.1%). Newer constructions increasingly favour split systems due to their improved efficiency and reduced air infiltration capabilities. These advancements in HVAC technology, such as variable refrigerant flow (VRF) systems and smart energy management systems, allow for better adaptation to occupancy patterns and ambient conditions, optimising energy use effectively.

The evolution of building standards, efficient HVAC technologies and strategic national initiatives marks significant progress in addressing the energy challenges in the KSA's residential and large building sectors. As these measures continue to be implemented, the potential for achieving sustainable energy consumption and reducing environmental impact in the Kingdom becomes increasingly attainable.

III. Solar Photovoltaic Potential

In countries with extreme climatic conditions such as the KSA, solar energy can potentially contribute to sustainable development. According to the Saudi Arabia Energy Report, the KSA is one of the leading countries in terms of per capita energy consumption and carbon dioxide emissions. The KSA is a desert country with a hot and arid climate and a high direct normal irradiance (DNI) of 4–8 kWh/m² per day [13] (Figure 1 and 3), where air conditioning accounts for 70% of the total building consumption [14]. DNI measures the amount of solar radiation received per unit area by a surface perpendicular to the sun's rays. It is a key indicator for concentrating solar power systems because it quantifies the intensity of sunlight reaching the Earth's surface without atmospheric scattering. Thus, the use of solar photovoltaic can help reduce energy consumption from the grid associated with air conditioning and contribute to sustainable development in the country.

The potential of sun radiation usually refers to the DNI, diffuse horizontal irradiance (DHI) and global horizontal irradiance (GHI) as the potential of solar radiation in a particular location. DNI indicates the amount of solar radiation received per unit area on a surface perpendicular to the sunlight. It quantifies the direct sunlight intensity, i.e. the solar radiation that reaches the Earth's surface without being diffused or scattered by the atmosphere. DNI is expressed in units of watts per square meter (W/m²). DHI simply means the amount of solar radiation that comes from the sky and is diffused by the atmosphere and reaches a horizontal surface. It includes sunlight that has been scattered by particles and molecules in the atmosphere, as well as radiation reflected by clouds.

GHI is the total amount of solar radiation received on a horizontal surface, taking into account both direct sunlight and diffuse. By determining the solar potential, we were able to make assumptions about the solar technology, such as concentrated solar power (CSP) and photovoltaic (PV) technology, applied in specific locations [16].

The building sector in the KSA is one of the most promising applications for solar PV generation. Rooftop PV is estimated to have more than 40% share of the world's total installed capacity [14].

$$E_{PV} = I_P \cdot \eta_{mod} \cdot \eta_{sys} \cdot A \cdot N_{mod} \cdot degrad \quad (1)$$

The amount of energy generation (E_{PV}) can be obtained by multiplying the solar irradiance in the panel (I_P) (kWh/m2), module efficiency (η_{mod}), system efficiency (η_{sys}), area of collector (A), number of modules (N_{mod}) and solar module annual degradation (degrad) [4].

The model of the PV modules that are used is CS6W-530 from Canadian Solar. The specifications are shown in Table 1.

The financeable life for a solar PV system is usually considered the manufacturer's guarantee period, often 20–25 years. However, the life of solar panels can often reach 30 years. One important thing to keep in mind is that the solar panels would continue to produce energy at a low cost even if the loan term were shorter. If we were to plot the levelised cost of energy (L_{COE}) for each year over time, using different equations for the period before and after the loan term and taking into account the annual cost of the loan, then the annual L_{COE} after the loan term would be significantly lower than what is currently being considered.

TABLE I
ELECTRICAL DATA OF THE SOLAR PV MODULE

Symbol	Definition	Unit
P_{max}	nominal max. power	530 W
V_{mp}	operating voltage	40.9 V
I_{mp}	operating current	12.96 A
V_{oc}	open circuit voltage	48.8 V
I_{sc}	short circuit current	13.8 A
η_{mod}	module efficiency	21.5%

TABLE II
EFFECT OF DEGRADATION RATE AND PERFORMANCE REQUIREMENT ON PV SYSTEM LIFE [17]

Degradation rate	Lifetime 80% Pmax [years]	Lifetime to 50% Pmax [years]
0.2%	100	250
0.5%	40	100
0.6%	33	83
0.7%	29	71
0.8%	25	63
1%	20	50

The high solar potential in KSA, characterised by substantial DNI and GHI values (Figure 1 to 4), significantly enhances the feasibility of solar-powered HVAC systems. This abundant solar resource allows for the efficient harnessing of renewable energy, thereby reducing the reliance on conventional electricity sources for air conditioning needs in residential and commercial buildings. HVAC systems account for a large portion of electricity consumption. Therefore, leveraging solar power not only curtails energy costs but also contributes to a reduction in carbon emissions, aligning with the Kingdom's sustainability goals. By optimising the use of their substantial solar resources, the KSA can support environmental objectives and energy diversification strategies, making solar-integrated HVAC systems a promising solution for the country's energy future.

IV. ELECTRICITY END USE OF AIR CONDITIONING

Figure 5 and 6 illustrates the number and type of air conditioning systems employed in KSA's current housing stock, sorted by regions [12]. Window AC units are predominantly used in residential buildings throughout the KSA to regulate temperature, particularly in the west and middle regions. Split and fan coils are the next most prevalent types of AC systems. Central AC systems and evaporative coolers are not frequently used in the KSA. Investigating the use of evaporative cooling systems may be worthwhile, especially in the KSA's middle region, which has hot and arid climates, as these systems could potentially be more energy-efficient than window AC units, fan coils and split AC systems.

Three main types of housing units are available in the KSA: villas, apartment units and traditional houses. The main features of KSA housing prototypes are summarised in Table 3 and Figure 7.

TABLE III
UNITS FOR MAGNETIC PROPERTIES

Building Model	Villa	Villa	Traditional House
Number of floors	2	3	2
Total floor area	525 m^2	1260 m^2	232 m^2
Cooling set point	23 °C	24 °C	24 °C
HVAC system	Split	AC window	AC window
Occupancy period	24 h/day	24 h/day	24 h/day
Cooled area	756	315	139.2
Area with installed PV	46.4	252	105

TABLE IV
REFRIGERATION REQUIRED

Location	Traditional Houses	Villas	Apartments
Number of floors	2	3	2
Total floor area	525m^2	1260m^2	232m^2
Cooling set point	23ºC	24ºC	24ºC
HVAC system	Split	AC Window	AC Window
Occupancy period	24-h/day	24-h/day	24-h/day
Cooled area	756	315	139.2
Area with installed PV	46.4	252	105

This work uses HVAC systems to generate cooling and meet the thermal load from the buildings. The energy consumption from the HVAC system is given by Eq. 2

$$E_{HVAC} = C_{HVAC} \cdot COP \cdot U_I \cdot h \quad (2)$$

where C_{HACV} is the refrigeration capacity of the HVAC system in (TON); COP represents the coefficient of performance in (kW/TON); U_I is the utilisation index, which represents the percentage of time the HVAC works in each period; and h represents the number of hours. Table 4 presents the annual HVAC energy consumption.

Air conditioning systems consume a significant portion of electricity within buildings, particularly in regions with intense climatic conditions such as the Kingdom of Saudi

Arabia. As highlighted in Table 3, the predominant use of window-type ACs across various residential housing types, such as villas and apartments, underscores the need for strategies to increase energy efficiency. With window units representing 71.3% of all systems used, it becomes evident why energy consumption is high in the residential sector. Table 3 illustrates a trend towards split air conditioning systems in newly constructed buildings, which mitigate energy loss by minimising air infiltration and demonstrate superior performance compared with traditional window AC units.

Despite these advancements, current air conditioning technologies still face several challenges that can limit their efficiency and broader adoption. Window ACs, while prevalent and cost-effective, often have lower energy efficiency ratios (EERs) than other systems do and are limited in their ability to reduce heat transfer effectively. Moreover, their reliance on centralised grids creates vulnerabilities in energy supply stability, especially as demand peaks during hotter months.

Alternatives to existing AC technologies include systems such as VRF and quantum cooling technologies, which offer greater efficiency and flexibility. Additionally, solar-powered air conditioning systems present a viable alternative, utilising the abundant solar resource in KSA to generate electricity for cooling, thus reducing dependence on the grid. This concept aligns well with the solar potential insights provided earlier, which highlighted the country's high DNI and GHI figures that promise effective solar energy capture (Figure 1 to 4).

Integrating these advanced technologies can not only improve energy efficiency but also aligns with national energy goals by decreasing carbon footprints and enhancing sustainability. However, large-scale implementation requires upfront investment and supportive policy frameworks to mitigate barriers related to cost and technical integration. As the industry progresses, embracing these alternatives will be crucial in overcoming the limitations of traditional air conditioning technologies and establishing a more sustainable energy consumption model in the KSA.

V. Economic Analysis

A. Levelised Cost of Electricity

L_{COE} serves as a crucial benchmarking tool in evaluating the economic feasibility of various energy generation technologies, including solar PV systems. L_{COE} provides a comprehensive measure by averaging the total lifetime costs of a solar PV project—encompassing capital, maintenance, and operational expenses—against the total energy produced over its life span [17]. This metric enables stakeholders to compare the cost-effectiveness of solar PV against traditional energy sources and other renewable technologies on a per-kilowatt-hour basis. Doing so ensures that L_{COE} can facilitate informed decision-making, helping investors, policymakers and energy providers assess the potential return on investment and sustainability of deploying solar PV systems. L_{COE} can be calculated by [19, 20]

$$L_{COE} = \frac{I_{tot} \cdot f_{cr} + OM_{annual}}{e_p} \quad (3)$$

where I_{tot} is the total investment cost, f_{cr} is the annuity factor, OM_{annual} is the annual operation and maintenance cost, and e_p is the produced electricity. Table V shows the cost electricity calculated using Eq. 3.

TABLE V
HVAC Installation, Operation and Maintenance Cost

HVAC	Traditional Houses	Villas	Apartments
Installation costs (USD)	3150	28798.94	14400
OM cost/year (USD)	525	2400	1200
Number of years	30	30	30

B. Electronic Image Files (Optional)

Air conditioning systems in residential houses are energy intensive, reaching almost 70% of electricity demand. Several programs have been launched to improve energy efficiency level of household appliances and air conditioning systems, with the goals of improving awareness with building codes, energy efficient behaviours as well as diversification of energy resources.

The Saudi Standards, Metrology, and Quality Organization published energy labels for window- and split-type ACs, providing a star rating to seven classes. Table 5 lists the current minimum EER value for AC's manufacturers in KSA. ACs have to be tested under two testing conditions for cooling operation:

- Test T_1 with the outdoor conditions set to 35 °C (95 °F) for dry-bulb temperature and 24 °C (75 °F) for wet-bulb temperature and the indoor conditions set to 27 °C (80.5 °F) for dry-bulb temperature and 19 °C (66 °F) for wet-bulb temperature.
- Test T_3 with the outdoor conditions set to 46 °C (115 °F) for dry-bulb temperature and 24 °C (75 °F) for wet-bulb temperature and the indoor conditions set to 29 °C (84 °F) for dry-bulb temperature and 19 °C (66 °F) for wet-bulb temperature.

TABLE VI
SASO 2663 Requirements for Window and Split ACs in KSA

AC Type	Cooling capacity at T_1 conditions in BTU/hr	EER at T_1	EER at T_3
Window AC	CC ≤ 24,000	9.8	7.0
	24,000 < CC ≤ 65,000	9.0	6.2
Split AC	CC ≤ 65,000	11.8	8.30

VI. Techno-Economic Performance of Residential PV for HVAC

The integration of solar PV systems with HVAC systems presents a significant opportunity for enhancing economic viability and environmental sustainability within residential settings in the KSA. This chapter explores the techno-economic performance of residential PV systems specifically used to power HVAC, offering insights into

L_{COE} across various residential building types, which can profoundly impact policy frameworks and consumer decisions.

A. Shaping Policy

The techno-economic analysis indicates that villas exhibit the lowest L_{COE} when equipped with solar PV systems, suggesting that these residences are particularly cost-effective for solar-powered HVAC integration. Policymakers can use these findings to design incentives and subsidies that encourage solar adoption in villa-style residences. For traditional homes, which generally face higher initial installation costs, targeted financial assistance programs or updated building codes promoting energy efficiency and renewable energy integration may be necessary.

Furthermore, the data highlight the importance of policy initiatives that streamline solar PV installation processes, enhance grid integration and facilitate net metering. These measures allow consumers to sell excess energy back to the grid, thereby improving economic returns and promoting broader adoption of renewable energy technologies. Insights from this analysis can support legislative changes that align with the sustainability and energy security goals of Saudi Vision 2030.

B. Influencing Consumer Choices

For consumers, this analysis provides a compelling economic rationale for adopting solar PV systems, especially in villa-type homes where the cost-effectiveness of solar-powered HVAC is most evident. Knowledge of potential electricity cost savings and environmental benefits can influence consumer preferences toward renewable solutions, prompting more informed purchase decisions and long-term energy planning.

Highlighting the economic and environmental advantages of integrating solar PV with HVAC systems ensures that consumers are better equipped to make choices fostered by the reduction in energy bills and a commitment to a lower carbon footprint. Although the initial investment costs pose a barrier, the prospect of substantial savings and environmental contributions offers a persuasive argument for the adoption of these sustainable technologies.

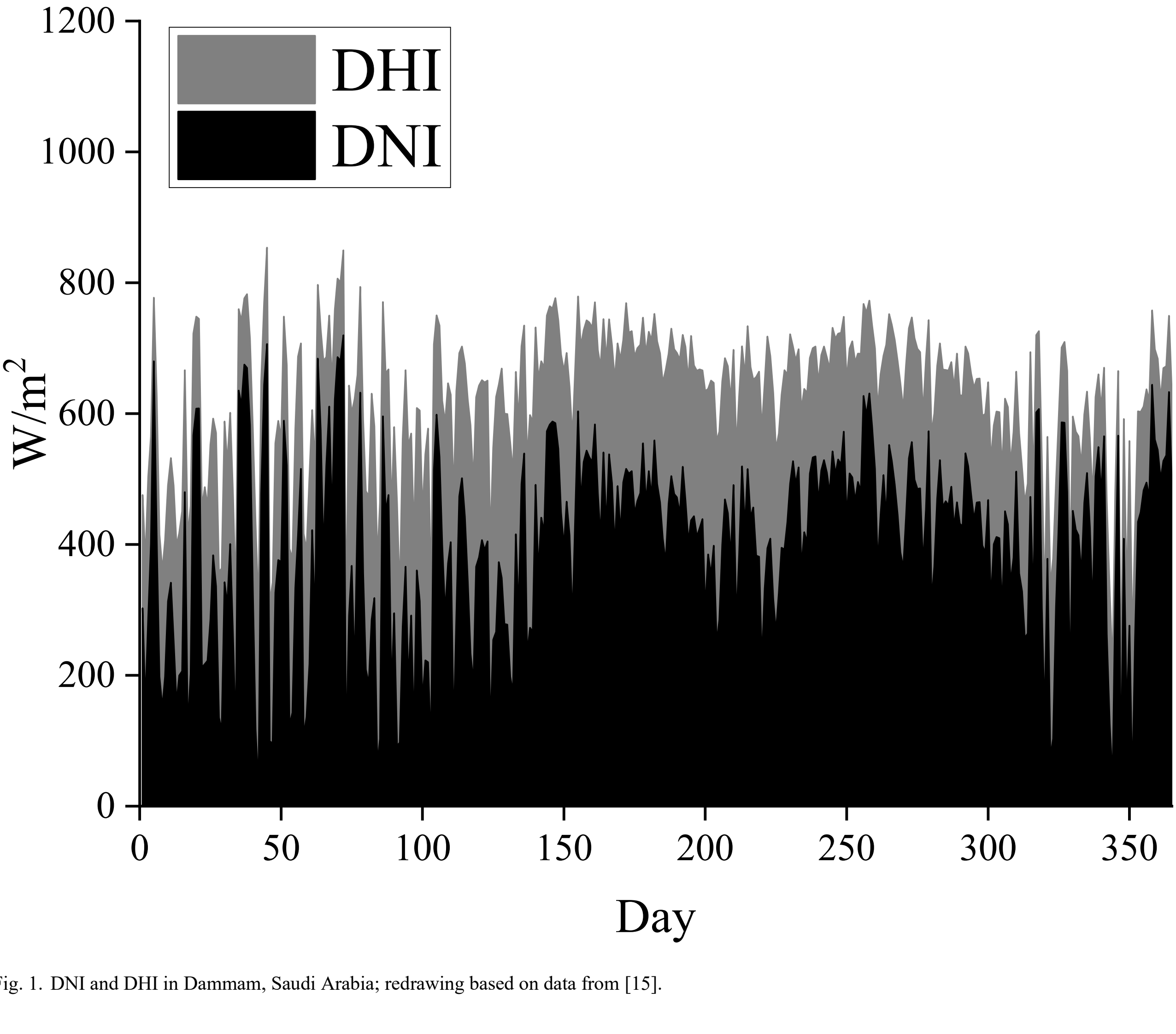

Fig. 1. DNI and DHI in Dammam, Saudi Arabia; redrawing based on data from [15].

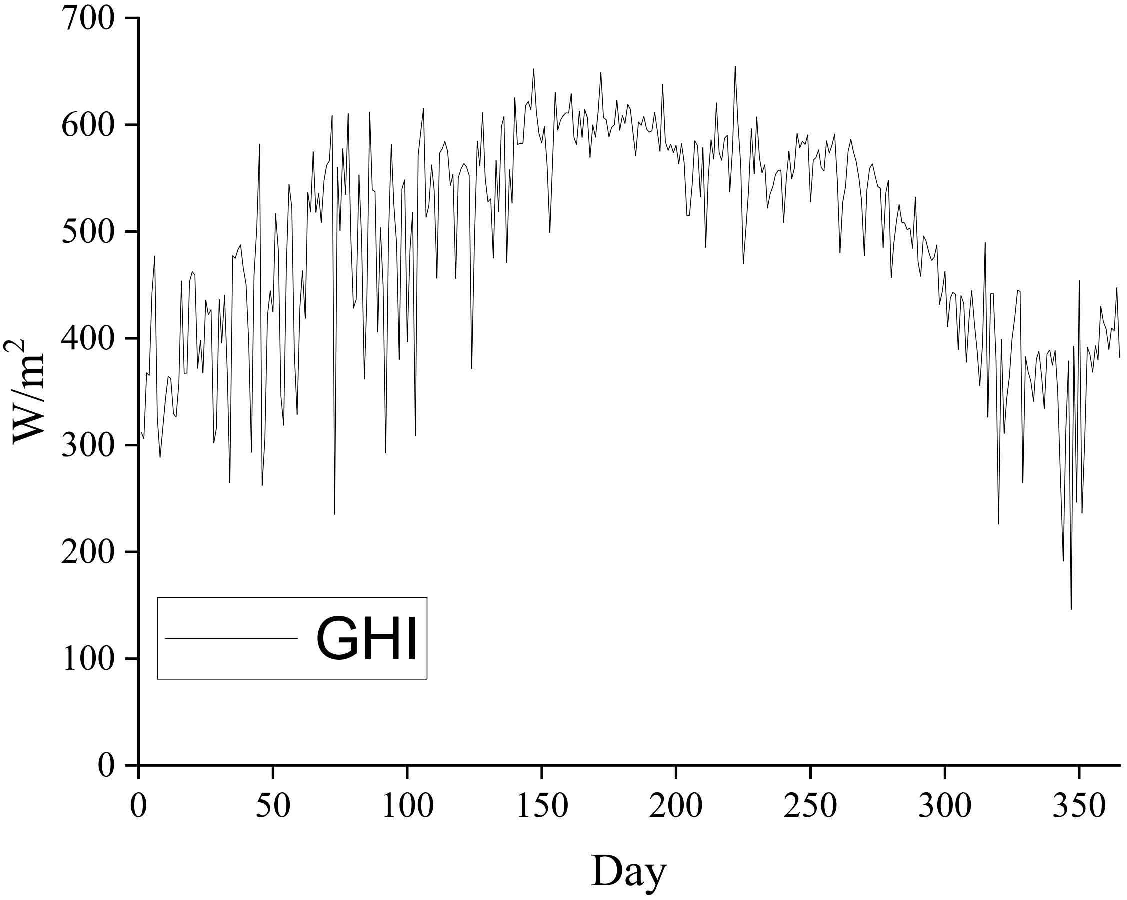

Fig. 2. GHI in Dammam, Saudi Arabia; redrawing based on data from [15].

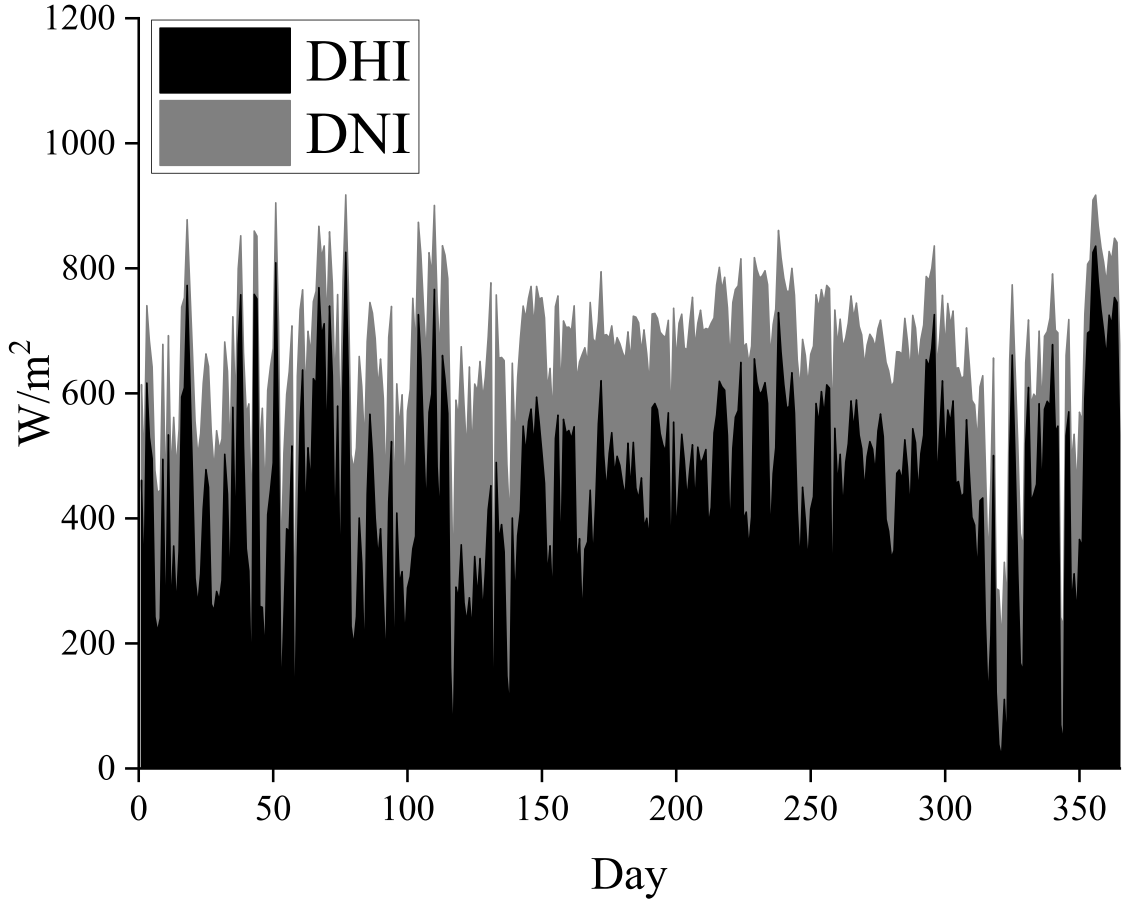

Fig. 3. DNI and DHI in Riyadh, Saudi Arabia; redrawing based on data from [15].

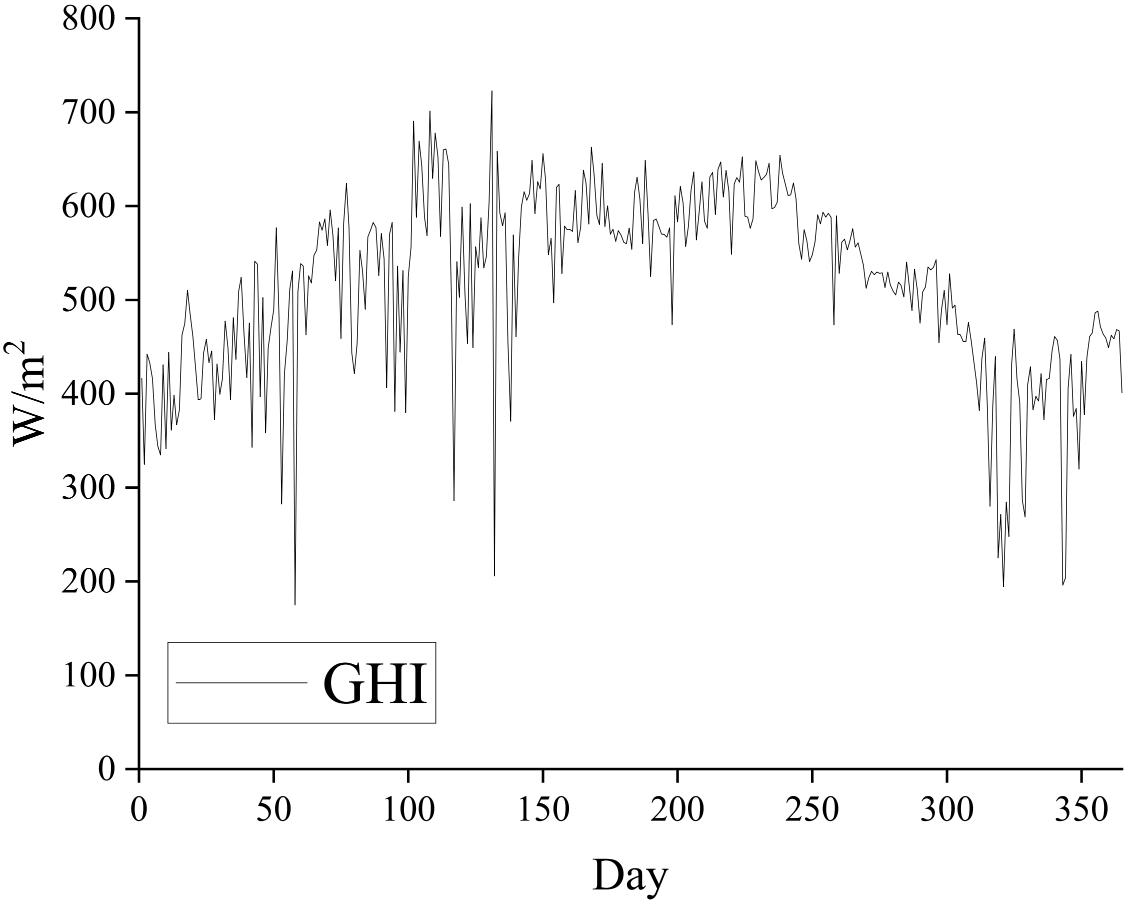

Fig. 4. Global solar irradiance for Riyadh; redrawing based on data from [15].

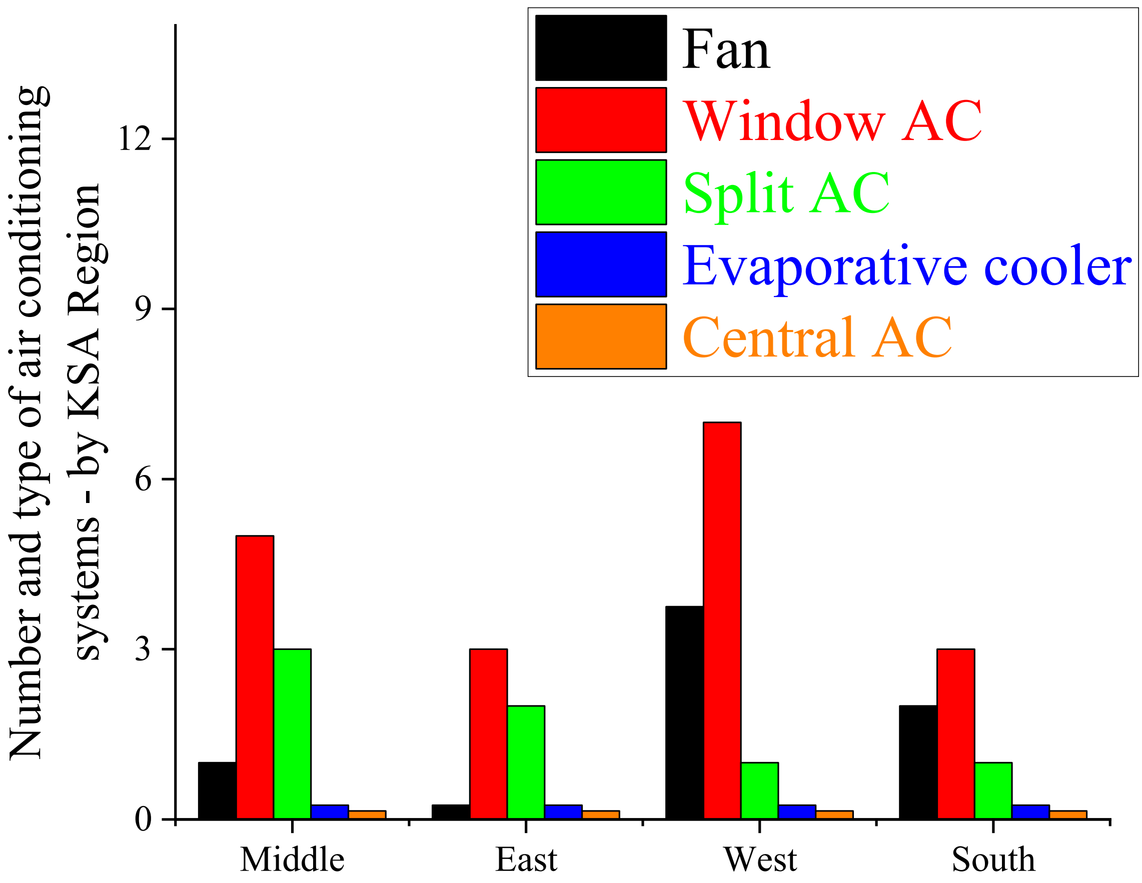

Fig. 5. Number and type of AC systems used in all housing units according to KSA region; redrawing based on data from [12].

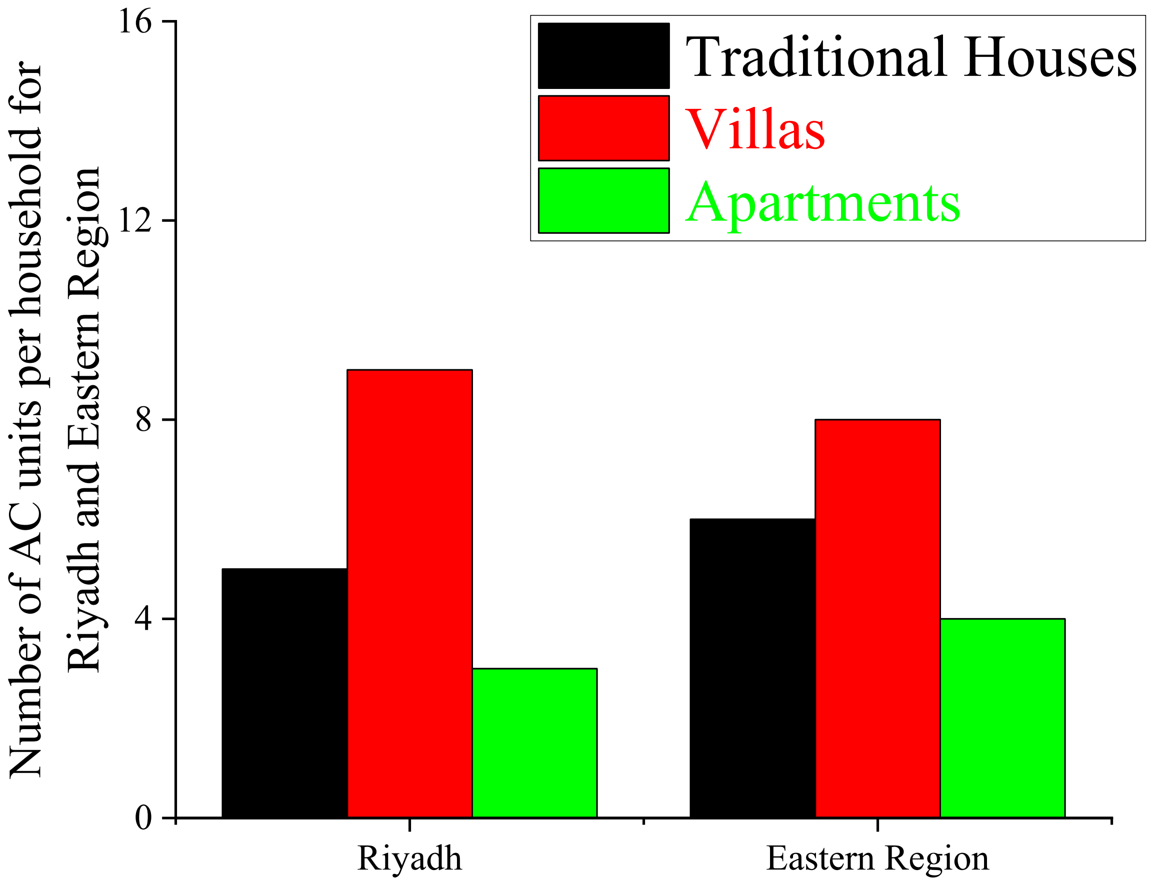

Fig. 6. Number of AC units and appliances per household for Riyadh and the eastern region.

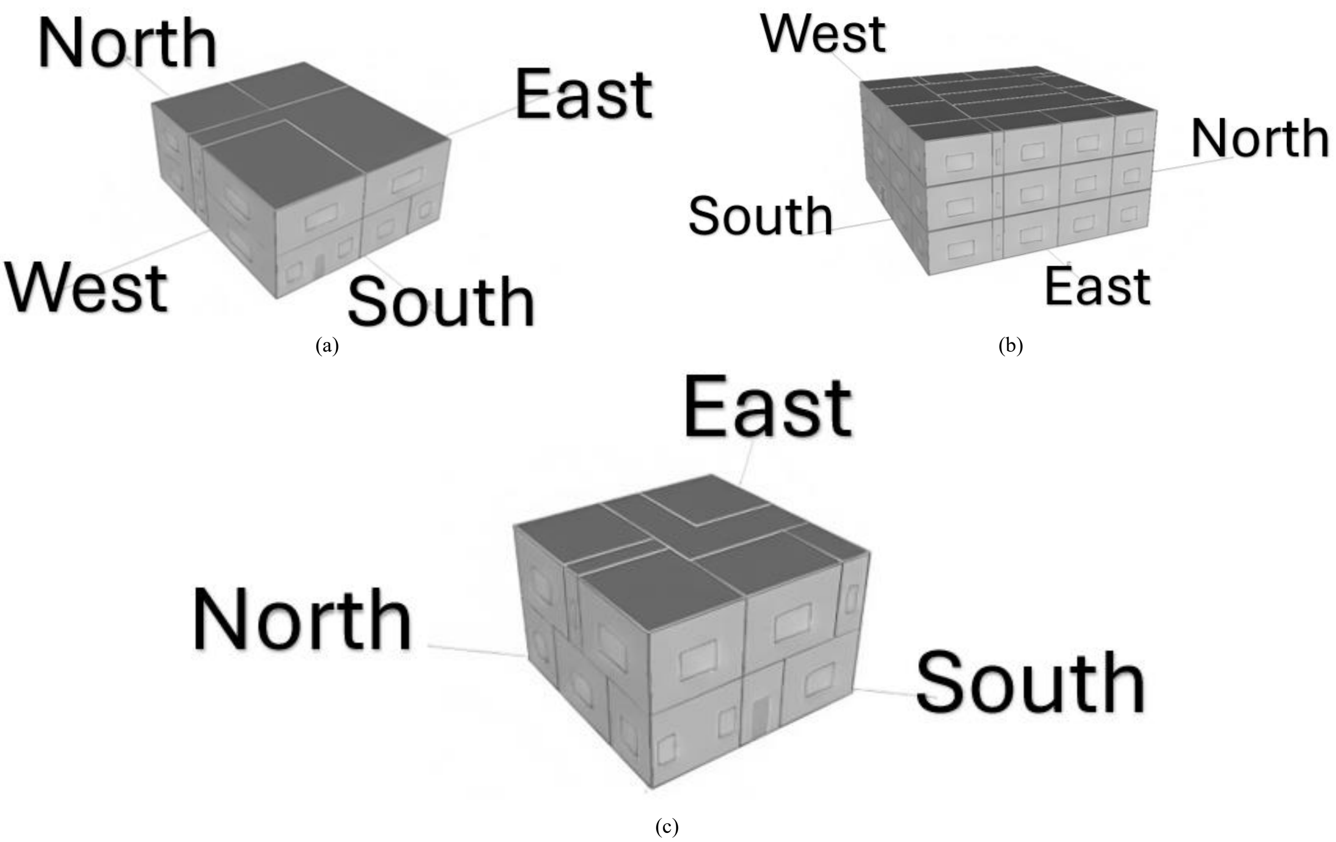

Fig. 7. Renderings of energy models for (a) villa, (b) apartment and (c) traditional house [18].

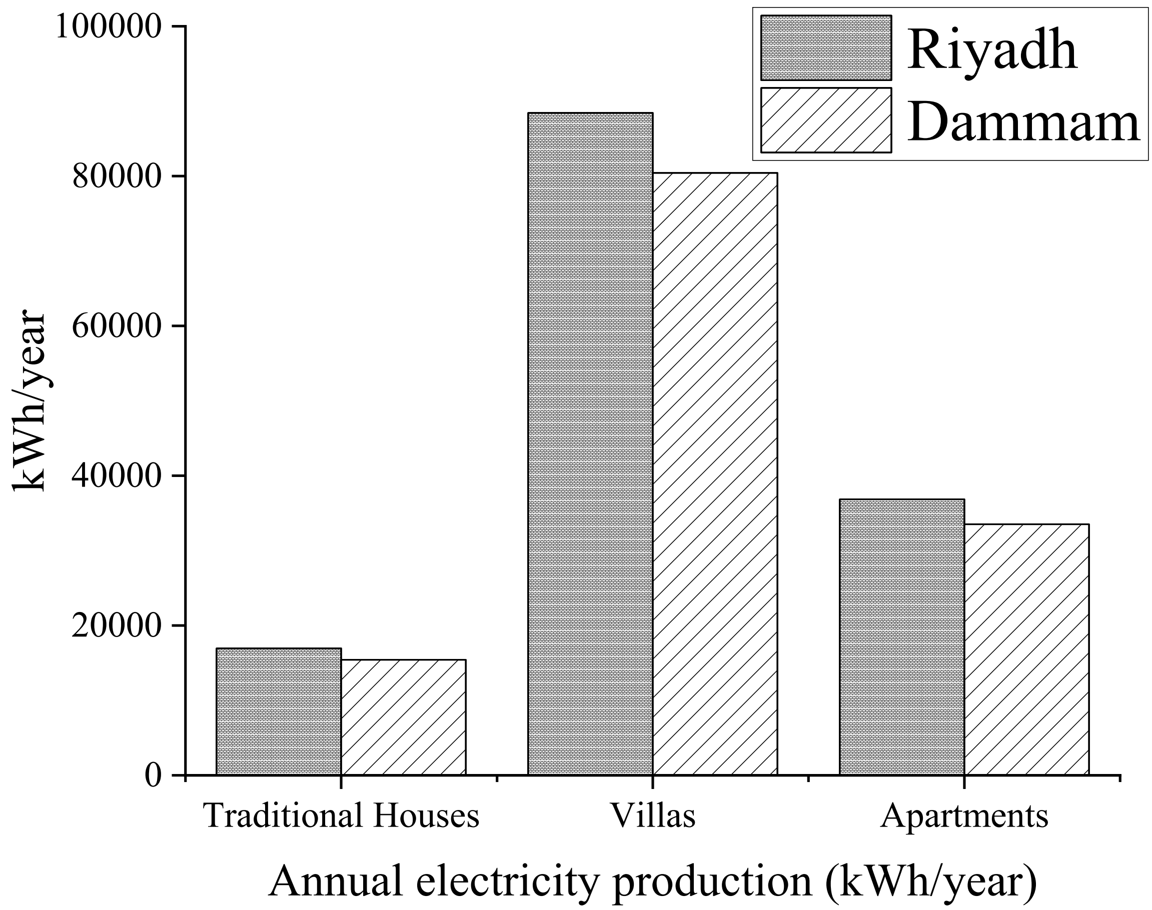

Fig. 8. Annual electricity production of different house types.

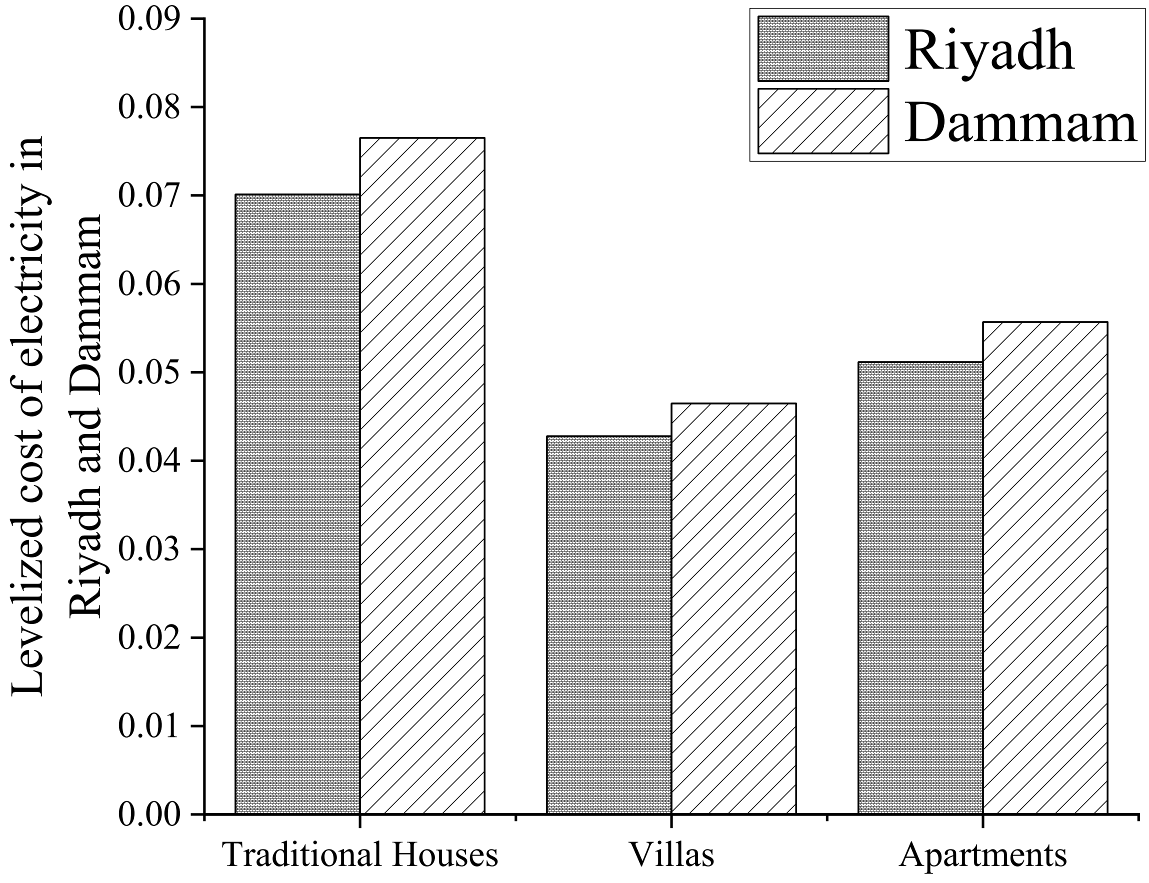

Fig. 9. L_{COE} of different house types.

C. Economic Insights

L_{COE} is a critical metric used to measure the total cost of energy production per unit over the system's lifetime, incorporating all cost elements. This chapter employs the annuity method to calculate the L_{COE} by distributing the initial system investment evenly over a designated 20-year life span at an interest rate of 6%, as set by the Central Bank of the KSA. The L_{COE} for residential PV systems powering HVAC ranges from $0.043 to $0.0765 per kWh across various housing types.

Notably, villas in cities such as Riyadh and Dammam demonstrate particularly lower investment costs per kWh due to their capacity to install larger solar PV systems. The L_{COE} is $0.043 per kWh in Riyadh and $0.046 in Dammam, showcasing the widespread application potential in these regions. The solar potential varies by location, with Riyadh having a greater potential than Dammam does, resulting in higher electricity production, as illustrated in Figures 8 and 9.

The techno-economic performance analysis of residential PV systems for HVAC integration in KSA highlights the feasibility and benefits of these systems. The findings serve as a catalyst for policy innovation and consumer adoption, aligning economic incentives with environmental benefits. This alignment directs policy formulation and consumer decisions towards a more sustainable and energy-efficient future, supporting the overarching objectives of Saudi Vision 2030.

VII. Conclusion

The techno-economic analysis demonstrates the diverse economic viability of integrating solar PV systems to power HVAC units across various residential building types in the KSA. This study focused on analysing the L_{COE} for villas, apartments and traditional houses, revealing distinct cost dynamics that inform consumers and policymakers.

- Villas: Among the different residential types, villas exhibit the most favourable economic viability for solar PV integration. The analysis indicates that villas achieve the lowest L_{COE} due to their larger roof space, which allows for higher-capacity solar installations and more efficient energy generation. This advantageous cost structure makes villas an ideal target for solar adoption initiatives.
- Apartments: While slightly less economically viable than villas, apartments still present a reasonable opportunity for solar PV integration, particularly when considering shared systems or community solar models. The L_{COE} is moderately competitive, providing a tangential but practical approach for enhancing energy sustainability in densely populated areas.
- Traditional houses: The economic viability for traditional houses is less favourable due to higher initial installation costs and limited roof space. These factors result in a higher L_{COE}, posing a challenge for widespread adoption without targeted financial assistance or technological advancements that reduce costs.

This study provides valuable insights into the economic feasibility of solar PV systems for residential HVAC applications, highlighting key areas for further research and acknowledged limitations. Future research should focus on technological innovations, exploring advancements in solar technology and energy storage solutions that could significantly lower costs and enhance efficiency, especially for traditional houses. Additionally, understanding consumer behaviour and the adoption rate of renewable technologies can offer a deeper comprehension of market dynamics, informing strategies to enhance uptake. Investigating the comprehensive impact of specific policy measures, such as tax incentives or rebates, on economic outcomes across different housing types would also be beneficial. Moreover, considering regional climatic variations and their impact on solar PV performance is essential for tailoring solutions to specific locales within KSA. Furthermore, incorporating more dynamic economic models that account for potential changes in energy prices and technological costs over time could refine L_{COE} projections. Addressing these limitations and exploring these areas will enable future research to enhance the understanding and effectiveness of integrating solar PV systems in residential settings, contributing significantly to the Kingdom's sustainability and energy diversification goals.

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