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Evaluating Energy Consumption in Residential Buildings in Qatar: A Case Study on Compounds

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Abstract: The global urgency to cut carbon emissions and pollution is clear. Qatar, rich in fossil fuels, is shifting towards sustainability to reduce carbon emissions. This paper analyzes the energy consumption patterns in residential buildings in Qatar, categorizing them by size and ownership, and establishing energy benchmarks for each building type, offering insights to guide energy efficiency policies. By examining the building size and ownership, the study helps establish benchmarks, supporting Qatar's sustainability goals in reducing carbon emissions. The study was conducted from 1 January 2019 to 31 December 2021, utilizing data from the Qatar General Electricity and Water Corporation (KAHRAMAA). A total of 172,796 residential buildings were analyzed, with data on building characteristics and demographic information incorporated into the analysis. A quantitative analysis revealed that the building size, ownership, and demographics significantly impact energy consumption, guiding efficiency strategies. The ownership and floor area significantly impact energy consumption. A strong positive correlation (R = 0.97) was found between energy consumption (kWh) and the total built area (m^2). The patterns of energy use varied across different residential building types. The findings highlight the importance of considering the ownership and building size in energy efficiency policies. Identifying specific energy use patterns supports the development of targeted strategies. This research offers valuable data on residential energy consumption in Qatar, providing a foundation for energy benchmarks. These benchmarks can guide policy decisions and strategies to enhance energy efficiency and promote sustainability in the residential sector. This study uniquely connects the ownership and building size with energy consumption patterns in Qatar, supporting the development of effective energy policies and contributing to global sustainability goals.

Keywords: energy consumption; energy efficiency; sustainable housing; Qatar

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1. Introduction

Human activities have emerged as significant contributors to the global climate change process through the release of substantial volumes of greenhouse gases into the atmosphere, marking global warming as one of the most pressing environmental challenges facing humanity to date [1,2]. Globally, the building sector, which is responsible for nearly one-third of greenhouse gas emissions and 40% of energy consumption, plays a pivotal role in this scenario [3]. Air-conditioning systems account for 60–80% of the total energy demand in buildings, particularly in hot countries like Qatar [4]. This has prompted researchers and industry experts to explore novel methods and technologies aimed at enhancing building energy efficiency within the built environment. Qatar is a country rich in resources, including energy and gas, with a more sustainable strategy to drive energy consumption reduction in residential buildings, which is essential to achieve sustainability. The effectiveness of the energy usage within buildings depends not only on the efficiency of the internal temperature control and lighting systems but also on the design of the building and its outer envelope to minimize heat losses and maximize natural lighting and ventilation, thereby meeting human comfort requirements [5].

Qatar holds the distinction of having one of the world's highest energy consumptions per capita, which is further exacerbated by heavy subsidies for its citizens, underscoring the urgent need for improving energy efficiency and reducing the energy demand as viable solutions to address global warming and climate change [6,7]. The country continues to witness a notable substantial increase in its annual electricity generation and consumption rates due to various factors, such as population growth, subsidized electricity tariffs, economic development, the high demand for cooling during the hot summers, and aspirations for an elevated standard of living [6]. This surge in electricity consumption per capita ranks among the highest globally and has exhibited rapid growth compared to the income per capita [5]. Understanding electricity consumption patterns in regions with similar meteorological conditions to those of Qatar, such as those found in the Arabian Peninsula or other arid climates, is crucial for effective energy management. Countries like Saudi Arabia and the UAE, with their extreme temperatures and high cooling demands, offer valuable insights into addressing energy challenges. By examining their strategies and practices, we can gain benchmarks that are relevant to Qatar's context. Additionally, exploring energy use in other arid regions, such as southern California or parts of Australia, can reveal successful technologies and practices that may be adapted to improve Qatar's energy efficiency and sustainability efforts. Fossil fuels such as oil and liquefied gas continue to form a very essential and strategic drive for Qatar's energy, contributing to over 80% of the total government revenue [6]. The current population is over 2.7 million people, which is projected to increase by 2050 to a population of about 3.8 million, with the vast majority residing in the country's capital, Doha, which serves as the administrative hub, located on the far eastern coast of the country, and which has embarked on several policies aimed at reducing its dependence on the non-hydrocarbon sector in its Gross Domestic Product (GDP) [7]. Notably, the country's economy is heavily reliant on oil export revenue, which amounts to over USD 55 billion, with the increasing energy exploitation contributing approximately 57.8% to the country's GDP [8]. Despite heavy investments, challenges persist, with significant household sizes—averaging five individuals per household—contributing to a noticeable upward trajectory in energy consumption trends [9]. In contrast to the declining energy consumption trends witnessed in the U.S. and Europe since the 1970s, driven by public awareness campaigns for renewable energy and energy conservation, Qatar faces unique challenges due to the absence of electricity charges for Qataris [10].

Energy policymaking is also an enabler that has encountered significant challenges in Qatar due to its unique climate conditions and rapidly increasing energy demand [10]. Qatar's climate, characterized by uniform aridity, imposes substantial cooling requirements [11]. Moreover, the majority of Qatar's population comprises 12% Qatari citizens and 88% non-citizen residents, and each group is subject to specific energy incentives and subsidies. Notably, Qatar has allocated a huge amount to its Qatari citizens, totaling over USD 46,000 per citizen/year towards more strategic power and desalinated water production over the past decade [12]. While Qatari citizens receive free electricity and water, non-Qatari residents pay monthly utility bills. Traditional economic-driven approaches for energy efficiency and subsidies may not yield optimal results in Qatar due to the existing energy subsidies and high per capita income, particularly within the residential sector [13]. Given this context, energy conservation in Qatari households assumes paramount importance in reducing the highly subsidized domestic energy consumption and identifying a more strategic way to reduce it, while also exploring better ways to sustain better renewable energy use and adoption amongst residents accustomed to high rates of energy consumption [14]. Thus, implementing and assessing theoretical energy efficiency or policy strategies often result in performance gaps between the expected and actual outcomes. To bridge this gap, we examine the energy consumption in residential buildings in Qatar and the significant factors influencing the electricity consumption in residential buildings based on the building size and ownership.

This research seeks to understand how the building size, ownership, and demographic factors influence the energy consumption patterns in residential buildings in Qatar, as

well as the implications for developing targeted energy efficiency strategies. While this study provides comprehensive benchmarks for energy consumption in various residential building types in Qatar, it lacks a detailed analysis of how distinct building types might require different models to capture specific energy use patterns. Further research is needed to explore whether separate regression models for each building type could yield more precise insights into energy consumption variations.

2. Energy Consumption in Qatari Buildings

In Qatar, air-conditioning systems are ubiquitous in virtually every building and typically account for the majority of energy bills (70–80%), arguably the highest globally. With average high temperatures exceeding 27 °C for nine months of the year and summer temperatures regularly surpassing 45 °C, continuous air-conditioning operation is a common practice, exacerbated by significant daily humidity fluctuations ranging from 40% to over 70%. Many residential buildings run air-conditioning systems around the clock throughout the year [15]. Lighting and refrigeration constitute the remaining electricity consumption components. The average household electricity consumption in Qatar is estimated at 34,000 kWh/year, ranking among the highest globally [12]. While Qatari citizens benefit from free electricity, gas, and water, the utility rates for expatriates remain comparably low, especially when compared to North America and Europe. Furthermore, approximately one-quarter of the housing units in Qatar consist of worker housing compounds for expatriates [16]. The expatriate population's transient nature often results in a reluctance to invest in high-efficiency equipment due to short-term residency plans. Nonetheless, the financial burden stemming from extensive air-conditioning usage has prompted some consumers to adopt conservation measures. Improvements in lighting and appliance efficiencies not only lead to direct savings but also contribute to reduced cooling loads throughout the year [17]. The country's recent strategy to reduce the energy usage in buildings includes the implementation of a Green Building Code, which is presently voluntary, but there are plans to transition to mandatory compliance as stakeholders become more acquainted with its requirements. The Global Sustainability Assessment System (GSAS) aims to establish a benchmarking framework for green building developments across the Gulf region [18]. Despite Qatar's capacity to procure the world's most efficient products, challenges such as the private reluctance to invest in efficiency, project completion urgency, and the presence of low-efficiency suppliers in the Middle East hinder the adoption of high-efficiency appliances. This is particularly evident in terms of small air conditioners [19].

3. Materials and Methods

This study conducted a thorough investigation into the energy usage patterns in residential buildings within the unique context of Qatar. Utilizing extensive datasets on energy consumption, building features, and demographic factors, the research employed quantitative analysis techniques to uncover the trends and drivers of energy use in residential settings. In addition to quantitative analysis, the study incorporated qualitative insights from interviews and surveys with residents to understand their attitudes, habits, and perceptions regarding energy use, providing a holistic understanding of the residential energy consumption. This study adopted an exploratory approach aimed at conducting preliminary investigations into relatively unexplored areas of research as adapted by the work [20]. Given the limited existing literature on energy behavior within the Gulf Cooperation Council (GCC) states, primary data collected by the regulatory body were deemed appropriate [21,22]. We utilized already collected data from KAHRAMAA, which serves as the Qatar General Electricity and Water Corporation Company, which comprised a comprehensive quantitative data survey of domestic consumers of Qatar's power supply. Data were compiled from KAHRAMA, which offers evidence into the energy consumption patterns with the need for energy solutions, particularly renewable ones. The data were cleaned, validated, and grouped as described by the studies [23,24], while the outcomes of interests were followed and analyzed as described by the studies [25,26].

3.1. Study Population

Qatar is located in the far eastern region of the Arabian Peninsula, spans approximately 11,437 square kilometers, and experiences an average annual rainfall of about 80 mm, with relative humidity ranging from 59% to 95% [27]. During the summer season in Qatar, temperatures frequently exceed 40 °C (104 °F), with peak temperatures reaching as high as 50 °C (122 °F). The relative humidity levels can be extremely high, often ranging between 60% and 80%, exacerbating the heat and increasing cooling demands. Conversely, the winter months, from November to March, bring milder temperatures ranging from 15 °C to 25 °C (from 59 °F to 77 °F), with significantly lower humidity levels, usually between 30% and 50%. This seasonal variation impacts the energy consumption patterns, particularly in relation to the cooling requirements and overall building energy performance [28]. Since its establishment in 1971, Qatar has undergone rapid population growth and economic development primarily attributed to the discovery of hydrocarbon energy sources [29,30]. These factors have significantly heightened the demand for electricity and intensified supply processes.

3.2. Data Collection

We utilized data from KAHRAMAA, which gives a comprehensive utilization of the electricity consumption in the country, covering between 1 January 2017 and 31 December 2021. This encompassed 172,796 residential buildings, and monthly flow data were gathered and measured in kilowatt hours (KWh) for two primary sectors: residential villas (referred to as "villas") and residential flats (referred to as "flats"). It is important to note that rigorous quality control measures were applied to the monthly electricity consumption data in order to remove any meters with zeros or missing values within individual months throughout the entire study period. Furthermore, the plot area sizes of the villa residential buildings were obtained from the Centre of GIS (CGIS) division of the Ministry of Municipality and Environment in Qatar (MME).

3.3. Statistical Analysis

The data analysis included using Pearson correlation (r) analysis to explore the association between the average annual electricity consumption and the total built area in the case studies of residential buildings. Regression analysis, a robust quantitative research technique, was employed to assess the relationships between a dependent variable, such as the energy use intensity (EUI), and one or more independent variables, such as the building size. Multiple linear regression models were developed using data from the case study buildings. The "Regression" tool in SPSS was utilized for this purpose, employing the least-squares method to fit a line through the observations of the dependent variable and providing an equation for this line by assigning values to each independent variable. Moreover, data were incorporated based on readily available information that were believed to influence the energy consumption of the buildings (i.e., total built area).

In this study, each compound underwent a separate analysis to ascertain the average EUI per villa within it. Subsequently, the data from the four villas per compound were aggregated and analyzed collectively. This approach allowed for a nuanced understanding of the energy consumption patterns within individual compounds before examining the broader trends across all the compounds. By conducting analyses at both the micro-level (per compound) and macro-level (across compounds), we aimed to capture variations in the energy usage efficiency within and across different villa settings. This methodological strategy contributes to a comprehensive assessment of the energy consumption dynamics in the studied residential complexes, thereby facilitating informed decision making regarding energy management and sustainability initiatives. The provided statistical data offer a comprehensive comparison of various villa types, shedding light on their built areas, energy consumption, EUIs, CO_2 emissions, and annual costs.

In this research focusing on conventional villas, a rigorous data-filtering process was implemented to ensure the accuracy and reliability of our analyses. Specifically, out of the

initial sample size of 61 villas, those properties that were unoccupied or that remained unrented for extended periods, accompanied by electricity consumption below 10,000 kWh and EUI values falling below 25 kWh/m^2, were excluded from the dataset. This meticulous approach was adopted to eliminate potential outliers and data inconsistencies that could skew the results, thereby enhancing the validity and robustness of our findings. By refining the dataset in this manner, we aimed to foster a more precise and nuanced understanding of the energy consumption patterns within the conventional villa context, facilitating more accurate interpretations and informed decision making regarding energy management strategies and sustainability initiatives.

3.4. Selection and Characteristics of Residential Compounds

The analysis focused on four residential compounds in Qatar, selected based on their diverse architectural and demographic characteristics. Villa/C1, Villa/C2, and Villa/C3 are located in Doha, while Villa/C4 is situated in Al-Rayan. The selection aimed to capture a range of villa sizes and energy consumption patterns. Table 1 details the number of villas, mean annual energy consumption, built area, and energy use intensity (EUI) for each compound. Villa/C1 and Villa/C2 are larger with higher energy consumption, while Villa/C3 has lower consumption. Villa/C4 represents a different area with intermediate consumption levels. This diversity ensured a comprehensive analysis of the energy usage across varying villa types and locations.

Table 1. Compound case studies in Qatar.

Ref.	Compound Location	Number of Analyzed Villas	Mean Annual Energy Consumption (kWh per Villa) (2019–2021)	Villa Built Area (m^2)	Mean Annual EUI (kWh/m^2) (2019–2021)	CO_2 Emissions for 50 Years (kgCO_2/m^2)
C1	Doha	18	86,801	540	161 ± 54	78,869
C2	Doha	9	95,339	600	132 ± 128	64,663
C3	Doha	34	32,936	400	82 ± 41	40,169
C4	Al-Rayan	40	47,774	400	119 ± 49	58,294

4. Results

Table 2 provides a comprehensive summary of the analyzed residential premises in Qatar, detailing the numbers and types of flats and villas categorized by ownership and customer type. This table categorizes residential properties, including flats, villas, palaces, and specialized premises, into various ownership and usage types, offering insights into the distribution and classification of residential energy consumers.

Table 2. Summary of the numbers and types of analyzed residential premises.

Premises Category	Premises Name	Customer Type	Number	Total Number by Customer Type	Total Number by Premises Category
Flat (residential)	Flat	Qatari owner	127	791	80,485
		Rented premises by Qatari's	664		
		Regular customer	62,811	62,811	
		Regular customer (VIP)	16,883	16,883	

Table 2. *Cont.*

Premises Category	Premises Name	Customer Type	Number	Total Number by Customer Type	Total Number by Premises Category
Villa (residential)	Villa/house	Qatari owner	26,030	37,422	89,088
		Rented premises by Qataris	11,293		
		Regular customer (Qatari)	103		
		Regular customer	46,159	46,159	
		Regular customer (VIP)	5507	5507	
	Palace	Qatari owner	28	28	28
	Mosque/imam's house	Regular customer	323	323	323
	Majlis	Qatari owner	888	961	1097
		Rented premises by Qataris	73		
		Regular customer	136	136	
	Guard room	Regular customer	19	19	19
	Room	Regular customer	88	8	8

Figure 1 shows the total annual electricity consumption in Qatar across all the sectors between 2017 and 2021. The peak was seen in 2019 (40,942 GWh), with the lowest in 2017 (35,906 GWh).

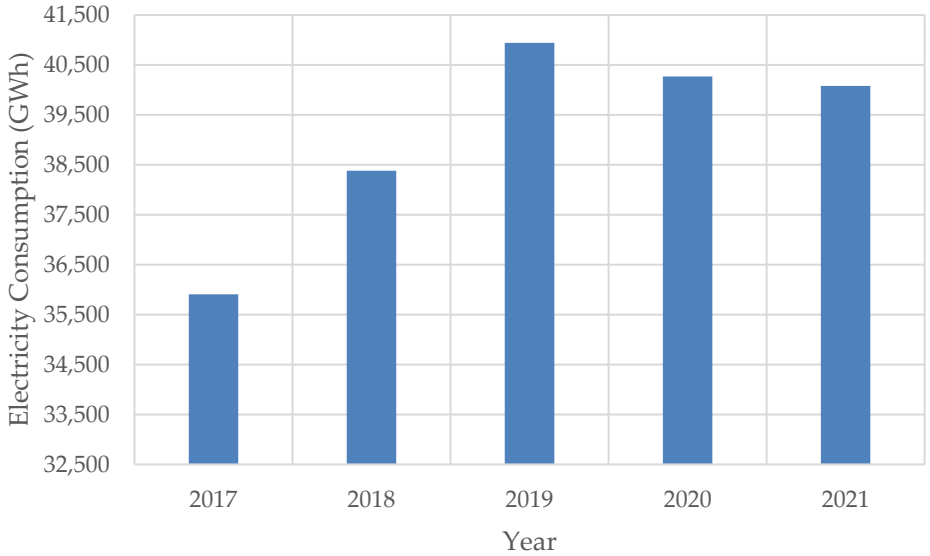


Figure 1. Energy consumption pattern in Qatar in all sectors included for 4 years (2017–2021).

Figure 2 depicts the electricity demand by sectors from 2017 to 2021, indicating that buildings accounted for 86.1% of all the city electricity consumption. Specifically, residential buildings contributed to 49.0% of the electricity demand, the commercial sector to 29.0%, and government buildings (such as mosques, police stations, offices, public hospitals, and schools) to 8.2%. The residential sector in Qatar emerged as the largest energy consumer, constituting over 40% of the total consumption.

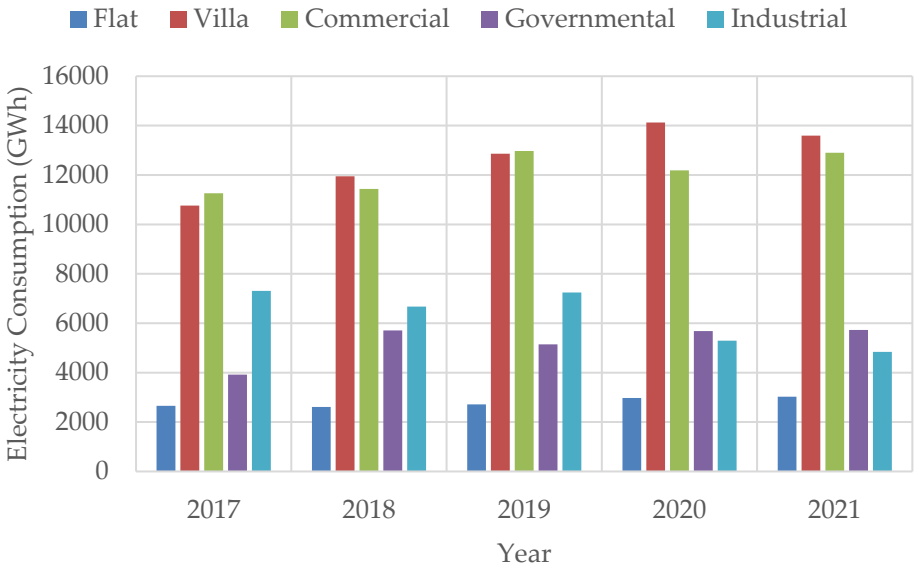


Figure 2. Sectorial energy consumption patterns in Qatar over 4 years (2017–2020).

Figure 3 shows the electricity consumption (GWh) in Qatar's residential sector—a large part of the electricity consumption is in villas (the highest in 2021 (13,592 GWh))—depicting the dominance of this building form in the residential sector.

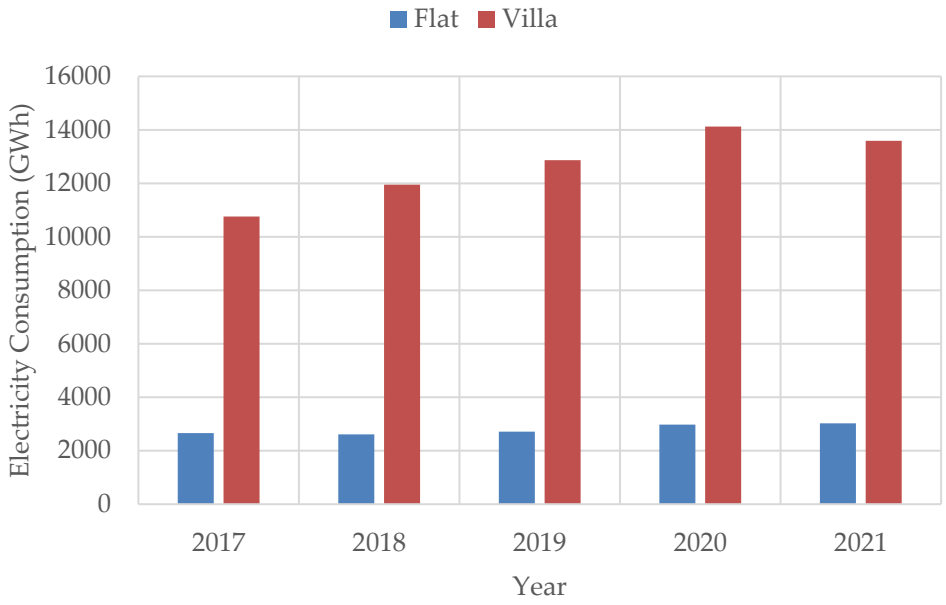


Figure 3. Electricity consumption (GWh) in Qatar—residential sector.

Table 3 presents the electricity tariffs per kWh for different sector types as of December 2021. For residential flats, the tariff is QAR 0.08 per kWh. Villas have a tiered rate: QAR 0.08 for usage up to 4000 kWh and QAR 0.10 for consumption beyond this threshold. This tiered pricing reflects the varying consumption levels across the residential sectors.

Table 3. Electricity prices per kw per sector for December 2021. Accessed on 23 May 2024. (source: https://www.km.qa/ExportedSites/Customer/Pages/Tariff.aspx).

Sector Type	From (KWh)	To (KWh)	Electricity Tariff (KWh) in QAR
Residential flat	1//4001	4000 Maximum	0.08
Villa (Residential)	1//4001	4000 Maximum	0.08//0.1

In evaluating the energy consumption of conventional compound villas in Qatar, this study selected four compound case studies. The average mean annual electricity consumption per compound villa for the specified timeframe is reported to be (124 ± 33) kWh/m^2, as presented in Table 1.

In analyzing the energy consumption patterns of residential buildings in Qatar, several key indicators offer valuable insights into the trends and differences across the various building types and periods. One crucial metric is the energy use intensity (EUI), which quantifies the average energy consumption per unit area (kWh/m^2). Table 1 and Figures 4–7 provide comprehensive EUI data for different villa compounds, revealing significant variations. For instance, Compound C1 has an average EUI of 131 ± 45 kWh/m^2, indicating higher energy consumption relative to Compound C3, which has a lower EUI of 99 ± 34 kWh/m^2. These variations underscore how factors such as the building design, insulation, and occupancy influence the overall energy use.

Moreover, this study highlights differences in the emission intensity, which reflects the environmental impact of energy consumption. The CO_2 emission data for each compound, presented in Table 1, further illustrate these disparities. For example, Compound C1 generates 78,869 kgCO_2 over a 50-year period, a significant amount reflecting its higher energy usage compared to other compounds. This metric is crucial for understanding the carbon footprint associated with different building types and helps in assessing their contributions to overall greenhouse gas emissions.

Table 1 provides detailed data on the energy consumption and building characteristics for villas in Qatar, showing variations in the mean annual energy consumption and CO_2 emissions across different compounds. For instance, Villa/C1 in Doha has the highest annual energy consumption per villa at 86,801 kWh, while Villa/C3 has the lowest at 32,936 kWh. Table 4 summarizes the annual mean electricity consumption per square meter for different villa schemes, distinguishing between individual and compacted (attached) villa types. The mean annual EUI in Table 4 ranges from 99 to 131 kWh/m^2, reflecting differences in the villa design and type.

Figures 4–7 show the annual consumption in kWh/m^2 in Compounds 1–4. Compounds 1–3 are all located in Doha, and Compound 4 is located in Al-Rayan, Qatar. Figure 4 shows a slight decline in the annual electricity consumption (kWh/m^2) for Compound C1 in Qatar during this period. Specifically, there is a 1.79% decrease observed from 2019 to 2020, followed by a 2.53% increase from 2020 to 2021. These findings shed light on potential shifts in the energy usage behaviors or efficiency improvements within the residential complex over time. Furthermore, the mean annual electricity consumption is reported to be (161 ± 54) kWh/m^2.

Table 4. Annual mean electricity consumption (kWh/m^2) for analyzed compound villa samples.

Ref.	Number of Analyzed Villas	Villa Built Area (m^2)	Mean Annual EUI (kWh/m^2) (2019–2021)	Scheme
C1	5	540	131 ± 45	Individual (non-attached villa type)
C2	5	600	115 ± 54	Individual (non-attached villa type)
C3	5	400	99 ± 34	Compacted (attached villa type)
C4	5	400	110 ± 30	Individual (non-attached villa type)

Figure 5 shows the annual consumption in kWh/m^2 in Compound 2. C2 is a residential complex that comprises nine individual villas, all of which are of the non-attached villa type and were occupied and rigorously analyzed for the study. The research focused on examining the trends in the annual electricity consumption per villa within C2 over a three-year period, spanning from 2019 to 2021. Notably, the analysis reveals a slight increase in the annual electricity consumption per villa during this timeframe. Specifically, there is a 5.87% rise observed from 2019 to 2020, followed by a more pronounced 18.75% increase from 2020 to 2021. Furthermore, the mean annual electricity consumption is reported to be (132 ± 128) kWh/m^2.

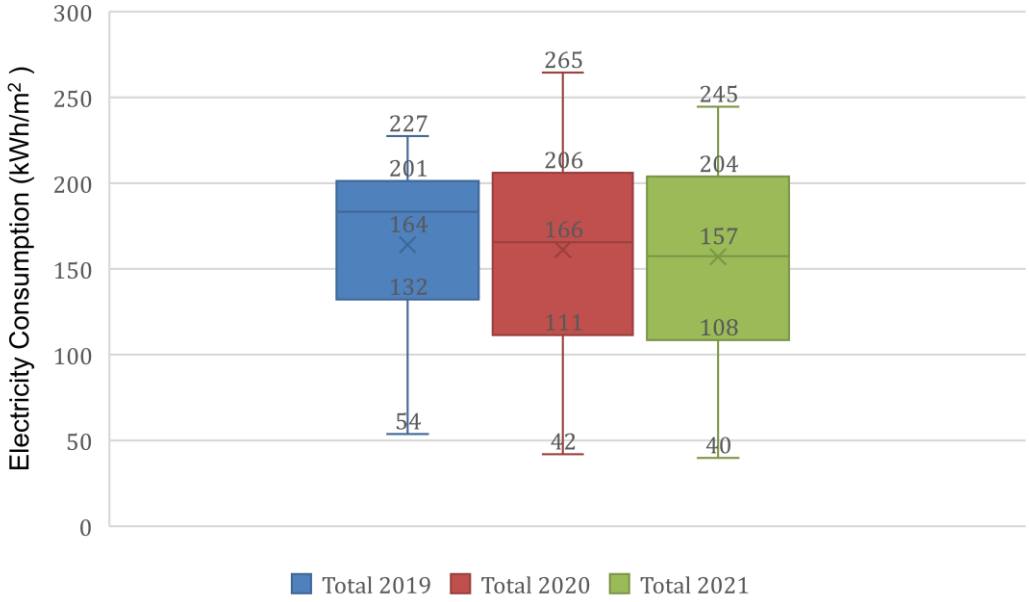


Figure 4. Annual electricity consumption (kWh/m^2)—Compound 1.

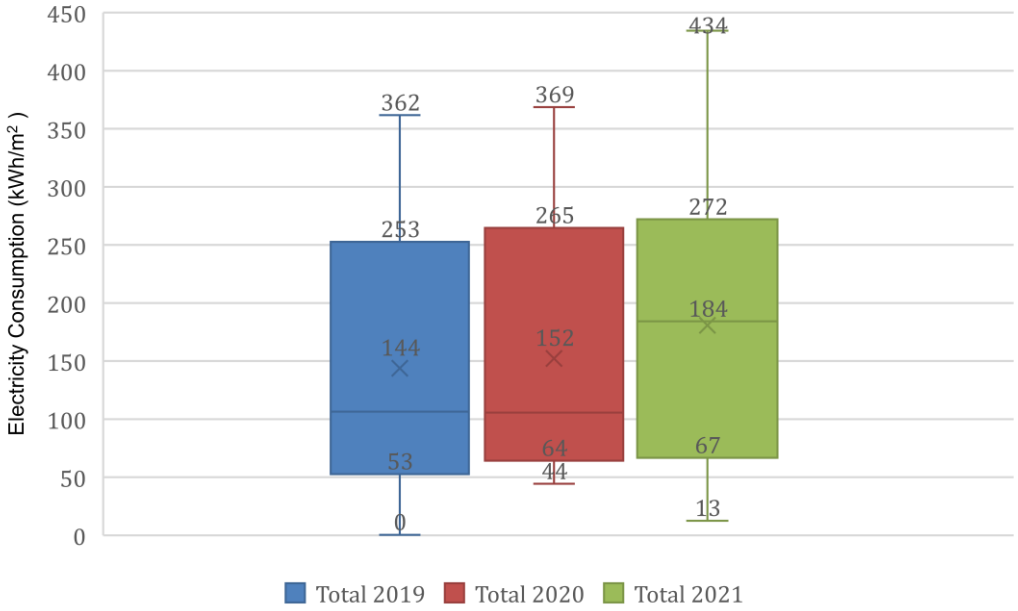


Figure 5. Annual electricity consumption (kWh/m^2)—Compound 2.

Figure 6 shows a slight decline in the annual electricity consumption per villa during this timeframe for C3. Specifically, there is a 5.63% decrease observed from 2019 to 2020, followed by a marginal 0.01% decline from 2020 to 2021. These findings provide insights into potential shifts in the energy usage behaviors or efficiency improvements within the residential complex over time, particularly within the context of compacted attached villas. Furthermore, the mean annual electricity consumption is reported to be (82 $\pm$ 41) kWh/m^2.

Figure 7 shows a notable increase in the annual electricity consumption from 2019 to 2020, with an 18.53% rise observed during this period for C4. However, there was a subsequent decrease in the electricity consumption from 2020 to 2021, with an 11.10% decline recorded. Furthermore, the mean annual electricity consumption is reported to be (119 $\pm$ 49) kWh/m^2.

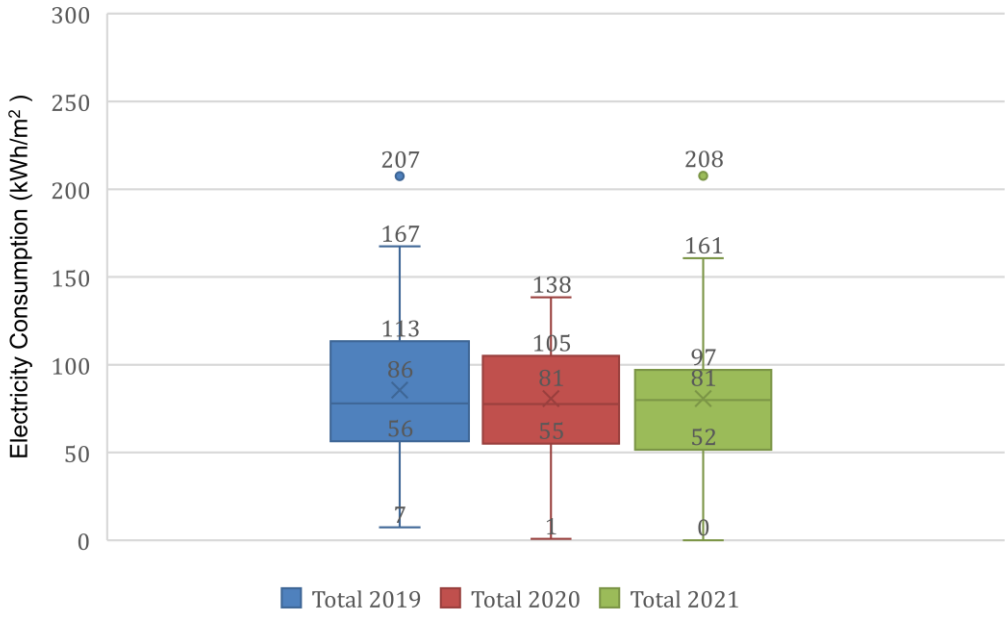


Figure 6. Annual electricity consumption (kWh/m^2)—Compound 3.

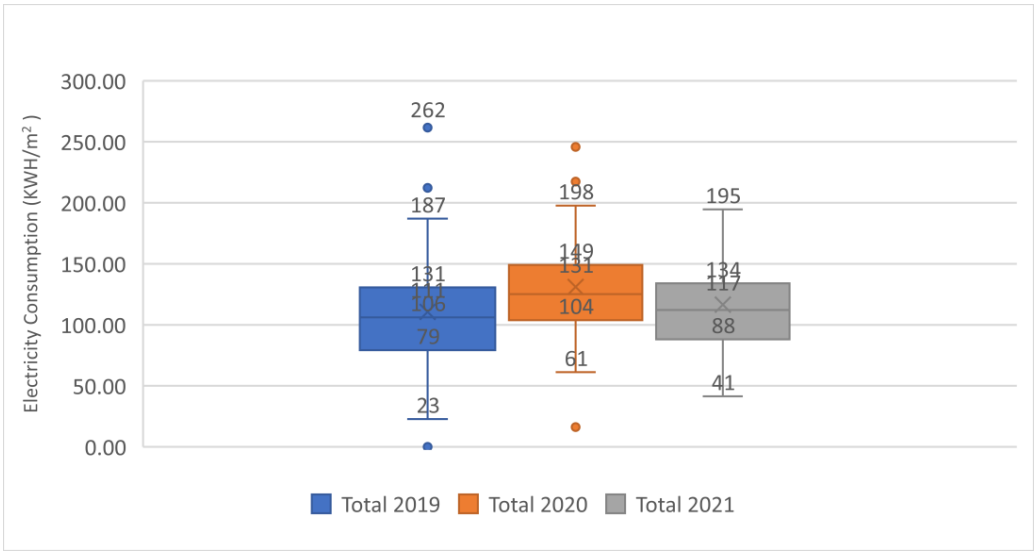


Figure 7. Annual electricity consumption (kWh/m^2)—Compound 4.

A correlation analysis conducted on the mean annual energy consumption (2019–2021) in kilowatt hours (kWh) and the total built area (m^2) of compound villas in Qatar yielded significant insights. With a correlation coefficient of R1 = 0.97, a strong positive correlation was identified between energy consumption (kWh) and the total built area (m^2). This indicates that as the total built area increases, the energy consumption tends to increase proportionally, and conversely, as the built area decreases, the energy consumption decreases.

5. Discussion

In this study, we assessed the energy consumption and its impact on residential buildings in Qatar. The present study shows that residential buildings account for the largest proportion of energy consumption in Qatar. This is similar to the studies reporting the same in Saudi Arabia [31], Panama [32], and Abu Dhabi [33]. However, our study also reveals a significant fluctuation in the electricity consumption patterns due to the global COVID-19 pandemic. The data for 2022 were projected. Subsequently, our analysis of these projections indicates a decline in consumption back to normalized levels by 2022, likely

due to the gradual easing of pandemic restrictions, the resumption of traditional activities, and the adoption of energy-saving measures. These findings underscore the intricate interplay between societal dynamics, environmental conditions, and energy behaviors, emphasizing the pandemic's impact on energy consumption [34–36]. In a study that assessed the electricity trends during COVID-19 among 58 countries, the results show that decreases were only seen during the pre-pandemic sensitivity to holidays and after the peak of the COVID-19 pandemic [36]. Therefore, understanding such fluctuations is imperative for policymakers, energy providers, and stakeholders to develop resilient energy management strategies amidst evolving challenges and to ensure sustainable energy practices in the face of future disruptions. In our study, the selection of the compound samples was based on the average total built area of compound villas, falling within the range of 400–600 m^2, with each villa comprising two stories. These chosen samples are deemed representative of the typical compound villas found in Qatar. The study's analysis of energy consumption reveals intriguing insights into the energy dynamics of various building categories. Initially, when analyzing energy consumption in kilowatt hours (kWh), C2 shows the highest energy use at 95,339 kWh, exceeding C1's 86,801 kWh. Despite having a smaller total built area, C2 consumes significantly more energy. C4, with 47,774 kWh, also surpasses C3's 32,936 kWh in energy consumption, though both have similar built areas. Conversely, C2, despite having the largest total built area, consumes the least amount of energy. These findings underscore the complex relationship between the building size and energy consumption, suggesting that factors beyond mere dimensions significantly influence energy usage patterns. These findings offer valuable insights into the energy usage patterns of conventional compound villas in Qatar, contributing to a broader understanding of the residential energy consumption dynamics and informing strategies for enhancing energy efficiency and sustainability within this housing typology. This growing concern is also shaping the conversation and dialogue related to the need for the effective management of energy resources and the planning of energy infrastructure for efficiency within the building industry [37,38]. When comparing the annual electricity consumption among villas within Compound 1 (C1), Compound 2 (C2), and Compound 4 (C4), discernible differences emerged, primarily attributed to variations in the total built area. Specifically, the mean annual electricity consumption in Villa C4 was found to be lower than that of Villas C1 and C2. This disparity can be largely attributed to the smaller total built area of Villa C4, indicating a direct correlation between the building size and energy utilization. Moreover, a notable observation arose from the comparison between Villas C3 and C4, which share an equal total built area. Despite this similarity, Villa C3 exhibited a 37% higher mean annual electricity consumption compared to Villa C4. This discrepancy can be attributed to the compacted and attached building type characteristic of the villas in Compound 3. The architectural configuration and spatial arrangement of the buildings within Compound 3 likely contribute to the increased energy consumption in Villa C3, highlighting the nuanced influence of the structural design on the energy efficiency outcomes within residential compounds. Such findings highlight the importance of considering not only the total built area but also the architectural layout and building typology when evaluating energy consumption patterns and informing targeted energy management strategies within residential developments. This has been validated and seen in many countries, including those in the same region as Qatar [39–41].

When the energy consumption is normalized to the build area (kWh/m^2), a nuanced shift in the energy dynamics emerges. In particular, while C4 previously appeared as the highest consumer in absolute terms, it now demonstrates lower energy consumption compared to C1 and C2. This discrepancy is attributed to the larger sizes of C1 and C2, highlighting the importance of considering the building scale when assessing energy efficiency. In a systematic review, the influence of the architectural space layout and building parameters showed a positive correlation with energy consumption [42]. This was similarly seen in our study, as the influence of architectural design on energy consumption is apparent when comparing C3 and C4. Despite their equal size, C3 consumes less

energy than C4, primarily due to its design featuring attached houses. This observation underscores the significance of architectural configuration in shaping energy usage patterns within buildings [41]. Overall, these findings contribute to a deeper understanding of the intricate relationship between building characteristics and energy consumption. They emphasize the need for holistic approaches to energy efficiency in the built environment [42]. Such insights are crucial for informing sustainable building practices and policy decisions aimed at reducing energy consumption and promoting environmental stewardship.

The correlation analysis conducted on the mean annual energy consumption (2019–2021) in kilowatt hours (kWh) and the total built area (m^2) of compound villas in Qatar yields significant insights. With a correlation coefficient of R1 = 0.97, a strong positive correlation is identified between energy consumption (kWh) and the total built area (m^2). This indicates that as the total built area increases, the energy consumption tends to increase proportionally, whereas as the built area decreases, the energy consumption decreases. Additionally, the correlation coefficient R2 = 0.7 suggests a positive correlation between the EUI in kWh/m^2 and the total built area (m^2). This implies that as the total built area increases, the energy consumption per unit area (EUI) also tends to increase, and vice versa. These findings underscore the intricate relationship between the building size and energy consumption patterns, highlighting the importance of considering such factors in formulating energy-efficient building designs and sustainability strategies within the realm of compound villa development in Qatar [43]. The highlight is the provision of valuable data and insights into the energy consumption patterns of residential buildings in Qatar, which will form the basis for the formulation of energy benchmarks and guide policymaking. This can inform policy planning and future energy efficiency initiatives, as well as policy decisions and strategies aimed at reducing energy consumption and promoting sustainability in the residential sector.

6. Conclusions

As governments globally strive to address the pressing issues of carbon emissions and pollution, there is a notable emphasis on finding sustainable solutions, particularly in the realm of energy consumption within buildings. Despite Qatar's substantial investment in energy resources, including fossil fuel, a deliberate shift is being made to more sustainable energy to reduce the energy usage. The lack of knowledge regarding the EUIs of residential buildings in Qatar prompted this study to investigate the energy consumption expressed in kWh/m^2, taking into account the building size and ownership. Significant findings emerged, highlighting the substantial impact of the ownership and floor area on the residential energy consumption. Moreover, observed patterns and trends in energy use across different types of residential buildings were identified. The results and methodologies used in this study provide a foundational framework for the formulation of energy benchmarks specific to Qatari residential buildings. These findings not only contribute valuable insights but also serve as a basis for enhancing energy efficiency in residential structures. As Qatar moves forward in its sustainability endeavors, this study's results can inform policies and strategies aimed at reducing energy consumption and advancing the overall environmental goals of the country. The study's findings emphasize the importance of using the EUI as a critical metric in assessing energy consumption patterns in residential buildings in the GCC region. The EUI normalizes energy consumption based on the building size, providing a nuanced perspective. This approach offers a more accurate reflection of the energy efficiency levels, as it considers the varying sizes across different housing units. In the context of the GCC region, the EUI serves as a valuable tool for evaluating and comparing the energy performances across different housing typologies and building sizes. By using the EUI as a measuring tool in energy consumption, policymakers, urban planners, and building professionals can gain deeper insights into the true energy efficiency of residential buildings and make informed decisions regarding energy management strategies and sustainable design interventions. Moreover, the adoption of the EUI as a standard metric in energy performance assessments can facilitate benchmarking efforts, support

the implementation of energy efficiency regulations, and incentivize the adoption of innovative technologies and practices aimed at reducing energy consumption and enhancing sustainability in residential developments across the GCC region. Thus, the study highlights the importance of incorporating the EUI as a key performance indicator in energy management frameworks and policy initiatives targeting residential buildings in the GCC. This serves as a foundational basis for the formulation of energy benchmarks, offering guidance for future energy efficiency initiatives and informing potential policy decisions and strategies aimed at reducing energy consumption and promoting sustainability in the residential sector. The study also underscores the importance of incorporating ownership and floor area considerations into future energy efficiency policies, providing practical guidance for the development of targeted and effective strategies to achieve substantial reductions in energy consumption in residential buildings. Furthermore, it emphasizes the study's relevance and significance in light of Qatar's sustainability goals and broader global environmental concerns.

Accessing architectural drawings of occupied residential houses in Qatar is difficult for several reasons. The consulting firms that designed the houses typically hold these drawings, which are considered private property and shared only at the owner's discretion. Design firms also refrain from sharing drawings due to client privacy. Additionally, only first-degree relatives are likely to share such drawings due to privacy and cultural considerations.

This study is limited by difficulties in accessing architectural drawings of residential buildings, which are often private. Future research should focus on integrating EUI metrics to refine energy performance evaluations. Additionally, expanding data sources and exploring diverse residential types in Qatar and the GCC can enhance energy efficiency strategies and policy development.

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