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Assessing residential sustainable energy autonomous buildings for hot climate applications

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ABSTRACT

This paper introduces an innovative solution for clean energy autonomous building (AB) sustainability, offering a 5Z concept—zero-carbon, zero-energy, zero grid connections, zero energy bills, and zero emission mobility. This paper focuses on fundamental research to design sustainable, energy-ABs striving for self-sufficiency in arid climates, using Kuwait as a case study. The study highlights the importance of stringent engineering AB modeling, renewable technology integration, and clean energy storage. The technical approaches include characterizing non-thermal and thermal demands, achieving net-zero energy generation, and custom sizing renewable energy and energy storage systems (ESS) for electric vehicle (EV) charging points. The research methodology involves local construction with yearly weather and energy profile data to simulate the actual system using ESP-r building model. The study's findings reveal the need for a large-scale energy system, energy demand reduction (EDR) inclusive of heating, cooling, appliances, and EV, with the corresponding changes in local energy production system size, battery capacity, and the number of photovoltaics (PVs). The results show varying EDR levels ranging from base case to 10% and to 50% leading to proportional changes in energy system size, size of battery from 3415 kWh to 1710 kWh and the number of PVs from 362 to 181, which means EDR not only optimizes space but also proves cost-effective. The significant implication of this study, not only bridging the knowledge gap and the lack of how-know, but also making a significant advancement and forward thinking in sustainable green electric home modernization and environmentally friendly transportation. This approach transforms energy management practices for more sustainable cities and societies, reducing emissions in both urban infrastructure and transportation.

1. Introduction

A residential building is one of the key elements and key aspects of human life. Inspired thinking is required to create a unique integrated technology design to provide the pro-active and intelligent buildings that we need in the 21st century. This study investigates the new electric building modeling with electric vehicle (EV) charging point that hundred percent clean electricity production to supply total energy demand at the point of final consumption for home and automobile. This innovative form of green electric housing and transportation is one of the novelties in this case study and engineering energy design and new development for both. Also, the energy system design process and storage path will be useful for individual integration and location to provide energy availability, accessibility and sustainability. This area of concern has many important elements, including theoretical and/or computational modeling, design and fabrication of energy efficiency in the autonomous building (AB).

1.1. Literature review

The AB was introduced in the last century by Vale & Vale (Vale et al., 1997). They defined an autonomous house as one operating independently, relying solely on its immediate environment for resources. Located in South-well, Nottinghamshire, England, the house was completed in 1990 after starting its design in 1975. It is not connected to gas, water, electricity, or drainage services, instead utilizing renewable sources like sun, wind, and rain for energy and waste processing. Resembling a land-based space station, it prioritizes sustainable and self-sufficient living, generating its own energy from renewables to create a suitable environment for life and building (Roaf et al., 2014).

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Moreover, Littler (1979a) introduced the concept of the autarkic house in 1979, emphasizing its energy self-sufficiency by harnessing wind power and solar energy, even in regions like cloudy Britain. This vision led a Cambridge team to design a house completely independent of mainstream services. An autarkic house aims to be off-grid and self-sufficient in all aspects, prioritizing low-energy consumption and reliance on ambient energy sources to meet the demand.

Efficient building and environmental design, coupled with advanced eco-tech energy modeling, are crucial for achieving sustainability in urban planning and energy management. This entails a focus on building design, real-time monitoring, comprehensive techno-economic-socio analysis, and the integration of essential renewable technologies within a systems approach for smart cities (Cosgrave et al., 2013). Integrating technology into building operations in real-time can enhance end-user experience, improve environmental friendliness, and minimize discrepancies between design and construction, thus driving innovation and setting new trends in smart city development. Various innovations (Neirotti et al., 2014; Asheim et al., 2005) show promise, particularly in the UK, where efforts are concentrated on reducing CO_2 emissions, promoting clean energy production through photovoltaic (PV) systems and fuel cells, and retrofitting existing housing (Jones et al., 2013).

Urban development significantly impacts the effectiveness of eco-design and energy efficiency in urban services, emphasizing zero waste and sustainable consumption (Lehmann, 2011). While various studies have explored green energy sustainability (Swart et al., 2004; Cobbinah et al., 2015), many overlook the need to investigate alternative building models crucial for addressing sustainability challenges, especially in hot climates. Achieving sustainable development in the built environment necessitates consideration of urbanization, poverty, and rethinking sustainable housing development, particularly in developing countries. Some scholars (McDonald, 2008; Harvey, 2009) have proposed sustainable strategies, yet there's a need for further exploration in engineering green urban development, green energy system production, and innovative housing design, with a focus on local regeneration and clean energy to promote social responsibility and sustainability. Emphasizing energy demand reduction (EDR) and energy efficiency (Stuggins et al., 2013) can combat fuel poverty, reduce environmental impact, and control energy consumption and costs while measuring the effects of green value (Fuerst et al., 2011).

In fact, green energy-AB technology, when combined with engineering design systems and low-energy-demand principles, becomes significant in local energy autonomy and carbon emissions reduction, as proposed by Dhakal et al. (Dhakal et al., 2010; Dhakal, 2010). This approach not only contributes to future smart city development (Batty et al., 2012), but also delves into alternative strategies for sustainable green energy-ABs review (Mohammadi, 2019), emphasizing efficient clean energy generation, energy savings, and automation services. Integration of technologies to enhance energy system efficiency and automation based on occupant behavior (Klein et al., 2012) is crucial. However, with the world's population projected to reach 10 billion in the next 50 years and urban populations expected to soar, reaching nearly 5 billion by 2030 (Yuan et al., 2012), and around 8 billion by 2050 (Boretti et al., 2019), rapid urbanization poses environmental challenges, including land shortages (Nielsen et al., 2012). Hence, the reason, alternative energy system designs tailored to local climates and construction model is more important than before.

1.2. Gap in literature and novelty

The development of energy-ABs has garnered significant attention in recent years, particularly in mitigating climate change and cleaner energy production and addressing the unique electricity challenges in hot climates. The growing body of research underscores the critical importance of integrating renewable energy sources, advanced energy storage systems, and local energy management technologies in building designs. Previous studies have primarily concentrated on singular aspects such as zero energy building (Marszal et al., 2011), nearly zero energy building (NZEB) (D'Agostino et al., 2019) or towards zero grid electricity networking (Marsan et al., 2013), and zero grid impact buildings (Arboleya et al., 2015). Hence, this paper introduces a novel concept for integrating green energy-ABs into green transportation with zero grid connection. Thereby, this study not only proposed a novel idea and approach that leverages an intelligent path, but also represented that the AB system facilitates active and power provision, alongside a green energy transport which is a significant progress and levels up clean energy storage, generation and load system shifts its focus towards the sustainable implementation of a pioneering AB system integrated with 5Z concept—zero-carbon, zero-energy, zero grid connections, zero energy bills, and zero emission mobility.

Table 1 summarizes relevant and recent work on energy-ABs (Franchini et al., 2019; Hassan et al., 2018; Littler, 1979b; Vale and Vale, 2000; Cohen and Anastasia, 2020), highlighting key advancements and findings in the field along with the limitations in the literature. Franchini et al. (2019) study limitations include long-term sustainability. Their study partially assessed the maintenance of high comfort levels in a solar-powered building under the Persian Gulf's extreme climate. Moreover, their study overlooked the energy-related office building with limited working hours or weekly open days, but the residential building energy demand could be any time for 24 h, 7 days for 365 days.

Hassan et al. (2018) had the limitation of generalization of design guidelines. Their study provided broad design guidelines for

Table 1
Reviews key research on energy autonomous buildings (ABs), focusing on various strategies for sustainability and independence from traditional energy sources, where these studies collectively underscore diverse approaches to achieving energy autonomy and sustainability in different climates and contexts.

Reference	Building	Key Focus	Findings
Franchini et al. (Franchini et al., 2019)	Office	To ensure a high level of internal comfort all over the year by using only solar energy.	A sustainable fully solar-powered building assuring a high level of comfort under the severe climate conditions of the Persian Gulf area is an achievable target.
Hassan et al. (Hassan et al., 2018)	Residential	Passive solar heating and cooling, rainwater harvesting, photovoltaic power systems and solar hot water heating.	Demonstrated construction includes the utilization of recycled materials such as black and grey water treatment systems.
Littler (Littler, 1979b)	Residential	Harvesting wind power and solar energy to provide its energy off-grid, and independent of all types of mains services.	Introduce the principles of the autarkic house, that independent houses can be built even in cloudy Britain.
Vale and Vale (Vale and Vale, 2000)	Residential	An independent house operating without any input, except those of its immediate environment.	Showed the house is not linked to the main service of gas, water, electricity or drainage, but instead uses the income-energy source of sun, wind and rain to service itself and process its waste.
Cohen et al. (Cohen and Anastasia, 2020)	Residential	A key design consideration was the ease of shipment and assembly gaining maximum advantage from minimal energy input.	Provided a round-shape aluminium house and maximize the amount of mass, volume, complexity, and function of all the furniture and interior structures that are inside of a habitat.

earth-sheltered buildings which may be use temporarily but lack specific details on adapting these guidelines to various hot-arid climates with different local conditions. Moreover, they opted to address how modern sustainable technologies, such as advanced photovoltaic systems or home energy storage solutions, can be integrated into earth-sheltered designs. Their proposed design guidelines failed to be explored thoroughly, leaving gaps in understanding earth-sheltered real-world applicability in comparison to localized design adaptation and incorporation of modern technologies in a residential home in Kuwait.

Littler (1979b) introduced the concept of the autarkic house but has different limitations including limited technological scope and focused only on early technologies for energy independence. He disregarded advancements in renewable energy technologies and modern housing practices. Moreover, the study discussed the autarkic house in the context of the UK's relatively mild climate but lacks in more extreme climates or regions with different weather patterns as well as practical feasibility and maintenance of autarkic houses, which is critical for real-world housing applications.

Vale and Vale (2000) presented an innovative vision for independent housing but has limitations in a few areas. For instance, they focused on autonomous houses without considering the challenges of implementing such solutions in urban areas, where space and infrastructure constraints are significant. Additionally, their big house was located on farmland and their study also failed to incorporate recent advancements in sustainable design, making its recommendations less relevant to current housing design and energy solutions and diminishing its applicability in today's context.

Cohen et al. (Cohen and Anastasia, 2020) introduced the Dymaxion House, despite its innovative design, it had significant drawbacks. For instant, the use of the metal house (aluminum) can cause excessive noise in rainy climates, noise pollution affecting livability. Moreover, the heavy reliance on aluminum, a resource in high demand and energy-intensive to produce, posed material challenges. This could strain global supply chains and lead to shortages, raising concerns about the house's environmental and sustainability. Without considering more abundant and eco-friendly alternatives, the feasibility and scalability of the Dymaxion House.

The aforementioned studies collectively illustrate the multifaceted approaches and significant advancements in energy-ABs, particularly in hot and arid climates. By synthesizing insights from previous works, this paper aims to explore innovative building designs that promote energy autonomy, reduce carbon footprints, enhance energy security, and provide practical solutions for energy management in extreme climates. Additionally, it addresses the integration of modern housing with EV charging points. This article introduces the novel concept of 5Z ABs, which are characterized by zero carbon, zero energy, zero grid connections, zero energy bills, and zero-emission mobility. This innovative approach to building design and clean energy management is distinguished by its comprehensive scope and integration of various sustainability aspects. An assessment of originality reveals that previous studies have not addressed modern clean electrified housing with green EV charging.

Furthermore, the existing body of knowledge lacks information on several key aspects. First, there is no evidence of a fully sustainable green energy system in a hot climate region that is completely clean energy self-sufficient residential. Second, there is a lack of research on the integration of green energy-ABs with green energy charging infrastructure to support EVs. Last, the field of innovative design engineering for ABs and EVs offers the potential to not only address these knowledge gaps and provide solutions, but also contribute to the overall uniqueness and sustainability of the design. Therefore, the research framework addresses these gaps and fulfils a significant academic knowledge deficit, the lack of know-how-autonomy of lessons-learned. In another words, the current body of literature does not provide a definitive response about the methods for designing sustainable off-grid autonomous buildings and electric vehicles (ABs&EVs) nor the resource requirements associated with these unique engineering designs.

This research explores AB systems, emphasizing their transformative potential with innovative designs and effective problem-solving capabilities. The study investigates their impact on the built environment and transportation, particularly focusing on sustainable development and resilience in hot arid climates. Notably, these ABs address challenges related to green heating, energy, and transportation, showcasing adaptability and sustainability. The research contributes by establishing the viability of AB systems in creating a blueprint for sustainable urban development in regions prone to extreme heat. The transformative potential of AB technology systems proves sustainability and resiliency in hot arid climates.

1.3. Scope of work and importance

The subject of sustainable energy-ABs holds significant importance, especially for clean energy independence, mitigating climate change and tackling the distinct energy challenges faced in hot climates. This article's focus on residential buildings in arid regions, such as Kuwait, is particularly pertinent given the growing global emphasis on sustainability and renewable energy. The paper's objective to investigate energy autonomy through innovative building designs is vital for promoting sustainable development and resilience in these climates. The relevance of this topic not only lies in its potential to lower carbon footprints and offer practical solutions for energy management in extreme climates, but also in increasing clean energy production, adding momentum to transition to net zero and improving energy security.

Moreover, AB led the design and development of the energy-efficient building, collaborating with clean energy investors such as PVs, and end-user empowerment advocates, and creating a comprehensive scope of novel *Deepenergy Asset Management.* As a result, the AB with EV charging at the villa site aimed to achieve 365 days of 100% clean energy autonomy, providing a full year of net-zero carbon emissions and zero energy bills for both the home and EV unprecedented globally. Table 2 lists the importance and the scope of the work in brief.

1.4. Impact of autonomous building (AB) study

The study of ABs significantly advances knowledge in engineering, energy design architecture and energy self-sufficient building technology. It influences policy and industry practices, shaping a sustainable future. Impacts of energy-ABs include.

1. Inspiring sustainable heating and energy systems based on ambient resources for homes and cars, and serving as a model for off-grid residential heating in rural areas globally, aligning with UN Sustainable Development Goals (United Nations. Sustainable Development Goals, 2017), to bridge infrastructure gaps, positively affecting energy security, emissions reduction, and air quality.
2. Responding to climate change through significant CO_2 emissions reduction and stablishing private-public partnerships for net-zero impact, job creation, zero emission mobility (ZEM) and green economic growth, impacting clusters for decarbonizing private and social housing and transportation in suburb cities and rural areas, extending impact beyond energy to include renewable tech integration, policy-making, COP in a petrostate and financing.
3. Influencing policymakers and industries, contributing to regulations, new standards and best practices, identifying and validating technologies to enhance design, construction, and operational efficiency, bridging gaps across disciplines and enriching knowledge in architecture, engineering, energy management and fosters holistic understanding.
4. Customizing products and services, fostering collaboration for green investing and education, and addressing the needs of homeless and vulnerable populations in various conditions and locations,

Table 2
Outlines the key work areas and significance of autonomous buildings (ABs) such as renewable energy integration, energy storage solutions, clean electric management systems (CEMS), and future green economic and environmental impact, which are important for sustainable urban development, energy efficiency and cost savings, reduction of greenhouse gas emissions, and resilience and energy security.

Scope of work	Importance
Renewable energy integration	**Sustainable urban development**
• Evaluation of various renewable energy sources • Design and optimization of clean energy systems	• Minimizes environmental impact and fossil fuel reliance • Increase clean energy productions • Increase number of clean vehicle EV charging points • Promotes low carbon society, green cities
Energy storage solutions	**Energy efficiency and cost savings**
• Investigation of advanced energy storage technologies • Analysis of energy storage capacity and efficiency	• Reduces energy consumption and operational costs • Lowers energy bills to zero
Clean electric management systems	**Reduction of greenhouse gas emissions**
• Development of intelligent clean electric management systems (CEMS) using IoT and AI • Integration of real-time monitoring and control systems	• Reduces greenhouse gas emissions • Lowers carbon footprint of built environment and transportation
Architectural and structural design	**Resilience and energy security**
• Exploration of sustainable architectural designs and materials • Structural considerations for renewable energy integration	• Less vulnerable to power outages and supply fluctuations & importing fossil gas • Provides reliable, available and accessible, self-sufficient clean energy supply
Economic and environmental impact assessment	**Technological innovation and economic growth**
• Cost-benefit analysis of clean energy solutions in rural and off-grid locations • Environmental impact assessment	• Drives innovation in construction and clean energy sectors •Fosters economic growth through new markets and green job opportunities
Case studies and pilot projects	**Global environmental goals**
• Examination of existing projects for best practices • Development and analysis of pilot projects	• Aligns with global commitments such as Paris agreement 2015, COP26 Glasgow 2022, COP27 Egypt 2023, COP28 UAE 2024 • Contributes to targets for renewable energy and carbon neutrality
Deepenergy asset management	**Impacts**
• Core services: Renewable energy investments, project development and management, asset management, sustainability consulting • Innovative solutions: Micro-grid integration, energy storage solutions, sustainable electric building & EV charging points integration, blockchain for energy trading, maximizing land use efficiency • Commitment to sustainability: Environmental stewardship, community engagement, local energy management.	• Local: Job creation, community development, energy savings, environmental protection. • National: Energy security, economic growth, environmental protection, policy support, carbon reduction targets • International: Global renewable energy adoption, climate change mitigation, technological advancement, international collaboration, sustainable development goals (SDGs)

delivering clean energy to historically underserved communities worldwide.

5. Enhancing clean energy production and storage (i.e., ESS), providing green charging points for EVs. This alleviates stress for EV drivers, promotes global EV up sales, and contributes to a worldwide sustainable clean energy solution for built environment and transportation.

This “greened” electric AB and using EV not only creates reasonable assumptions for future EV charging points’ increase in remote villages, rural and coastal areas, highlands and islands, but also creates reasonable assumptions for EV efficiency and carbon rates of the electric sector, home battery green electric vehicles (HBGEVs) provide a novel path for reducing both transportation and building sectors greenhouse gas (GHG) emissions impact. Electrification pathways for the economy and the environment (Rocco et al., 2020), create economy-wide decarbonization and the potential for significant electrification to help complexities of transport electrification and emerging opportunities for energy-related business growth (Weiss et al., 2017).

1.5. Aims and objectives

The objective of this study is to address the challenges associated with charging point energy demand requirement plus residential energy-AB energy consumption while only a roof area is available for on-site energy production, and energy supply-demand management in a manner that eliminates the need for energy bills and reliance on the grid. Therefore, this paper frameworks a model for simulating ABs performance, with a specific focus on determining the optimal sizing of their renewable energy storage system (ESS) and energy storage solutions. The study primarily concentrates on the utilization of PV systems as the chosen renewable energy technology, given the abundant solar radiation available, particularly in a Middle Eastern villa in Kuwait to ensure the electric building is off-grid and assess the impact of potential energy demand reduction (EDR).

2. Methodology

2.1. Framework scheme

The model procedure described in this study combines building simulation with the use of ESP-r software (ESRU) and green energy custom toolkit to know the size of clean energy generation and energy storage system (ESS). A technique was created by Mohammadi (2023) to enable the sizing of storage and green energy production for autonomous buildings (ABs), functioning 100% on clean electrical energy, and ESS requirements for energy flexibility over varying timescales, related the work described in (Allison et al., 2018). To assist define demand and supply for any potential energy-AB, the following methodology was developed.

1. Characterization of non-thermal demand – Time-use profiles are developed to identify the non-thermal electrical demands in an AB.
2. Characterization thermal load – AB model developed and simulated in ESP-r (Hand, 2015) using representative climate data to discover the heating and cooling requirements. The electrical loads determined in step 1 are used in this thermal simulation. Assuming that 100% of the electrical demand translates to heat, the thermal loads are converted to equal electrical needs.
3. Net-zero generation – the AB model is modified to take renewable technology into account (in this research, only photovoltaic (PV) is considered, but the method is extendable to other renewables). A typical on-site clean energy generation was created in the model.
4. Sizing and simulation – In order to calculate the size of the renewable energy installation needed to fulfil the demand over time and the amount of storage needed so that demand and supply must be balanced, the profiles from stages 1 through 3 are imported into a bespoke sizing tool.

2.2. Building simulation tool (ESP-r)

The study utilized the ESP-r building simulation software (ESRU) to model and simulate the AB. ESP-r strategies for deploying virtual representations of the built environment (Hand, 2015) accurately calculates a building's energy and environmental performance, considering climate data, solar radiation, radiant heat exchanges, air movements, control systems, and thermal properties of building materials.

ESP-r (Hand, 2015) disassembles the building's physical attributes into multiple "control volumes" where energy (thermal and electrical) and species equations are applied. A typical model comprises numerous volumes, each organized by the energy system. These equations, paired with real-time climatic data and occupancy conditions, generate dynamic temperature profiles, energy flows, and fluid movements within the building and its support systems.

2.3. Simulation validation for ESP-r

Strachan et al. (2008) examined the reliability of the ESP-r tool. McElroy et al. (2001) offered a more thorough explanation of the technological underpinnings of ESP-r. According to a summary by Strachan et al. (Strachan, 2000) and later by Monari (Monari and Paul, 2014), ESP-r has undergone rigorous validation. The creation of ABs can benefit from energy simulation. It may be used to calculate the required heating and cooling as well as the possible power output from local renewable energy sources. Simulation, however, is unable to size the parts needed to give a building autonomy on its own. This requires a sizing methodology, which has been demonstrated in this work.

2.4. ESP-r profiles

ESP-r model (ESRU) employs three separate profile types, electric demand, cooling/heating demand, and PV system profiles. The electrical demand profiles (including EV charging) that can be used directly, as these detail electrical demand vs. time. As for the cooling/heating demand profile, ESP-r calculates time-varying heating and cooling loads, which can be converted to the electrical demand of the heating and cooling system using an assumed seasonal performance factor (SPF) (Fraga et al., 2017). In this study, cooling is assumed to have an SPF of 3, and heating is assumed to be from a resistive system, equivalent to an SPF of 1. The electrical output of the PV system on the AB's roof is the last generated profile.

2.5. ESP-r sizing spreadsheet

To process the time series supply and demand data from the ESP-r simulation, a custom spreadsheet was created (IP required). This spreadsheet takes input data from ESP-r and calculates the PV area and battery size for AB operation, ensuring there is no energy deficit over a simulated year. The simulation used half-hourly timesteps, resulting in 17,520 timestep values for each data element. The specific demand data types imported from ESP-r include appliances demand, heating demand, cooling demand, and PV generation.

2.5.1. Total electrical demand

The cooling and heating demand convert into electrical demand, each timestep is divided by a coefficient of performance (COP). Both COP of heating (COP_H) and cooling (COP_C) is assumed to equal 2.

The total electrical demand (W) at each time step is then calculated as follows:

$$E_T = E_a + \frac{E_h}{COP_H} + \frac{E_c}{COP_C} \tag{1}$$

where the E_T is total electrical demand, E_a is appliances demand and E_h and E_c are heating and cooling demands, respectively.

$$E_{TY} = \left(\sum_{i=1}^{17520} E_{T_i}\right) \times 0.0005 \tag{2}$$

where the E_{TY} is the total energy demand (kWh) over the year and E_{Ti} is total electrical demand for timestep i (W).

2.5.2. Sizing local production

Once the total electrical energy demand is known, the required PV area to fully offset this demand over a year can be determined as follows:

$$A_{PV} = A_b + \frac{E_{dt}}{E_g} \tag{3}$$

where the A_{PV} is required area, A_b is PV area in base model and E_{dt} and E_g are annual energy demand and annual PV energy generation, respectively.

The PV energy is the sum of total PV generation timesteps (W) x 0.0005:

$$E_{PV} = \left(\sum_{i=1}^{17520} E_{g_i}\right) \times 0.0005 \tag{4}$$

where the E_{PV} is the PV energy, and E_{gi} is total PV generation for timestep i (W).

2.5.3. Battery sizing

Net electrical power flow is calculated at each timestep by subtracting the demand from the supply. A positive value means surplus power is available for battery charging, while a negative value indicates a deficit and the need to draw power from the battery to maintain the balance. The net electrical power flows (W) are then converted into energy exchange quantities (kWh) per half-hour timestep by multiplying by 0.0005, assuming constant power draw within each timestep. Besides, the energy exchanges can be positive or negative, depending on the supply and demand at each timestep. Therefore, estimating the required battery size for energy autonomy is an iterative process, considering the initial battery size (kWh) and its initial energy content (% full). Hence, rules guide this process are.

- The battery energy content should not drop to zero, indicating the battery is too small.
- The energy content at the end of the year should roughly match the initial energy content, or adjustments to the generation array or initial charge level should be revised.
- If the battery reaches capacity, any excess net energy from local generation needs to be spilled.

To facilitate battery sizing the spreadsheet therefore required the input of a battery size (kWh) and the initial charge level (%). The initial battery charge for the first timestep is therefore:

$$C_0 = S_b \times \frac{C_L}{100} \tag{5}$$

where the C_0 is initial charge, S_b is battery size and C_L is initial charge level.

The dataset includes additional columns with values for the following parameters at each timestep: net electrical power flow (W), net electrical energy exchange (kWh), battery charge (kWh), charge %, and energy spilled (kWh). To establish an appropriate initial battery charge level, a preliminary annual simulation is conducted, assuming a charge level of 50%. The final charge level obtained from this simulation is used as the initial charge level for battery sizing. This approach reduces the number of parameters that need adjustment in each run. The iterative process adjusts the battery size (kWh) until the aforementioned rules are satisfied while minimizing spilled power.

2.5.4. Energy demand reduction (EDR)

The spreadsheet includes additional functionality to assess the impact of potential energy demand reduction (EDR) on generation and storage requirements. A scalar demand reduction value can be input, which modifies the timestep values of the appliances demand. While this simplified representation of demand reduction may not be consistent over all timesteps, it offers an initial indication of how electrical energy efficiency measures affect autonomous generation and storage sizing requirements.

2.6. Case study

2.6.1. Location and weather data

Kuwait, located in the Middle East (Lat 29.31, Lon 47.48), borders the Persian Gulf between Iraq and Saudi Arabia, as shown in Fig. 1. Its population is 4.45 million, with 1.45 million Kuwaiti citizens and others from over 100 countries. Kuwait covers an area of 17,820 square kilometers, with dimensions of approximately 200 km north to south and 170 km east to west. The country includes 10 islands and is predominantly desert. Kuwait is a significant carbon dioxide emitter per capita compared to other nations (Islam et al., 2009), consistently ranking among the world's highest in terms of CO_2 emissions per capita in recent years (Omran, 2000). Summers in Kuwait are extremely hot, with the highest recorded temperature of 54 °C in Mitribah on July 21, 2016 (Merlone et al., 2019). Table 3 shows the weather data for Kuwait City, while Table 4 provides the global horizontal solar radiation which is a measure of the total amount of solar radiation by a horizontal surface. These details were inputs in the ESP-r (Hand, 2015) model including both direct and diffuse radiations, as shown in Fig. 2.

2.6.2. Materials and building geometry

This section provides details on the AB geometry, encompassing floor and wall area, window area, and selected construction specifics. This data has been integrated into the ESP-r configuration system file (Hand,

Fig. 1. Shows Kuwait's position at the head of the Persian Gulf, illustrating its position in the northeastern part of the Arabian Peninsula known for its scorching and arid climate, Kuwait experiences some of the highest temperatures and lowest rainfall in the region (a), where these climatic extremes have significant implications for energy consumption and building design, as well as daily life in the country.

Table 3
Presents comprehensive climate data for Kuwait City, essential for input into the ESP-r building energy simulation model (ESRU), it includes monthly record high and low temperatures, average high and low temperatures, rainfall, rainy days, and sunshine hours, where these data are crucial for accurately modeling building energy performance in Kuwait City's harsh climate, aiding the development of sustainable and energy-efficient building designs.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	29.8 (85.6)	35.8 (96.4)	41.2 (106.2)	44.2 (111.6)	49 (120.2)	49.8 (121.6)	52.1 (125.8)	50.7 (123.3)	47.7 (117.9)	43.7 (110.7)	37.9 (100.2)	30.5 (86.9)	52.1 (125.8)
Average high °C (°F)	19.5 (67.1)	21.8 (71.2)	26.9 (80.4)	33.9 (93.0)	40.9 (105.6)	45.5 (113.9)	46.7 (116.1)	46.9 (116.4)	43.7 (110.7)	36.6 (97.9)	2.8 (82.0)	21.9 (71.4)	34.3 (93.7)
Average low °C (°F)	8.5 (47.3)	10.0 (50.0)	14.0 (57.2)	19.5 (67.1)	25.4 (77.7)	28.9 (84.0)	30.7 (87.3)	29.5 (85.1)	26.2 (79.2)	21.5 (70.7)	14.5 (58.1)	9.9 (49.8)	19.9 (67.8)
Record low °C (°F)	−4.0 (24.8)	−1.6 (29.1)	−0.1 (31.8)	6.9 (44.4)	14.7 (58.5)	20.4 (68.7)	22.4 (72.3)	21.7 (71.1)	16.0 (60.8)	9.4 (48.9)	2.2 (35.6)	−1.5 (29.3)	−4.0 (24.8)
Average rainfall mm (inches)	30.2 (1.19)	10.5 (0.41)	18.2 (0.72)	11.5 (0.45)	0.4 (0.02)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.4 (0.06)	18.5 (0.73)	25.5 (1.00)	116.2 (4.57)
Average rainy days (≤0.1 mm)	5	3	3	1	0	0	0	0	0	1	3	3	19
Mean monthly sunshine hours	198.1	222.5	217.6	229.3	272.5	304.5	307.1	301.6	285.1	252.2	216.5	193.5	3000.5
Mean daily sunshine hours	7.1	7.7	7.5	7.9	9.4	10.5	10.6	10.8	10.2	9.0	7.7	6.9	8.8
Percent possible sunshine	68	69	63	62	69	77	76	78	77	79	72	67	72

Table 4
Summarizes the global horizontal solar radiation and temperature data for Kuwait (D'Agostino et al., 2022), highlighting the region's substantial solar energy potential and extreme thermal conditions, and emphasizes the high solar radiation and extreme heat, critical for developing energy-efficient and resilient building designs in Kuwait's challenging climate.

	Solar Radiation (kWh/m^2)		Temperature (°C)		
	Mean	Maximum	Minimum	Maximum	Mean
Kuwait	475.69	2081.63	5.3	47.7	28.0

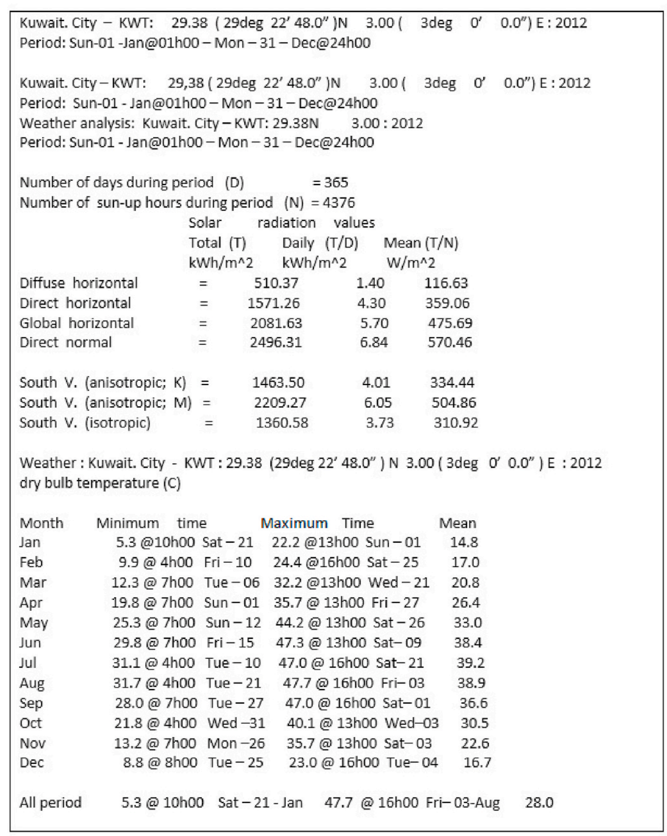
2015), where Table 5 presents information for a typical small-size house in the Middle East (Yuce et al., 2016). Table 5 outlines the main constructions of the AB, including internal wall, external windows, fenestration frame, door, external wall, floor, and roof details. These tables illustrate the information incorporated into the ESP-r data construction system file (Hand, 2015).

In hot climates, it is important to use construction materials that can survive high temperatures and humid environments to protect buildings from heat (Mai et al., 2018). Some examples of commonly used construction materials in hot climates are stones (i.e., natural stone, such as limestone or sandstone) and white color paint (i.e., reflective materials, such as white walls, roofing or reflective coatings) because they can help to reduce heat absorption and keep buildings cooler in hot climates. Table 5 also shows materials related to the external wall, different layers to the ground floor and different construction materials related to roofs in the region, respectively.

2.6.3. *Appliances ownership data*

This section describes the method used to identify appliances ownership information (Yuce et al., 2016), using the example of a typical small villa from Kuwait as a regional benchmark, modeling and forecasting end-use energy consumption for residential buildings in Kuwait (Alajmi et al., 2020). This data is crucial for defining non-thermal demands and creating demand profiles to estimate the energy storage system (ESS) and renewable energy supply requirements for in AB model.

According to Jaffar et al. (2018), the residential building sector in Kuwait uses over 60% of the electricity produced, which is among the


Kuwait. City – KWT: 29.38 (29deg 22′ 48.0″)N 3.00 (3deg 0′ 0.0″) E : 2012
Period: Sun-01 -Jan@01h00 – Mon – 31 – Dec@24h00

Kuwait. City – KWT: 29,38 (29deg 22′ 48.0″)N 3.00 (3deg 0′ 0.0″) E : 2012
Period: Sun-01 - Jan@01h00 – Mon – 31 – Dec@24h00
Weather analysis: Kuwait. City – KWT: 29.38N 3.00 : 2012
Period: Sun-01 - Jan@01h00 – Mon – 31 – Dec@24h00

Number of days during period (D) = 365
Number of sun-up hours during period (N) = 4376

Solar radiation values		Total (T) kWh/m^2	Daily (T/D) kWh/m^2	Mean (T/N) W/m^2
Diffuse horizontal	=	510.37	1.40	116.63
Direct horizontal	=	1571.26	4.30	359.06
Global horizontal	=	2081.63	5.70	475.69
Direct normal	=	2496.31	6.84	570.46
South V. (anisotropic; K)	=	1463.50	4.01	334.44
South V. (anisotropic; M)	=	2209.27	6.05	504.86
South V. (isotropic)	=	1360.58	3.73	310.92

Weather : Kuwait. City - KWT : 29.38 (29deg 22′ 48.0″) N 3.00 (3deg 0′ 0.0″) E : 2012
dry bulb temperature (C)

Month	Minimum	time	Maximum	Time	Mean
Jan	5.3 @10h00	Sat – 21	22.2 @13h00	Sun – 01	14.8
Feb	9.9 @ 4h00	Fri – 10	24.4 @16h00	Sat – 25	17.0
Mar	12.3 @ 7h00	Tue – 06	32.2 @13h00	Wed – 21	20.8
Apr	19.8 @ 7h00	Sun – 01	35.7 @ 13h00	Fri – 27	26.4
May	25.3 @ 7h00	Sun – 12	44.2 @ 13h00	Sat – 26	33.0
Jun	29.8 @ 7h00	Fri – 15	47.3 @ 13h00	Sat– 09	38.4
Jul	31.1 @ 4h00	Tue – 10	47.0 @ 16h00	Sat– 21	39.2
Aug	31.7 @ 4h00	Tue – 21	47.7 @ 16h00	Fri– 03	38.9
Sep	28.0 @ 7h00	Tue – 27	47.0 @ 16h00	Sat– 01	36.6
Oct	21.8 @ 4h00	Wed –31	40.1 @ 13h00	Wed–03	30.5
Nov	13.2 @ 7h00	Mon –26	35.7 @ 13h00	Sat– 03	22.6
Dec	8.8 @ 8h00	Tue – 25	23.0 @ 16h00	Tue– 04	16.7
All period	5.3 @ 10h00	Sat – 21 - Jan	47.7 @ 16h00	Fri– 03-Aug	28.0

Fig. 2. Illustrates Kuwait's weather conditions and solar radiation metrics utilized in the ESP-r model (Hand, 2015), these data play a pivotal role in simulating building performance, particularly for energy consumption and efficiency along with evaluating cooling requirements and optimizing solar energy use, as well as accurately predict and enhance building performance under Kuwait's harsh environmental conditions, leading to more effective and sustainable energy solutions.

Table 5
Details the geometry and materials of an Autonomous Building (AB) used in the ESP-r model (Alrashed et al., 2015; Al-Ajmi et al., 2008), it includes floor area, external windows, doors, walls, and internal space volumes, along with detailed construction layers for internal and external walls, windows, frames, doors, roof, and floor.

	Building elements	Area (m^2)
Autonomous building (AB) geometry	Floor	200
	External windows	5
	External doors	4
	External walls	153
		Volume (m^3)
	Internal living space	200

Internal wall

	Number of Layers	Thickness (mm)	Material
Internal Wall with a total 174 mm thickness	1	12	Perlite plasterboard
	2	150	Breeze block
	3	12	Perlite plasterboard

External window

	Number of Layers	Thickness (mm)	Material
Triple glazing window with 1.8 U value and total 42 mm thickness	1	6	clear float
	2	12	gap 0.17 0.17 0.17
	3	6	clear float
	4	12	gap 0.17 0.17 0.17
	5	6	clear float

Fenestration frame

	Number of Layers	Thickness (mm)	Material
Passive house aluminum frame with a total 79 mm thickness	1	3	grey cotd alum
	2	8	gap 0.06 0.06 0.06
	3	3	aluminum
	4	8	gap 0.06 0.06 0.06
	5	3	aluminum
	6	40	EPS k 0.05
	7	3	aluminum
	8	8	gap 0.06 0.06 0.06
	9	3	grey cotd alum

Door

	Number of Layers	Thickness (mm)	Material
Passive house door with a total 115 mm thickness	1	12.5	oak
	2	90	wood wool
	3	12.5	oak

External wall

	Number of Layers	Thickness (mm)	Material
External wall with a total 350 mm thickness	1	90	Sand-lime block
	2	20	Cement plaster
	3	220	AAC block
	4	20	Cement plaster

Building roof

	Number of Layers	Thickness (mm)	Material
Building roof with a total 332 mm thickness	1	20	Mosaic tiles
	2	20	Cement mortar
	3	20	Sand screed
	4	50	Insulation
	5	0.30	Water proofing
	6	20	Sand screed
	7	50	Foam concrete
	9	150	Concrete slab

Floor

	Number of Layers	Thickness (mm)	Material	Conductivity (kW/m-K)	Density (kg/m^3)
Ground floor thickness 230 mm	1	150	Concrete slab	4.372	2297
	2	40	Sand	1.213	1800
	3	20	Sand cement	3.4	2080
	4	20	Mosaic tiles	3.974	2284

highest (per capita) in the world (Kellow, 1989; Cerezo et al., 2017). This energy consumption is mostly electrical which is one of the most important components of economic well-being, and strategies of appliance energy efficiency to 2050 (Alotaibi, 2011; Energieagentur, 2010; Kavousian et al., 2015). The common end-user requirements for a domestic house are shown in Table 6 (Jones et al., 2016). These are thought to be typical Middle Eastern ideals, with the rooms cooler with the A/C thermostat set at 23 °C (Al-Mumin et al., 2003). Electrical appliances make a very significant contribution to a household's electricity consumption (Jones et al., 2015). The pattern of electricity consumption in Kuwait is high (Al-Qudsi, 1989), but electrification pathways have positive implications for the economy and the environment in different scenarios of electric technology adoption and power consumption for the USA (Mai et al., 2018) and solar energy potentials and benefits in Persian Gulf (Mas'ud et al., 2018). This villa is designed to accommodate four people, typically a young family consisting of two parents and two children, representative of the region, small population.

2.6.4. *Energy profiles*

Electronic devices fall into two categories, fixed electrical appliances (e.g., lights, televisions, refrigerators, etc.) with consistent usage patterns based on home lifestyle, and flexible appliances (e.g., vacuum cleaners, dryers, washing machines, dishwashers, etc.) with variable and shiftable operations. It is also important to note that electric vehicles (EVs) are considered in the demand calculation because their electrification would eventually merge with household loads (Mai et al., 2018). Typical power requirements (W) are provided, while cooling and heating loads are for informational and simulation purposes.

Table 7 creates a more thorough set of hourly electrical demand profiles for appliances that can be used in the simulation using the data from Table 6 energy use information. The profiles can be combined to create an electrical demand profile and be used to produce corresponding heat gain data for thermal modeling. To be noted that refrigeration devices are on always, whereas space heating is normally on later in the evening, based on information from the literature (Yuce et al., 2016; Alajmi et al., 2020; Jaffar et al., 2018; Kellow, 1989; Cerezo et al., 2017; Alotaibi, 2011; Energieagentur, 2010; Kavousian et al., 2015; Jones et al., 2016). The heater is supposed to be activated before 9 a.m. since hot water must be available before then. Timing data was utilized to create Table 7.

3. Results

This section reported the sized renewable energy production and battery storage for the autonomous building (AB), using the previously described ESP-r tool (ESRU) with the structures and physical appearance of the energy demand for the case study of Kuwait. The photovoltaic (PV) area was also calculated to balance the AB's energy demand for the Kuwaiti villa, as shown in Fig. 3. The size of the battery required was then determined to deliver a reliable, off-grid energy supply. The effect of energy efficiency improvements was also evaluated on the necessary roof-mounted PV capacity and battery size.

Table 6
Lists electric appliance metrics that include energy requirements, average run time, and useful life in Kuwait to create the energy profile in the ESP-r model (Jones et al., 2016), where this data breakdown is crucial for optimizing energy management and planning for both peak demand and overall consumption, and to help in designing more efficient energy systems and schedules for clean energy autonomous buildings in Kuwait.

No	Appliance	Related Power (W)	UEC (kWh/year)	Minimum Running Time (minutes)	Useful Lifetime (years)	Required Usage Frequently	Required Start Time Between
1	Air Condition (AC)	3570	19,544	900	~10	Twice a day	(00:00–23:45)
2	Water Heating	5189	1894	~60	~15	Twice a day	(00:00–23:45)
3	Space Heating	2395	1749	~120	~15	Twice a day	(00:00–23:45)
4	Refrigerator	103.5	907 (United Nations. Sustainable Development Goals, 2017)	1440	14	Ongoing	(00:00–23:45)
5	Freezer	117.23	1027 (United Nations. Sustainable Development Goals, 2017)	1440	11	Ongoing	(00:00–23:45)
6	Water cooler	91.27	799 (United Nations. Sustainable Development Goals, 2017)	1440	10	Ongoing	(00:00–23:45)
7	Washing Machine	407	297	120	10	Twice a day	(00:00–23:45)
8	Dishwasher	814	297	60	10	Twice a day	(00:00–23:45)
9	Microwave	4471	408	15	9	Twice a day	(05:00–09:00) (17:00–22:00)
10	Electric oven	~2000	–	120	10	Twice a day	(05:00–09:00) (17:00–22:00)
11	Electric Stove	~2000	–	60	10	Once a day	(00:00–23:45)
12	Iron	1027	375	60	7	Once a day	(00:00–23:45)
13	Dryer	1208	882	120	14	Once a day	(00:00–23:45)
14	TVs (2 x 138)	277		300	7	Once a day	(00:00–23:45)
15	Satellite Receiver	~150	–	300	~5	Once a day	(00:00–23:45)
16	Computers (x 2)	600	- (United Nations. Sustainable Development Goals, 2017)	120	5	Once a day	(00:00–23:45)
17	Lighting	1512	3864	420	~5	Any time	(00:00–23:45)
18	Vacuum Cleaner	2000 (Strachan et al., 2008)		60	5	Once a day	(00:00–23:45)
19	Phone Charger	0.015	–	120	5	Once a day	(00:00–23:45)
20	Water Pump	684 (ESRU)	–	60	~5	Twice a day	(00:00–23:45)
21	Ketel	~500	–	60	~5	Twice a day	(00:00–23:45)
22	Toaster	~500	–	60	~5	Twice a day	(00:00–23:45)
23	Car Charger	5200 (Strachan et al., 2008)	–	180	~10	Once a day	(00:00–23:45)
24	Miscellaneous	5184	–	90	–	Ongoing	(00:00–23:45)
Total Energy Consumption (kWh)		40,000					

Table 7
Highlights the variations in energy demand from different appliances throughout the day, where high-consumption appliances such as air conditioners and car chargers significantly impact the overall energy profile, contributing to the peaks in energy use, whereas constantly running appliances like refrigerators and freezers show steady energy consumption, while others like microwaves and ovens create spikes during different hours.

Appliance	Hr	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
AC	14	0	0	0	0	0	0	0	0	0	3570	3570	3570	3570	3570	3570	3570	3570	3570	3570	3570	3570	3570	3570	0	49950
Water Heating	1	0	0	0	0	0	0	0	0	0	5189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5189
Space Heating	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2395	2395	0	4790
Refrigerator	24	0	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	103.5	2380.5
Freezer	24	0	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	117.23	2696.29
Water Cooler	24	0	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	91.27	2099.21
Washing machine	2	0	0	0	0	0	0	0	0	0	0	407	407	0	0	0	0	0	0	0	0	0	0	0	0	814
Dishwasher	1	0	0	0	0	0	0	0	0	0	0	0	0	814	0	0	0	0	0	0	0	0	0	0	0	814
Microwave	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4471	0	0	0	0	0	0	0	0	0	0	4471
Electric Oven	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2000	2000	0	0	0	0	0	0	0	0	0	4000
Electric Stove	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2000	2000	0	0	0	0	0	0	0	0	0	4000
Iron	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1027	0	0	0	0	0	0	0	0	1027
Dryer	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1208	1208	0	0	0	0	0	0	2416
TVs(2x138)	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	277	277	277	277	277	277	1662
Satellite Receiver	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	150	150	150	150	150	150	900
PC (X2)	2	0	0	0	0	0	0	0	0	0	0	600	600	0	0	0	0	0	0	0	0	0	0	0	0	1200
Lightning	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1512	1512	1512	1512	1512	1512	1512	10584
Vacuum Cleaner	1	0	0	0	0	0	0	0	0	0	0	0	0	2000	0	0	0	0	0	0	0	0	0	0	0	2000
Phone Charger	2	0	0	0	0	0	0	0	0	0	0	0	0	0.015	0.015	0	0	0	0	0	0	0	0	0	0	0.03
Water pump	1	0	0	0	0	0	0	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500
Ketel	1	0	0	0	0	0	0	0	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500
Toaster	1	0	0	0	0	0	0	0	0	500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	500
Car charger	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5200	5200	5200	15600
Miscellaneous	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5368	5368	0	10736
Total		0	312	312	312	312	312	812	812	812	9071	4889	4889	6696.015	12353.015	7882	4909	5090	6602	5821	5821	5821	18784	18784	7451	
Average		0	312	312	312	312	312	812	812	812	9071	4889	4889	6696.015	12353.015	7882	4909	5090	6602	5821	5821	5821	18784	18784	7451	

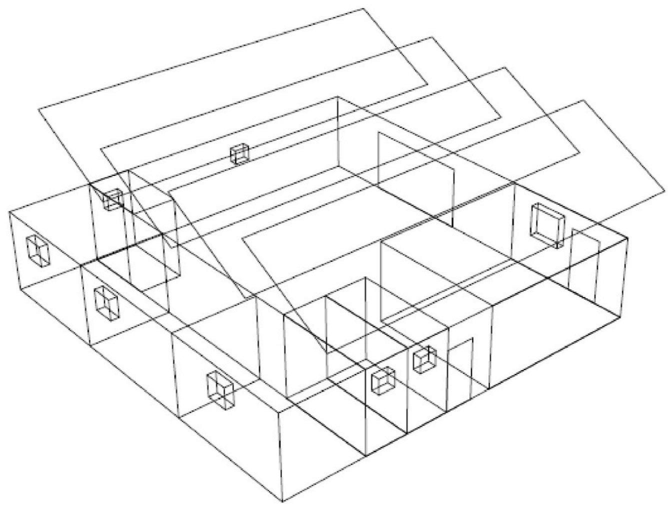


Fig. 3. Displays the simulation model of a 200 m^2 Kuwaiti villa with 4 bedrooms, utilized in the ESP-r tool (ESRU), it showcases the building's physical structure and roof-mounted photovoltaic (PV) area needed to meet the villa's energy requirements for a reliable off-grid energy supply.

3.1. Autonomous building (AB) simulation results

Democratization of energy by engineering ABs, reliability, scalability and managing local energy systems and green asset management using renewable integration technologies is the first step towards a federated green energy network of sustainable blockchain ABs. In the first stage, the Kuwaiti villa test was employed, and the results were reported in Table 8. The base case scenario represents the existing green energy system depth. In cases two to six, significant energy demand reductions (EDR) are evaluated, potentially leading to revised energy storage system (ESS) sizing. These scenarios assess the impact of EDR on simulation outcomes, including energy system sizes and costs.

Table 8 shows the production of green energy, including the number of PVs and EDR in Kuwait. The results for the base case scenarios with no implementation of energy efficiency showed that the size of the energy system production and the size of ESS were higher. Therefore, the total costs of the AB system can be reduced. This means a smaller size of the renewable energy system and a smaller size of the battery storage implementations, which leads to significant cost reductions. This confirms that the implementation of EDR can lead to saving energy, money and the environment.

Furthermore, the results showed that despite the huge amount of solar radiation available in the region, the AB with 50% EDR required 181 PVs and 1710 kWh battery capacity due to the high cooling energy demand, and the reliability on 100% clean energy from batteries (for both electric building and EV). This gains advantages to AB engineering where it provides engineers with consistency and confidence not only in analyzing and simulating ABs in hot climate, but also in presenting the AB results in that location and help to make better engineering decisions and design.

3.2. Energy demand reduction (EDR) results

Investigating the impact of EDR on the sizing of AB's EES is shown in Fig. 4. The waterfall chart shows the current state of AB from the base case scenario to EDR strategy 1 to EDR strategy 5 (final proposal). The bar chart clearly provides the condition and values from the base or current state through the application of each single EDR strategy until the final configuration because the final bar shows the EDR impact on the sizing of the AB energy system due to the significant reduction of 50% in energy demand.

Figs. 5–7 show the relationship between EDR and the number of PVs (energy supply) for Kuwaiti's AB. In addition, the effect of reduced demand and energy efficiency typically illustrates the relationship between energy consumption and various factors that can influence it, such as improvements in energy efficiency and changes in energy demand. Fig. 5 shows the variation between energy demand and the number of PVs required to gain energy autonomy. The graph shows the implementation of energy efficiency in the building not only reduced energy demand from 49661 kWh to 24831 kWh, but also with 50% EDR led to a reduction of the number of PVs from 362 (in the base case) to 181 panels, which optimizes space and signifies the cost savings of about 50%.

Fig. 6 shows the AB in the base case scenario and the effects of EDR from 10% to 50%. With 10% EDR, the size of the battery storage was reduced from 3415 kWh to 3071 kWh. In addition, the graph shows with a 50% EDR, the size of the battery storage reduced from 3415 kWh to 1710 kWh.

Fig. 7 shows the variation related to the number of PVs required for AB and the size of the battery required for autonomous operation. As the graph shows, the 10% EDR led to both reductions in battery size from 3415 kWh to 3071 kWh and the number of PVs from 362 to 326. While, with 50% EDR affects both 50% reductions of battery capacity (BC) from 3415 to 1710 kWh, and 50% reductions in the number of PVs from 362 to 181 panels.

4. Discussion

This study bridges the gap between engineering energy design and the AB market, emphasizing energy services and solutions, with a specific focus on sustainable AB in Kuwait and computer modeling. It underscores the importance of holistic solutions in the built environment and transport systems, advocating a problem-solving approach to combat fuel poverty, energy crises, and climate change.

AB simulation and results in the previous section highlighted the

Table 8
Demonstrates that as energy demand reductions (EDR) are implemented, the number of photovoltaic (PV) panels required decreases significantly, leading to a more efficient and cost-effective solar energy system, where with reduced demand, less PV capacity is needed, which also reduces the initial energy storage requirements for batteries, and less space is needed that highlights the benefits of energy demand management in optimizing clean energy production and storage as well as efficient use of generated solar power.

	Base case	−10% demand	−20% demand	−30% demand	−40% demand	−50% demand
Energy Demand (kWh)	49661	44695	39729	34763	29797	24831
Required number of PV panels	362	326	290	254	217	181
PV energy supplied (kWh)	49888	44900	39911	34922	29933	24944
BC required (kWh)	3415	3071	2730	2390	2050	1710
Battery initial energy (kWh)	370	350	295	257	220	190
Battery final energy (kWh)	596	534	475	416	356	301
Battery minimum energy (kWh)	4	1	1	2	1	5
Battery size reduced (%)	0.00 %	10.00 %	20.00 %	30.00 %	40.00 %	50.00 %
Number of PV reduced (%)	0.00 %	10.00 %	20.00 %	30.00 %	40.00 %	50.00 %
Spilled energy (kWh)	1	20	2	0	0	3

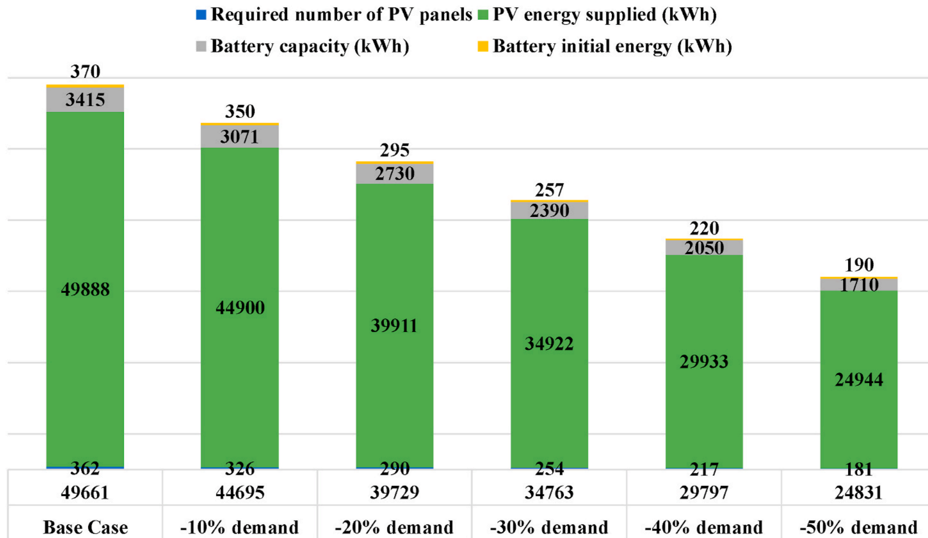


Fig. 4. Demonstrates how energy demand reduction (EDR) strategies influence the sizing of the energy storage system (EES) for an autonomous building (AB) in Kuwait, where the waterfall chart visualizes the transition from the base case to various EDR strategies, culminating in the final 50% demand reduction scenario, and showcasing how improved energy efficiency leads to substantial reductions in storage requirements and also better use of land and space.

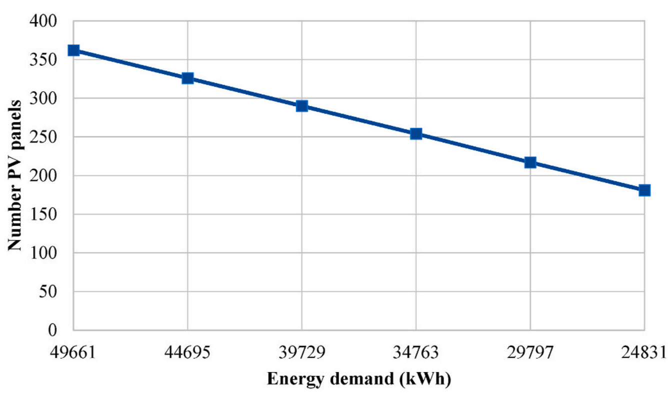


Fig. 5. Illustrates the variation between energy demand reduction (EDR) and the number of photovoltaics (PVs) required to gain energy autonomy, where it shows the implementation of energy efficiency in the building not only reduced energy demand from 49661 kWh to 24831 kWh, but also with 50% EDR led to a reduction of the number of PVs from 362 (in the base case) to 181 panels, which optimizes space and signifies the cost savings of about 50%.

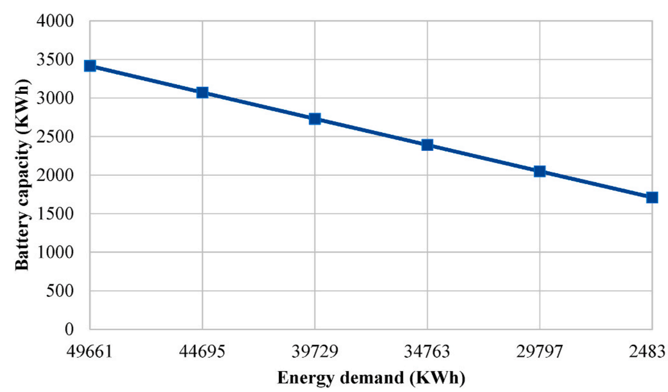


Fig. 6. Shows that by implementing energy demand reduction (EDR) measures, the necessary battery capacity (BC) can be significantly decreased, when energy demand is reduced, the BC requirement drops from 3415 kWh to 1710 kWh highlighting the impact of energy efficiency improvements on battery size requirements, and suggesting that optimizing energy consumption is crucial for minimizing the battery capacity needed for autonomous operation as well as demand-side management in energy systems.

importance of reducing energy demand in self-sufficient buildings. Custom-sizing energy toolkit systems (CSETS) and efficient AB design offer economic and environmental benefits. Integrating renewable technology ensures sustainability at an experimental level, with a focus on correctly sizing energy production and ESS to achieve long-term decarbonatization with ABs.

Moreover, insights from the Kuwaiti's AB research can address energy and environmental concerns, including local CO_2 emissions mitigation and climate change efforts. It also informs design strategies for improving livability and environmental compatibility in various settings like remote villages, rural and coastal areas, urban/suburban areas. This research can promote green energy design, public realm energy management, and innovative engineering processes for implementing ABs.

The prototype of this novel approach has the potential for global replication, offering a solution to reduce CO_2 emissions, mitigate the risk of global warming, and accelerate the pace of climate change mitigation. This niche pattern, applicable in suburban cities, coastal and rural areas, highlands and islands, showcases the versatility of AB&EV applications, attracting attention at local, national, and international levels. AB&EV projects emerge as pivotal decisions, anchoring green business growth and circular economic development, ultimately contributing to the transition to net-zero carbon and renewable energy resources. This aligns with broader objectives of advanced buildings, a low-carbon society, and a greener economy. It also addresses the climate crisis, offering moral and economic opportunities.

AB technology has the potential for future studies for new approaches in combination with the built environment and transportation for future green heat and energy developments across the world. Future works include commercial and industrial energy-ABs (e.g., autonomous hotel and agricultural autonomous warehouse), medium and large scale. Furthermore, the current focus is to calibrate operational scenarios in small-scale ABs via computer simulation. However, future plans will be to replicate knowledge in medium and large-scale ABs with diverse designs and locations for sustainable and clean energy production and resilient success.

Furthermore, there is some number of potential future works for clean energy autonomous buildings particularly in off-grid locations not only to be energy self-sufficient and problem-solving in energy access and help green transportation, but also ABs have the potential to look

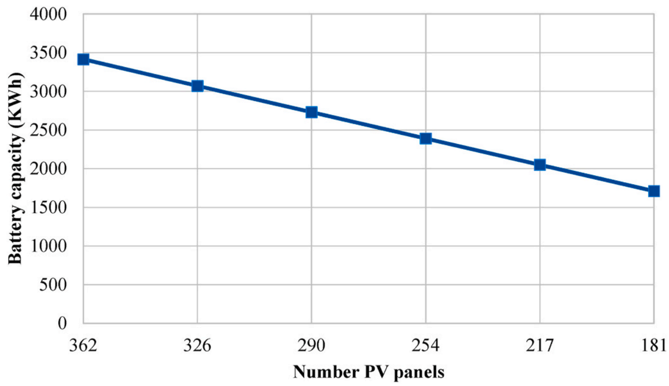


Fig. 7. Demonstrates the variation between the number of photovoltaic (PV) panels required for autonomy and the size of the battery needed for autonomous operation, where a 50% decrease in energy demand reduction (EDR) significantly reduces the battery capacity (BC) needed from 3415 kWh to 1710 kWh and decreases the number of PV panels required from 362 to 181 panel, which highlights the importance of energy efficiency measures in designing sustainable and autonomous energy systems.

into the different issues and offer another novel solution and problem-solving in several other matters related to water access or sustainable application of a water cycle (Liu et al., 2016), or water resources application for coastal and inland regions (Liu et al., 2021), and integrated with wastewater treatment and transformation, energy balance and economic analysis (Zan et al., 2020) with the problem-solving hat on to provide solutions and help and extend the current AB discussion to make sure clean energy solutions, evidence-based information is the staple for informing policy discussions and guiding future research directions.

4.1. Policy implications and future perspectives

These findings have significant implications, particularly in informing decisions and policymakers and guiding future research. Integrating 100% clean electric technologies, such as the concept of the AB&EV&5Z package, into green transportation and building practices, can lead to substantial advancements in sustainability. By reducing reliance on fossil gas, importing crude oil and decreasing greenhouse gas (GHG) emissions, this concept and related technologies align with global efforts to combat climate change and promote cleaner energy production and environmental conservation. This shows that advanced zero-carbon and zero-energy houses do not have to appear radically different from conventional homes (Mohammadi, 2019).

In terms of policy and lawmakers, governments and regulatory bodies can use AB&EV&5Z findings to develop and implement more stringent engineering and energy efficiency standards and incentivize the adoption of clean energy technologies. Policies that support the deployment of green autonomous building systems can stimulate innovation, attract green investments, and create green jobs, further bolstering economic development while saving energy and addressing environmental concerns.

For future research, these results highlight the need to explore additional applications such as commercial buildings (i.e., hotels, offices, etc.), industrial buildings (i.e., warehouses, car showrooms, data centers, manufacturing, etc.), public buildings (i.e., schools, hospital, airport, etc.), and improvements of AB technologies in different countries and climates. Researchers can investigate the scalability of these systems, their energy performance in diverse climatic conditions, and their integration with other renewable energy sources. Additionally, studying the socio-economic impacts of widespread adoption can provide valuable insights into how AB technologies can be helpful to serve disadvantaged communities (i.e., in coastal and rural areas, remote villages, highlands and islands, etc.) and can be used to level up society and more accessible and beneficial to a broader population, and not only creates more green jobs in their areas and slow down migration from villages to cities, but also slow down the speed of climate change process.

Ultimately, the practical significance of these findings lies in their potential to transform how buildings and green energy systems are designed, constructed, right sized and operated in hot climates. Enhancing sustainability practices, reducing fossil energy consumption, and improving living conditions can lead to better air quality, healthier end users, energy democratization, people empowerment and more resilient communities. This broader context underscores the importance of continued innovation and collaboration among scientists, policymakers, and industry stakeholders to maximize the benefits of such concepts and technological advancements.

5. Conclusions

The autonomous building (AB) presented in this paper introduces a groundbreaking approach to creative energy design, disrupting existing literature by relying solely on roof-mounted PV for power generation. This innovative sustainable green electrified modern home design supports clean power for electric vehicles (EV) in arid hot climates without an energy grid connection, marking a significant advancement in home modernization and decentralized energy decarbonization and democratization. This unique solution sets the stage for new knowledge and sustainable development, emphasizing the combination of green electrified autonomous building and electric vehicles (AB&EV) with zero grid connection as a distinctive feature.

The research proposes a novel method for energy engineering by utilizing a building simulation tool (ESP-r) with homeowner energy demand profiles, aiming to modernize Kuwaiti villas and promote a zero-emission mobility (ZEM) or green transport society through battery storage applied green energy autonomy. This research not only applies green energy in built environments and transportation for societal benefit but also contributes to the advancement of science. Scientific energy simulation data results demonstrated that the innovative engineering design approach leads to energy demand reduction (EDR) for end-users, ranging from 10% to 50% (final proposal). The results proved the effectiveness of the approach in sizing energy storage systems (ESS) batteries and reducing the number of PVs (from 362 to 181 panels), which would lead to minimizing over-sizing of building energy systems, and decreasing associated costs and space requirements in complex residential AB.

The introduced conversion concepts for electrified buildings offer independent full spectrum clean electricity utilization for houses and cars in off-grid locations in hot climates without energy bills, presenting a replicable solution on a global scale. This novel energy system design, previously unused in Kuwait, addresses both the unfamiliarity of the topic and provides a complex engineering solution for a unique combined structural product (i.e., AB&EV&5Z) with diverse green energy demands. This green combination approach can also help construction companies and governments reach their carbon targets, decision and policymakers and the local authorities in their future green policy and CO_2 reduction regarding climate change emergency and green action plans.

CRediT authorship contribution statement

Saeed Mohammadi: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Data curation, Conceptualization. **Ammar M. Bahman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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