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Towards Energy-Autonomous Buildings in Kuwait: A Case Study

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ABSTRACT

This research paper examines the concept of energy-autonomous buildings (ABs) in Kuwait, focusing on their sustainable design and integration of renewable technologies. ABs aim to achieve energy self-sufficiency and zero grid connection, resulting in zero carbon emissions and energy bills. The paper presents a pioneering example of an AB in Kuwait, featuring roof-mounted solar panels. Detailed climate and local construction research are conducted to develop innovative housing and transportation solutions with 100% green energy supply and demand. The study emphasizes the importance of combining integrated renewable technologies and new approaches to meet energy requirements in a hot arid climate. The results demonstrate the feasibility and cost-effectiveness of ABs when considering offset costs. Additionally, the study highlights the role of ABs in decarbonization, digitalization, decentralization, and democratization of energy, while emphasizing the significance of green cooling, heating, and electricity in reducing Co² emissions. This paper contributes to the advancement of real-time energy-autonomous buildings that are environmentally friendly, adaptable, and resource-efficient.

INTRODUCTION

Residential buildings are pivotal to human life, necessitating innovative integrated technology designs to meet the demands of the 21st century (Roaf, 2014). This study explores novel approaches to housing and engineering energy design, emphasizing both economic viability and sustainability. Theoretical and computational modeling, energy-efficient construction, and real-time monitoring and evaluation are integral aspects to consider for effective future city planning (Cosgrave, 2013). An inclusive perspective and proactive problem-solving are essential to mitigate risks and address potential challenges (Neirotti, 2014).

This paper presents an intriguing concept of a modern energy-autonomous villa in the hot climate of the Arabian Peninsula, with a 100% green energy system. The research aims to establish a model for universal application by examining a specific case study, a villa in Kuwait, where photovoltaic systems are deployed due to the region's abundant solar radiation (102,103). The findings contribute to the development of environmentally sustainable green energy communities and cities, aligning with the long-term goal of universal human well-being (Neirotti, 2014).

By integrating housing, energy, and climate change solutions within a unified framework, this research addresses the needs of stakeholders involved in Kuwait's new green urban zone. It highlights the importance of energy-autonomous buildings (ABs) as central components in creating low-carbon communities (Roaf, 2014). The study explores climate change

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adaptation, local construction materials, energy performance evaluation, and the significance of sustainable development for future cities (Roaf, 2014).

The paper's simulation model focuses on AB performance, specifically optimizing the sizing of renewable energy suppliers and energy storage. The insights gained from this research contribute to practical knowledge and can be applied as best practices for similar projects (Sitorus, 2020; Javed, 2021). This paper offers a valuable contribution to the advancement of sustainable housing, energy efficiency, and the establishment of green energy communities and cities.

Objectives

Including assessing autonomous building energy modelling, energy efficiency, sustainability features, automation systems, and overall energy performance.

Types of Operating Conditions:

Autonomous building operating conditions exhibit considerable natural energy converting and diversity, contingent upon the context, but fall into the following categories:

Autonomous Building Location or Environmental Conditions

Kuwait (Lat 29.31, Lon 47.48), is a country in the Middle East, located at the head of the Persian Gulf. Kuwait is about 200 km north to south, and 170 km east to west. Kuwait has 10 islands and summer is some of the hottest on earth. The highest recorded temperature was 54 °C at Mitribah on 21 July 2016. Hence, the reason, this study considers the state of Kuwait's ambient resource is the local solar radiation as the natural energy source. Kuwait produces a lot of carbon dioxide per person compared to other countries and is regularly ranked among the world's highest countries in terms of CO_2 per capita emissions. (Bou-Rabee, Mohammed, et al. 2017)

Autonomous Building Review the Current and Previous Assessment

Mohammadi, S. (2019, November) article showcases key examples of autonomous buildings from various corners of the world, demonstrating their pivotal role, but this autonomous building have emerged as groundbreaking innovations in sustainable architecture, blending cutting-edge technology with eco-conscious design principles, shaping the future of the sustainable built environment. Hence, the reason, this autonomous building is not only supporting the built environment's transition to net zero, but also supporting the transport system and facilitating net zero emission mobility (ZEM). Smarter transformation.

Boundary Constraints:

These constraints stipulate the parameters within the autonomous building in which a system operates. In structural energy self-sufficient engineering, for instance, boundary conditions include fixed heating and cooling points, which in this case are between 19º to 23º.

- **Time Constraints:**

Certain energy-autonomous systems in this study adhere to specific timeframes. For instance, one electric vehicle charging point qualifies as a time-based operating condition and I related the time of use of 9 to 11 pm to constraints.

- **End user Constraints:**

Certain number of people in this residential building assuming four people (two children with male and female parents) are living with one electric vehicle.

Boundary Limits:

Delimiting the parameters within which the autonomous building technology system operates serves to ensure the analysis remains relevant and valid.

Analyse the AB Technologies, or Energy Systems Components

Renewable energy integration includes a roof-mounted photovoltaic (PV) and energy storage system (battery) and an electric vehicle (EV) charging point.

- Strengths and Weaknesses

A huge amount of solar radiation is available for long days all year round. The free energy and its availability not only encourage eco-friendly engineering, but also provide sustainability and resiliency. Although, the current weakness is the cost of technology, but this can be set off against the cost of grid connection.

- Quantitative Data and Visuals.

Figure 1 incorporates relevant appliance and quantitative data, such as energy consumption figures, daily and monthly. This can help to make the assessment more engaging and comprehensible to modern residential buildings.

- Tilt

Considering the Latitude of Kuwait (29.31°S), this result is very close to the rule of thumb set above, i.e. a non-tracking PV system is recommended to have a tilt angle approximately equal to the local latitude angle and to orientate towards true south (Yan, Ruifeng, et al. 2013).

Impact on Analysis and Simulation:

The ramifications of operating conditions loom large over analyses, energy simulations, and predictive endeavors. Precisely delineating these conditions culminates in outcomes that are more reliable and true-to-life. Deviations from real-world operating conditions can precipitate inaccuracies in predictions and erroneous designs.

Autonomous building operation strategies.

Autonomous building operation strategies refer to a set of principles, approaches, and technologies employed to enable a building to operate energy self-sufficient, efficiently, intelligently, without grid and energy independently while minimising human intervention. These strategies leverage advanced autonomous building technologies and energy automation systems and optimize various aspects of building energy performance, including energy consumption, production and storage, comfort, security, and maintenance. Although, some of these points are out of the scope of this study. The goal is to create energy-self-sustaining buildings that adapt to changing conditions and user needs. Here are some of the key components and concepts related to autonomous building operation strategies:

1. Energy Management:

Autonomous buildings prioritize energy efficiency through construction materials, energy design architecture, and intelligent systems that optimize energy consumption. Strategies include:

Predictive Analytics: Using historical data and real-time information to predict energy usage patterns and adjust building systems accordingly.

Demand Response: Shifting energy-intensive operations to off-peak hours or reducing energy consumption during high-demand periods.

Renewable Integration: Incorporating solar panels, wind turbines, and other renewable energy sources to generate on-site power. (This study only considers roof-mounted PV.)

Energy Storage: Storing excess energy for later use, especially from renewables, to balance supply and demand.

2. HVAC and Comfort Control:

Heating, ventilation, and air conditioning (HVAC) systems are crucial for maintaining occupant comfort. Autonomous strategies include:

Zoning: Dividing the building into zones with separate temperature controls based on occupancy and usage patterns.

Occupancy Sensing: Using sensors to detect occupancy and adjust HVAC settings accordingly.

Adaptive Control: Continuously adjusting HVAC settings based on indoor and outdoor conditions and user preferences.
Thermal Storage: Storing thermal energy during low-demand periods and using it to regulate temperature during peak hours.

3. Lighting and Daylighting:

Efficient lighting (for example, LED) strategies enhance energy savings and user comfort:
Daylight Harvesting: Automatically adjust artificial lighting based on available natural light to minimize energy consumption.
Occupancy-Based Lighting: Turning lights on or off based on occupancy sensor data.
Smart Lighting Controls: Integrating lighting systems with occupancy sensors, timers, and dimmers for optimized usage.

4. User Interaction:

User comfort and engagement are essential:
Smart Interfaces: Providing occupants with user-friendly interfaces to control building and energy systems and personalize settings.
Feedback Mechanisms: Gathering user feedback to improve building operation and tailor systems to occupant preferences.

5. Grid Interaction:

Autonomous buildings operate without grid connections, but they can interact with the larger energy grid:
Grid Services: Participating in demand response programs and providing grid support by adjusting energy consumption based on grid conditions.
Energy Sharing: Sharing excess energy generated on-site with the grid and neighbouring buildings.
In conclusion, autonomous building operation strategies leverage cutting-edge technologies and data analysis to create buildings that operate efficiently without an energy grid connection, which has a significant cost reduction to the project and prioritizes user comfort and energy efficiency and energy storage. The battery is a direct connection control. These strategies are essential for achieving sustainable, intelligent, self-sustaining built environments and energy autonomy.

METHODOLOGY

Simulation Tool

The performance of energy-autonomous buildings (ABs) was modeled and simulated using the ESP-r building simulation tool in this study. ESP-r offers the capability to model both the building's performance and the energy sources that supply its energy. By defining a user-specified time interval (e.g., day, week, year), ESP-r enables the determination of the building's energy and environmental performance.

The tool comprehensively calculates various energy and mass transfer processes underlying building performance, including conduction and thermal storage in building materials, convective and radiant heat exchanges (including solar processes), air flows, and interactions with plant and control systems. To achieve this, the building's physical characteristics such as materials, construction, and geometry are divided into numerous "control volumes".

In this context, a control volume represents a defined region of space where conservation equations for continuity, energy (thermal and electrical), and species are applied, forming one or more characteristic equations. A typical building model consists of thousands of such control volumes, with equation sets organized based on the energy system they represent.

Solving these equation sets using real-time climate data, coupled with boundary conditions related to control and occupancy, provides insights into the dynamic evolution of temperatures, energy exchanges, and fluid flows within the building and its associated systems.

By utilizing the ESP-r simulation tool, this study enables a comprehensive assessment of AB performance and aids in understanding the intricate interactions between various building components and energy systems.

Simulation Validation

The reliability of the ESP-r tool (ESRU, Hand, 2015, and ESP-r software) has been assessed and reviewed by Strachan (Strachan, 2008). For a more comprehensive understanding of the technical foundation of ESP-r, readers can refer to Clarke's detailed description (McElroy, 2001). Extensive validation studies have been conducted on ESP-r, as summarized by Strachan (Strachan et al., 2000) and later by Monari (Monari, 2014).

Simulation plays a crucial role in the design of energy-autonomous buildings (ABs). It enables the determination of heating and cooling demands, as well as the potential power generation from on-site renewable sources. However, it is important to note that simulation alone cannot determine the sizing of components necessary to achieve building autonomy. A separate sizing methodology is required for this purpose.

Case study

In this section, the application of the ESP-r tool and methodology, described earlier, is demonstrated for sizing renewable generation and battery storage in an autonomous building (AB). The specific energy system requirements (Figure 1) to support the energy-autonomous villa in Kuwait are highlighted. The determination of the required PV area to offset the energy demand of the villa (Figure 2) is presented. Additionally, the calculation of the necessary battery size to ensure a reliable off-grid energy supply is performed. The study also examines the impact of energy efficiency enhancements on the required PV capacity and battery size. The completed building geometry is depicted in Figure 2.

List of household appliance metrics that include electricity requirements, average run-time and useful life in Kuwait

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	49980
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
Washingmachine	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 (2 x 138)	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
Computers (x 2)	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
Lighting	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	

Figure 1 Kuwaiti building energy usage data with a detailed set of hourly electrical demand.

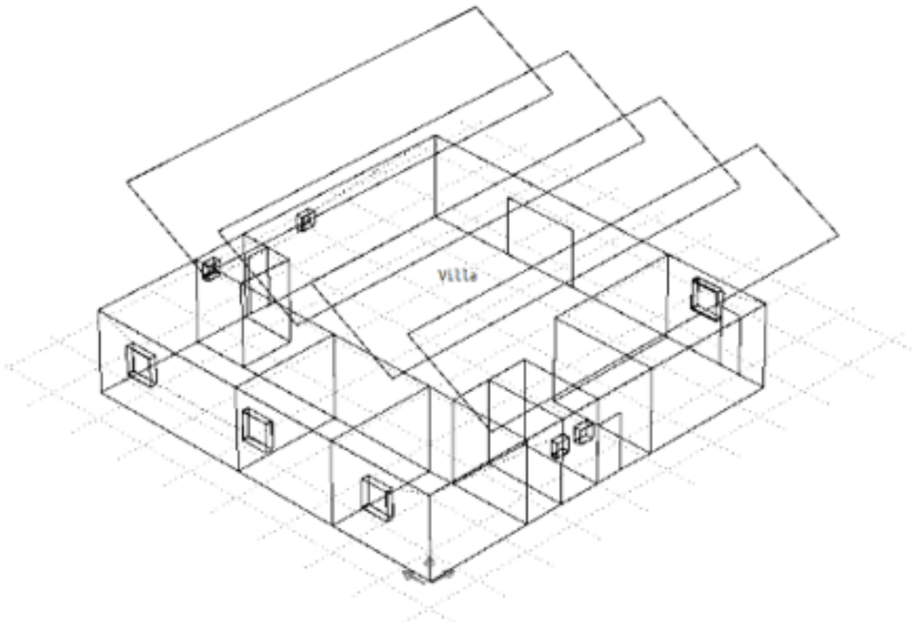

Figure 2 Kuwaiti autonomous building (AB) model in ESP-r software.

Kuwait EDR & Pvs	Kuwaiti AB -362PVs & Energy Demand Reductions (W)					
	AB Base	10% EDR	20% EDR	30% EDR	40% EDR	50% EDR
Initial Energy (kwh)	370	350	295	257	220	190
Battery Capacity (kwh)	3415	3071	2730	2390	2050	1710
Final Energy (kwh)	596	534	475	416	356	301
Minimum energy	4	1	1	2	1	5
Max energy	3415	3071	2730	2389	2048	1710
Total supply energy (kwh)	49888	44900	39911	34922	29933	24944
Total demeand energy (kwh)	49661	44695	39729	34763	29797	24831
Total splilled energy	1	20	2	0	0	3
Battery %	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%
Pvs %	0.00%	10.00%	20.00%	30.00%	40.00%	50.00%
Number of Pvs reduced	0	36	72	108	145	181
Total Required Pvs	362	326	290	254	217	181
kwh/m2a	248	223	199	174	149	124

Figure 3 Energy demand reduction (EDR) and number of PVs for green energy production using autonomous building (AB) in Kuwait.

RESULTS AND DISCUSSION

The findings are presented and discussed in this section. Figure 3 illustrates the green energy production, including the number of photovoltaic (PV) panels and energy demand reduction (EDR) in Kuwait. The relationship between energy demand reduction and the number of PV panels (energy supply) is demonstrated in Figure 3. Furthermore, the impact of reduced energy demand and energy efficiency improvements is explored, highlighting the interplay between energy consumption and various influential factors.

The democratization of energy through the engineering of autonomous buildings is crucial for establishing reliable, scalable, and locally managed green energy systems. Integrating renewable technologies facilitates effective green asset management, paving the way for a federated green energy network of sustainable blockchain-based autonomous buildings. In the initial stage, the study focuses on a test case of a Kuwaiti villa, and the outcomes are depicted in Figure 3.

This paper investigates and addresses the cooling and heating demands of the building. It engages in a comprehensive discussion, presenting multiple perspectives on the importance of green buildings, green energy systems, the adoption of green cooling and heating technologies, and the strategic roadmap for implementing energy-autonomous buildings based on advanced building modeling and design (Figure 2). These efforts are aimed at meeting the energy demand and optimizing facility operations.

CONCLUSIONS

This research study represents a significant contribution to the understanding and application of Autonomous Buildings (ABs), particularly in the context of Kuwait. It provides a comprehensive roadmap for achieving energy-autonomous buildings with a focus on cooling and heating facility design, electric vehicle integration, and implementation and operation strategies.

The study demonstrates that achieving zero carbon and zero energy buildings through Decentralized Autonomous Buildings (DABs) is not an unattainable goal. It identifies potential challenges and offers engineering solutions to overcome them, providing guidance for public and private housing developers to reduce carbon emissions, increase energy efficiency, and save costs while benefiting the environment.

The study bridges the gap between engineering energy design and the AB market by employing building modeling and positioning techniques to deliver energy services and solutions for a greener future. The research specifically concentrates on sustainable autonomous buildings in Kuwait, employing computer modeling as a key tool.

The results and graphics obtained from AB simulations emphasize the importance of incorporating energy demand reduction in new residential buildings. The study highlights the economic and environmental benefits of custom-sizing energy systems and implementing energy-efficient designs.

Renewable technology integration is proven to enable green energy self-sufficiency, and the study showcases its viability at the experimental level. The custom sizing energy toolkit presented in this research ensures effective utilization and supports the vision of fully energy-autonomous buildings.

Energy-autonomous buildings not only contribute to long-term CO2 reduction but also demonstrate neutrality in terms of greenhouse gas emissions during the building phase. The study underscores the feasibility of energy self-sufficiency in buildings and the potential for reducing overall greenhouse gas emissions.

Moreover, the research highlights the role of energy efficiency (EE) in promoting the decarbonization of the power sector. By implementing EE measures, the size and costs of renewable energy systems can be significantly reduced, leading to greater energy independence and decreased greenhouse gas emissions.

The scientific contributions of this research extend beyond the Kuwaiti case. The proposed building modeling approach and methodology have potential applicability in other systems with high renewable energy shares and varying levels of energy efficiency. Further research is required to explore the economic benefits associated with different levels of energy efficiency and the replicability of the methodology in different power systems.

Ultimately, this study has generated valuable knowledge, supported scientific advancements, and identified new opportunities in the areas of clean energy systems, green transport, and the built environment. It contributes to the educational, local community, and scientific domains, with significant potential for international and local business development and research advancements in Kuwait.

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