International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 11-No.3 (2025) pp. 3786-3792
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Energy Performance Evaluation of a near-Zero Energy Solar House Demonstrator

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Article Info:

DOI: 10.22399/ijcesen.633
Received : 14 November 2024
Accepted : 01 June 2025

Keywords :

Near Zero Energy Building
Rooftop PV system
Battery energy storage
Energy performance evaluation
Positive-energy house

Abstract:

This study evaluates the compliance of a solar house demonstrator with the near Zero Energy Building (nZEB) standard. Initially, high-efficiency passive and active measures were implemented to reduce energy consumption. Subsequently, a combination of a photovoltaic (PV) system with battery energy storage (BES) and a solar water heater was deployed to harness renewable energy sources. The demonstrator's energy performance is evaluated by assessing its energy balance, grid independence, and renewable energy ratio over one year. The findings indicate that the installed PV system produces 4,439.68 kWh annually, which exceeds the estimated household consumption of 3,368.95 kWh/year, resulting in a 30.58% annual energy production surplus. The demonstrator thus surpasses the zero-energy house requirements, effectively operating as a positive-energy building. The PV system supplied up to 71.9% of the energy needs, with the grid providing the remaining 28.10%. The annual energy performance indicators for the demonstrator include a Direct Consumed Ratio (DCR) of 50.76%, a Capacity Factor (CF) of 73.97%, and a Renewable Energy Ratio (RER) of 160.42%. This case study provides insights into optimising the performance of near-Zero Energy Homes, particularly within the specific climatic context of Algeria.

1. Introduction

Since the building sector accounts for approximately 40% of global energy consumption [1], experts have proposed the nZEB concept to reduce energy use and CO_2 emissions in this sector. Numerous definitions of the nZEB concept vary according to the policies applied in each country. D'Agostino and Mazzarella [2] investigated the technologies utilised, the strategies and procedures implemented, the standards applied in nZEB design, and the assessment criteria used to determine whether a building meets nZEB certification. According to the most widely accepted definition in the literature, an nZEB is a building with extremely high energy performance that meets most of its energy needs through renewable energy sources produced on-site or nearby, with minimal reliance on fossil fuels. Due to growing concerns about climate change, there is increasing emphasis on energy efficiency and nZEB design in buildings. Various techniques and design elements are proposed for incorporating the nZEB concept, such as enhancing the thermal insulation of the building envelope, using energy-efficient appliances and lighting, optimising heating, ventilation, and air-conditioning systems, and installing renewable electricity generation systems. Today, several countries worldwide have integrated the nZEB concept into their energy strategies. For instance, the European Union has adopted a policy mandating that all new buildings be nZEB by 2020 [3]. In the United States, the government has committed to making all commercial buildings nZEB by 2050 [3]. In Algeria, as part of the national energy efficiency program, the government is promoting advanced technologies for renovating existing buildings and designing new housing, aiming to reduce energy consumption in the building sector by 15% by 2030 [4]. In the following paragraph, the cited research highlights the growing interest in the nZEB concept and various approaches that have been explored. For example, the authors in [5] emphasise the importance of the building envelope in nZEB design, presenting a conceptual study for an innovative multi-storey residential wood construction in southern Italy. The energy analysis, conducted using the TRNSYS code, showed that the wood construction reduced annual thermal energy consumption by 32%. Similarly, [6] demonstrated that optimising the geometry and orientation of buildings can reduce electricity use for heating and cooling systems by 21.08% and 34.77%, respectively. [7] found that combining daylighting with smart artificial lighting control can be one of the most effective approaches to ensure the successful implementation of the nZEB concept. [8] developed a strategy to optimise a building's Heating, Ventilation, and Air Conditioning (HVAC) system to meet nZEB standards. This method combines dynamic simulation models created in TRNSYS software with the Non-dominated Sorting Genetic Algorithm (NSGA-II) to minimise total costs and primary energy use. The actual energy performance of a renovated hotel in Croatia's Adriatic region demonstrates a reduction in primary energy consumption from 176.4 to 170.2 kWh/m², resulting in energy savings with economically attractive payback periods. Furthermore, on-site generation of electrical energy from renewable sources is one of the primary solutions used to reduce fossil fuel usage and CO_2 emissions. Numerous studies have demonstrated the efficacy of adopting solar PV systems to meet nZEB goals. [9] assessed the potential for self-consumption in line with European directives for five three-story structures across five Spanish provinces with varying climatic conditions.

Their findings revealed that nZEB status can be achieved by combining solar systems with light storage systems in areas of high solar radiation, ensuring a good match between energy consumption and PV production. [10] examined the energy balance and performance of PV systems installed at the Solar Energy Laboratory in Florianópolis, Brazil, designed as an nZEB building. Their analysis, which accounted for solar irradiation availability, variations in the number of building occupants, installed PV system capacity, and energy production and consumption, revealed that PV production could meet 97% of the laboratory's energy requirements. The literature on the nZEB concept includes substantial research focused on residential buildings. [11] evaluated the energy performance of an nZEH in China, equipped with a solar system, hot water, and HVAC system. Simulation results using EnergyPlus software showed strong energy performance, achieving a positive energy balance of 60.22 kWh. [12] estimated the energy performance of two dwellings in Innsbruck, Austria, designed to meet Passive House criteria to obtain nZEB certification. Their analysis revealed that minimising heat loss and auxiliary energy usage are critical steps for achieving nZEB status. [13] analysed the energy performance of a passive house in Portland, Oregon, USA, exploring the feasibility of converting it to an nZEB. Installing PV panels offset the annual energy demand, with a payback period of 15.4 years. Furthermore, the adoption of solar thermal water heating reduced energy consumption by 64%. [14] provided a comprehensive modelling and cost-effectiveness analysis of new single-family homes in California that incorporate rooftop solar PV panels and battery storage as part of the nZEB design. Their analysis considered various net metering policies, finding that the profitability of all-electric nZEBs depends on both the capital costs of electrical appliances and the compensation received for surplus PV energy. Additional options for optimising nZEB residential buildings and reducing consumption include integrating small wind systems with PV systems, using thermal or electrical storage, and developing energy and demand management algorithms [15].This article presents a case study conducted in the Mediterranean climate zone of northwestern Algeria, examining a Solar House Demonstrator (SHD) to evaluate its energy performance and potential to achieve nZEB status. The house employs high-efficiency passive solutions to reduce energy consumption and is equipped with an on-grid PV system with BES and

Figure 1. *Front view of the solar house demonstrator.*

Demand Side Management strategy to maximise self-consumption. The objective is to assess the solar home's current standing in relation to the nZEB standard.

2. Overview of the Solar House Demonstrator

2.1. Building Description

The SHD is located in Bou-Ismaïl, near the city of Tipaza, in the Mediterranean region of Algeria. It has been constructed to achieve a zero or near-zero energy balance, meaning that the energy consumed is less than or equal to the energy generated locally by the PV system, aligning closely with the nZEB concept. The house has a total area of 57 m² and comprises a living room, a kitchen, and a bedroom. The house is south-facing to maximise natural light and optimise the performance of the PV system. Its architectural design includes an attic roof to enhance air circulation and facilitate heat dissipation from the interior to the exterior. The SHD operates entirely on electricity. Primarily occupied by one or two researchers during the day, the SHD also hosts students for training from March to July, along with occasional visitors. Figures 1 and 2 depict the front and interior views of the house, respectively.

Figure 2. *Interior view of the solar house demonstrator.*

2.2 Passives Solutions

The SHD envelope is designed for effective thermal insulation and reduced energy consumption. The exterior walls are constructed with 15mm-thick wood, while the interior walls consist of 40mm-thick flat polyurethane panels. Additional passive strategies to achieve nZEB performance include using low-energy appliances in class A, A+, and A++, highly insulated and airtight windows, electric venetian blinds, and LED lighting. The active solutions of the solar home comprise a rooftop PV system, an electrical energy storage system, and a solar water heater. Further details on these active components are provided in the following sections.

2.3 Actives Solutions

2.3.1. Rooftop PV System

A PV system was installed on the roof of the SHD with a 20-degree tilt angle. The 3.2 kWp PV rooftop consists of 16 monocrystalline silicon modules of 200 Wp each. These panels are organized in two parallel strings, each with eight modules in series.

2.3.2. BES System

The battery bank of the PV system has a capacity of 7.92 kWh. It consists of four 12 V lead-acid batteries with a total capacity of 165 Ah. The batteries used to store excess PV production to supply the house's loads during times when PV energy is insufficient, which is frequently the case at the beginning and the end of the day.

2.3.3. Solar Water Heater System

The solar water heater system, which includes a 1.63 m² solar thermal panel collector and a 150 L water tank was designed to meet the daily home's hot water needs [16].

3. Analysis Parameters

To evaluate and analyze the energy performance of the SHD, three standard building assessment criteria at nZEB were used: Direct Consumed Ratio (DCR), Capacity Fraction (CF), and Renewable Energy Ratio (RER). The DCR is defined as the ratio of PV electricity directly consumed by nZEB loads to total on-site PV energy production [17]. A high DCR indicates greater energy autonomy for the building, as indicated by the equation (1):

$$DCR = \frac{Directly\ consumed\ PV\ electricity}{Total\ PV\ electricity\ generated} \tag{1}$$

CF is used to determine a building's ability to meet its energy needs with on-site renewable energy. A high CF means a lesser reliance on the power grid [17]. CF is expressed by the following equation (2):

$$CF = \frac{Directly\ consumed\ PV\ electricity}{Total\ electricity\ consumed\ by\ the\ load} \tag{2}$$

The RER is an indicator that measures the contribution of renewable energy sources to total energy consumption. The higher the RER, the greater the proportion of renewable energy in the energy mix [9]. It is calculated by dividing the entire quantity of renewable energy produced by the total amount of energy consumed over a given period, using equation (3).

$$RER = \frac{Total\ PV\ electricity\ generated}{Total\ electricity\ consumed\ by\ the\ load} \quad (3)$$

The equation (4) describes how DCR, CF, and RER are mathematically related:

$$CF = DCR \times RER \quad (4)$$

For this study, the energy stored in the batteries was taken into account in the calculation of the three energy performance parameters as the energy generated by the PV system and consumed by the loads of the house.

4. Results and Discussions

4.1 Weather Data Analyses

Two essential factors affecting nZEB status are ambient temperature and solar radiation. These parameters significantly influence both the energy required for heating and cooling in the house and the production of PV energy. Daily ambient temperature fluctuations are obtained from data measured by PT100 probes, while solar irradiance is recorded by a pyranometer installed on the house's roof. Figure 3 presents the data for these two climatic variables from January to December 2023. It should be noted that solar radiation peaks in summer (June, July, and August), with a maximum value of 160 kWh/m² recorded in July 2023. The lowest recorded irradiation for 2023 was 95 kWh/m², measured in February. The total annual solar radiation received during the selected period was 1531 kWh/m². Additionally, Figure 3 shows that the average monthly temperature ranged from 12.38 °C to 26.63 °C, with its maximum occurring in July and August.

4.2Energy Production and Consumption Balance

Figure 4 shows the cumulative monthly trend in PV energy generation and energy consumption. Overall, the PV system's production exceeds the energy consumption of the SHD, except during the summer months, when the use of air conditioning results in consumption exceeding PV energy output by 96.142 kWh in June and 290.934 kWh in July. Despite rising ambient temperatures (as shown in Figure 3), consumption remained relatively low in August, as this period coincides with the vacation time when the SHD is mainly occupied by one person. Additionally, the results reveal that January and July have the lowest (181.9 kWh) and highest (779.284 kWh) monthly energy consumption, respectively. In contrast, the monthly PV production peaked at 498.35 kWh in July and reached its lowest level of

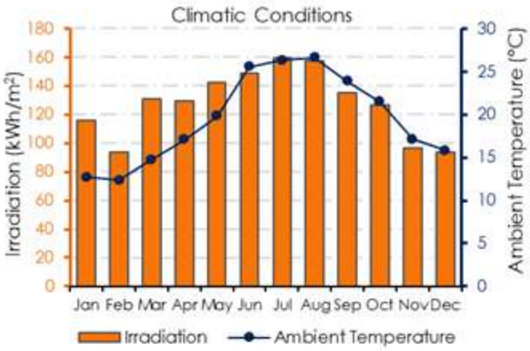

Figure 3. *Evolution of monthly inclined irradiation and ambient temperature available on the UDES site, Bou-Ismail from January to December 2023.*

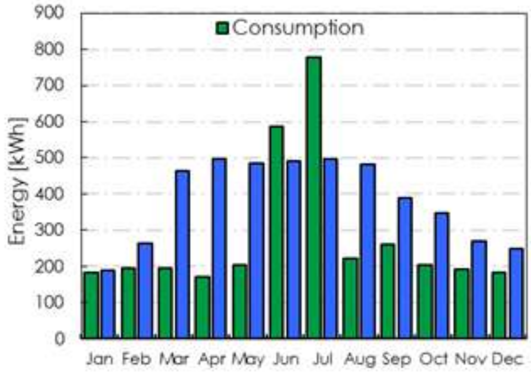

Figure 4. *Cumulative monthly energy consumption and PV generation.*

187.796 kWh in January. In 2023, the PV system generated a total of 4620.118 kWh, while the total energy consumed was 3376.676 kWh. These findings indicate that the SHD achieved a positive energy balance of 1243.442 kWh. According to the study presented by [18], a dwelling built in accordance with Algerian standards uses an average of 156.36 kWh/m²/year. The SHD under study consumed 37% less energy than a conventional house, thanks to superior thermal insulation and energy efficiency. The contribution of each energy source (PV, battery, and grid) to meeting the SHD's energy demand has been evaluated using data collected throughout 2023. As shown in Figure 5, PV generation, either directly or through storage, meets the majority of the energy demand, which ranges monthly between 39.24% and 30.88%. Furthermore, the power grid was heavily relied upon during the summer months when the air conditioning system operates continuously. In July 2023, for example, the grid supplied up to 53.45% of the SHD's energy needs. Figure 6 compares the contribution of each energy source to the SHD's energy consumption over one year of monitoring, revealing that the grid accounts for 28.1% of overall energy consumption, while PV contributes the remaining 71.9%.

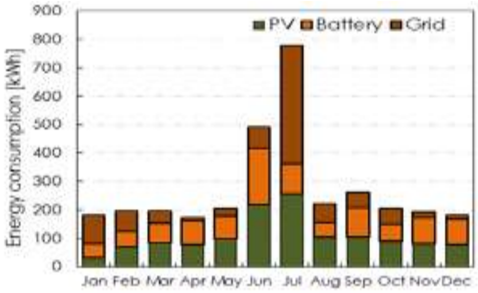

Figure 5. *Monthly energy contribution of each source.*

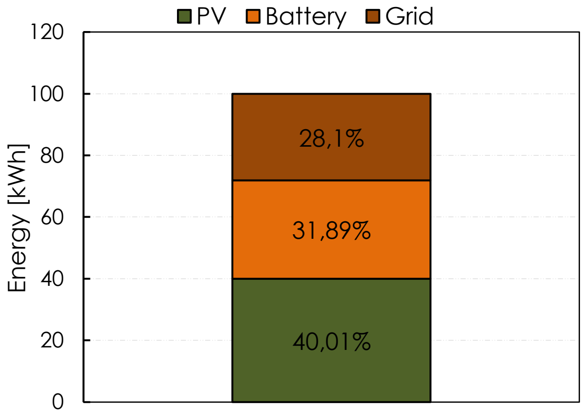

Figure 6. *Yearly energy contribution of each source.*

4.3 Grid – SHD Energy Exchange

The graphs in Figure 7 show the total monthly energy exchange between the grid and the SHD over the year. Positive values indicate energy withdrawn from the grid to meet the energy demand gap, while negative values represent the amount of excess PV energy exported to the grid. The quantitative analysis reveals that the SHD interacts with the grid year-round, with significant seasonal differences in the amount of energy exchanged.As shown in Figure 7, the cumulative PV energy surplus is high in the spring (March, April, and May) and autumn (September, October, and November). This is partly due to the favorable weather conditions in Bou-Ismail for PV production and the lower energy consumption during these periods, with no need for air conditioning or heating. Despite the presence of storage, the PV system generated 4620.118 kWh throughout the year, with a cumulative energy surplus of 27% of total PV production. This suggests that the battery bank's capacity was undersized, considering the typical daily PV output. The data analysis also shows that 416.56 kWh of energy was withdrawn from the utility grid in July, accounting for 43.66% of the total energy imported from the grid over the year. In other words, the air conditioning system is the primary energy consumer in the SHD.

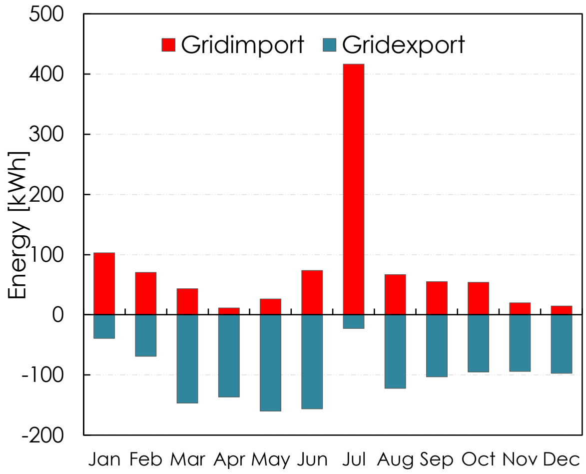

Figure 7: *Monthly Energy Exchanged with the Grid for SHD.*

4.4 Energy performance criteria

Figure 8 illustrates the evaluation of the SHD's compliance with nZEB status through three energy performance parameters: the Direct Consumed Ratio (DCR), the Capacity Factor (CF), and the Renewable Energy Ratio (RER). The DCR ranges from 32.11% in August to 85% in June. The lowest value observed in August corresponds to the vacation month. During this period, although the high solar radiation (160 kWh/m²/month) leads to high PV energy production (481.339 kWh/month), most of this energy (122.56 kWh/month) was fed into the grid due to low consumption. The average monthly DCR value is 50.76%, with a significant portion of the PV generation injected into the grid, as shown in Figure 7. This is due to a mismatch between the energy demand profile and the PV generation. A previous study (Kaci et al., 2023) revealed the real impact of scheduling the operating hours of deferrable loads (washing machine, dishwasher, and air conditioner) in a SHD on the DCR. It was found that adjusting the consumption profile to better match the PV generation improves the DCR by 1 to 11%, depending on the season. Regarding CF, it is important to note that it measures the home's degree of independence from the grid. The monthly CF values are shown in Figure 8, demonstrating that PV generation can cover between 43.53% and 93.36% of the SHD's monthly energy demand. The CF is impacted by both PV output and energy demand. During the spring (March, April, May) and autumn (September, October, November) seasons, the SHD's CF values are above 70%, which can be attributed to the good alignment between demand and production profiles. This suggests that the PV system is appropriately sized to effectively supply the SHD with energy during these periods, contributing to near-zero energy performance.

Furthermore, as shown in Figure 8, the RER of the SHD ranges from 64% to 288%. The RER exceeds 100% throughout the measurement period, except in June and July, where it reaches 64% and 84%, respectively. This variability is due to significant monthly fluctuations in energy demand. In general, increasing the size of the PV array can enhance the CF values, while increasing storage capacity can improve the DCR. However, when sizing PV power plants, it is advisable to aim for an RER of 100%, as CF and DCR would then be equal, making it easier to meet the nZEB objectives.

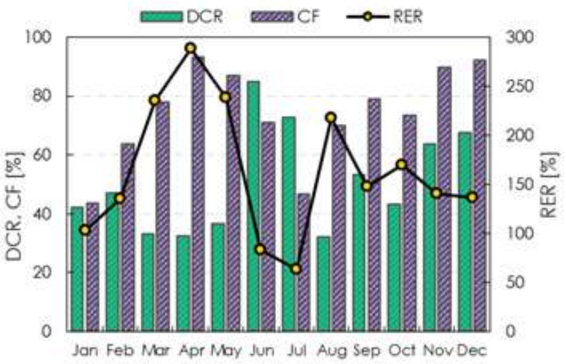

Figure 8*. Direct Consumed Ratio (DCR), Capacity Fraction (CF), and Renewable Energy Ratio (RER) of SHD.*

4. Conclusions

This study evaluates the energy performance of a SHD in northwest Algeria to determine whether it meets nZEB requirements. To achieve nZEB status, a variety of passive and active techniques were implemented in the SHD, including thermal insulation of the building envelope, strategic orientation of the house, an attic roof, the use of A, A+, and A++ class energy-saving appliances, a PV system, electrical energy storage, and a solar water heater. The findings revealed that the SHD's annual energy consumption (3376.67 kWh) and PV energy production (4620.11 kWh) exceeded nZEB requirements, operating as a positive energy house. Up to 71.9% of the energy consumed by the SHD was supplied by the PV system, while the remaining 28.10% was drawn from the grid. The average annual energy performance indicators for nZEB status were a Direct Consumed Ratio (DCR) of 50.76%, a Capacity Factor (CF) of 73.97%, and a Renewable Energy Ratio (RER) of 160.42%. To fully meet the nZEB requirements, certain improvements should be introduced to the SHD. On one hand, the operation of the air conditioning system, which is primarily energy-intensive, needs to be optimised through enhanced thermal insulation and the application of more efficient ventilation techniques [19]. On the other hand, the implementation of Demand-Side Management strategies will improve the direct consumption of PV energy, enabling the SHD to meet the nZEB standards [20].

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of 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
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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