POLITYKA ENERGETYCZNA – ENERGY POLICY JOURNAL

2025 ✦ Volume 28 ✦ Issue 4 ✦ 151–180

DOI: 10.33223/epj/209049

Mohammed Laour[1], Fethi Akel[2], Douadi Bendib[3], Souhil Mouassa[4]

Optimal operating strategy of a net-zero electricity solar photovoltaic building for a sustainable energy future: a case study in northern Algeria

Abstract: The vast solar potential of Algeria underscores the need for adopting strategies helping to integrate solar energy in residential buildings to meet growing energy consumption and alleviate the financial pressures caused by energy subsidies. This paper presents a study on the optimal operational strategy and economic analysis for residential buildings aiming to achieve net-zero electricity (NZE) through cost-effective solutions. The methodology involves the development of a high-performance simulation model for NZE solar homes. This model integrates several algorithms designed to optimize the sizing of the photovoltaic (PV) system and implement an efficient energy management strategy. The results show that an optimal PV peak power of 4.218 kWp and a battery capacity of 5.578 kWh lead to a net annual energy surplus of

✉ Corresponding Author: Mohammed Laour; e-mail: laour.mohammed@cu-tipaza.dz

[1] Electronic Department, Institute of Science, University Center of Tipaza, Tipaza, Algeria; ORCID iD: 0000-0003-2485-3596; e-mail: laour.mohammed@cu-tipaza.dz

[2] Solar Equipment Development Unit, UDES, Renewable Energy Development Center, CDER, Tipaza, Algeria; ORCID iD: 0000-0001-5408-7306; e-mail: akel.fethielt@gmail.com

[3] Electronic Department, Institute of Science, University Center of Tipaza, Tipaza, Algeria; ORCID iD: 0000-0002-4760-9126; e-mail: bendib.douadi@cu-tipaza.dz

[4] Electrical Engineering Department, Bouira University, Algeria; Electrical Engineering Department, University of Jaén, Linares, Spain; ORCID iD: 0000-0001-7812-8184; e-mail: souhil.mouassa@univ-bouira.dz

approximately 58 kWh and an electricity cost of 0.1204 USD/kWh, resulting from the investment in the NZE solar home. On average, the system supplies 0.433 kW to the grid during midday peak hours in summer while maintaining full electrical autonomy during evening peak hours. Therefore, the proposed optimal strategy maximizes the use of solar PV energy and minimizes reliance on grid electricity. It also ensures net-zero electricity by accounting for long-term interaction with the grid. Additionally, a detailed cost-benefit analysis reveals potential savings of 7,176.00 USD per household, representing a 68% reduction in government energy subsidies over a 25-year period. These findings offer a practical roadmap for the large-scale deployment of NZE homes in Algeria, helping to reduce both grid stress and the financial burden of energy subsidies, while also contributing to the reduction of CO_2 emissions.

Keywords: NZE solar buildings, PV system sizing, sustainable energy, optimal scheduling, efficient energy management

Introduction

Fossil energy sources, such as natural gas, constitute the main resource for electricity production in Algeria. However, the reserves of this resource are vulnerable to depletion; furthermore, electricity consumption in this country is increasing every year due to population growth, urbanization, economic development, and climate change (Hadjout et al. 2023). The residential sector represents a significant and growing share of total electricity consumption, posing new challenges in terms of renewable energy and demand management (Afaifia et al. 2021; Sedaoui et al. 2023; Bouraiou et al. 2020).

Fortunately, Algeria also has some of the highest solar potential in the world (Müller et al. 2024; Mohamed and Meriane 2024). However, the reluctance of residents to exploit photovoltaic (PV) renewable energy is a common issue, primarily due to the high investment costs and the relatively low price of electricity per kilowatt-hour offered by the electricity company compared to solar PV. The government currently supports electricity prices by covering a significant portion of production costs, thus keeping consumer prices relatively low. However, future changes in policy or economic conditions may affect these subsidies and, consequently, energy prices. In this context, the Algerian government is seeking solutions to reform energy subsidies by gradually reducing subsidies on energy product prices. Therefore, it is essential to adopt optimal strategies that encourage residents to benefit from solar PV energy and actively participate in the transition toward a sustainable energy future.

One of the effective solutions that can succeed in the long term and help encourage the inhabitants to exploit photovoltaic solar energy and facilitate their involvement in the energy transition system is the net-zero electricity solar homes (Ahmed et al. 2022; Godin et al. 2021; Wei and Skye 2020). A Net-Zero Electricity (NZE) solar home is a building designed to produce electricity equal to more than what it consumes over the course of a year, primarily through solar photovoltaic (PV) systems. While an NZE home may still draw electricity from the grid during low-sunlight periods, it offsets this by exporting excess energy back to the grid, ensuring a net-zero annual energy balance (Ismaeil and Sobaih 2023; Moghaddasi et al. 2021).

Furthermore, the key challenge in ensuring the success of NZE solar homes lies in implementing effective energy management strategies and optimizing system sizing. This includes balancing energy production and consumption, enhancing battery storage efficiency, maximizing the use of solar energy and adopting demand-side management techniques to ensure reliability and cost-effectiveness (Ochs et al. 2024; Niveditha and Singaravel 2022; Gong et al. 2020). Additionally, managing peak hours in the electrical grid presents several challenges and opportunities. Therefore, studies, strategies, and solutions are necessary to overcome these challenges and realize the full potential of solar homes integration with the electrical grid.

In the literature, a multitude of strategies, methods, and algorithms have been developed aimed at optimizing energy management in net-zero energy buildings and reducing investment cost (Shivanaganna et al. 2024; Alden et al. 2024; Baldoni et al. 2021; Arif et al. 2023; Aldahmashi and Ma 2024). Other approaches encompass a diverse array of strategies, ranging from load shifting and demand response to the integration of smart technologies, predictive control algorithms, and Artificial Intelligence Methods (Alden et al. 2021; Nabavi et al. 2021; Bao and Zhang 2024). However, these studies have focused on optimizing net-zero energy homes, which aim to achieve an overall energy balance, encompassing all forms of energy consumption, such as electricity, heating, cooling, and providing hot water. These buildings often require the design and installation of a large photovoltaic system or the incorporation of additional renewable energy sources such as wind turbines, solar thermal systems, green hydrogen, geothermal heat pumps, or thermal energy storage (Awad et al. 2024; Deymi-Dashtebayaz et al. 2022). Consequently, the overall cost of these systems is typically much higher than that of net-zero electricity homes.

For this reason, and to reduce the initial investment cost of NZE solar homes, this study focuses on net-zero electricity homes that aim to balance electricity consumption and production. To achieve this goal, the study adopts a strategy that optimizes the sizing of a solar PV system combined with battery storage (PV-BES), along with the implementation of an efficient energy management approach. The integration of optimized design strategies enhances the overall efficiency and operational effectiveness of PV-BES systems. For instance, an optimization strategy for sizing PV-BES systems has shown promising results in off-grid solar homes by targeting high efficiency, reducing energy consumption, and providing sustainable cooling solutions (Elnaggar et al. 2024). Another study demonstrated the techno-economic performance of PV-BES systems using optimization tools adapted to various consumer categories and operational scenarios (Benalcazar et al. 2025).

Another important factor that can contribute to reducing the initial investment cost is Algeria's status as one of the world's largest natural gas producers (Camporeale et al. 2021). The natural gas grid supplies over 65% of the population (Algérie Eco 2022), making natural gas the primary energy source for cooking, space heating, and water heating. Given this, we prioritize the direct use of natural gas for such applications during peak hours, as it achieves a high efficiency of approximately 90% or more (Brand and Rose 2012), significantly outperforming its efficiency when used for electricity generation. In contrast, the electricity production process incurs substantial energy conversion losses at various stages, resulting in a considerably lower overall efficiency. Even in advanced configurations such as combined-cycle for advanced gas turbines, the efficiency typically reaches only around 62% (Gulen and Zachary 2022).

Since the majority of Algeria's population resides in the northern region along the Mediterranean coast, residential energy consumption in these areas tends to be significantly higher, particularly during the summer months. Due to recurring summer heatwaves, the Algerian electricity company (Sonelgaz) reports record-high electricity consumption and new peak levels each year, highlighting the increased strain on Algeria's power grid during peak hours.

In this context, our study proposes an optimal strategy to facilitate the conversion of a large number of existing residential buildings in densely populated regions into net-zero electricity homes by integrating solar PV modules and battery storage (PV-BES). The proposed approach aligns with national efforts to support the transition toward a sustainable energy future. This strategy is based on a long-term vision for optimizing PV system sizing and the energy flow between PV systems, loads, batteries, and the grid. The strategy ensures long-term economic benefits by minimizing the overall costs of the PV system, eliminating homeowners' electricity bills, and reducing the government's long-term financial burden of subsidizing electricity bills. Additionally, it contributes to making the converted buildings more energy-efficient and enhances their participation in the long-term balance of the electricity network by maximizing self-consumption and reducing pressure on it during peak demand periods.

The study examines the long-term performance assessment of NZE solar buildings to ensure net metering over a 25-year period. It considers hourly, daily, and seasonal variations that affect the performance of photovoltaic system components. It also includes other key factors such as long-term interaction with the grid, the gradual degradation of photovoltaic modules and solar batteries.

To achieve these objectives, we developed a simulation model in the MATLAB/Simulink environment. This model provides a robust platform for the design, simulation, and optimization of energy systems. It facilitates the development of various control algorithms for intelligent power management, optimizes the sizing of photovoltaic systems, analyzes their performance, and provides a flexible environment for simulation and development.

1. Methodology

To achieve a sustainable energy future in northern Algeria, we propose an optimal operating strategy for the development of the NZE solar photovoltaic buildings. This strategy relies on optimizing the size of solar photovoltaic systems and implementing an efficient energy management system.

First, we developed an advanced model of the NZE solar home under MATLAB Simulink environment. This demonstrator model includes all essential components of the solar home, such as the solar PV generator, the battery storage system, the electrical network, the energy loads demand profile (home appliances), and a smart energy management system. The model takes into account all factors representing conversion losses in the overall system, such as solar irradiance, temperature, efficiency of the inverter and battery, cable losses, as well as the effect of other system losses representing performance losses in a real system.

We then appropriately sized the PV system to support net metering by estimating the daily load demand profile for each month of the year and incorporating seasonal meteorological data, including local solar radiation, ambient temperature, and wind speed. Additionally, we enhanced the electrical efficiency of the house by using energy-efficient appliances for heating, cooling, and lighting to minimize electricity consumption.

The initial calculation of the PV generator peak power using mathematical equations based on average annual energy consumption, average annual coefficient of performance, and average annual solar radiation does not directly provide an optimized value ensuring net metering over the year. To achieve this requirement, the resulting value of PV generator peak power was then optimized by running the simulation model of NZE solar home and an optimization algorithm, where the simulation model takes into account all monthly variations in consumption, temperature, and solar radiation, as well as the effects of shading and soiling.

In the final stage of our study, we presented and analyzed the results obtained, illustrating the operational performance and long-term net-metering assessment of the NZE solar home. Based on the results obtained by the optimized simulation regarding the peak power of the photovoltaic generator, the battery capacity, and the maximum power of the inverter, we assessed the long-term economic viability and financial benefits of the NZE solar home by calculating and analyzing the investment cost of the entire PV system and electricity bill prices. We highlighted how quickly the initial investment in solar technology recovered through energy cost savings.

2. Modeling and sizing of the NZE solar home

2.1. Modeling and sizing of the PV solar generator

The efficiency of solar PV modules depends on the real environmental conditions; these conditions include various factors such as temperature, sunlight intensity, shading, soiling, and atmospheric conditions (Nwokolo et al. 2023; Hasan et al. 2022; Sauer et al. 2014). In order to optimize the size of the photovoltaic system, the implementation of the real environmental conditions effect was carried out using the mathematical model in a custom MATLAB code. Several models have been published to present the effect of real environmental conditions (Singla et al. 2016; Sauer et al. 2014; Durisch et al. 2007). In our study, the efficiency model developed by W. Durisch is used; this mathematical model is based on the calculation of the efficiency of a PV module as a function of temperature (T), solar irradiance (G), and the air mass (AM).

The efficiency model (η_{PV_m}) used is expressed by the Equation (1) (Durisch et al. 2007):

$$\eta_{PV_m} = p\left[q\left(\frac{G}{G_0}\right)+\left(\frac{G}{G_0}\right)^m\right].\left[1+r\left(\frac{T_{PV_m}}{T_0}\right)\right]+s\left(\frac{AM}{AM_0}\right)+\left(\frac{AM}{AM_0}\right)^u \tag{1}$$

where:

T_0, G_0 and AM_0 – the three standard test conditions: $T_0 = 25°C$; $G_0 = 1000\ W/m^2$; $AM_0 =$ $= 1.5$,

T_{PV_m} – the PV module temperature [°C]; in this study, we take the average daily PV module temperature per month and the average daily solar radiation per month [W/m^2].

The empirical coefficients (p, q, m, r, s, and u) vary depending on the type of photovoltaic module and the materials used in its construction.

In this study, we chose Monocrystalline solar modules because they are more widely used than Polycrystalline due to their higher efficiency, better performance, and competitive pricing. According to (Durisch et al. 2007), the empirical coefficients for the efficiency model of a Monocrystalline solar module are:

$$p = 23.62;\ q = –0.2983;\ m = 0.1912;\ r = –0.09307;\ s = –0.9795;\ u = 0.9865;\ h = 0.028$$

The performance ratio of PV modules (PR_{PV_m}) which represents the coefficient for PV modules losses, is calculated using the following formula (Equation 2):

$$PR_{PV_m} = \frac{\eta_{PV_m}}{\eta_{PV_{mST}}} \tag{2}$$

where:

$\eta_{PV_{mSTC}}$ – the efficiency of *PV* module at standard conditions.

The ideal surface area for the *PV* generator A_{PV_G} in square meters [m^2] is calculated using the following formula (Equation 3):

$$A_{PV_G} = \frac{E_{consumption}}{E_{Radiation}\ .\ PR_{PV_{sys}}\ .\ \eta_{PV_{mST}}} \tag{3}$$

where:

$E_{consumption}$ – the average daily energy consumption per year [Wh/day/year],

$E_{Radiation}$ – the average daily energy of solar radiation per year [Wh/m^2/day/year].

The peak power of a photovoltaic generator (PP_{PV_G}) is determined using the following formula:

$$PP_{PV_G}\left(Wc\right) = A_{PV_G} \cdot \eta_{PV_{mSTC}} \cdot 1000 \tag{4}$$

Where, the following formula is used to calculate the Performance Ratio of full PV system " $PP_{PV_{sys}}$ ":

$$PR_{PV_{sys}} = PR_{PV_m} \cdot PR_{other\ losses} \cdot PR_{DC\text{-}AC} \tag{5}$$

$PR_{other\ losses}$ – includes seasonal performance losses in the real system that cannot be accurately predicted such as: (Soiling, Shading, Mismatch, Wiring, losses at weak radiation),

$PR_{DC\text{-}AC}$ – the performance of *DC-AC* conversion.

The Number of *PV* modules N_{PV_m} can be calculated using the following formula:

$$N_{PV_m} = \frac{PP_{PV_G}}{PP_{PV_{mST}}} \tag{6}$$

where:

$PP_{PV_{mSTC}}$ – the peak power of a photovoltaic module (Wc), at *STC* standards (G = 1000 W/m^2).

The Faiman model was used to assess the *PV* modules temperature at outdoor conditions (Barykina et al. 2017).

$$T_{PV_m} = T_a + \frac{G}{u_0 + u_1 \cdot Ws} \tag{7}$$

where:

T_{PV_m} – the *PV* module temperature [°C],

T_a – ambient air temperature [°C],

u_0 – the constant heat transfer component [W/m^{2}k],

u_1 – the convective heat transfer component [W/m^{3}sk] and Ws: is wind speed [m/s].

2.2. Estimation of the load profile (household energy consumption)

The adopted approach in our study for the load profile prioritizes the comfort of the household inhabitants without imposing restrictions on their level of energy consumption; this strategy focuses on optimized energy planning that enhances comfort while promoting energy efficiency and grid-friendly behavior. In this study, the load profile curve was predicted based on household activities and time-dependent demand profiles. Since most homes in northern Algeria consist of three to five rooms, we selected a four-room house as a representative model to reflect more accurately the average household electricity consumption. The average daily consumption curve for each month of the year was derived from a survey on household appliance usage among several residents.

To model energy consumption, each household appliance was simulated in MATLAB Simulink, with its usage linked to domestic activities. The energy consumption of each device was determined based on its energy efficiency class, the duration of its usage, and the number of household members engaging in energy-intensive activities. The power consumption of each appliance was defined in terms of apparent power, considering its respective power factor.

Finally, the household consumption curve was modulated through the implementation of a priority load strategy, as well as scheduling high-energy-consuming appliances based on solar energy production and electricity demand levels on the grid.

2.3. Optimization algorithm for determining the peak power of the PV generator

The proposed algorithm is based on iterative simulation runs to determine the optimal peak power of the PV generator required to achieve net-zero electricity exchange with the grid over the course of one year. The main flowchart of the optimization algorithm is presented in Figure 1.

2.4. Energy management system

In order to simulate the dynamic interactions of energy flow across multiple components of the PV system, such as the PV modules, battery storage, and grid connection, the energy management model was programmed using MATLAB, exploiting the capabilities of S-functions. These S-functions provide a flexible way to implement different energy management algorithms, enabling real-time control and the execution of complex management scenarios and strategies. Figure 2 illustrates the main cases implemented in the management of energy flow in the NZE solar home.

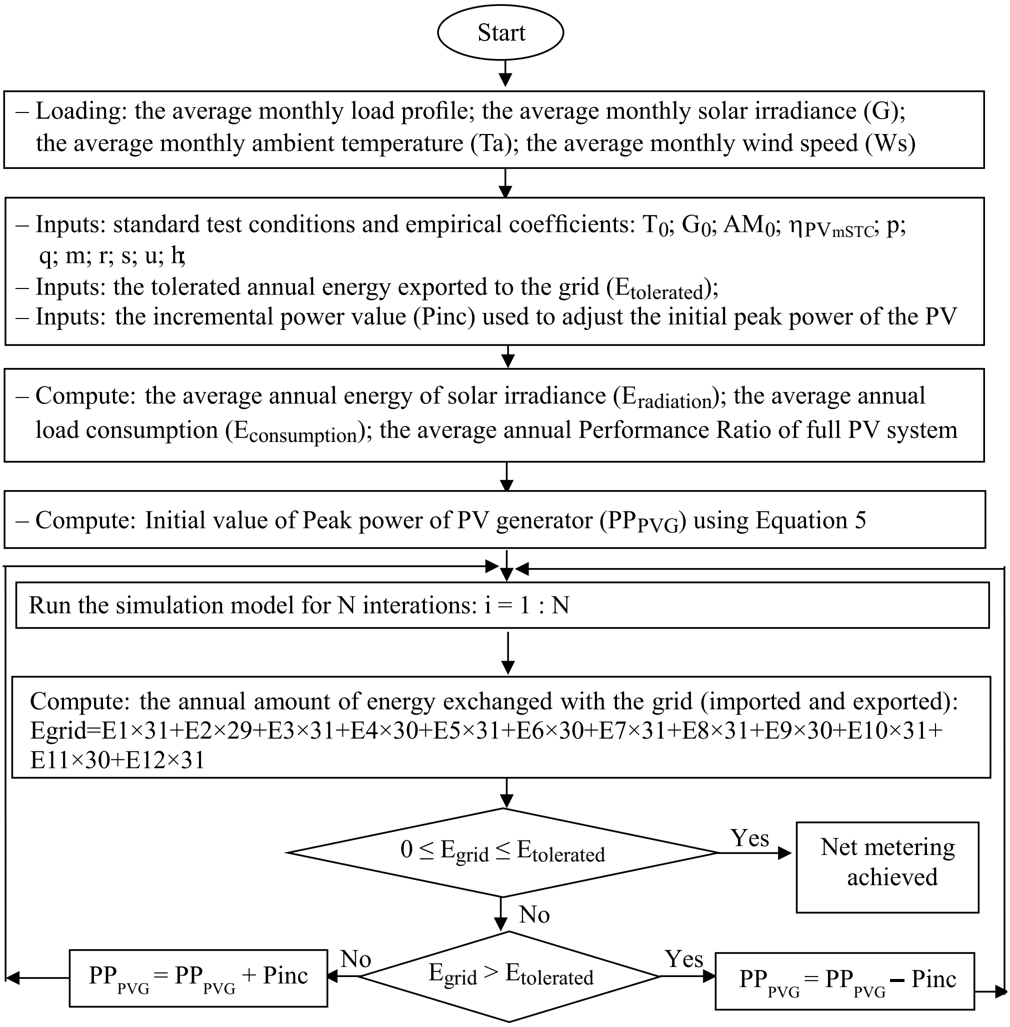


Fig. 1. Flowchart of optimization algorithm for determining the peak power of the PV generator

Rys. 1. Schemat blokowy algorytmu optymalizacji służącego do określania mocy szczytowej generatora fotowoltaicznego

The developed energy management system was adapted to optimize the consumption and storage of energy as well as the import/export to the grid. For instance, during periods of high solar output and low household demand, the algorithm prioritizes charging the battery and sending excess energy to the grid during midday peak demand. Conversely, during evening peak demand times, when solar generation is unavailable, the system ensures minimal or zero electricity import by maximizing the use of stored energy from the battery and drawing energy from the grid at night during off-peak demand periods.

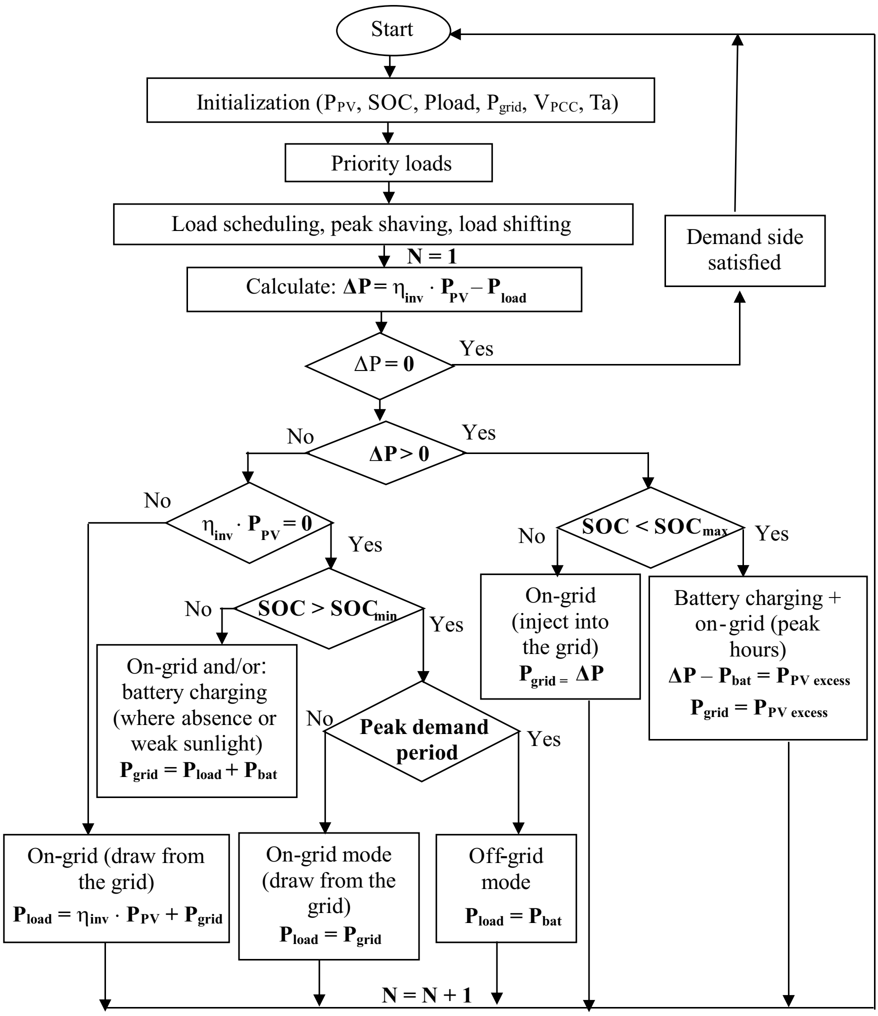


Fig. 2. Flowchart illustrating the main algorithm for managing energy flow between the photovoltaic (PV) source, battery storage, electrical load, and the grid

Rys. 2. Schemat blokowy ilustrujący główny algorytm zarządzania przepływem energii między źródłem fotowoltaicznym (PV), akumulatorem, obciążeniem elektrycznym i siecią energetyczną

Furthermore, the system was adapted to the potential implementation of dynamic electricity pricing in the future, which would change according to the typical daily load curve of the Algerian electricity grid. The management system for electricity exchanged with the grid was programmed based on the peak and off-peak demand periods that correspond to fluctuations in electricity pricing, where lower prices apply during off-peak hours and higher prices during peak hours.

Through this dynamic energy management strategy, the system can achieve a balance between energy efficiency, cost reduction, and grid stability, while also promoting the use of solar energy.

2.5. Presentation of the NZE solar home simulation model

To evaluate the performance of our optimal operating strategy and conduct an economic assessment of the NZE solar home, an NZE solar home model was developed. This model, created in the MATLAB Simulink environment, does not use physical power electronic converter models; instead, the inverter is represented by a model that shows its losses. The comprehensive model includes all essential components, such as a solar PV generator, battery, electrical network, load profile, and the management system. The S-Function was used to implement the algorithms for managing energy from PV production, the battery, load consumption, and interactions with the utility grid.

The model takes into account factors representing conversion losses in the overall system, such as solar irradiance, temperature, efficiency of the inverter and battery, cable losses, as well as the effect of other system losses representing performance losses in a real system (Ghosh et al. 2022; Fan et al. 2021).

Figure 3 presents the complete simulation model, which includes all essential components such as the solar PV generator, battery storage, electrical grid, load consumption (home appliances), and energy management system algorithms implemented using S-Functions (grid and battery management and load management).

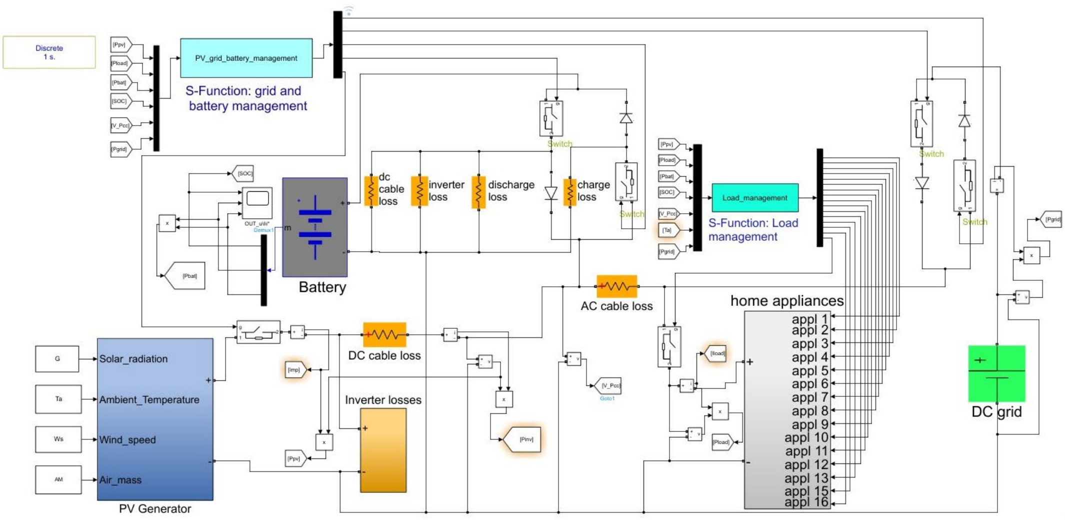


Fig. 3. Simulation model developed using MATLAB-Simulink for a NZE home powered by a PV generator

Rys. 3. Model symulacyjny opracowany przy użyciu MATLAB-Simulink dla domu NZE zasilanego generatorem fotowoltaicznym

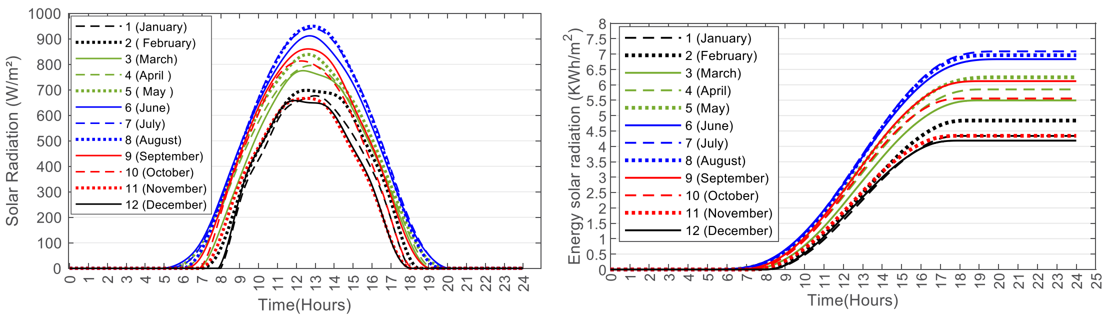
3. Results and discussion

3.1. Assessment of the efficiency of PV modules under real environmental conditions

To evaluate the proposed energy management strategies and verify the results, simulation tests were carried out using the developed model. The study uses the Tipaza region in northern Algeria as a case study.

To increase the accuracy of our simulation model, the average monthly solar radiation and ambient temperature data obtained from the online database PVGIS (PVGIS 2024) were resampled to a time step of $\Delta t = 1$ s. Wind speed data, representing the average daily variation per month, were obtained from the online platform "Global Wind Atlas" (GWA 2024).

The curves of the average monthly total daily solar radiation and energy are shown in Figures 4(a) and 4(b), respectively, where the time between (0–24 hours) presents the first month (January), between (24–48 hours) presents the second month (February), and so on.



(a) (b)

Fig. 4. (a) Daily variation of the average monthly solar radiation [W/m^2/day/month]; (b) Daily evolution of the average monthly solar radiant energy [kWh/m^2/day/month]

Rys. 4. (a) Dzienne wahania średniego miesięcznego promieniowania słonecznego [W/m^2/dzień/miesiąc]; (b) Dzienne zmiany średniej miesięcznej energii promieniowania słonecznego [kWh/m^2/dzień/miesiąc]

Figures 5(a) and 5(b) show, respectively, the daily variation of average monthly PV modules temperature evaluated using the Faiman model. As well as the daily variation of the average monthly Performance Ratio ($PR_{PV_{system}}$) evaluated using the W. Durisch model.

The results observed that the efficiency of the PV module decreases with increasing temperature, which leads to a significant reduction in the efficiency of the entire photovoltaic system. If we take the month of August as an example, as shown in the figure, we see that the efficiency of PV modules' decreased from 88% to 77% (a decrease of 11%) throughout the

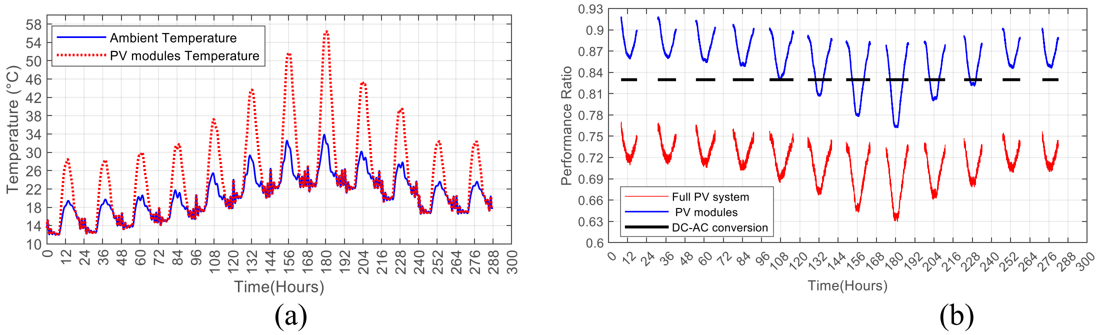


Fig. 5. (a) Daily variation of the average monthly ambient temperature and PV modules temperature (b) Daily variation of the average monthly Performance Ratio of the PV system

Rys. 5. (a) Dzienne wahania średniej miesięcznej temperatury otoczenia i temperatury modułów fotowoltaicznych (b) Dzienne wahania średniego miesięcznego współczynnika wydajności systemu fotowoltaicznego

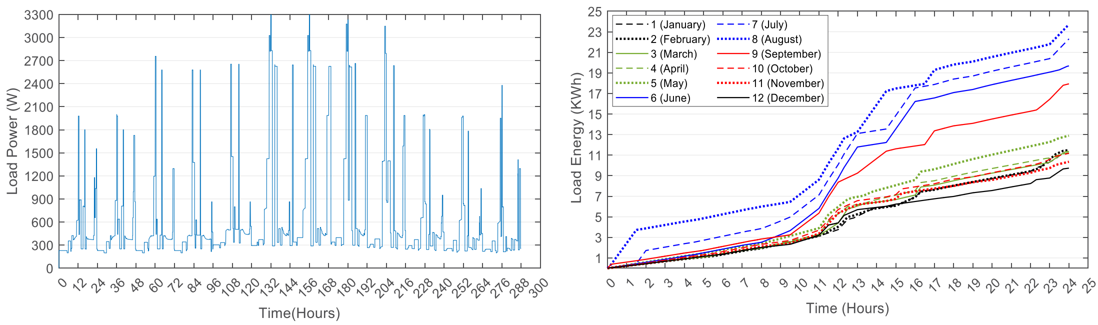
midday period (10:30 a.m.–2:00 p.m.). Consequently, the efficiency of the entire PV system decreased by up to 64% during this period, where this period corresponds to the sunniest time of the day, which greatly affects the performance of the photovoltaic installation and causes a reduction in the power generated by the PV generator.

Therefore, the hourly evaluation of PV modules performance throughout the day is crucial for the optimal sizing of the photovoltaic system, as it provides detailed insights into how the system responds to varying solar conditions. This approach ensures a cost-effective and energy-efficient PV system design by avoiding oversizing and undersizing, thereby achieving an optimal balance among PV generation, storage capacity, and grid exchange.

3.2. Presentation of the optimized load profile curve

Figure 6 shows the daily variation of the average monthly load profile (household consumption), evaluated using both priority-based and optimal scheduling strategies. These load profile curves offer valuable insights into the patterns and dynamics of daily household energy use. The time intervals are as follows: 0–24 hours represent the first month (January), 24–48 hours represent the second month (February), and so on.

The results demonstrate the effectiveness of the optimized scheduling approach, which reflects a demand-side management (DSM) strategy that integrates user comfort, solar energy availability, and grid interaction. The consumption load profile in Figure 6(a) is varied based on solar energy production and the electricity demand levels on the grid. Furthermore, this optimized planning enhances the self-consumption rate and reduces the need for additional energy storage or grid dependency, making the system more cost-effective and playing a key role in achieving net-zero electricity goals while maintaining user satisfaction and comfort level.



(a) (b)

Fig. 6. (a) Daily variation of the average monthly household electric power consumption curve (load demand); (b) Daily evolution of the average monthly household electrical energy consumption curve (load demand)

Rys. 6. (a) Dzienne wahania średniej miesięcznej krzywej zużycia energii elektrycznej przez gospodarstwa domowe (zapotrzebowanie na moc); (b) Dzienne zmiany średniej miesięcznej krzywej zużycia energii elektrycznej przez gospodarstwa domowe (zapotrzebowanie na moc)

The curves in Figure 6(b) illustrate how average monthly electricity consumption varies throughout the day, highlighting both seasonal and behavioral trends in energy demand. This seasonal variation shows our dynamic energy planning approach, which takes into account climatic factors, user behavior, and appliance usage patterns.

These curves show a significant increase in electricity consumption during the summer season, primarily due to high ambient temperatures and the intensive use of air conditioning systems to maintain indoor comfort. In contrast, electricity consumption tends to be lower in winter, as most residents rely on gas-based heating systems, such as gas heaters, which substitute electrical heating and thus reduce the overall electrical load. The spring and fall months feature mild and stable climates, thereby reducing the need for both cooling and heating. Consequently, electricity consumption is lower during these transitional seasons, where these periods offer ideal conditions for maximizing the self-consumption of photovoltaic production and achieving net metering, as energy demands are minimal while solar generation can still be considerable, especially in spring.

3.3. Electrical power balance simulation results

The net energy balance of the NZE solar home was determined by comparing energy consumption with solar PV production, where the interactions of the system with the grid allowed the evaluation of net metering. This energy balance highlights the importance of the methodology and energy management techniques used to optimize the use of the electricity produced and to adjust consumption levels according to the PV energy produced, the peak consumption hours, and off-peak hours. The simulation results clearly demonstrate the effectiveness of the proposed strategy and energy management algorithms.

Table 1 presents the parameters of the full PV system components found with optimal sizing.

Table 1. Parameters of the PV system components

Tabela 1. Parametry elementów systemu fotowoltaicznego

PV system parameters	Values
Peak power of PV generator [kWp]	3.750
Battery capacity [kWh]	5.578
Maximum apparent AC power of PV inverter [kVA]	4.0

Source: own elaboration.

Figures 7 and 8 present the output data for daily variations of the average monthly electrical power of the NZE solar home photovoltaic system, simulated by the developed model.

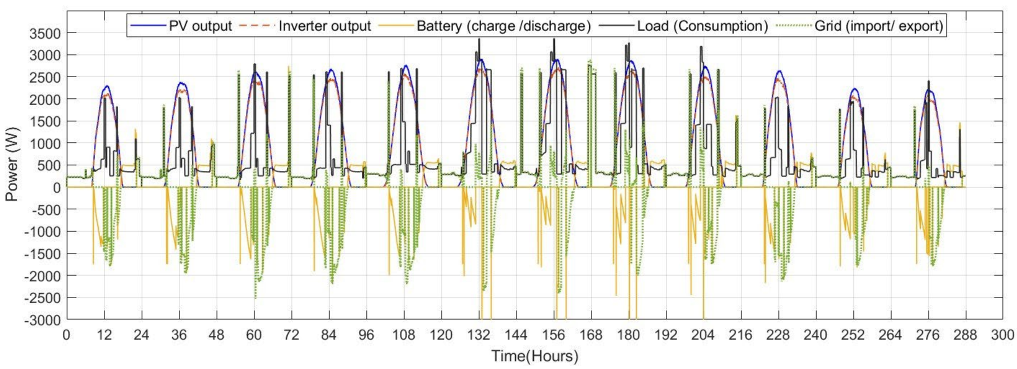
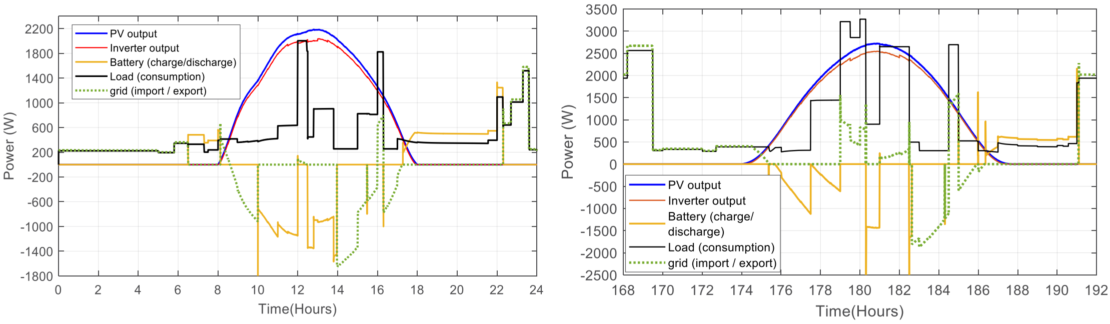


Fig.7. Average monthly power variation over the year for PV generator output, load demand, battery usage, and grid interaction. Positive values for the battery indicate discharging, while negative values indicate charging. For the grid, positive values represent imported power, and negative values represent exported power.

Rys. 7. Średnia miesięczna zmienność mocy w ciągu roku dla mocy wyjściowej generatora fotowoltaicznego, zapotrzebowania na obciążenie, zużycia baterii i interakcji z siecią. Dodatnie wartości dla baterii oznaczają rozładowanie, natomiast ujemne wartości oznaczają ładowanie. W przypadku sieci dodatnie wartości oznaczają importowaną moc, a ujemne wartości oznaczają eksportowaną moc.

As illustrated in Figures 7 and 8, which show the daily power variation of PV generator output, load demand, battery, and grid interaction, we observe a well-optimized energy management approach. High-energy-consuming appliances are scheduled to align with periods of high solar generation, ensuring maximum PV self-consumption and reducing dependence on the grid during peak hours.



(a) (b)

Fig. 8. Example of phases of daily operation: (a) during the month of January (winter), (b) during the month of August (summer)

Rys. 8. Przykładowe fazy codziennej eksploatacji: (a) w styczniu (zima), (b) w sierpniu (lato)

Our strategy also prioritizes battery charging during the initial hours of solar radiation by utilizing surplus PV energy. This approach ensures maximum battery storage before critical consumption periods. Once the battery is fully charged, any excess solar energy is exported to the grid during midday peak demand, helping to reduce stress on the grid.

In the evening, when solar production stops and grid demand typically increases, the system operates autonomously. The battery discharges to meet the household's energy needs, minimizing or eliminating the need to import electricity from the grid.

Table 2 demonstrates the effectiveness of our strategy for making the NZE solar home more efficient, where it shows the instantaneous powers supplied by the NZE solar home during peak hours for summer and winter seasons. These findings were extracted from the curves in Figure 7.

Table 2. Average daily electric power supplied by NZE home during peak hours

Tabela 2. Średnia dzienna moc elektryczna dostarczana przez dom NZE w godzinach szczytu

Monthly average daily electric power [kW]	August [kW]	January [kW]
Supplied by PV inverter (PV generator) during midday peak hours (12:30 p.m.–4:30 p.m.)	2.371	1.840
Injected in the grid during midday peak hours (12:30 p.m.–4:30 p.m.)	0.433	0.641
Supplied by battery during evening peak hours (5:30 p.m.–10:30 p.m. in winter and 07:00 p.m–11:30 p.m. in summer)	0.422	0.411
Supplied by battery during morning peak hours (6:30 a.m–08:00 a.m.)		0.319
Supplied by PV inverter (PV generator) during morning peak hours (6:00 a.m–10:00 a.m.)	0.851	0.707

Source: own elaboration.

The analysis of the power supplied by the PV inverter and battery during peak hours in different seasons shows the seasonal performance of the proposed efficient strategy for operating the NZE solar home. In August, the PV inverter supplies significantly more power during midday peak hours (2.371 kW) compared to January (1.840 kW), reflecting the higher solar irradiance and longer daylight hours in summer. Additionally, during the same period in August, surplus energy (0.433 kW) is injected into the grid, highlighting the home's ability to produce more energy than required.

3.4. Net-Metering evaluation

To validate the performance of the proposed NZE solar home and confirm that it meets net-zero electricity criteria, a detailed annual net-metering analysis was conducted. This evaluation aims to demonstrate that, over the course of one year; the total electrical energy generated by the PV system is equal to or exceeds the total energy consumed by the household, based on the adopted operational strategy.

The figure above (Fig. 9) illustrates the daily evolution of average annual electrical energy across the key components of the system, including solar production, household consumption, battery storage activity, and grid interaction (export/import).

Based on the simulation results, in this figure, the daily evolution of average annual energy distribution across different components of the NZE solar home is as follows: the photovoltaic generator produces 17.27 kWh, while the household's energy consumption is 14.42 kWh. After

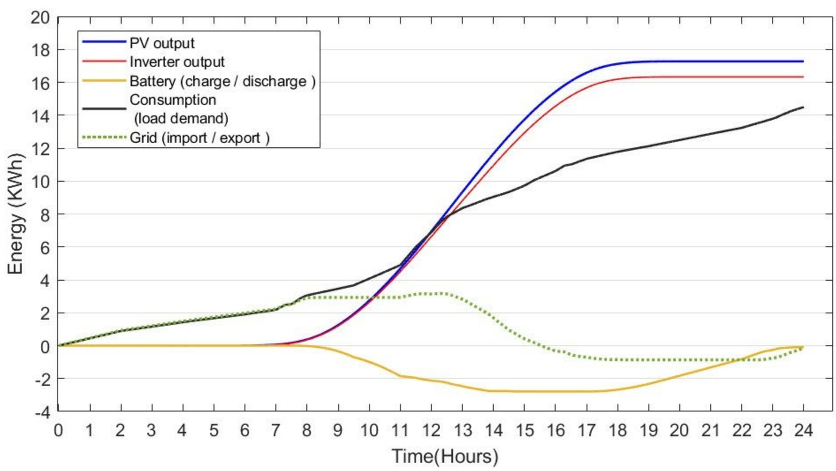


Fig. 9. Daily evolution of the average annual electric energy in different component of the PV system

Rys. 9. Dzienne zmiany średniego rocznego zużycia energii elektrycznej w różnych elementach systemu fotowoltaicznego accounting for inverter efficiency, the PV system delivers 16.32 kWh. Where, the net metering of grid interaction shows that 0.159 kWh of excess energy is injected into the grid daily, resulting in a total annual surplus (net-metering) of 58.56 kWh. These results confirm that the home operates as a net-zero electricity consumer on an annual basis and maintains a positive energy balance throughout the year.

The evolution curves of the average daily energy per month that is exchanged with the grid are presented in the following figure (Fig. 10).

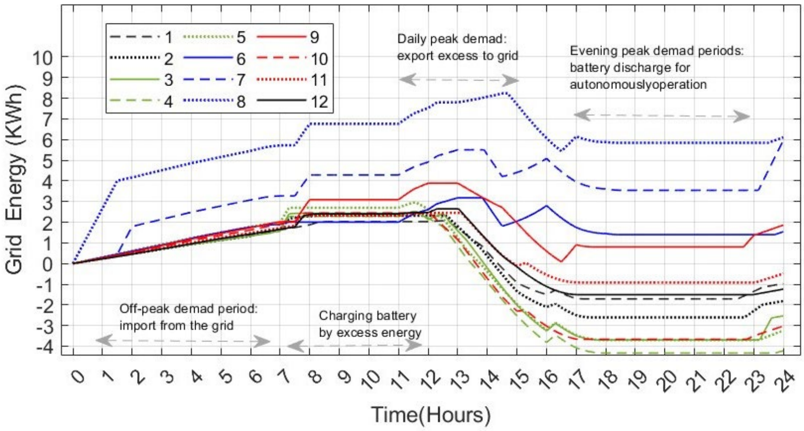


Fig. 10. Daily variation of the average monthly electrical energy exchanged with the grid (import/export). The negative value indicates power injected into the grid (export), corresponding to a positive balance; conversely, a positive value indicates power drawn from the grid (import), corresponding to a negative balance.

Rys. 10. Dzienne wahania średniej miesięcznej energii elektrycznej wymienianej z siecią (import/eksport). Wartość ujemna oznacza energię wprowadzoną do sieci (eksport), co odpowiada dodatniemu saldu; natomiast wartość dodatnia oznacza energię pobraną z sieci (import), co odpowiada ujemnemu saldu.

The direction of energy variation in these curves (Figs 10 and 11) determines the status of the grid's electricity flow and the operation mode of the NZE solar home. The upward and downward curve indicates the operation is on-grid, where the upward curve indicates that the grid is supplying electricity to the home appliances, while the downward curve signifies that the solar home is injecting surplus electricity into the grid. If the curve remains constant, it indicates that the house is in autonomous mode operation.

The seasonal energy balance study is based on PV output and load demand for each season. Figure 10 shows that the balance is positive in winter, spring, and autumn but negative in summer. Consequently, our grid-tied net-zero solar home exports excess power to the grid during midday in all seasons, then imports electricity during off-peak hours under net metering policies, while maintaining a positive balance during midday peak hours.

As shown in Figure 10, the daily net-metered energy is 0.159 kWh/day, which corresponds to an annual net-metering value of approximately 58.04 kWh/year.

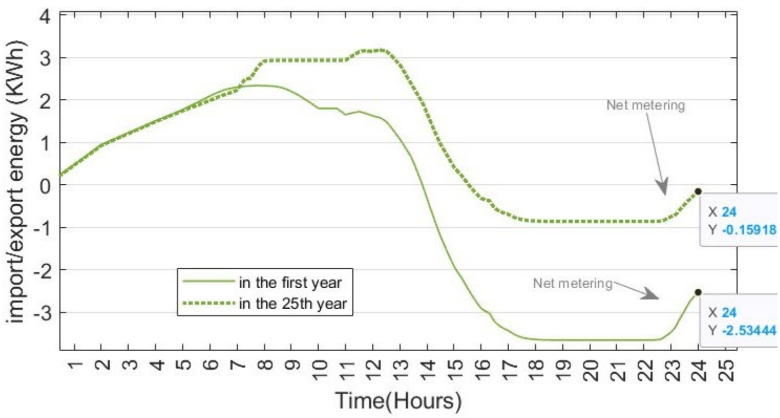


Fig. 11. Daily variation of the average annual electrical energy exchanged with the grid (import/export)

Rys. 11. Dzienne wahania średniej rocznej energii elektrycznej wymienianej z siecią (import/eksport)

Knowing that, the optimized peak power of the PV generator (3.75 kWp) is sufficient to meet the net-zero electricity target during one year of operation. However, to consider net-zero metering over 25 years, it is essential to consider the gradual degradation of PV modules, which directly affects long-term energy production.

Depending on the panel technology, the region, and environmental conditions, the high-quality monocrystalline silicon (mc-Si) PV modules have an average degradation rate of –0.5% per year (Deline et al. 2024; Theristis et al. 2023). Where, over this period, the PV output may decline by –12.5%. This reduction is included in the estimation of the total investment cost of the PV system to ensure continued net-zero electricity performance over the long term. Consequently, an additional power of 468.75 W was added to the initially calculated peak power of the generator (3.75 kWp), which corresponds to 12.5% of 3.75 kW. The actual peak power of the PV generator should therefore be 4.218 kWp. As shown in Figure 11, in the first year, with this peak power, the excess energy injected into the grid is estimated at 2.53 kWh/day (923.45 kWh/year). This energy output gradually decreases each year due to the natural degradation of the PV modules, reaching approximately 0.159 kWh/day (58.04 kWh/year) after 25 years of operation, when the effective peak power of the PV generator is reduced to 3.75 kWp.

3.5. Evaluation of the performance of the battery energy management system

For energy storage, a lithium battery was used, as it is more suitable for NZE homes, offering a longer lifespan, higher efficiency, and greater depth of discharge, despite its higher initial cost.

The solar PV battery management involves controlling the charging (SOC) and discharging (DOD) of the battery to extend its lifespan and efficiency. This is achieved using a battery management system that optimizes charging and discharging processes based on solar conditions, energy load demand, and grid interaction.

The evolution curves of the average daily energy per month for the battery and the State Of Charge (SOC) have been presented in the following figures (Figs 12 (a) and (b)).

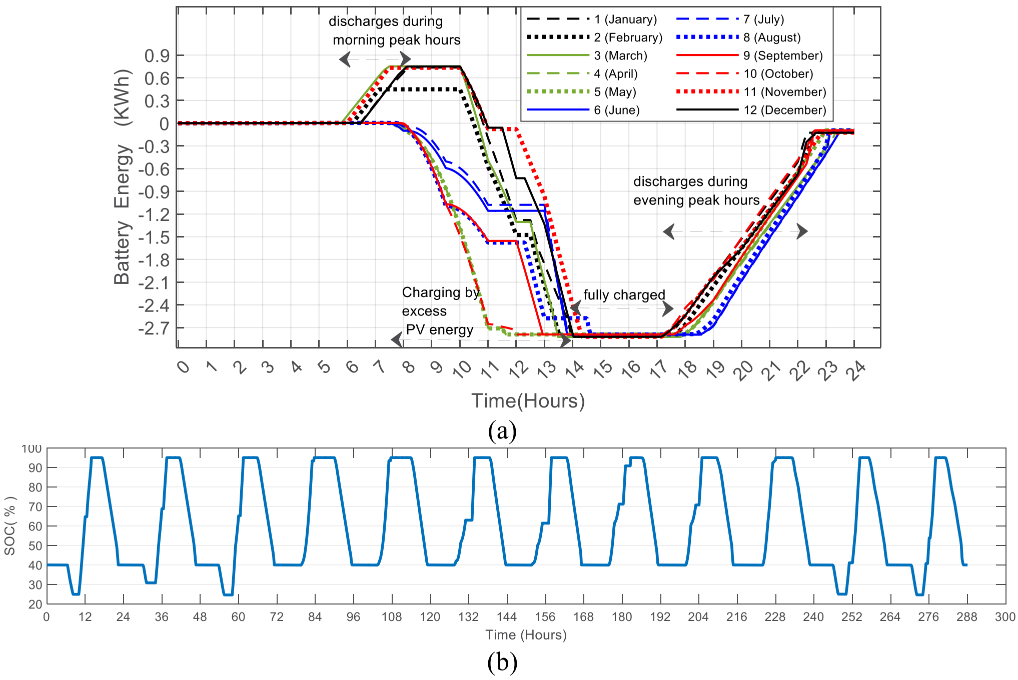


Fig. 12. (a) Daily variation of the average monthly energy of battery, (b) Monthly variation of the State of Charge (SOC) of the Battery

Rys. 12. (a) Dzienne wahania średniej miesięcznej energii akumulatora, (b) Miesięczne wahania stanu naładowania (SOC) akumulatora

The results show that, during all seasons, the battery charges based on relative variations in PV production and load demand (consumption). When the battery is fully charged (SOC = 95%), excess energy is returned to the grid during midday peak hours, then it discharges during evening peak hours, and the system switches from on-grid to off-grid state, when the battery is discharged to a state of charge = 40% and the peak hour period is over, the system returns to the connected state. During the winter season, the battery discharges (to minimum state of charge = 25%) during morning peak hours until sunrise, and the system switches from on-grid to off-grid state, then the battery disconnects, the load is powered by the PV generator, and the system returns to the on-grid state. However, in the event of absence or weak sunlight, it is possible to recharge the solar battery from the grid during periods of lower electricity demand (off-peak hours). This stored energy is then used during peak hours to power the home's electrical needs.

3.6. Investment cost estimation and long-term economic evaluation

Given the current absence of regulations allowing Algerian households to feed excess photovoltaic electricity into the grid, assessing cost savings requires a different approach than in countries with net metering or feed-in tariff systems. Therefore, the current economic benefit of adopting NZE solar homes comes solely from offsetting their own long-term electricity bills, assuming the same price per kWh for both imported electricity from the grid and exported solar PV electricity to it.

As we know, the cost of a kilowatt (kW) for a solar photovoltaic (PV) system integrated with an energy storage system in a building varies depending on the technologies used for each key component. High-quality PV system components have been selected for the NZE Solar Home to ensure optimal performance, durability, and long-term efficiency.

The prices shown in Table 3 are sourced from specialized online supplier websites that offer a wide range of products using different technologies, as well as services related to photovoltaic solar energy systems (Alma Solar 2024; Solar Electric Supply 2024). This includes solar

Table 3. Estimated average investment cost of the entire PV system over 25 years

Tabela 3. Szacunkowy średni koszt inwestycji w cały system fotowoltaiczny w ciągu 25 lat

PV system components	Cost [USD]	Cost [USD/kW]
PV Generator: 4.218 kWp (a set of 10 SUNPOWER P7 monocrystalline solar modules, each rated at 428 W); warranty 25 years	1,969.50	466.92
Battery Energy Storage System (Brand SOLAX POWER Lithium battery: 5.8 kWh; lifetime: up to 8,000 cycles, and up to: 25 years); warranty 10 years	2,594.96	447.4
Residential Hybrid Single-Phase PV Inverter (SMA inverter Sunny Boy SMART ENERGY 4.0KW, AC; output); warranty 10 years	2,104.52	526.13
Mounting structure installation	500.00	0.1185
Balance of System (BOS) Components: wiring, junction boxes, combiner boxes, fuses, breakers, and other electrical components	700.00	0.1660
Labor costs	750.00	0.1778
Total investment cost without VAT	13,318.00	2,845.90
Total investment cost with VAT (19%)	15,848.00	3,386.70
Initial investment cost without VAT	8,619.00	1,860.40
Initial investment cost with VAT (19%)	10,257.00	2,213.90

Source: Alma Solar 2024; Solar Electric Supply 2024.

panels, inverters, batteries, mounting hardware, and other components needed to produce solar photovoltaic energy in the residential sector.

Table 3 presents the estimation of the overage investment cost of the entire PV system over 25 years.

Since both the hybrid PV inverter and the lithium solar battery have a 10-year warranty, their costs were factored twice into the total investment cost to reflect the probability of needing to replace them over the system's 25-year lifetime.

To analyze and discuss this investment cost figure, it is necessary to compare it with the electricity bills that the owner of this home would have to pay over 25 years. This involves adopting the current government subsidized price as well as the real price without government subsidy.

In Algeria, the average electricity price with government subsidies is 0.04 USD/kWh for residential users (Global Petrol Prices 2025). However, the actual cost of a kilowatt-hour (kWh) of electricity without government subsidies exceeds 16 DZD/kWh, or approximately 0.12 USD/kWh (Algeria Press Service 2021). Therefore, the government provides a subsidy of approximately 0.08/kWh.

The following formula is used to calculate the electricity bill prices estimated over 25 years.

$$Electricity\ bills\ prices = E_{consumption} \cdot 365 \cdot 25 \cdot Electricity\ price \tag{8}$$

where:

$E_{consumption}$ – the household's average daily energy consumption (demand).

From Figure 8, we find that, $E_{consumption}$ = 14.4252 kWh/day.

The annual energy consumption (demand) is then equal to:

14.4252 · 365 = 5,265 kWh/year.

The average cost per kilowatt-hour (kWh) of electricity generated by the PV-BES system, resulting from an investment in a NZE solar home over 25 years, is calculated as follows:

$$\text{Cost}_{KWh\ from\ PV} = \frac{\text{NZE Solar home estimated cost}}{E_{consumption} \cdot 365 \cdot 25} \tag{9}$$

Therefor:

- the electricity bill prices estimated over 25 years, with government subsidies with VAT included, are: subsidized electricity bills prices = 5,265 ·25 · 0.04 = 5,265 USD;
- the electricity bill prices estimated over 25 years without government subsidies, are: unsubsidized electricity bills prices = 5,265 · 25 · 0.12 = 15,795 USD;
- the subsidy provided by the government is then equal to 10,530.00 USD;
- the PV electricity cost from the total investment cost with VAT is equal to 0.1204 USD/kWh.

Based on these data findings in Table 3, the estimation of net initial investment costs can provide greater insight into our strategy to identify the most effective solution for promoting the adoption of NZE solar homes. Therefore, we calculate the net investment cost over 25 years using the following formula:

$$Net\ investment\ cost = investment\ cost - subsidized\ electricity\ bills\ prices \quad (10)$$

We then find:

- the initial net investment cost of the NZE solar home, including VAT, is equal to: 10,257.00 – 5,265.00 = 4,992.00 USD;
- the initial net investment cost of the NZE solar home without VAT, is equal to: 8,619.00 – 5,265.00 = 3,354.00 USD.

Table 4 provides a comparison of the calculated electricity bill prices with the net investment cost for a net-zero energy (NZE) solar home over a 25-year period.

Table 4. Estimated of the initial net investment cost

Table 4. Szacunkowy początkowy koszt netto inwestycji

Initial net investment cost	Cost [$]
Electricity bill prices at government-subsidized rates, with VAT included	5,265.00
Electricity bills at real price without government subsidies	15,795.00
The subsidy provided by the government	10,530.00
Initial net investment cost of the NZE solar home, including VAT	4,992.00
Initial net investment cost of the NZE solar home without VAT	3,354.00

Source: own elaboration.

From the results in Table 4, it is evident that the adoption of NZE solar homes, particularly with a reduced net initial investment cost of 3,354.00 USD (excluding VAT), presents a highly cost-effective alternative for the government. This amount represents only about a third of the 10,530.00 USD in government subsidies typically allocated for grid electricity over a 25-year period.

Therefore, we consider this finding one of the most sensible and practical solutions for the government, by covering this initial investment, an expense that is significantly less than the long-term financial burden of subsidizing electricity bills. The adoption of a single NZE solar home is estimated to result in savings of 7,176.00 USD over 25 years, representing a 68% reduction in government subsidies.

3.7. Comparison of the present study with previous research on integrating PV-BES systems

Table 5 presents a comparative analysis of the present study with similar studies that integrated PV-BES systems and were conducted in Mediterranean regions, including Izmir in Türkiye and Morocco from the North African region (Forrousso et al. 2024; Eksi et al. 2025). This analysis provides valuable insights into effective design strategies, energy management practices, investment costs, and supportive policy frameworks for achieving energy neutrality.

Table 5. Comparison of the present study with similar studies integrating PV-BES systems and conducted in the Mediterranean and North African region

Tabela 5. Porównanie niniejszego badania z podobnymi badaniami dotyczącymi systemów PV-BES przeprowadzonymi w regionie Morza Śródziemnego i Afryki Północnej

Authors	Main objectives, methods, findings, and policy context
The present study by the authors	✦ Achieving net zero electricity residential building using PV-BES-grid (PV/Battery system ensured 100% of annual electricity demand). ✦ Conducting a techno-economic analysis to get cost-effective NZE solutions. ✦ Optimizing the sizing of solar photovoltaic systems. ✦ Implementing an efficient energy management strategy by considering long-term interaction with the grid. ✦ The use of natural gas for cooking, space heating, and water heating during peak demand periods. ✦ An estimated 68% reduction in government electricity subsidies over 25 years. ✦ The investment cost of 15,848.00 (with VAT included) leads to an electricity cost of approximately 0.1204 USD/kWh over 25 years. ✦ Reducing strain on the national power grid by supplying, on average, 0.433 kV to the grid during midday peak hours in summer. ✦ Encourages the transition to renewable energy consumption in residential buildings. ✦ Supports Algeria's strategy for low-carbon and reform energy subsidies.
Forrousso et al. 2024	✦ Achieving net zero energy residential building using a hybrid system BIPV with PV-BES system by determining the optimal sizing of PV, BIPV, and battery systems. ✦ Minimize Total Annualized Cost (TAC). ✦ Optimizing system sizing using the Particle Swarm Optimization algorithm. ✦ Employing a hybrid system that combines PV, BIPV, and battery storage. ✦ The levelized cost of energy ranges from 0.366 USD/kWh (Ouarzazate) to 0.664 USD/kWh (Ifrane). ✦ Lowest cost (TAC: 600.152 kUSD, LCOE: 0.425 USD/kWh) was achieved in Rabat (moderate climate). ✦ BIPV increases the load cover factor by 0.68–2.58%. ✦ Integration of BIPV reduces Levelized Cost of Energy (LCOE) by 8.7–20.72%. ✦ Supports Morocco's strategy for low-carbon and energy-autonomous housing. ✦ Reducing pressure on centralized grids.
Eksi et al. 2025	✦ Study of the techno-economic and environmental feasibility for achieving net zero energy residential building using PV-BES-grid. ✦ Improved insulation and building envelope using passive efficiency. ✦ Replacing natural gas with active heating systems. ✦ Modelling energy efficiency scenarios using Design Builder (DB) software and system optimization with HOMER Grid software. ✦ Reference consumption: 177.55 kWh/m²/year, ✦ Scenario 2: 72% reduction in primary energy and 99.1% reduction in CO_2. ✦ Support Türkiye's 2053 net-zero emissions goal and reduce household energy consumption and CO_2 emissions. ✦ Reducing reliance on imported natural gas for electricity production.

3.8. Limitations of the study

Although the proposed strategy offers a promising solution to increase the adoption of renewable solar energy buildings in northern Algeria, its success depends on overcoming several key constraints that may limit its long-term effectiveness.

NZE solar buildings in this country could face challenges. One of the most significant constraints is the reliance on idealized assumptions about household behavior, such as stable energy consumption patterns and active involvement in effective energy management practices. These assumptions may be difficult to guarantee in practice without strong community awareness campaigns and effective incentive programs. Another constraint is the initial investment, which corresponds to the cumulative electricity costs over a 25-year period, and may be financially inaccessible to low-income households unless installment payment schemes are available.

In addition, the current electrical grid infrastructure may not be sufficiently prepared to handle the growing share of locally generated solar energy. This calls for technical upgrades and substantial investment in smart grid technologies to ensure system stability and efficient energy integration.

Another major challenge is the long-term maintenance and replacement of key system components, such as solar batteries, PV inverters, and the regular cleaning of solar panels. Without proper maintenance, the efficiency of the PV system can significantly reduce, and the risk of premature component failure and unexpected replacement costs substantially increases.

Conclusions

This study highlighted the feasibility and importance of both policy measures and technological investments for the development of future NZE solar buildings in northern Algeria, aiming to accelerate progress toward energy sustainability. The research conducted in this study relied on a methodology combining optimal sizing of solar energy systems with advanced energy management strategies to achieve long-term net-zero energy performance while reducing net initial investment costs.

The results of this research provide a practical solution to support the development of net-zero electricity solar homes and to facilitate the conversion of a large number of existing buildings in northern Algeria into net-zero electricity through the integration of PV-BES systems. To clarify this vision, the adoption of the proposed optimal operating strategy with conversion of 422,000 existing homes to net-zero electricity could generate, during maximum peak demand times at midday in summer (example: August), an amount of net electrical energy equivalent to that produced by conventional power plants using fossil fuels and with a capacity of 1 GW. This avoids the use of carbon-intensive fossil fuel generators to prevent disturbances and involuntary disconnections during these peak hours.

Therefore, increasing the number of NZE solar homes across northern Algeria by adopting the proposed strategy helps reduce strain on the national power grid during peak demand periods, decreases reliance on traditional energy sources, and reduces electricity losses that occur during transmission and distribution. Additionally, it significantly reduces the financial burden of electricity subsidies on the Treasury. Each NZE solar home would save approximately 7,176 USD over 25 years in avoided subsidies. If 422,000 existing homes were converted, the total expected savings would be approximately 3.028 billion USD over 25 years.

These findings help the government develop a long-term strategy to gradually phase out grid electricity subsidies and reduce the fiscal burden associated with them. Subsidizing the initial net investment costs of NZE solar homes will create a just energy transition pathway that aligns with long-term sustainability goals. The strategy would also encourage more homeowners to adopt solar energy in their residential buildings. Where our study has illustrated to residents the importance of accepting this approach in the long term by reducing or eliminating their electricity bills. Moreover, the study demonstrated the importance of ensuring a continuous supply of electricity to their homes throughout all times of the day and year, thus avoiding the frequent power outages that occur during periods of peak consumption and severe weather disturbances.

In future work, the integration of advanced energy pricing models, such as time-of-use or dynamic tariffs, can allow for a more accurate assessment of the economic viability and payback period of NZE solar homes. Additionally, a hybrid renewable energy strategy, combining solar PV, wind power, and hydrogen storage (PV + wind + hydrogen storage), can complement PV-BES systems to enhance the reliability of Net Zero Energy buildings. This approach would thus contribute to the complete elimination of natural gas use in household activities, the extension of autonomous operating time, and the reduction or even elimination of dependence on the electricity grid.

The Authors have no conflicts of interest to declare.

References

Afaifia et al. 2021 – Afaifia, M., Djiar, K.A., Bich-Ngoc, N. and Teller, J. 2021. An energy consumption model for the Algerian residential building's stock, based on a triangular approach: Geographic Information System (GIS), regression analysis and hierarchical cluster analysis. *Sustainable Cities and Society* 74, DOI: 10.1016/j.scs.2021.103191.

Ahmed et al. 2022 – Ahmed, A., Ge, T., Peng, J., Yan, W.C., Tee, B.T. and You, S. 2022. Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy and Buildings* 256, 111755, DOI: 10.1016/j.enbuild.2021.111755.

Aldahmashi, J. and Ma, X. 2024. Real-time energy management in smart homes through deep reinforcement learning. *IEEE Access* 12, pp. 43155–43172, DOI: 10.1109/ACCESS.2024.3375771.

Alden et al. 2021 – Alden, R.E., Gong, H., Jones, E.S., Ababei, C. and Ionel, D.M. 2021. Artificial intelligence method for the forecast and separation of total and HVAC loads with application to energy management of smart and NZE homes. *IEEE Access* 9, pp. 160497–160509, DOI: 10.1109/ACCESS.2021.3129172.

Alden et al. 2024 – Alden, R.E., Jones, E.S., Poore, S.B. and Ionel, D.M. 2024. Smart home HVAC digital twin ML meta-model for electric power distribution systems with solar PV and CTA-2045 controls. *IEEE Transactions on Industry Applications*, DOI: 10.1109/TIA.2024.3458941.

ALGERIA PRESS SERVICE 2021. Electricité: Le tarif moyen appliqué au citoyen inférieur au coût réel. [Online:] https://www.aps.dz/economie/117852-electricite-le-tarif-moyen-applique-au-citoyen-inferieur-au-cout-reel [Accessed: 2025-03-02].

Algérie Eco 2022. Plus de 65% des foyers algériens sont raccordés au gaz naturel. [Online:] https://www.algerie-eco.com/2022/02/22/tebboune-plus-de-65-des-foyers-algeriens-sont-raccordes-au-gaz-naturel [Accessed: 2025-02-18].

Alma Solar 2024. Online shop for solar panels, batteries, and inverters. [Online:] https://www.alma-solarshop.com [Accessed: 2025-03-28].

Arif et al. 2023 – Arif, S., Taweekun, J., Ali, H.M., Ahmed, A. and Bhutto, A.A. 2023. Building resilient communities: Techno-economic assessment of standalone off-grid PV powered net zero energy (NZE) villages. *Heliyon* 9(11), DOI: 10.1016/j.heliyon.2023.e21426.

Awad et al. 2024 – Awad, M., Said, A., Saad, M.H., Farouk, A., Mahmoud, M.M., Alshammari, M.S. et al. 2024. A review of water electrolysis for green hydrogen generation considering PV/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application. *Alexandria Engineering Journal* 87, pp. 213–239, DOI: 10.1016/j.aej.2023.12.032.

Baldoni et al. 2021 – Baldoni, E., Coderoni, S., D’Orazio, M., Di Giuseppe, E. and Esposti, R. 2021. From cost-optimal to nearly Zero Energy Buildings’ renovation: Life cycle cost comparisons under alternative macroeconomic scenarios. *Journal of Cleaner Production* 288, DOI: 10.1016/j.jclepro.2020.125606.

Bao, X. and Zhang, J. 2024. Multi-objective decision optimization design for building energy-saving retrofitting design based on improved grasshopper optimization algorithm. *International Journal of Renewable Energy Development* 13(6), pp. 1058–1067, DOI: 10.61435/ijred.2024.60483.

Barykina, E. and Hammer, A. 2017. Modeling of photovoltaic module temperature using Faiman model: Sensitivity analysis for different climates. *Solar Energy* 146, pp. 401–416, DOI: 10.1016/j.solener.2017.03.002.

Benalcazar et al. 2025 – Benalcazar, P., Andrade, C. and Guamán, W. 2025. Prosumer policy options in developing countries: a comparative analysis of feed-in tariffs, net metering, and net billing for residential PV-battery systems. *Polityka Energetyczna – Energy Policy Journal* 28(1), pp. 77–98, DOI: 10.33223/epj/202801.

Bouraiou et al. 2020 – Bouraiou, A., Necaibia, A., Boutasseta, N., Mekhilef, S., Dabou, R., Ziane, A., Sahouane, N., Attoui, I., Mostefaoui, M. and Touaba, O. 2020. Status of renewable energy potential and utilization in Algeria. *Journal of Cleaner Production* 246, DOI: 10.1016/j.jclepro.2019.119011.

Brand, L. and Rose, W. 2012. Measure guideline: High efficiency natural gas furnaces. *Partnership for Advanced Residential Retrofit*. [Online:] https://www1.eere.energy.gov/buildings/publications/pdfs/building_america/highefficiency_gas_furnaces.pdf [Accessed: 2025-04-05].

Camporeale et al. 2021 – Camporeale, C., Del Ciello, R. and Jorizzo, M. 2021. Beyond the hydrocarbon economy: The case of Algeria. [In:] Nyangon, J. and Byrne, J. eds. *Sustainable Energy Investment: Technical, Market and Policy Innovations to Address Risk*. IntechOpen, p. 165, DOI: 10.5772/intechopen.91033.

Deline et al. 2024 – Deline, C., Jordan, D., Sekulic, B., Parker, J., McDanold, B. and Anderberg, A. 2024. PV Lifetime Project – 2024 NREL Annual Report (No. NREL/TP-5K00-90651). National Renewable Energy Laboratory, Golden, CO, USA. [Online:] https://www.nrel.gov/docs/fy24osti/90651.pdf [Accessed: 2025-03-22].

Deymi-Dashtebayaz et al. 2022 – Deymi-Dashtebayaz, M., Baranov, I.V., Nikitin, A., Davoodi, V., Sulin, A., Norani, M. and Nikitina, V. 2022. An investigation of a hybrid wind-solar integrated energy system with heat and power energy storage system in a near-zero energy building – a dynamic study. *Energy Conversion and Management* 269, DOI: 10.1016/j.enconman.2022.116085.

Durisch et al. 2007 – Durisch, W., Bitnar, B., Mayor, J.C., Kiess, H., Lam, K.H. and Close, J. 2007. Efficiency model for photovoltaic modules and demonstration of its application to energy yield estimation. *Solar Energy Materials and Solar Cells* 91(1), pp. 79–84, DOI: 10.1016/j.solmat.2006.05.011.

Eksi et al. 2025 – Eksi, M., Akarsu, R.T. and Ozcan, M. 2025. Net-zero energy building transformation: Techno-economic and environmental evaluation in the Mediterranean Region. *Environ Dev Sustain*, DOI: 10.1007/s10668-025-06389-9.

Elnaggar et al. 2024 – Elnaggar, A.E.M., Sharaf, S., Abedel Rehim, Z.S., Mustafa, H.M.M. and El Zoghby, H.M. 2024. Optimizing COP by RSM and MATLAB model of mini refrigerator based on thermoelectric units driven by solar photovoltaic. *Scientific Reports* 14(1), DOI: 10.1038/s41598-024-72500-1.

Fan et al. 2021 – Fan, S., Wang, Y., Cao, S., Sun, T. and Liu, P. 2021. A novel method for analyzing the effect of dust accumulation on energy efficiency loss in photovoltaic (PV) system. *Energy* 234, DOI: 10.1016/j.energy.2021.121112.

Forrousso et al. 2024 – Forrousso, S., Kaitouni, S.I., Mana, A., Wakil, M., Jamil, A., Brigui, J. and Azzouzi, H. 2024. Optimal sizing of off-grid microgrid building-integrated-photovoltaic system with battery for a net zero energy residential building in different climates of Morocco. *Results in Engineering* 22, DOI: 10.1016/j.rineng.2024.102288.

Ghosh et al. 2022 – Ghosh, S., Roy, J.N. and Chakraborty, C. 2022. A model to determine soiling, shading and thermal losses from PV yield data. *Clean Energy* 6(2), pp. 1137–1156, DOI: 10.1093/ce/zkac014.

Global Petrol Prices 2025. Electricity prices. [Online:] https://www.globalpetrolprices.com/electricity_prices/ [Accessed: 2023-12-14].

Godin et al. 2021 – Godin, K., Sapinski, J.P. and Dupuis, S. 2021. The transition to net zero energy (NZE) housing: An integrated approach to market, state, and other barriers. *Cleaner and Responsible Consumption* 3, DOI: 10.1016/j.clrc.2021.100043.

Gong et al. 2020 – Gong, H., Rallabandi, V., Ionel, D.M., Colliver, D., Duerr, S. and Ababei, C. 2020. Dynamic modeling and optimal design for net zero energy houses including hybrid electric and thermal energy storage. *IEEE Transactions on Industry Applications* 56(4), pp. 4102–4113, DOI: 10.1109/TIA.2020.2986325.

Gulen, S.C. and Zachary, J. 2022. Feasibility of achieving 62% combined cycle efficiency with a 200 MW gas turbine. *In Turbo Expo: Power for Land, Sea, and Air* 86021, p. V005T09A003, DOI: 10.1115/GT2022-81807.

Hadjout et al. 2023 – Hadjout, D., Sebaa, A., Torres, J.F. and Martínez-Álvarez, F. 2023. Electricity consumption forecasting with outliers handling based on clustering and deep learning with application to the Algerian market. *Expert Systems with Applications* 227, DOI: 10.1016/j.eswa.2023.120123.

Hasan et al. 2022 – Hasan, K., Yousuf, S.B., Tushar, M.S.H.K., Das, B.K., Das, P. and Islam, M.S. 2022. Effects of different environmental and operational factors on the PV performance: A comprehensive review. *Energy Science & Engineering* 10(2), pp. 656–675, DOI: 10.1002/ese3.1043.

Ismaeil, E.M. and Sobaih, A.E.E. 2023. Heuristic approach for net-zero energy residential buildings in arid region using dual renewable energy sources. *Buildings* 13(3), DOI: 10.3390/buildings13030796.

Moghaddasi et al. 2021 – Moghaddasi, H., Culp, C., Vanegas, J. and Ehsani, M. 2021. Net zero energy buildings: Variations, clarifications, and requirements in response to the Paris Agreement. *Energies* 14(13), DOI: 10.3390/en14133760.

Mohamed, H. and Meriane, Y. 2024. Fossil and renewable energy, conflict, economic growth, and military expenditure: The case of Algeria. *Environmental Economics and Policy Studies* 26(1), pp. 1–21, DOI: 10.1007/s10018-024-00403-6.

Müller et al. 2024 – Müller, V.P., Eichhammer, W. and van Vuuren, D. 2024. Paving the way: Analysing energy transition pathways and green hydrogen exports in developing countries–The case of Algeria. *International Journal of Hydrogen Energy* 67, pp. 240–250, DOI: 10.1016/j.ijhydene.2024.04.153.

Nabavi et al. 2021 – Nabavi, S.A., Motlagh, N.H., Zaidan, M.A., Aslani, A. and Zakeri, B. 2021. Deep learning in energy modeling: Application in smart buildings with distributed energy generation. *IEEE Access* 9, pp. 125439–125461, DOI: 10.1109/ACCESS.2021.3110960.

Niveditha, N. and Singaravel, M.R. 2022. Optimal sizing of hybrid PV–Wind–Battery storage system for Net Zero Energy Buildings to reduce grid burden. *Applied Energy* 324, DOI: 10.1016/j.apenergy.2022.119713.

Nwokolo et al. 2023 – Nwokolo, S.C., Obiwulu, A.U., Amadi, O. and Ogbulezie, J.C. 2023. Assessing the impact of soiling, tilt angle, and solar radiation on the performance of solar PV systems. *Trends in Renewable Energy* 9(2), pp. 121–137, DOI: 10.17737/tre.2023.9.2.00156.

Ochs et al. 2024 – Ochs, F., Franzoi, N., Dermentzis, G., Monteleone, W. and Magni, M. 2024. Monitoring and simulation-based optimization of two multi-apartment NZEBs with heat pump, solar thermal and PV. *Journal of Building Performance Simulation* 17(1), pp. 1–26, DOI: 10.1080/19401493.2023.2227605.

Photovoltaic Geographical Information System (PVGIS) 2023. [Online:] https://ec.europa.eu/jrc/en/pvgis [Accessed: 2023-09-15].

Sauer et al. 2014 – Sauer, K.J., Roessler, T. and Hansen, C.W. 2014. Modeling the irradiance and temperature dependence of photovoltaic modules in PVsyst. *IEEE Journal of Photovoltaics* 5(1), pp. 152–158, DOI: 10.1109/JPHOTOV.2014.2364133.

Sedaoui, R. 2023. Energy vulnerability and pathway towards sustainable energy systems in the Arab region. *The Journal of World Energy Law & Business* 16(2), pp. 91–111, DOI: 10.1093/jwelb/jwac039.

Shivanaganna et al. 2024 – Shivanaganna, N., Shivamurthy, K.P. and Boddapati, V. 2024. Optimal strategy for transition into nearly zero energy residential buildings: A case study. *Energy* 307, DOI: 10.1016/j.energy.2024.132742.

Singla et al. 2016 – Singla, A., Singh, K. and Yadav, V.K. 2016. Environmental effects on performance of solar photovoltaic module. [In:] *Proceedings of the 2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy* (*PESTSE*), Bengaluru, India, DOI: 10.1109/PESTSE.2016.7516480.

Solar Electric Supply 2024. Leading Wholesale Solar Panels & Solar Electric Systems Suppliers. [Online:] https://www.solarelectricsupply.com/ [Accessed: 2024-11-10].

Theristis et al. 2023 – Theristis, M., Stein, J., Deline, C., Jordan, D., Robinson, C., Sekulic, W., Anderberg, A., Colvin, D.J., Walters, J., Seigneur, H. and King, B.H. 2023. Onymous early-life performance degradation analysis of recent photovoltaic module technologies. *Progress in Photovoltaics: Research and Applications* 31(2), pp. 149–160, DOI: 10.1002/pip.3615.

Wei, W. and Skye, H.M. 2020. Residential net-zero energy buildings: Review and perspective. *Renewable and Sustainable Energy Reviews* 142, DOI: 10.1016/j.rser.2021.110859.

Mohammed Laour, Fethi Akel, Douadi Bendib, Souhil Mouassa

Optymalna strategia eksploatacji budynku z zerowym zużyciem energii elektrycznej, zasilanego energią słoneczną, dla zrównoważonej przyszłości energetycznej: studium przypadku z północnej Algierii

Streszczenie

Ogromny potencjał słoneczny Algierii podkreśla potrzebę przyjęcia strategii pomagających w integracji energii słonecznej w budynkach mieszkalnych, aby sprostać rosnącemu zużyciu energii i złagodzić presję finansową spowodowaną dotacjami energetycznymi. W niniejszym artykule przedstawiono badanie dotyczące optymalnej strategii operacyjnej i analizy ekonomicznej dla budynków mieszkalnych, mające na celu osiągnięcie zerowego zużycia energii elektrycznej netto (NZE) poprzez opłacalne rozwiązania. Metodologia obejmuje opracowanie wysokowydajnego modelu symulacyjnego dla domów słonecznych NZE. Model ten integruje kilka algorytmów zaprojektowanych w celu optymalizacji wymiarów systemu fotowoltaicznego (PV) i wdrożenia efektywnej strategii zarządzania energią. Wyniki pokazują, że optymalna moc szczytowa PV wynosząca 4,218 kWp i pojemność akumulatora wynosząca 5,578 kWh prowadzą do rocznej nadwyżki energii netto wynoszącej około 58 kWh i kosztu energii elektrycznej wynoszącego 0,1204 USD/kWh, wynikającego z inwestycji w dom solarny NZE. Średnio system dostarcza 0,433 kW do sieci w godzinach szczytu w południe w okresie letnim, zachowując pełną autonomię elektryczną w godzinach szczytu wieczornego. W związku z tym proponowana optymalna strategia maksymalizuje wykorzystanie energii słonecznej PV i minimalizuje zależność od energii elektrycznej z sieci. Zapewnia również zerowy bilans energii elektrycznej, uwzględniając długoterminową interakcję z siecią. Ponadto szczegółowa analiza kosztów i korzyści wykazuje potencjalne oszczędności w wysokości 7176,00 USD na gospodarstwo domowe, co stanowi 68-procentową redukcję rządowych dotacji energetycznych w okresie 25 lat. Wyniki te stanowią praktyczny plan działania dla wdrożenia na szeroką skalę domów o zerowym zużyciu energii w Algierii, pomagając zmniejszyć obciążenie sieci energetycznej i finansowe obciążenie związane z dotacjami energetycznymi, a jednocześnie przyczyniając się do redukcji emisji CO_2.

Słowa kluczowe: budynki solarne NZE, dobór wielkości instalacji fotowoltaicznej, zrównoważona energia, optymalne planowanie, efektywne zarządzanie energią