Journal of Energy Storage 72 (2023) 108525

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research papers

Intelligent energy management system for smart home with grid-connected hybrid photovoltaic/ gravity energy storage system

Arechkik Ameur, Asmae Berrada *, Anisa Emrani

International University of Rabat, College of Engineering and Architecture, LERMA, Sala Al Jadida, Morocco

ARTICLE INFO

Keywords:
Dynamic SHEMS
Solar radiation
GES
PV power
Forecast model

ABSTRACT

A dynamic smart home energy management system (SHEMS) is proposed in this study to address the growing concerns of energy conservation and environmental preservation. This study contributes a novel one-week dynamic forecasting model for a hybrid PV/GES system integrated into a smart house energy management system, encompassing dynamic electricity pricing, smart appliance control, PV generation forecasting, and gravity energy storage state of charge prediction. The findings of this study demonstrate that the developed dynamic SHEMS model significantly reduces household energy use and lowers the cost of power. With this SHEMS model, the hybrid PV/GES can supply the house's energy needs for eight and a half hours each day. In addition, it offers the advantage of low electricity price for charging the battery of the electric vehicle. Performance indicators such as RMSE and MAPE are employed, yielding forecast error results ranging from 13.45 % to 23.16 % for RMSE and 4.06 % to 11.27 % for MAPE.

1. Introduction

The increasing concerns about the environmental effects of traditional energy sources and fossil fuels finite live, have shifted emphasis to renewable energy sources [1,2]. These latter significantly contribute to reducing greenhouse gas (GHG) emissions and traditional energy consumption based primarily on electric grid supply [3]. Recent statistics prove that buildings, and particularly the civic sector, require more than 40 % of the total energy consumed in comparison with other sectors [4]. A significant portion of this consumption could be met by the integration of renewable energy systems combined with energy storage technologies [5]. Different sources of renewable energy can be integrated into buildings to cover the heating, cooling, and electrical needs of the occupants [6]. Among the most widely used renewable energy resources, solar energy draws increasing attention for building applications as a way to achieve sustainable buildings [7]. Solar energy is collected by photovoltaic (PV) modules or thermal panels in buildings [8]. The amount of energy gained is considerably affected by the weather conditions, mainly the magnitude of solar radiation, which output intermittent energy and therefore requires support from energy storage systems [9]. However, the integration of such decentralized and intermittent power technologies with variable capacity into the traditional electrical power system will create a new challenge for the stability and reliability of the electric grid [10]. These crucial challenges have prompted academics to consider smart grid as a more comprehensive and effective solution.

The smart grid concept can be defined as the future power system which utilizes communication and advanced technologies to optimize energy production, distribution, and consumption [11,12]. In recent years, rising urbanization has resulted in an influx of new homes and buildings as well as increased energy usage. Household energy usage is often a visible issue, accounting for significant consumption [13]. As a result, domestic energy conservation and efficiency enhancements are required, particularly considering the current energy crisis and environmental emissions. Household consumers will be actively involved in energy management through demand response programs, thanks to the development of smart grid technologies [12]. These latter technologies include smart house energy management systems, which have the goal of achieving demand reduction goals while lowering electricity purchasing prices [14]. In addition to smart appliances, SHEMS is one of the most important infrastructures for managing the energy produced, stored, and consumed [13,15]. SHEMS is an essential system that aims to achieve a successful demand response. It combines power generation, consumption, and energy storage devices into a single management and control system [15]. SHEMS can increase the efficiency of residential renewable energy and help clients save money on their electricity bills.

* Corresponding author.
E-mail address: as.berrada@aui.ma (A. Berrada).

https://doi.org/10.1016/j.est.2023.108525
Received 24 February 2023; Received in revised form 6 July 2023; Accepted 25 July 2023
Available online 8 August 2023

The conventional power system market lacks customer interaction and has a single electricity pricing, resulting in insufficient electricity supply during peak hours and wasted electricity during off-peak hours. Following that, the off-peak and peak tariff mechanisms are implemented, which help customers adjust their energy consumption times. It is, however, less adaptable, and unable to reflect the true link between power demand and supply. Furthermore, SHEMS can entirely interact with the power system in order to obtain accurate real-time prices, production, load forecasting, and PV prediction. In addition, it enables the user to perform intelligent household energy allocation, optimize household load allocation in the time dimension, achieve customer demand response, relieve grid pressure during peak hours, and improve grid stability.

Solar PV is extensively employed in smart homes due to its ease of installation and inexpensive cost. The installed PV capacity in the residential sector reached 39.4 %, prompting extensive research into the best way to integrate PV systems into houses [16]. An accurate PV output power forecast is generally an essential input required for adequate load and resource scheduling, and specifically for the operation of the energy management system (EMS) in residential applications.

Several studies in the literature focused on PV forecasting in EMS. El-Baz et al. conducted a numerical comparison of the possibilities of utilizing a probabilistic PV forecast in a demand-side management (DSM) algorithm instead of the traditional deterministic algorithms. The results of the comparison demonstrate that the probabilistic PV forecasting algorithms may offer greater potential in DSM [16]. Klinger et al. presented a forecast-based modeling strategy for using a battery coupled with a PV system connected to the grid. The authors concluded that an accurate PV output power forecast is an essential need for a hybrid PV/battery system connected to the grid [17]. El-Baz et al. present a novel model of a day-ahead probabilistic PV power output forecast for buildings. The results show that the developed model is accurate and reliable for EMS applications [18]. Hanna et al. showed that inaccurate forecasts can significantly affect the behavior of the battery discharging mode [19].

Optimal self-scheduling of building energy management systems with the integration of PV power and batteries has been investigated by Javadi et al. [20]. The study considers a dynamic time pricing scheme to determine the optimal scheduling for different case studies. Another study by Javadi et al. explored the same problem by including the end-user's discomfort, which has been evaluated using a linear penalizing mechanism [21]. The Epsilon-Constraint Method has been employed in [22] to deal with the self-scheduling of home energy management systems; While a risk-constrained model has been deployed in [23]. Ali et al. conducted an overview of smart home energy management systems with smart grid optimizations strategies [24]. The authors discussed the architectures, scheduling techniques, as well as some challenges of energy management systems. In addition, the demand-side management and demand response programs have been reviewed by the authors. The presence of ventilation and air conditioning system together with inverter-based heating, has been included in the optimal operation of building energy management [25]. The model has the capability to significantly decrease electricity expenses while ensuring that the consumer's desired level of comfort is adequately upheld.

Zafar et al. provided a HEMS overview with emphasis on key principles, configurations, and enabler technologies. In addition, a description of HEMS computing developments and demand response communication technologies has been discussed by the authors [26]. Qureshi et al. conducted a trust-aware EMS study for smart houses (TEMSH), by employing time management and intelligent scheduling based on the management of uncontrollable and controllable appliances. The obtained results indicate that the proposed system is capable of managing and reducing energy costs by roughly 55 % in terms of bills, and is best for the environment [27]. Rocha et al. proposed a scheduling algorithm based on artificial intelligence for DSM in smart houses. The results of the algorithm show that when smart houses without and with distributed generation and battery storage are compared, the efficiency of the suggested system is demonstrated by a cost savings of 51.4 % [28].

The authors in [29] proposed an optimized EMS (OHEMS) with the integration of renewable energy and energy storage, as well as the incorporation of the residential sector into DSM activities. The optimized solution showed that the use of renewable energy and energy storage systems reduced the electricity bill by 19.94 % and the peak-to-average ratio by 21.55 %. Zheng et al. developed an integrated SHEMS model based on a pyramid taxonomy for residential buildings with a hybrid PV-battery system. The developed model demonstrates that it is more beneficial to model load/PV forecast uncertainties rather than averaging or disregarding them. The DA-RT retail power market and the two-stage stochastic programming model are useful for leveraging imprecise forecasts. Sharing PV and battery investments for revenue or trading with local small prosumers for cost savings could benefit each household by coordinating many prosumers [30].

The growing interest in electric vehicles has been driven by the increasing demand for environmentally friendly transportation. By integrating electrical vehicles into the utility grid, reduced pollution from transportation could be achieved. Therefore, many studies have evaluated various optimal strategies for grid-connected electrical vehicles. In [31], the authors provide a comprehensive review of the key implications associated with grid-connected electric vehicles. The study highlighted the exciting potential for energy exchange between vehicles and the grid. The same conclusion was drawn by [32]. In this study, the authors discussed the impact of intelligent charging stations on the distribution sector. An economic investigation of coordinating electric vehicle parking lots and home energy management systems has been addressed in [33]. The authors use real-life case studies and data to prove the effectiveness of the proposed model.

According to a review of relevant literature, the most used energy management system models for a smart house give light to a home with renewable energy integration, usually solar PV coupled with batteries as an energy storage device with or without forecast. Furthermore, the majority of these models provide very short-term forecasting and do not investigate the prediction of PV output power for one week.

Gravity energy storage system (GES) has recently received a lot of interest as a new storage system technology that is still under development. GES concept is similar to that of a pumped hydro energy storage system (PHES). This latter is considered as one of the most mature and reliable energy storage systems, especially due to its long lifetime compared to other energy storage systems. Several studies addressed the operation, development, and optimization of GES. Berrada et al. investigated the optimal design of GES equipment [34]. The piston and container materials used to build GES were studied in [35]. The dynamics model of the GES was studied in [36]. In [37], the authors developed a model to simulate the performance of two configurations of GES system. The study compares the dynamic behavior of the two setups and highlights the potential capabilities of GES system. The financial assessment of gravity energy storage has been addressed in [38]. The study proves the cost effectiveness of renewable power plants integrating gravity storage. The same conclusion has been reached in [39]. Authors in [34] analyzed the techno-economic performance of GES system. The resulting LCOE of GES based on these studies varies between 0.038 €/kWh and 0.15 €/kWh. A detailed financial model of GES is presented in [40]. The study demonstrates that GES has an attractive LCOS of 202 $/MWh. The operation of hybrid renewable plant/GES system has been studied in [41]. The authors relied on efficiency and reliability performance indicators to select the best configuration of PV/Wind/GES. The same study have been established by [42] but with different indicators including, mainly the robustness of GES structure. In [43], the authors compared the operation of PV/Wind power plants while integrating GES or battery storage. However, none of the past studies has addressed the energy management system, which includes a dynamic electricity price and a forecasting model of a smart house with a hybrid PV system and gravity energy storage for a week. The absence of such research studies prompted the current work.

The specific contributions of this study are as follows:

- The development of a novel one-week dynamic forecasting model of a hybrid PV/GES connected to the grid for a smart house energy management system (SHEMS).
- The integration of dynamic electricity pricing, smart appliance control, PV generation forecasting, and prediction of gravity energy storage state of charge into a single SHEMS model.
- The demonstration of the effectiveness of the proposed SHEMS model in reducing household energy use and lowering the cost of power.
- Validation of the proposed model by comparing the experimental and simulated results.

The findings of this study have the potential to make a significant contribution to the field of smart home energy management. It presents a novel approach to integrating existing techniques into a single, holistic system. This integration allows the system to make more informed decisions about how to conserve energy and reduce power costs. The findings of this study can be used to improve the design and implementation of future SHEMS systems.

This paper is organized as follows. Section 2 presents a description of the proposed SHEMS model, including the PV system forecast model, GES model, scheduling load model, and dynamic electricity price. Gravity energy storage system. The case study investigated in this work is presented in Section 3. In Section 4, the discussions of the obtained results are described. Finally, conclusions are drawn in Section 5.

2. Modeling of SHEMS

The SHEMS infrastructure consists of a SHEMS center, smart meters, communication and networking systems, and other smart devices [44] (see Fig. 1). Through these smart infrastructures, SHEMS can access, monitor, manage, and improve the functioning of various distributed generator sources (renewable energy systems, energy storage, as well as the electric grid), electric vehicles, and household appliances. In addition, the SHEMS supports two-way communication between smart home users and grid utilities. SHEMS should be more flexible in managing and controlling smart home appliances, renewable energy resources, and energy storage systems in order to participate in electricity conservation and demand response. The SHEMS employed in this current study is composed of a dynamic PV forecast model, GES state of charge forecast model, the electricity price, and the scheduled load on the horizon for one week. Fig. 1 illustrates the concept of SHEMS investigated in this study.

The control system within the SHEMS is responsible for balancing the distribution of power between various sources and loads. The system initially prioritizes powering the loads using the electricity generated by the photovoltaic system. PV power is utilized to meet the energy demands of the loads within the house. If the PV production exceeds the immediate energy requirements of the loads, the excess power is diverted to two different purposes: charging the gravity energy storage (GES) system and injecting any remaining surplus power back into the electrical grid. This ensures that the excess energy is stored for later use and potentially contributes to the overall energy grid. When the PV power alone is insufficient to meet the total energy demand of the loads in the house, the control system activates the GES. The power stored in the GES is then utilized to supplement the energy required by the loads.

In situations where neither the PV power nor the GES power is sufficient to cover the entire energy demand of the loads, the system draws power from the electrical grid. The grid acts as a backup source of electricity to ensure that all the loads in the house receive the required power.

The control system of priority within the SHEMS ensures that the power balance is maintained by utilizing PV power as the primary source, followed by GES power and grid power when needed. The aim is to optimize the use of renewable energy sources while ensuring uninterrupted power supply to the loads in the house.

The proposed method is a combination of existing techniques, such as dynamic forecasting, smart appliance control, and dynamic electricity pricing. However, the novelty of the proposed method lies in its integration of these techniques into a single, holistic system. This integration allows the system to make more informed decisions about how to conserve energy and reduce power costs. For example, the dynamic forecasting model can be used to predict the output power of the PV system and the state of charge of the GES. This information can then be used by the smart appliance control system to determine which appliances should be turned on and off at any given time. The dynamic electricity pricing information can also be used to determine when to

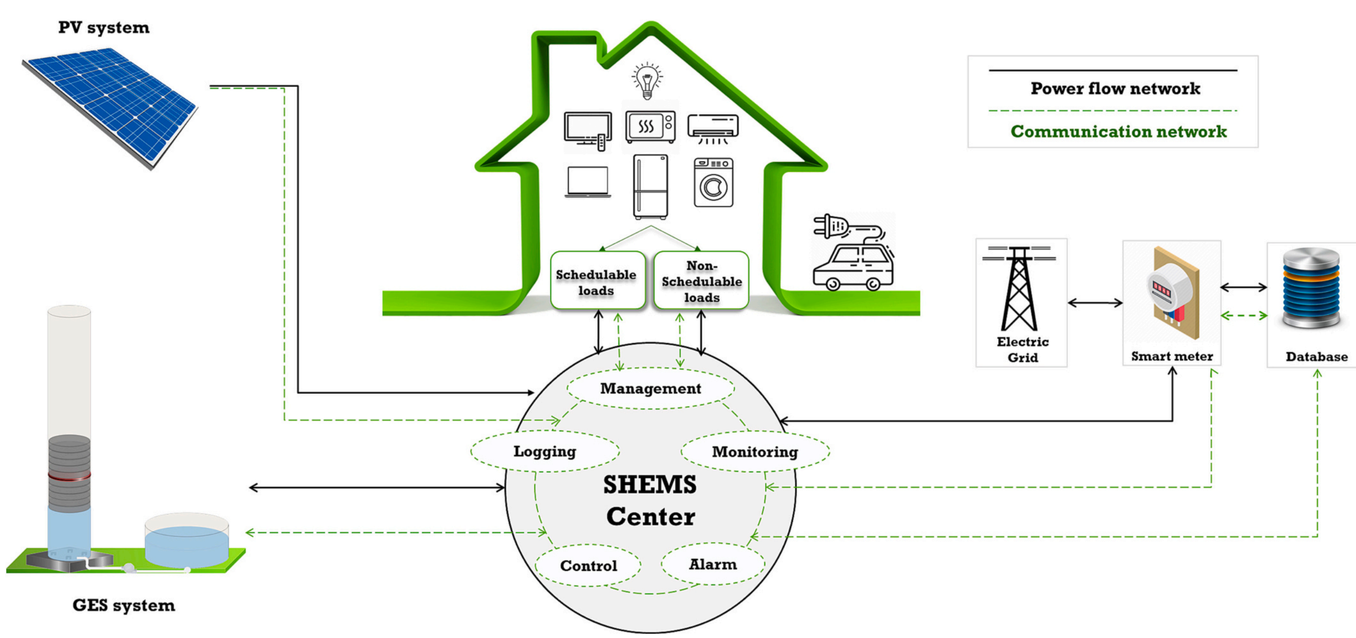

Fig. 1. SHEMS infrastructure.

charge the battery of the electric vehicle. The integration of existing techniques into a single, holistic system allows the system to make more informed decisions about how to manage energy use. This can lead to significant energy savings and cost savings for homeowners.

2.1. Photovoltaic system forecast model

The forecast of PV output power is a function of solar radiation and temperature predictions. The PV output power forecast can be expressed in Eq. (1) [45]:

$$\begin{cases} P_{PV}(t) = P_p \dfrac{H(t)}{G_{STC}}[1 + k(T(t) - T_{STC})] \\ T(t) = T_{air}(t) + 0.0318 \times H(t) \times (1 + 0.031 T_{air}(t)) \times (1 - 0.042 \times V) \end{cases} \tag{1}$$

where $P_{PV}(t)$,P_p,$H(t)$,G_{STC},k,$T(t)$,T_{STC},$T_{air}(t)$,V are the PV output power, the maximum output power under standard test conditions (STC), the actual solar radiation, the rated solar radiation under STC, the coefficient of temperature, the cell module temperature at the actual moment, the ambient temperature, the reference temperature, and the actual wind speed, respectively. The prediction of solar radiation is performed using Eqs. (2), (3), (4), and (5). The cloud cover temperature forecast data is imported from the Dark Sky Application Programming Interface (API) [46]. This latter is considered one of the most accurate sources of weather forecasts. The dynamic forecast model is performed using Python software. After a forecast request, which includes the longitude and latitude, to the Dark Sky API using a link connection. The cloud cover and temperature data of the specific site were sent to the model system each morning after midnight in a format of a JSON file. These data were analyzed and used as input to estimate the solar radiation forecast. These latter were employed in addition to the specifications, tilt, and orientation of the used PV modules by using mathematical PV equations in order to predict the PV output power.

$$DNI = G_0 * 0.73^{\left(\frac{1}{\cos(Zenith\ angle)}\right)^{0.678}} \tag{2}$$

$$I_f = (1 - cloud\ cover\ precent) * DNI \tag{3}$$

$$D_f = 0.2 * I_f \tag{4}$$

$$G_f = I_f + D_f \tag{5}$$

where G_0, DNI, I_f, D_f, and G_f stand for solar constant which is equal to 1366 W/m^2, direct irradiance, predicted direct irradiance, predicted diffuse irradiance, and predicted global irradiance, respectively.

2.2. Gravity energy storage forecast model

Gravity energy storage forecast model is primarily concerned by the system state of charge during both the charging and discharging processes. GES remaining capacity is expressed in Eq. (6) as:

$$I_{SOC}(t+1) = \frac{C_a}{C_n} \times 100\% = \begin{cases} I_{SOC}(t) + \mu_{ch} C_p(t) \Delta t \\ I_{SOC}(t) - \dfrac{D_p(t)\Delta t}{\mu_{dis}} \end{cases} \tag{6}$$

where $I_{SOC}(t+1)$, $I_{SOC}(t)$, C_a, C_n, $C_p(t)$, $D_p(t)$, μ_{ch}, μ_{dis}, Δt are the next state of charge, the actual state of charge, the current charge capacity, the nominal capacity of charge, the actual charge power, the actual discharge power, the charging efficiency, the discharging efficiency, and the charge and discharge time.

Fig. 2 presents gravity energy system components. GES consists of a heavy piston split into several pieces placed inside the cylinder, an external water tank, a pipe connecting the cylinder to the tank, and a motor pump and turbine-generator which are connected to the pipe. In the charging mode, the motor consumes extra energy to run the pump, which pumps water from the tank to move the piston upward inside the container. In the discharging mode, the downward motion of the piston forces water to pass through the pipe under pressure. The kinetic energy of the water flow is converted to electrical energy by the turbine-generator.

The cylinder height (h_c) and diameter (D) as well as the piston density and its height (h_p) are the main parameters to determine the energy storage capacity of GES system. The relative piston density (ρ_{rel}) is expressed in Eq. (7)

$$\rho_{rel} = \rho_{piston} - \rho_{water} \tag{7}$$

where ρ_{piston} and ρ_{water} in (Kg/m^3) are the density of the piston and the density of water, respectively. The energy consumed by the motor in order to elevate the piston could be written as Eq. (8).

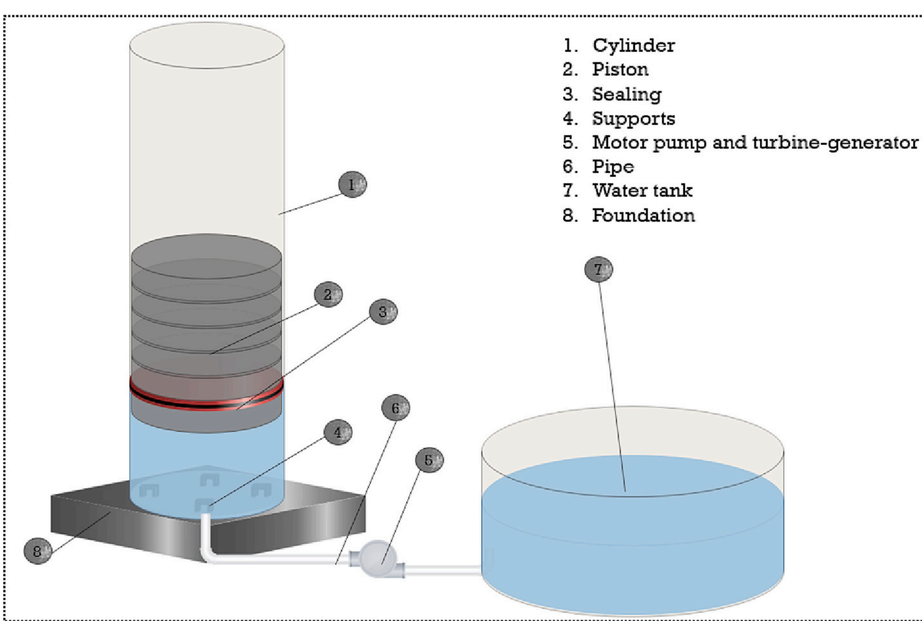

Fig. 2. Schematic of GES system used in this study.

$$P_{pump} = \eta_{RPT}\rho_{rel} g z Q_{charge} \quad (8)$$

where η_{RPT}, z, g, and Q_{charge} are the efficiency of the reversed pump turbine, the water height in (m), the gravitational acceleration, and the flow rated during the charging mode.

The energy stored and the power generated by gravity energy storage system are presented in Eqs. (9) and (10), respectively.

$$E_{GES} = \mu\rho_{rel} g \left(\frac{1}{4}\pi D^2 H_p\right)(H_c - H_p) \quad (9)$$

$$P_{gen} = \eta_{RPT}\rho_{rel} g z Q_{disch} \quad (10)$$

2.3. Scheduling load model

Scheduling loads in the SHEMS can be classified into four categories based on their control level. i) Temperature-controlled loads with a specific degree of cooling or heat storage capability, such as HVAC and refrigerators; ii) Active controlled loads with a predetermined working cycle and some flexibility in use time, such as washing machines, dishwashers' machine, and rice cookers; iii) passive controllable loads that can be intelligently regulated but have limited operating hours, such as lighting, TV, computer, and fans; iv) non-controllable loads.

2.4. Dynamic electricity pricing

There are various electricity price policies, such as those described and illustrated in [26,47,48]. The majority of the schemes described in those references are studied in this part in order to determine which structure best suits the suggested study-case. The first strategy to look into is flat tariffs, which keep the price constant regardless of other conditions. Because there is no financial incentive for users to transfer their consumption load from peak hours to maximum generated energy times, this pricing plan does not incentivize individuals to change their behavior or habits. Unlike flat tariffs, block rate tariffs rise in price as the amount of energy consumed increases, based on a defined set of kWh thresholds. As a result, crossing this line places customers in a high tariff category, resulting in a higher cost. Seasonal tariffs cause energy prices to fluctuate according to the seasons. During high-demand periods, prices are high, while during low-demand periods, prices are substantially lower.

Time-of-use (TOU) tariffs are the best dynamic pricing strategy for

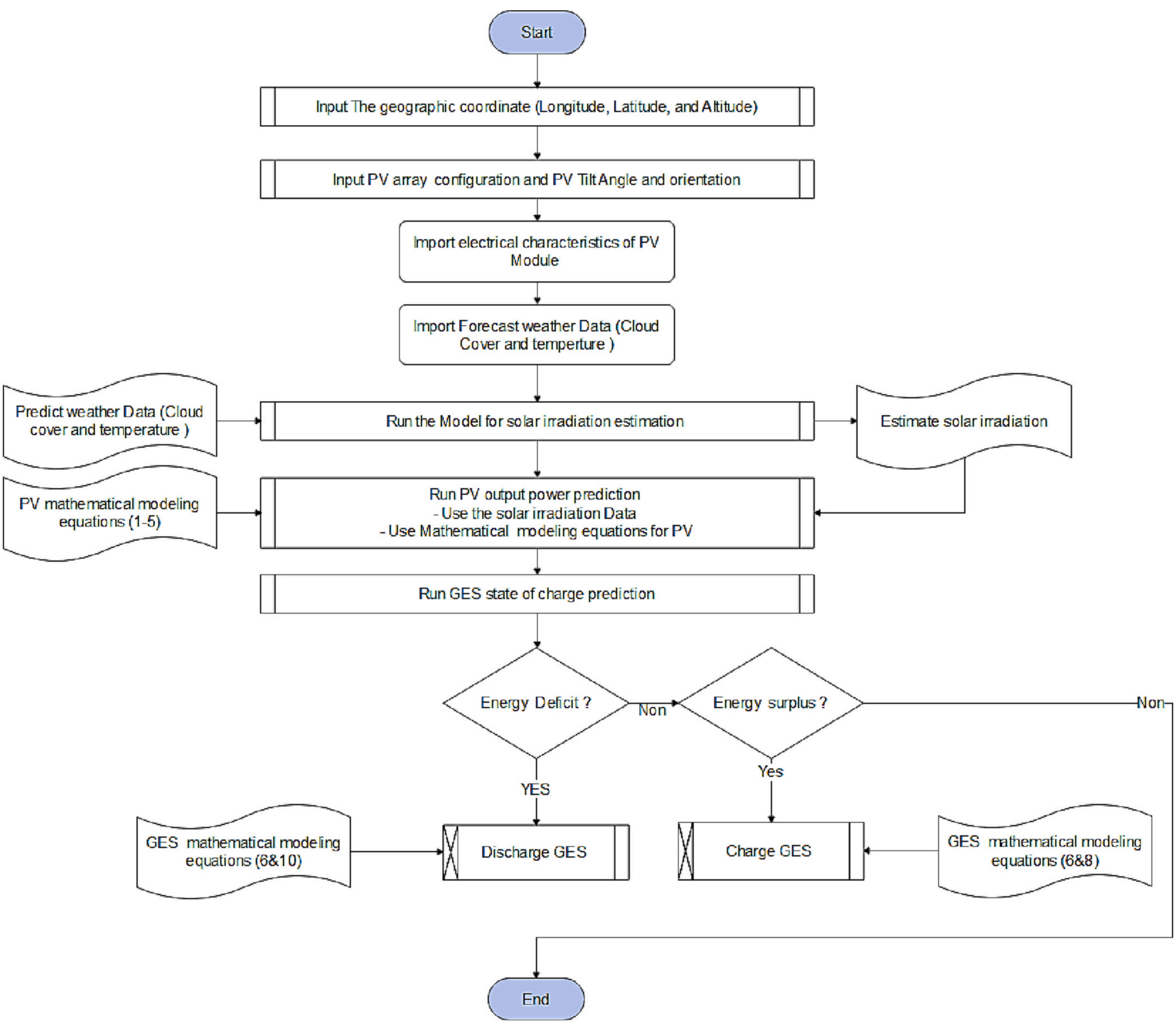

Fig. 3. Flowchart of the developed model.

load scheduling since they offer various prices at different periods throughout the day. It is the one that will be used in this case study. Time-of-use tariffs are a more efficient variant of real-time pricing. This policy's efficiency is enhanced by the fact that prices are updated at relatively short intervals. Frequent upgrades, on the other hand, can have a negative effect because they can be too expensive to handle.

2.5. SHEMS flowchart and algorithm

A flowchart depicting the proposed model is presented in Fig. 3. The developed model incorporates an algorithm that accurately predicts the performance of a photovoltaic (PV) system. The algorithm begins by taking into account the geographic coordinates (longitude, latitude, and altitude) to determine location-specific solar irradiation. The user provides information about the PV array configuration, including tilt angle and orientation. Electrical characteristics of the PV module and forecasted weather data, such as cloud cover and temperature, are also incorporated.

Using solar irradiation equations and mathematical modeling equations specific to PV systems, the algorithm forecasts the PV output power. Furthermore, it simulates the charging and discharging of the energy storage system (GES) to estimate its state of charge. By considering these factors, the algorithm offers valuable insights into optimizing the performance of the PV system and comprehending the influence of weather conditions on power generation and energy storage.

3. Case study

The effectiveness of the proposed model is validated by the case study presented in this section. The energy management system used is based on a forecast model of a hybrid PV/ gravity energy storage system. The forecast model considers the prediction of weather conditions, PV system production, and gravity energy storage state of charge in order to cover the load profiles scheduled over one week. The investigated house is located in Madrid, Spain.

The aim of this model is to optimize the house's consumption. In addition, the charging of the car's battery is only based on the energy price variation. In this case, neither the PV system nor GES are used to charge the battery of the electric vehicle. However, for all the used loads, PV installations as well as GES will be considered for the supply of energy. Those loads' scheduling can be described as a linear optimization problem that aims to either minimize consumption at the peak pricing hours or increase consumption at peak PV and GES generation hours.

In the presented scenarios, household appliances are supposed to account for the majority of electricity consumption. Appliances are divided into two categories: shiftable and non-shiftable equipment. The model will place emphasis on shiftable equipment because the user's satisfaction must be continually considered. A washing machine and dryer, a dishwasher, and an electric vehicle are examples of these appliances. Non-shiftable appliances, on the other hand, will continue to consume at the same rate because scheduling may be impossible owing to the nature of the appliance or have a negative impact on customer satisfaction. This set can include, but is not limited to, a fridge, an HVAC system, and a lighting set. The fridge is set to run all hours of the day, while the HVAC will only be running during the heat peaks of the day. As for lighting, it will be considered during the times of day when lighting is needed.

The characteristics of the two types of PV modules used are presented in Table 1.

The different features and parameters of GES used in this study are presented in Table 2. Indeed, a 5 kW/0.5 kWh system with a water tank volume of 28.63 m^3 is deployed. The required system specifications [49], sizing [43], technical design [50], and cost analysis [40] have been established in our previous works.

It is worth mentioning that the principles of the Water-Energy Nexus can be applied to address various concerns related to the operation of GES system and provide a more comprehensive understanding of its potential benefits. This approach can offer additional benefits such as optimizing water usage, reducing environmental impacts, and maximizing overall system efficiency. Indeed, the Water-Energy Nexus emphasizes the interdependence of water and energy resources, recognizing that water is required for energy production and energy is needed for water supply and treatment. In the case of a gravity energy storage system which utilizes the force of water to raise the piston and store or generate electricity, the Water-Energy Nexus can be leveraged to address its related concerns and optimize its operation. For example, by considering the availability and management of water resources, such as rainfall patterns and reservoir capacity, the system can be designed and operated to ensure optimal utilization of water resources while maximizing energy storage and minimizing water usage. Furthermore, the integration of renewable energy sources, such as hydropower or solar power, can enhance the sustainability and efficiency of the system. This holistic approach, considering the water-energy interdependencies, can lead to a more resilient and environmentally friendly GES system. To delve deeper into this topic, research studies and publications focusing on the Water-Energy Nexus, such as the work by Shokri et al. [51] and Siddiqi et al. [52], provide valuable insights and frameworks for applying these principles to energetic systems such as GES.

Fig. 4 presents the optimal dynamic pricing used in Madrid, Spain. Based on this dynamic pricing, solar radiation forecast, and PV output power prediction for different times of the day, an energy management study of a smart house is performed in this present work.

Table 1
PV module characteristics.

PV module characteristics		
Brand	Type 1: Solar World 255	Type 2: JINCO
Cell type	Monocrystalline PERC (m-Si)	Polycrystalline half cell (p-Si)
Module dimensions (mm)	1675 × 1001 × 35	1987 × 992 × 27
Electrical characteristic	At STC	At STC
Maximum power (Wp)	255	345
Open circuit voltage (V)	38.0	47.8
Short circuit current (A)	8.88	9.29
Voltage at maximum power (V)	30.9	38.4
Current at maximum power (A)	8.32	8.98
Efficiency (%)	20.5	17.5

Table 2
Parameters and features of GES systems.

Component	Parameters/features	Value
Cylinder	Height	10,000 mm
	Diameter	1910 mm
	Thickness	8 mm
	Water volume	28.63 m^3
Piston	Height	3000 mm
	Diameter	1860 mm
	Mass (several full cylinder)	50,000 Kg
Turbine	Type	Cross flow
	Runner diameter	300 mm
	Runner length	85 mm
	Turbine speed	405 rpm
Generator	Type	Asynchronous generator
	Electric power	5 kW
	Speed	1535 rpm

4. Results and discussion

Figs. 5 and 6 present the I-V and P—V characteristics of the two PV

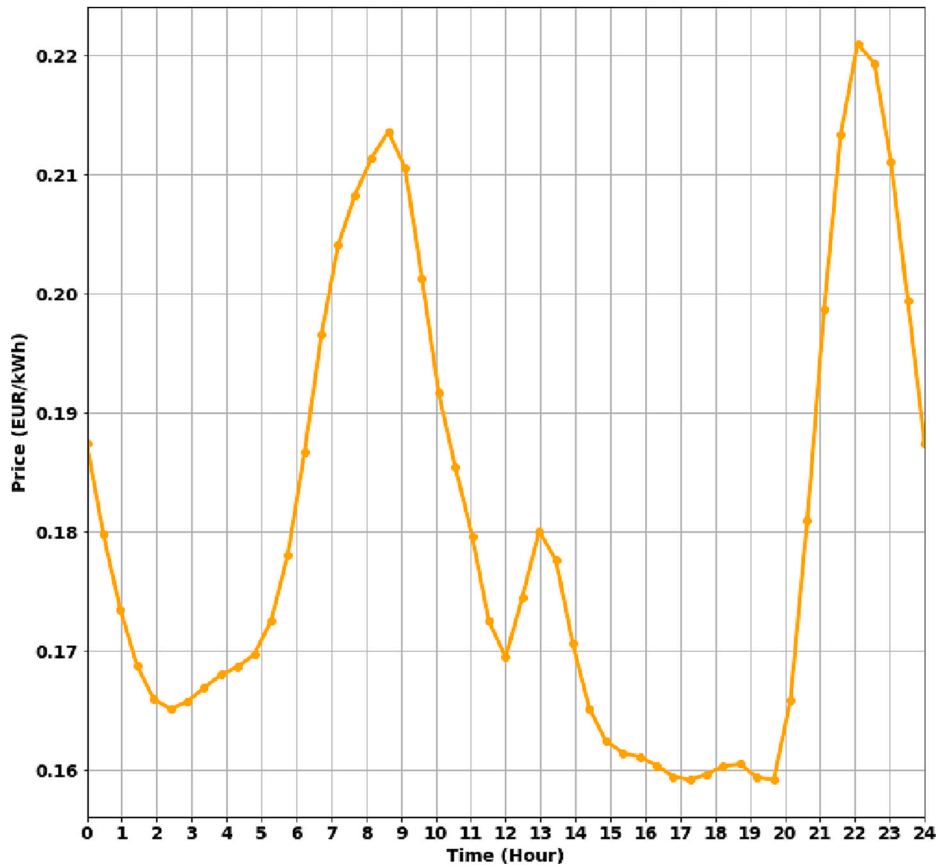

Fig. 4. Dynamic electricity price of grid in Madrid, Spain.

module types used in the present study. The current-voltage (I-V) and power-voltage (P—V) curves, are crucial for understanding the efficiency and performance of the PV modules. For the first PV module type (m-Si), the open voltage is measured at 47 V, while the short circuit current is recorded at 8.8 A. In contrast, the second PV module type (p-Si) exhibits an open voltage of 36 V and a short circuit current of 8.5 A. These values point out the maximum voltage and current that can be obtained from the PV modules when there is no external load connected.

The red point on the green curve indicates the optimal current and voltage in the I-V curve as well as the optimal power in the P—V curve (P_{pm1} = 350 Wp and P_{pm2} = 255 Wp). This point indicates the current and voltage values that result in the highest power output from the PV modules.

Analyzing the I-V and P—V characteristics of the PV modules is essential for understanding their behavior and determining the optimal operating conditions. These findings provide valuable insights for system design, performance optimization, and effective utilization of the PV modules in the present study.

The weather conditions forecast over one week in the studied region are shown in Fig. 7. This figure presents several key parameters related to weather conditions, including cloud cover, temperature, and solar irradiance predictions.

At the top of the figure, the cloud cover prediction is illustrated. It is observed that there is a significant variation in cloud cover during the first, second, and third days, with a high percentage of cloud cover expected. This implies that these particular days may experience reduced solar radiation due to the obstructive nature of clouds.

The temperature forecast is shown in the figure's central portion. PV module performance and efficiency are greatly influenced by temperature. The PV system's conversion efficiency may drop as a result of higher temperatures. By examining the temperature prediction, potential thermal impacts on the PV modules could be taken into consideration when designing and operating the system. In our case, having a temperature range between 290 K and 311 K indicates that the PV modules will function in settings that are moderately warm to warm. The bottom section of the figure presents the solar irradiance forecast, specifically direct (If), diffuse (Df), and global (Gf) solar radiation. The obtained results indicate significant variation in solar radiation during the first, second, and third days of the predicted week, primarily due the high percentage of cloud cover. This can result in lower solar irradiances and subsequently affect the performance of the PV system during these specific days. In contrast, the remaining days are expected to have mostly clear skies, resulting in substantial solar irradiances.

Based on the obtained results, it is evident that the predicted week experiences notable fluctuations in solar radiation, primarily attributed to the varying cloud cover. During the first, second, and third days, when the cloud cover is high, it is expected that solar irradiance will be significantly affected and potentially reduced. However, the subsequent days are anticipated to have mostly clear skies, resulting in substantial solar irradiance levels.

Understanding the predicted weather conditions and their impact on solar irradiance is crucial for assessing the potential energy generation of solar power systems.

To provide a more detailed examination of solar radiation variations within a single day, Fig. 8 presents the weather conditions for the first day of the predicted week. The obtained results demonstrate that there is a significant variation in solar radiation over the eight hours of the day. These fluctuations are primarily influenced by cloud cover, which varies according to the prediction model, ranging from nearly 90 % to below 5 % on the first day. Consequently, there are abrupt decreases in global solar irradiance fluctuating between 0 and 800 Wm^{-2}. These variations have a direct impact on the prediction of the PV output power.

Fig. 9 illustrates the predicted PV power output for the two studied PV systems throughout a week. The results demonstrate that PV

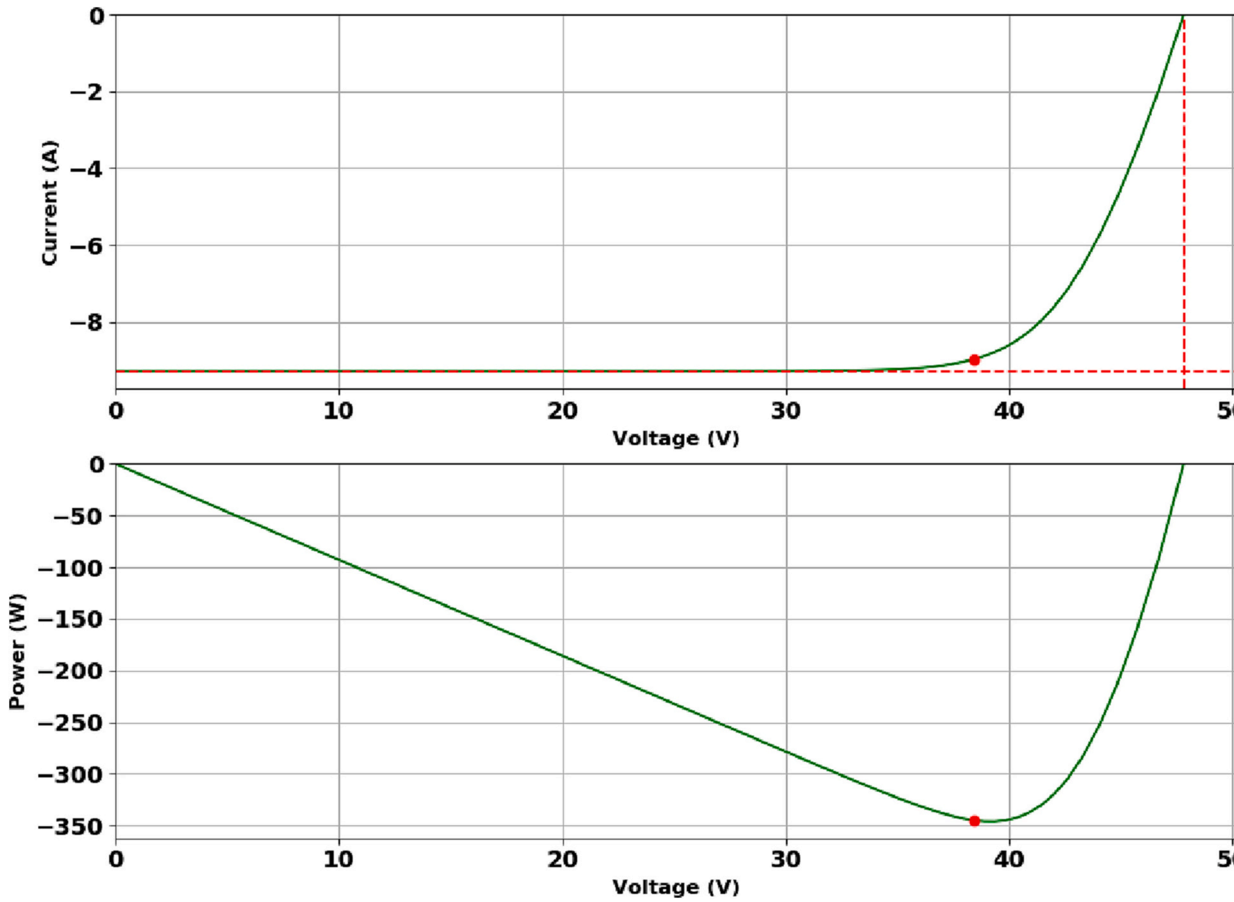

Fig. 5. I-V and PV characteristics for the first type of PV module used.

production fluctuates during the predicted week due to variations in solar radiation. Specifically, on the first and third days, PV production is low, resulting in insufficient coverage of household energy needs. As a result, users are compelled to either switch off unnecessary loads or shift their operation to other days or periods when electricity prices are lower. This approach maximizes the use of PV energy during periods of increased production by taking advantage of price changes in the power market. Users can maximize their self-consumption and perhaps lower their electricity costs by scheduling energy-intensive activities for periods of sufficient PV power production. Conversely, on the remaining days of the week, PV production is substantial, allowing it to effectively meet the load consumption requirements and charge the energy storage system (GES). This stored energy can be used when PV generation is minimal. GES helps therefore to improve self-sufficiency and optimize energy management.

To facilitate a more detailed analysis of daily PV production, Fig. 10 provides a focused PV prediction for the first day, offering hour-by-hour information on PV output power. This enables users to easily manage their loads, either by switching them off or shifting their operation to hours when the PV production prediction is adequate.

Fig. 11 presents the prediction of PV output power versus the scheduled loads consumption, including the charge and discharge of gravity energy system (GES) over a week. The PV output power of the two aforementioned PV systems (PV1 and PV2) is presented as negative values, and their sum is represented by the green curve. The combined contribution of both PV systems to the overall energy generation demonstrates the value of integrating different PV systems to increase energy output and lessen reliance on the grid. The house consumption is presented as positive values with different colors to indicate the consumption of the different appliances/equipment used. The total instantaneous power consumed by all loads is given by the red curve.

The analysis of the figure reveals that, over the predicted week, a significant portion of the load is supplied by both the PV and GES systems, while the remaining portion is sourced from the electric grid. This can be attributed to factors such as low PV production resulting from low solar radiation and the presence of low energy prices. This proves that the integrated system successfully uses energy storage capabilities and renewable energy sources to meet a significant amount of the household's energy demands.

The HVAC consumption changes during the predicted week as it depends on the house's exterior and interior heat. This latter is estimated based on the transfer of heat due to conduction through the house's windows and walls. This emphasizes the requirement for users to take into account outside environmental factors and modify their energy consumption appropriately by maximizing energy efficiency and minimizing energy waste.

To optimize energy utilization and cost savings, the electric vehicle battery is programmed to charge during the period between 1 am and 5 am. This time window takes advantage of the low energy prices and ensures that the vehicle is fully charged by the morning. Other loads are scheduled to operate when there is available PV production, except for the refrigerator, lighting, TV, computer, and fans. However, a portion of the energy consumption for these appliances can be supplied by the energy storage system (GES).

Fig. 11 provides a comprehensive visualization of the interplay between PV output power, scheduled loads consumption, and the utilization of the gravity energy system (GES) over the course of a week. This information enables users to make informed decisions about load scheduling, energy storage management, and optimizing energy usage patterns based on available PV production and energy prices.

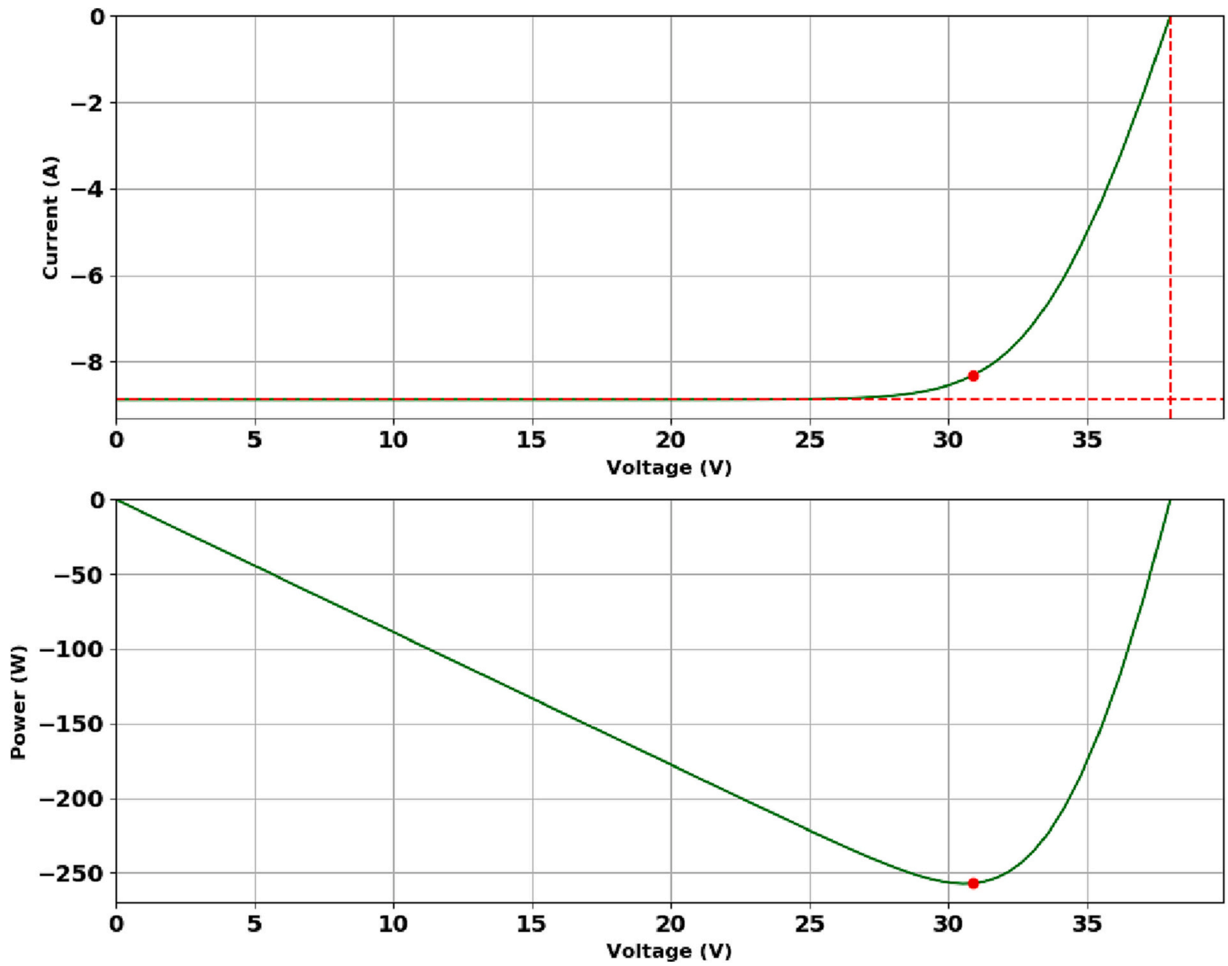

Fig. 6. I-V and PV characteristics for the second type of PV module used.

To enhance the accuracy of the Smart Home Energy Management System (SHEMS) during different hours of the day, Fig. 12 provides valuable insights. This figure illustrates the predicted PV output power and the scheduled loads for the first day. The total production and consumption are presented by green and red curves, respectively. The thorough understanding of how energy flows throughout the system is made possible by the exact breakdown of production and consumption, allowing for efficient load control and energy optimization techniques.

The loads are prioritized in the following order: PV system, energy storage system (GES), and then the grid. This prioritization ensures that renewable energy sources are utilized first, followed by stored energy and, if necessary, energy from the grid. Indeed, when there is an excess of PV production, the GES system is fully charged. Conversely, the GES system discharges its stored energy to power the loads as a secondary source. If both the PV system and GES output powers are insufficient to meet the load requirements, the grid acts as a third source to provide energy. Prioritizing different energy sources not only encourages self-consumption of renewable energy but also gives consumers control over their energy usage, reducing their reliance on traditional energy sources.

The green dotted curve on the graph indicates the power portion consumed by loads from PV and the grid, as well as the excess PV output power portion. The load consumption between the horizontal axis and the green dotted line is supplied by the grid (e.g., between 0 am and 4:30 am). The load portion powered by the PV systems is above the green dotted line. The excess PV output power is depicted when the green dotted line displays negative values (e.g., between 7:30 am and 3 pm). The excess PV output power is primarily utilized to charge the GES unit until it reaches full capacity. Any remaining excess power is then injected back into the grid.

Fig. 13 displays the predictions for net power, gravity energy storage state of charge, and epsilon. The net power describes the proportion of excess PV output power in negative values and the load portion supplied by the grid and GES in positive values. The dashed red line in the net power curve indicates the average of the total excess PV output power and the total power of the loads supplied by the grid and GES, allowing to quickly evaluate the overall balance between energy generation and consumption. A positive value indicates that the portion of load powered by the grid and GES is higher than the total excess PV power, and vice versa.

In this case study, the load supplied by the grid and GES is higher than the excess PV power output, resulting in a positive mean. This can be explained by the low PV production during the predicted week.

Gravity energy storage system begins charging when there is excess PV power output (blue curve) and discharges when the PV production is insufficient to meet the entire load consumption. GES is essential in maintaining a balance between the supply and demand for energy. This enables the system to increase self-consumption and utilize renewable energy to its fullest potential. If the aforementioned energy systems cannot meet the demand, the grid intervenes unless the loads are shut down or rescheduled. The capacity of the proposed system to use the grid as a backup energy source highlights its adaptability to varying energy demands. The epsilon curve (purple curve) presents the percentage of load consumption supplied by PV and GES systems. This allows the house manager to know the efficiency of the hybrid PV/GES system.

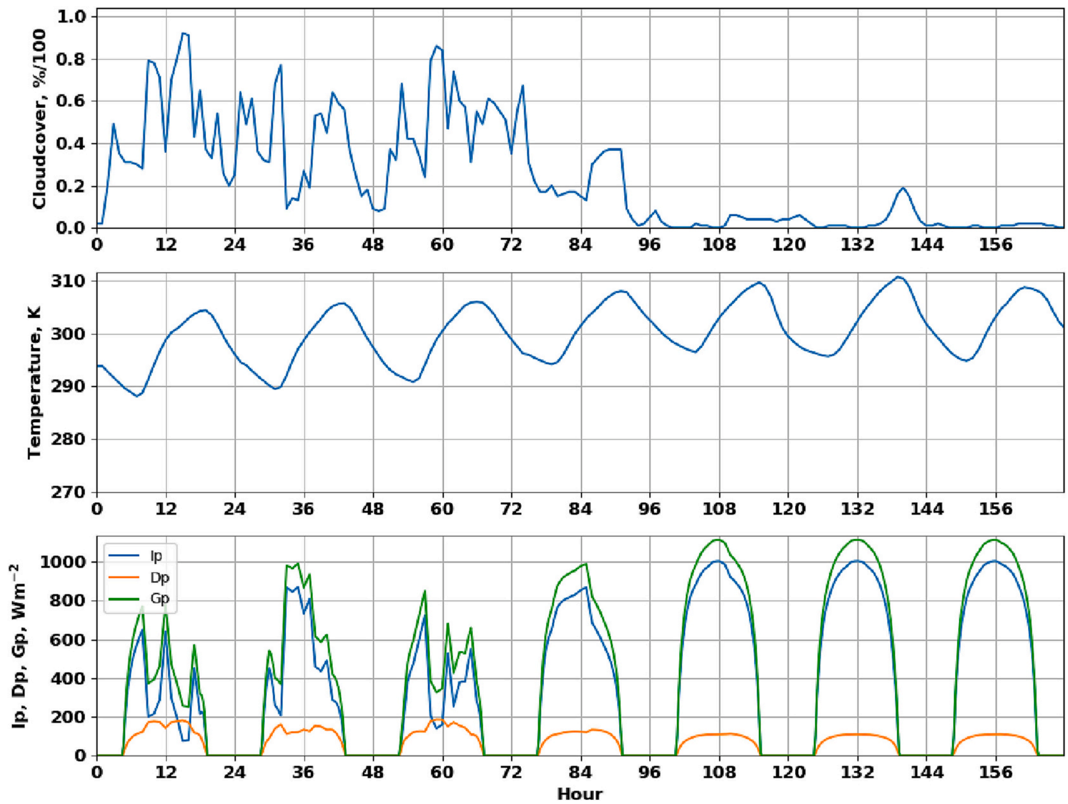

Fig. 7. Weather condition forecast over one week in the investigate region.

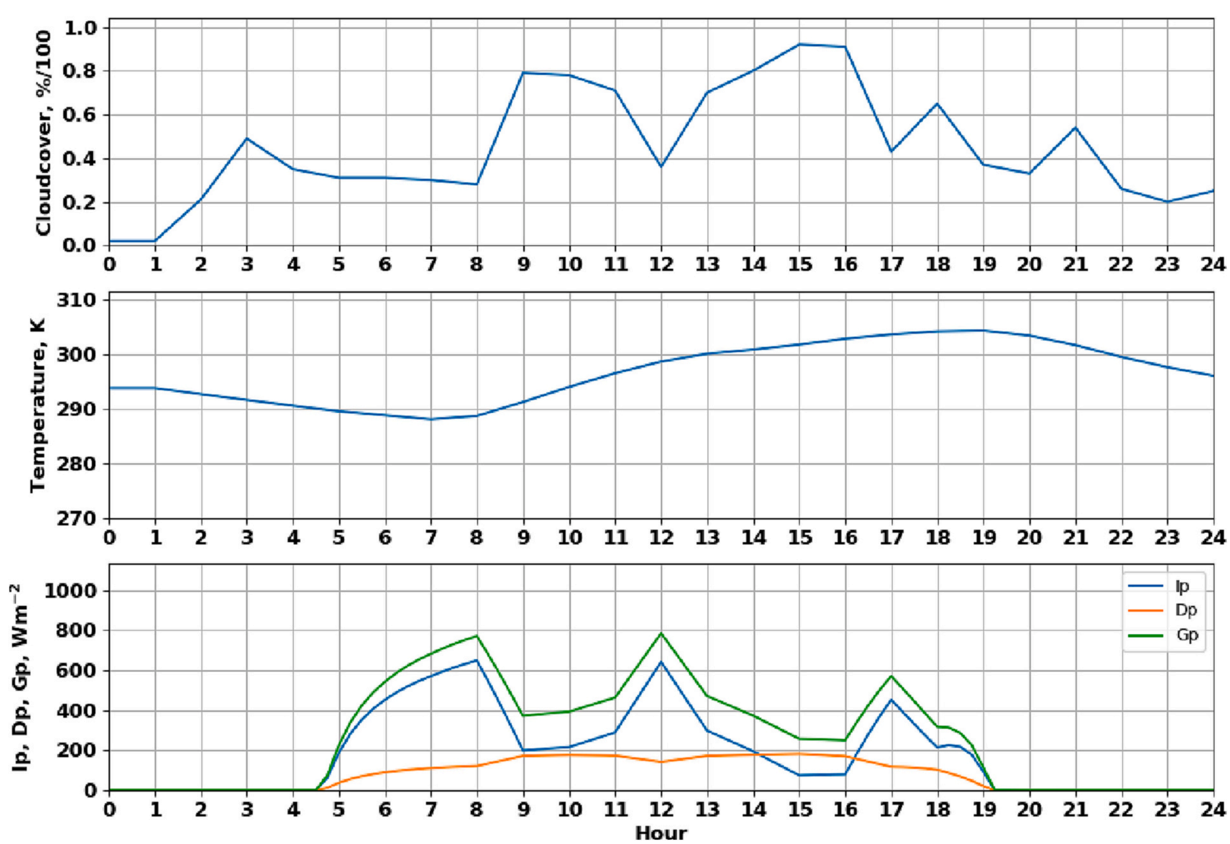

Fig. 8. First day prediction of weather conditions.

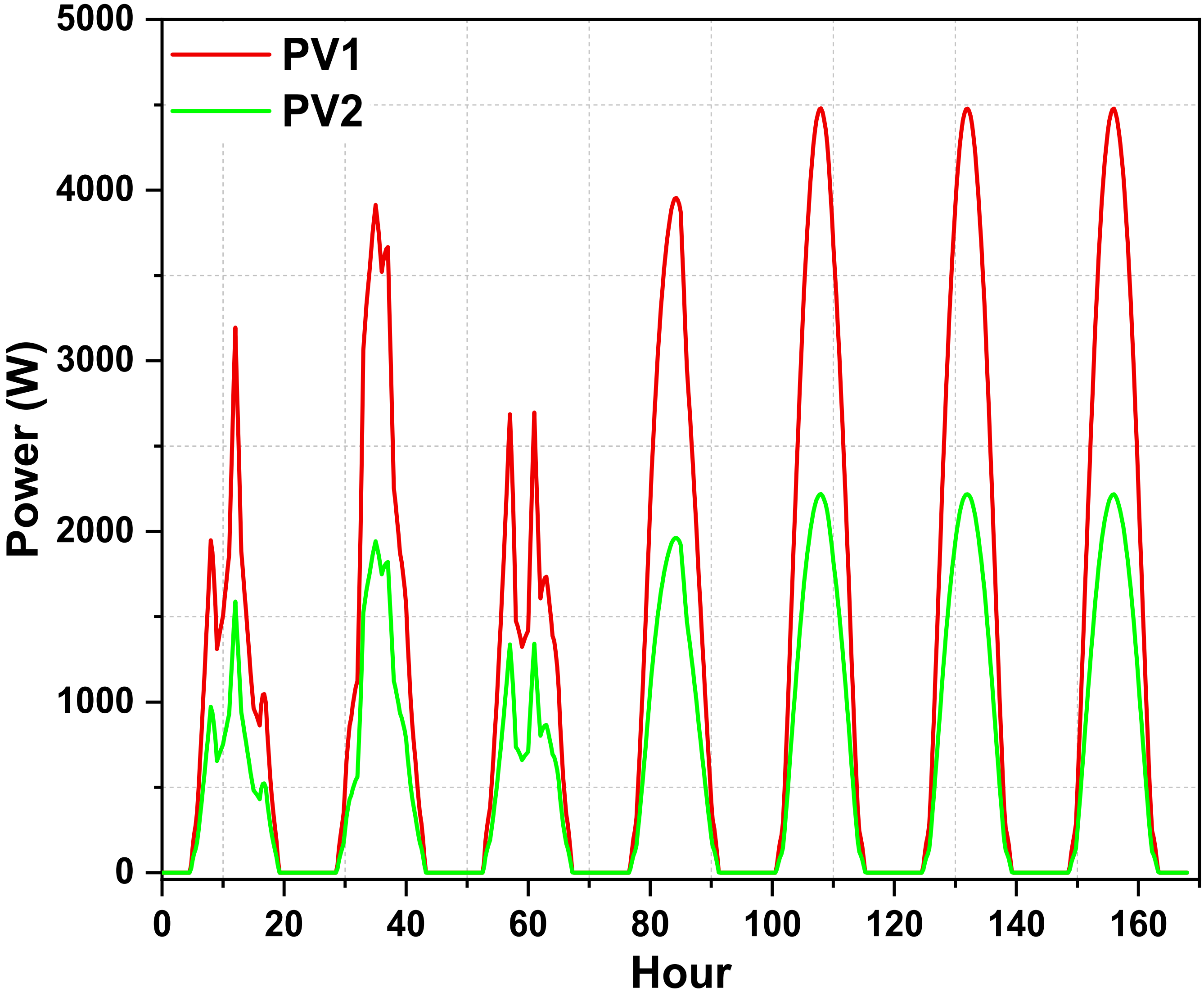

Fig. 9. PV output power prediction of two studied PV systems.

The proposed scheduling and energy management system demonstrates high efficiency by meeting nearly 100 % of the load demand from 6:30 am to 4:30 pm, and an average of 40 % between 4:30 pm and 7 pm using only solar energy combined with the GES system on the first day.

Fig. 14 illustrates the net power, GES states of charge, and epsilon for the first and second prediction days., providing hour-by-hour details of the hybrid system's operation. This detailed information helps determine when GES charges and discharges and provides insights into the hybrid PV/GES system's contribution to the household's energy needs. This figure helps the user make informed decisions regarding load management, such as switching on or off less important loads or shifting their operation to a different hour.

The findings from the analysis of the smart house reveal that on the first day, the GES is charged for a half hour (from 7:30 am to 8:00 am), while on the second day, it is charged for nearly an hour (from 7:30 am to 8:30 am). The system stores energy for approximately 8 h until the PV production is insufficient to cover all the loads. Discharging occurs between 4 pm and 5 pm on both days. The epsilon curve presents the portion of load consumption power by the PV and GES for the two days. Remarkably, the hybrid PV/GES system supplies 100 % of the load for eight and a half hours (from 6:30 am to 4:30 pm) on both days. The detailed information provided assists users in making informed decisions regarding load management strategies, optimizing energy utilization, and leveraging the hybrid PV/GES system's capabilities to meet the household's energy demands.

5. Model validation

To assess the accuracy of the developed forecast model, a comparison between the PV predicted and measured production was performed. The experimental data were obtained from the PV system's inverter, utilizing Amorphous silicon (a-Si) modules with a maximum total rated power of 1.86 kWp. The findings of this comparison are depicted in Fig. 15.

The results demonstrate a strong alignment between the predicted PV production and the actual measured data. However, a noticeable discrepancy arises between the two curves when the PV production reaches its peak. Several factors contribute to this discrepancy. Firstly, the infrequent cleaning of the PV installation can have an impact on the actual PV output. Accumulated dust on the PV modules can reduce their efficiency, leading to a suboptimal energy production compared to the predicted values. Therefore, it is crucial to ensure regular maintenance and cleaning of the PV system to maximize its performance. Additionally, there is an inherent prediction error associated with forecasting weather conditions, specifically cloud cover. The forecast model relies on data obtained from the Dark Sky API to estimate cloud cover, which can introduce uncertainties into the accuracy of the predictions.

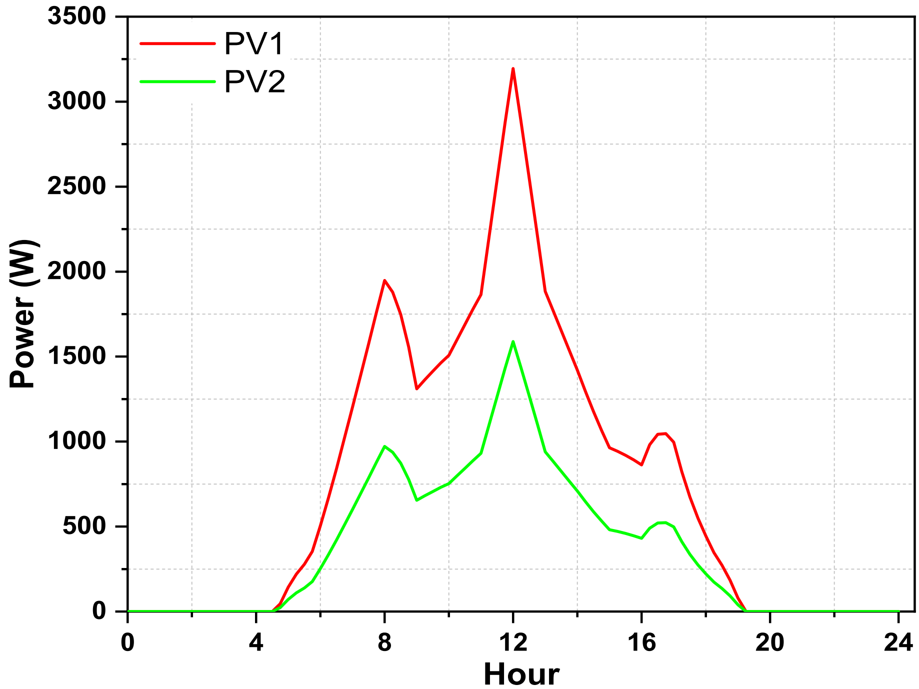

Fig. 10. First day prediction of PV systems studied.

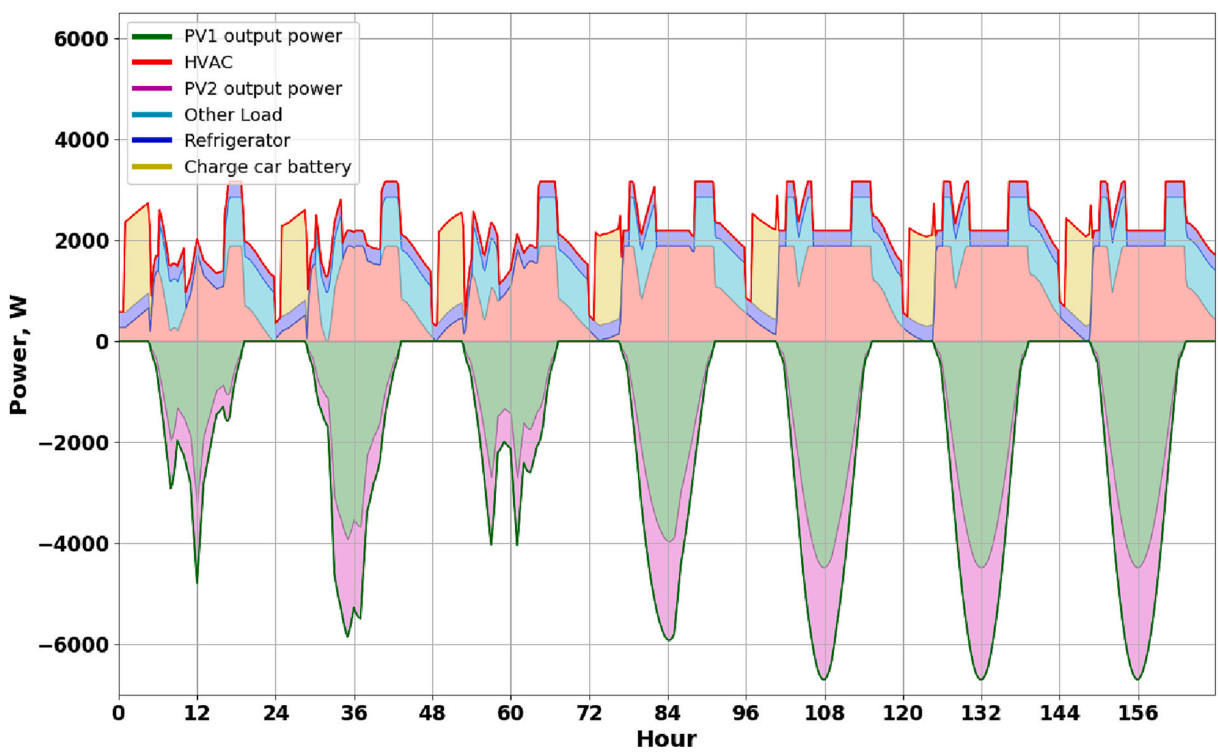

Fig. 11. SHEMS based on PV output power forecast, GES state of charge prediction, dynamic electricity price, and scheduled loads over a week.

Variations in actual cloud cover compared to the forecasted values can influence the amount of solar radiation reaching the PV modules, resulting in deviations between the predicted and measured PV production.

To evaluate the performance of the developed model, two important metrics, namely RMSE (Root Mean Square Error) and MAPE (Mean Absolute Percentage Error), are employed (Eqs. (11) and (12)). The calculated prediction errors range from 13.45 % to 23.16 % for RMSE and from 4.06 % to 11.27 % for MAPE. Similar error ranges have been observed in other PV forecast models documented in the literature [53,54].

$$RMSE = \frac{\sqrt{\frac{1}{m}\sum_{i=1}^{m}(S_i - Y_i)^2}}{Y_m} \tag{11}$$

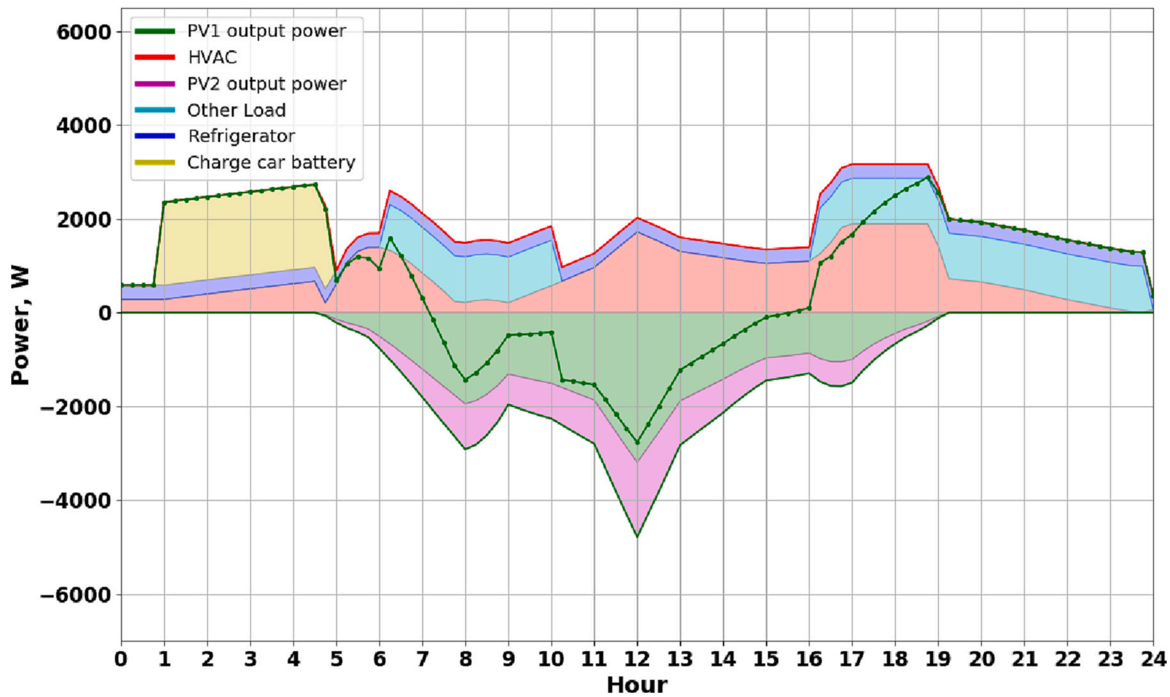

Fig. 12. SHEMS of the first day according dynamic electricity price, predicted PV production, GES state of charge forecast, and scheduled loads.

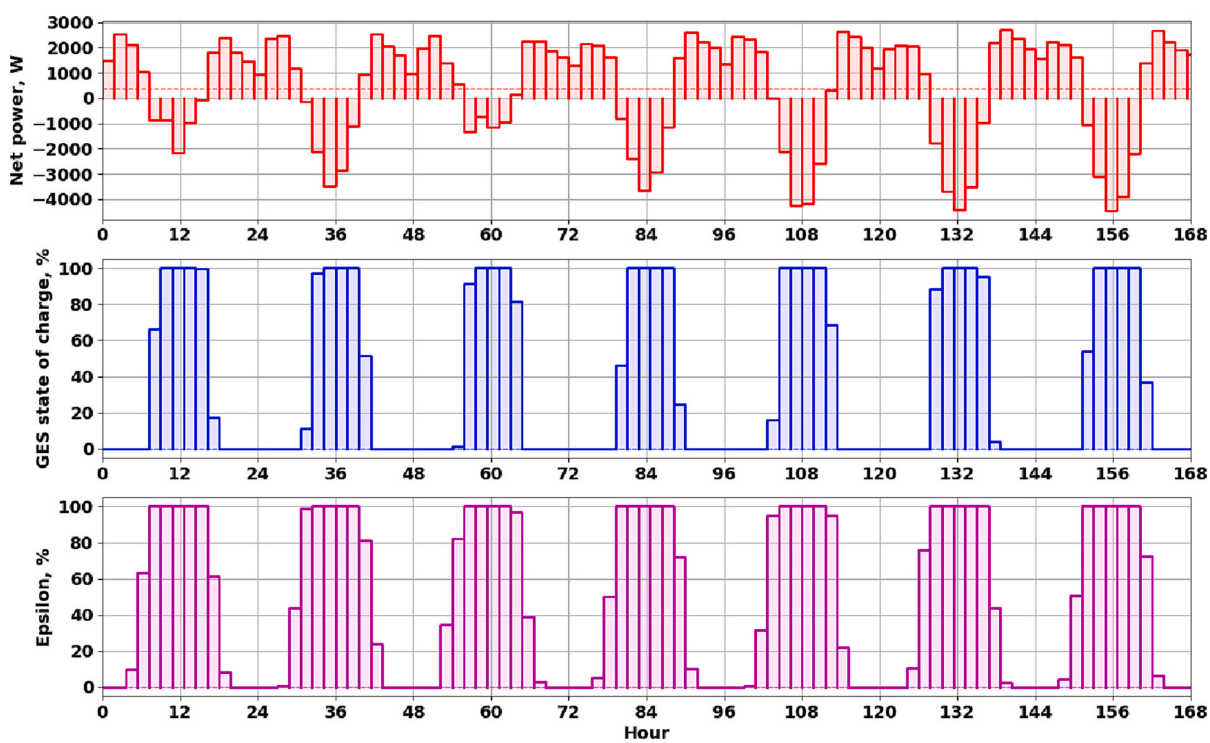

Fig. 13. Prediction of net power (at the top), GES state of charge, and epsilon over a week.

$$MAPE = \frac{1}{m}\left(\sum_{i=1}^{m}\left|\frac{S_i - Y_i}{Y_t}\right|\right) \tag{12}$$

where, S_i, Y_i, Y_m, and Y_t are the PV production forecast value at time i, the PV output power measured value at time i, the mean PV production of each period, and the total rated power of the PV system used which is 1.86 kWp in this study.

Table 3 presents the validation of Eqs. (11) and (12), which are used to assess the accuracy of a prediction model for PV power production. The table includes a set of predicted values (S) and actual values (Y), along with the corresponding squared differences and the differences divided by the true value. The calculated values demonstrate the performance of the prediction model. RMSE values indicate the average deviation between the predicted and actual values, normalized by the true value. MAPE values represent the average percentage error between the predicted and actual values. Overall, the validation results provide

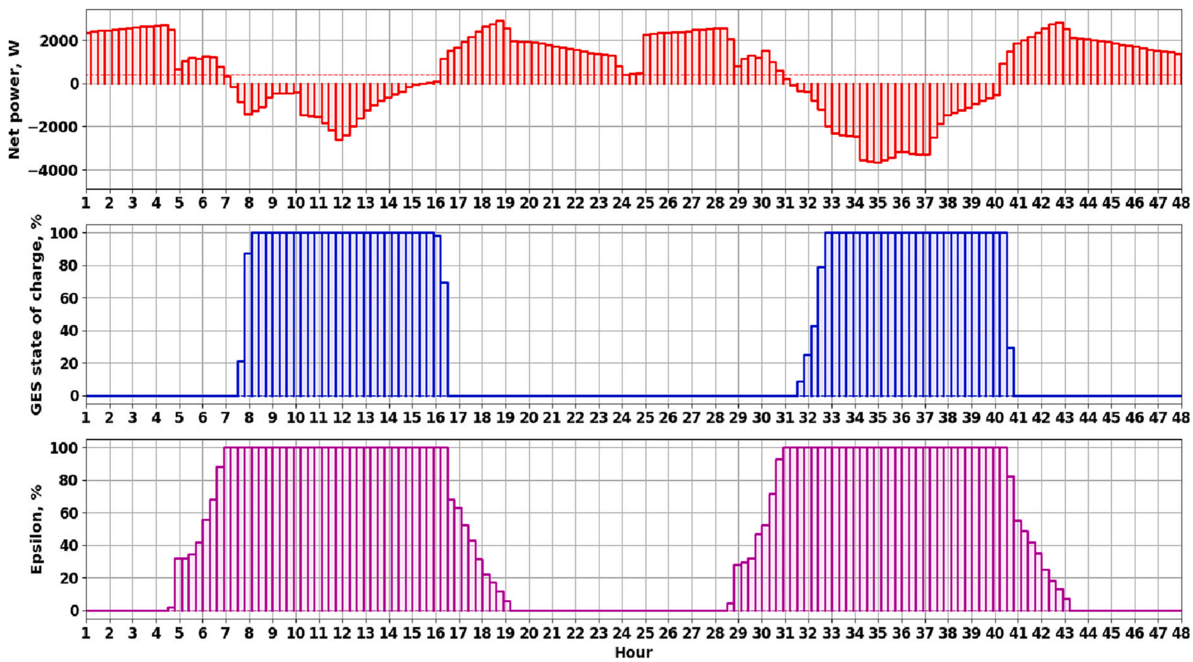

Fig. 14. First and second days of net power (at the top), GES state of charge, and epsilon forecast.

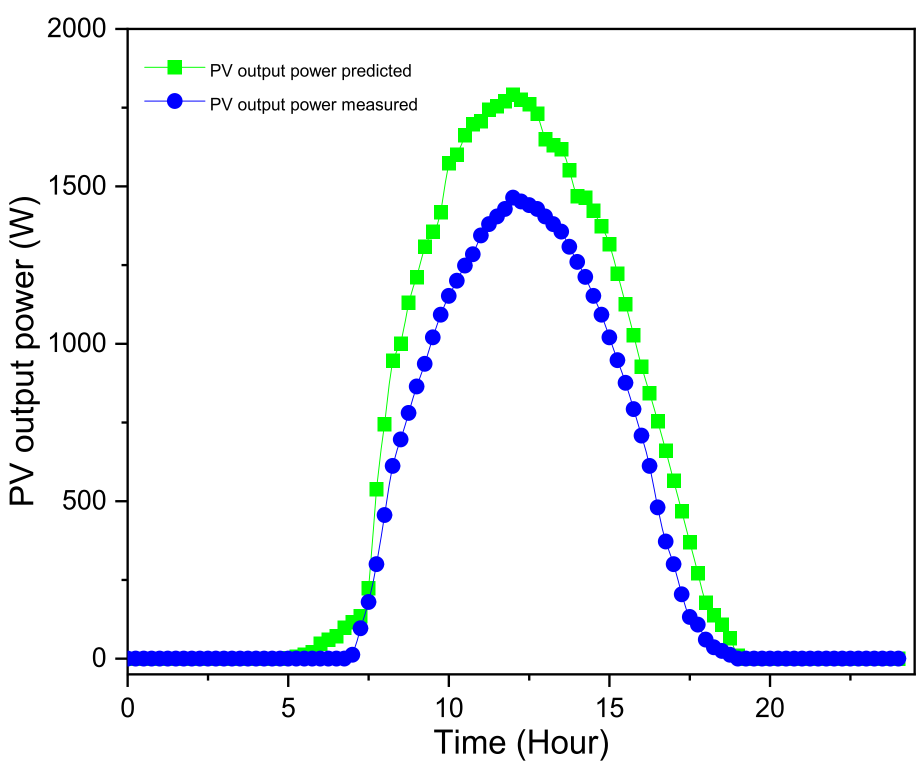

Fig. 15. Comparison between predicted and measured PV output power.

insights into the accuracy and precision of the prediction model for PV power production.

To assess the accuracy of the developed model, a comparison with other existing models was conducted, focusing on the evaluation metrics of RMSE and MAPE. Table 4 presents a comparison of the RMSE and MAPE values for the developed model with several other models. According to the results, the developed model achieved an RMSE of 13.45 %–23.16 % and an MAPE of 4.06 %–11.27 %. These results indicate that the developed model performed competitively compared to the other models in terms of RMSE and MAPE. However, further analysis and consideration of other evaluation metrics may be necessary to obtain a comprehensive understanding of the model's performance.

6. Conclusions

The integration of a smart home energy management system (SHEMS) within the smart grid domain is crucial for achieving efficient electricity usage and facilitating demand response. By leveraging digital

Table 3
Validation of RMSE and MAPE equations.

Index	Si	Yi	(Si-Yi)^2	(Si-Yi)/Yt	RMSE	MAPE
1	1356.46	1020	113,203.88	0.18	0.22	0.10
2	223.87	180	1924.41	0.02	0.22	0.10
3	1650.27	1404	60,647.55	0.13	0.22	0.10
4	9.86	0	97.31	0.01	0.22	0.10
5	753.95	480	75,051.22	0.15	0.22	0.10
6	927.90	708	48,354.81	0.12	0.22	0.10

Table 4
Compares the created model's RMSE and MAPE to those of other models.

Method	RMSE	MAPE
Model C—C DNN [55]	–	9.58 %
Method using a parallel-series CVNN [56]	–	3.92 %
Method using a parallel-series spline [56]	–	5.98 %
Theory of Grey Systems [57]	–	4.84 %
Statistical techniques based on Elman ANN and multiple regression (MR) analyses [58]	10.91 %– 23.99 %	–
WT, fuzzy ARTMAP (FA), and Firefly (FF) [59]	12.11 %– 13.13 %	3.38 %– 11.83 %,
Present study	13.45 % - 23.16 %	4.06 % - 11.27 %

inhabitant services, smart home appliances, wireless communication, and smart sensor technologies, SHEMS has the potential to raise living standards while preserving social and environmental resources. SHEMS has grown in popularity in recent years as a result of enhanced accessibility, convenience, and cost via tablet and smart phone connectivity. Furthermore, advancements in smart grid infrastructure, encompassing two-way communication, monitoring, metering, and devices, have laid a robust foundation for SHEMS applications.

This paper presents a novel forecast model for smart house energy management system over the span of one week. The smart home appliances are interconnected through smart communication technologies to a hybrid PV/GES system as well as the power utilities. The SHEMS algorithm implemented allows users to optimize their energy consumption and reduce electricity bills by shifting the house's demand over the course of one week. The scheduling of loads is determined by dynamic electricity prices, PV generation predictions, and GES state of charge forecasts.

The forecast model utilized in this SHEMS employs a dynamic simulator to forecast PV output power over one week. This is accomplished by considering the characteristics and mathematical equations of PV modules, as well as predictions of solar radiation based on solar irradiance equations, cloud cover, and temperature obtained from one of the most accurate sources of weather prediction, namely the Dark Sky API. The case study examined in this work involves a smart house with smart appliances and communication technologies, with a maximum instantaneous power consumption of approximately 6 kW. It incorporates a 5 kWp PV power system and a gravity energy storage system with a maximum capacity of 0.55 kWh.

The results indicate that by implementing SHEMS, the hybrid PV/GES system can effectively cover the total load consumption of the house for approximately eight and a half hours each day. This leads to significant reductions in the house's energy costs and its adverse environmental footprint. Various performance metrics are employed to evaluate the accuracy of the developed forecast model, with prediction errors ranging from 13.45 % to 23.16 % for RMSE and from 4.06 % to 11.27 % for MAPE. A comparison between the developed model and other existing models was performed, evaluating the metrics of RMSE and MAPE. The results demonstrate that the proposed model falls within the range of performance observed in the other models. This indicates that the developed model shows promising accuracy and can be considered competitive among existing models for the task of PV power production prediction.

Future studies could explore the enhancement of the proposed model by incorporating additional renewable resources such as wind, biomass, and geothermal energy, thereby further advancing the capabilities and sustainability of SHEMS.

CRediT authorship contribution statement

Arechkik Ameur: Original draft preparation, Methodology, Data curation, Visualization, Writing.

Asmae Berrada: Supervision, Writing, Original draft preparation, Methodology, Visualization, Validation, Reviewing, and Editing.

Anisa Emrani: Writing - Software, Methodology, Visualization, Data curation, Editing.

Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

Author's name	Affiliation
Ameur Arechkik	International University of Rabat
Asmae Berrada	International University of Rabat
Anisa Emrani	International University of Rabat

Data availability

Data will be made available on request.

Acknowledgement

The research leading to these results has received funding from IRESEN and CDTI (2021-2024) –GESYS project.

References

[1] L. Amabile, D. Bresch-Pietri, G. El Hajje, S. Labbé, N. Petit, Optimizing the self-consumption of residential photovoltaic energy and quantification of the impact of production forecast uncertainties, Adv. Appl. Energy 2 (May 2021) 100020, https://doi.org/10.1016/J.ADAPEN.2021.100020.

[2] A. Tascikaraoglu, A.R. Boynuegri, M. Uzunoglu, A demand side management strategy based on forecasting of residential renewable sources: a smart home system in Turkey, Energy Build. 80 (Sep. 2014) 309–320, https://doi.org/10.1016/J.ENBUILD.2014.05.042.

[3] C. Zhang, C. Cui, Y. Zhang, J. Yuan, Y. Luo, W. Gang, A review of renewable energy assessment methods in green building and green neighborhood rating systems, Energy Build. 195 (Jul. 2019) 68–81, https://doi.org/10.1016/J.ENBUILD.2019.04.040.

[4] A. Ahmed, T. Ge, J. Peng, W.C. Yan, B.T. Tee, S. You, Assessment of the renewable energy generation towards net-zero energy buildings: a review, Energy Build. 256 (Feb. 2022) 111755, https://doi.org/10.1016/J.ENBUILD.2021.111755.

[5] K. Hara Chakravarty, M. Sadi, H. Chakravarty, A. Sulaiman Alsagri, T. James Howard, A. Arabkoohsar, A review on integration of renewable energy processes in vapor absorption chiller for sustainable cooling, Sustain. Energy Technol. Assess. 50 (Mar. 2022) 101822, https://doi.org/10.1016/J.SETA.2021.101822.

[6] Y. Luo, L. Zhang, M. Bozlar, Z. Liu, H. Guo, F. Meggers, Active building envelope systems toward renewable and sustainable energy, Renew. Sust. Energ. Rev. 104 (Apr. 2019) 470–491, https://doi.org/10.1016/J.RSER.2019.01.005.

[7] F. Harkouss, F. Fardoun, P.H. Biwole, Optimization approaches and climates investigations in NZEB—A review, Build. Simul. 11 (5) (May 2018) 923–952, https://doi.org/10.1007/S12273-018-0448-6, 2018 11:5.

[8] D.J.C. MacKay, Solar energy in the context of energy use, energy transportation and energy storage, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 371 (1996) (Aug. 2013), https://doi.org/10.1098/RSTA.2011.0431.

[9] E. Kabir, P. Kumar, S. Kumar, A.A. Adelodun, K.H. Kim, Solar energy: potential and future prospects, Renew. Sust. Energ. Rev. 82 (Feb. 2018) 894–900, https://doi.org/10.1016/J.RSER.2017.09.094.

[10] A.Q. Al-Shetwi, Sustainable development of renewable energy integrated power sector: trends, environmental impacts, and recent challenges, Sci. Total Environ. 822 (May 2022) 153645, https://doi.org/10.1016/J.SCITOTENV.2022.153645.

[11] N. Arghira, L. Hawarah, S. Ploix, M. Jacomino, Prediction of appliances energy use in smart homes, Energy 48 (1) (Dec. 2012) 128–134, https://doi.org/10.1016/J.ENERGY.2012.04.010.

[12] G. Dileep, A survey on smart grid technologies and applications, Renew. Energy 146 (Feb. 2020) 2589–2625, https://doi.org/10.1016/J.RENENE.2019.08.092.

[13] S. Sharda, K. Sharma, M. Singh, A real-time automated scheduling algorithm with PV integration for smart home prosumers, J. Build. Eng. 44 (Dec. 2021) 102828, https://doi.org/10.1016/J.JOBE.2021.102828.

[14] A.C. Duman, H.S. Erden, Ö. Gönül, Ö. Güler, A home energy management system with an integrated smart thermostat for demand response in smart grids, Sustain. Cities Soc. 65 (Feb. 2021) 102639, https://doi.org/10.1016/J.SCS.2020.102639.

[15] S. Zamanloo, H. Askarian Abyaneh, H. Nafisi, M. Azizi, Optimal two-level active and reactive energy management of residential appliances in smart homes, Sustain. Cities Soc. 71 (Aug. 2021) 102972, https://doi.org/10.1016/J.SCS.2021.102972.

[16] W. El-Baz, M. Seufzger, S. Lutzenberger, P. Tzscheutschler, U. Wagner, Impact of probabilistic small-scale photovoltaic generation forecast on energy management systems, Sol. Energy 165 (May 2018) 136–146, https://doi.org/10.1016/J.SOLENER.2018.02.069.

[17] A.L. Klingler, L. Teichtmann, Impacts of a forecast-based operation strategy for grid-connected PV storage systems on profitability and the energy system, Sol. Energy 158 (Dec. 2017) 861–868, https://doi.org/10.1016/J.SOLENER.2017.10.052.

[18] W. El-Baz, P. Tzscheutschler, U. Wagner, Day-ahead probabilistic PV generation forecast for buildings energy management systems, Sol. Energy 171 (Sep. 2018) 478–490, https://doi.org/10.1016/J.SOLENER.2018.06.100.

[19] R. Hanna, J. Kleissl, A. Nottrott, M. Ferry, Energy dispatch schedule optimization for demand charge reduction using a photovoltaic-battery storage system with solar forecasting, Sol. Energy 103 (May 2014) 269–287, https://doi.org/10.1016/J.SOLENER.2014.02.020.

[20] M.S. Javadi, M. Gough, M. Lotfi, A. Esmaeel Nezhad, S.F. Santos, J.P.S. Catalão, Optimal self-scheduling of home energy management system in the presence of photovoltaic power generation and batteries, Energy 210 (Nov. 2020) 118568, https://doi.org/10.1016/j.energy.2020.118568.

[21] M.S. Javadi, et al., Self-scheduling model for home energy management systems considering the end-users discomfort index within price-based demand response programs, Sustain. Cities Soc. 68 (May 2021) 102792, https://doi.org/10.1016/j.scs.2021.102792.

[22] M. Javadi, et al., A multi-objective model for home energy management system self-scheduling using the epsilon-constraint method, in: 2020 *IEEE 14th International Conference on Compatibility,* Power Electronics and Power Engineering (CPE-POWERENG), Jul. 2020, pp. 175–180, https://doi.org/10.1109/CPE-POWERENG48600.2020.9161526.

[23] M.S. Javadi, et al., Conditional value-at-risk model for smart home energy management systems, e-Prime – Adv. Electr. Eng. Electron. Energy 1 (Jan. 2021) 100006, https://doi.org/10.1016/j.prime.2021.100006.

[24] A.O. Ali, M.R. Elmarghany, M.M. Abdelsalam, M.N. Sabry, A.M. Hamed, Closed-loop home energy management system with renewable energy sources in a smart grid: a comprehensive review, J. Energy Storage 50 (Jun. 2022) 104609, https://doi.org/10.1016/J.EST.2022.104609.

[25] M. Javadi, et al., Optimal operation of home energy management systems in the presence of the inverter-based heating, ventilation and air conditioning system, in: 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Jun. 2020, pp. 1–6, https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160629.

[26] U. Zafar, S. Bayhan, A. Sanfilippo, Home energy management system concepts, configurations, and Technologies for the Smart Grid, IEEE Access 8 (2020) 119271–119286, https://doi.org/10.1109/ACCESS.2020.3005244.

[27] K.N. Qureshi, A. Alhudhaif, A. Hussain, S. Iqbal, G. Jeon, Trust aware energy management system for smart homes appliances, Comput. Electr. Eng. 97 (Jan. 2022) 107641, https://doi.org/10.1016/J.COMPELECENG.2021.107641.

[28] H.R.O. Rocha, I.H. Honorato, R. Fiorotti, W.C. Celeste, L.J. Silvestre, J.A.L. Silva, An artificial intelligence based scheduling algorithm for demand-side energy management in smart homes, Appl. Energy 282 (Jan. 2021) 116145, https://doi.org/10.1016/J.APENERGY.2020.116145.

[29] A. Ahmad, et al., An optimized home energy management system with integrated renewable energy and storage resources, Energies 10 (4) (Apr. 2017) 549, https://doi.org/10.3390/EN10040549, 2017, Vol. 10, Page 549.

[30] Z. Zheng, Z. Sun, J. Pan, X. Luo, An integrated smart home energy management model based on a pyramid taxonomy for residential houses with photovoltaic-battery systems, Appl. Energy 298 (Sep. 2021) 117159, https://doi.org/10.1016/J.APENERGY.2021.117159.

[31] A.A. Ismail, N.T. Mbungu, A. Elnady, R.C. Bansal, A.-K. Hamid, M. AlShabi, Impact of electric vehicles on smart grid and future predictions: a survey, Int. J. Model. Simul. (Dec. 2022) 1–17, https://doi.org/10.1080/02286203.2022.2148180.

[32] S. Chadha, V. Jain, H.R. Singh, A review on smart charging impacts of electric vehicles on grid, Mater. Today: Proc. 63 (2022) 751–755, https://doi.org/10.1016/j.matpr.2022.05.122.

[33] T. Almeida, M. Lotfi, M. Javadi, G.J. Osório, J.P.S. Catalão, Economic analysis of coordinating electric vehicle parking lots and home energy management systems, in: 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Jun. 2020, pp. 1–6, https://doi.org/10.1109/EEEIC/ICPSEurope49358.2020.9160594.

[34] A. Berrada, K. Loudiyi, Operation, sizing, and economic evaluation of storage for solar and wind power plants, Renew. Sust. Energ. Rev. 59 (Jun. 2016) 1117–1129, https://doi.org/10.1016/j.rser.2016.01.048.

[35] A. Berrada, K. Loudiyi, Modeling and material selection for gravity storage using FEA method, in: 2016 International Renewable and Sustainable Energy Conference (IRSEC), IEEE, Marrakech, Nov. 2016, pp. 1159–1164, https://doi.org/10.1109/IRSEC.2016.7983956.

[36] A. Berrada, K. Loudiyi, R. Garde, Dynamic modeling of gravity energy storage coupled with a PV energy plant, Energy 134 (Sep. 2017) 323–335, https://doi.org/10.1016/j.energy.2017.06.029.

[37] A. Emrani, A. Berrada, M. Bakhouya, Modeling and performance evaluation of the dynamic behavior of gravity energy storage with a wire rope hoisting system, J. Energy Storage 33 (Jan. 2021) 102154, https://doi.org/10.1016/j.est.2020.102154.

[38] A. Berrada, A. Emrani, A. Ameur, Life-cycle assessment of gravity energy storage systems for large-scale application, J. Energy Storage 40 (2021) 102825, https://doi.org/10.1016/j.est.2021.102825.

[39] A. Berrada, K. Loudiyi, I. Zorkani, Sizing and economic analysis of gravity storage, J. Renew. Sustain. 8 (2) (Mar. 2016) 024101, https://doi.org/10.1063/1.4943119.

[40] A. Berrada, Financial and economic modeling of large-scale gravity energy storage system, Renew. Energy 192 (2022) 405–419, https://doi.org/10.1016/j.renene.2022.04.086.

[41] H. Hou, T. Xu, X. Wu, H. Wang, A. Tang, Y. Chen, Optimal capacity configuration of the wind-photovoltaic-storage hybrid power system based on gravity energy storage system, Appl. Energy 271 (2020) 115052, https://doi.org/10.1016/j.apenergy.2020.115052.

[42] A. Emrani, A. Berrada, M. Bakhouya, Optimal sizing and deployment of gravity energy storage system in hybrid PV-wind power plant, Renew. Energy 183 (Jan. 2022) 12–27, https://doi.org/10.1016/J.RENENE.2021.10.072.

[43] A. Emrani, A. Berrada, A. Arechkik, M. Bakhouya, Improved techno-economic optimization of an off-grid hybrid solar/wind/gravity energy storage system based on performance indicators, J. Energy Storage 49 (May 2022) 104163, https://doi.org/10.1016/J.EST.2022.104163.

[44] B. Mahapatra, A. Nayyar, Home energy management system (HEMS): concept, architecture, infrastructure, challenges and energy management schemes, Energy Syst. (2019) 1–27. Nov. 2019, https://doi.org/10.1007/S12667-019-00364-W.

[45] Y. Ma, X. Chen, L. Wang, J. Yang, Study on smart home energy management system based on artificial intelligence, J. Sens. 2021 (2021), https://doi.org/10.1155/2021/9101453.

[46] Dark sky - Madrid, Madrid. https://darksky.net/forecast/40.4169,-3.7036/us12/en (accessed Jun. 26, 2022).

[47] G. Dutta, K. Mitra, A literature review on dynamic pricing of electricity, J. Oper. Res. Soc. 68 (10) (Oct. 2017) 1131–1145, https://doi.org/10.1057/S41274-016-0149-4/TABLES/4.

[48] X. Zhao, W. Gao, F. Qian, J. Ge, Electricity cost comparison of dynamic pricing model based on load forecasting in home energy management system, Energy 229 (Aug. 2021) 120538, https://doi.org/10.1016/J.ENERGY.2021.120538.

[49] A. Emrani, A. Berrada, A. Ameur, M. Bakhouya, Assessment of the round-trip efficiency of gravity energy storage system: analytical and numerical analysis of energy loss mechanisms, J. Energy Storage 55 (2022) 105504, https://doi.org/10.1016/j.est.2022.105504.

[50] A. Ameur, A. Berrada, A. Emrani, Dynamic forecasting model of a hybrid photovoltaic/gravity energy storage system for residential applications, Energy Build. 271 (2022) 112325, https://doi.org/10.1016/j.enbuild.2022.112325.

[51] A. Shokri, M. Sanavi Fard, Water-energy nexus: cutting edge water desalination technologies and hybridized renewable-assisted systems; challenges and future roadmaps, Sustain. Energy Technol. Assess. 57 (Jun. 2023) 103173, https://doi.org/10.1016/j.seta.2023.103173.

[52] A. Siddiqi, L.D. Anadon, The water–energy nexus in Middle East and North Africa, Energy Policy 39 (8) (Aug. 2011) 4529–4540, https://doi.org/10.1016/j.enpol.2011.04.023.

[53] A.U. Haque, M.H. Nehrir, P. Mandal, Solar PV power generation forecast using a hybrid intelligent approach, undefined (2013), https://doi.org/10.1109/PESMG.2013.6672634.

[54] M.G. De Giorgi, P.M. Congedo, M. Malvoni, Photovoltaic power forecasting using statistical methods: impact of weather data, IET Sci. Meas. Technol. 8 (3) (May 2014) 90–97, https://doi.org/10.1049/IET-SMT.2013.0135.

[55] F. Mei, Q. Wu, T. Shi, J. Lu, Y. Pan, J. Zheng, An ultrashort-term net load forecasting model based on phase space reconstruction and deep neural network, Appl. Sci. 9 (7) (2019) 1487.

[56] S. Sepasi, E. Reihani, A.M. Howlader, L.R. Roose, M.M. Matsuura, Very short term load forecasting of a distribution system with high PV penetration, Renew. Energy 106 (2017) 142–148.

[57] S. Sreekumar, K.C. Sharma, R. Bhakar, Grey system theory based net load forecasting for high renewable penetrated power systems, Technol. Econ. Smart Grids Sustain. Energy 5 (1) (2020) 1–14.

[58] M.G. De Giorgi, P.M. Congedo, M. Malvoni, Photovoltaic power forecasting using statistical methods: impact of weather data, IET Sci. Meas. Technol. 8 (3) (May 2014) 90–97, https://doi.org/10.1049/IET-SMT.2013.0135.

[59] A.U. Haque, M.H. Nehrir, P. Mandal, Solar PV power generation forecast using a hybrid intelligent approach, undefined (2013), https://doi.org/10.1109/PESMG.2013.6672634.