University of Zawia Journal of Engineering Sciences and Technology (UZJEST)
Volume 3, Issue 2, (2025), pp 261-275, ISSN 3006-2764

Performance Analysis and Sizing Optimization of a Utility Scale Stand-Alone Renewable Energy PV/Battery Storage System for Urban Zones

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Received: 14-10-2025 | Accepted: 12-12-2025 | Available online: 15-12-2025 | DOI:10.26629/uzjest.2025.21

ABSTRACT

The intermittent nature of renewable energy sources requires an effective solution for long-term energy storage. Battery integration has proven its economic viability as an effective technology for storing and ensuring the continuity of electricity, as well as its viability with renewable energy systems (RESs), particularly those utilizing photovoltaic (PV) technologies. However, determining the optimal size of system components remains a major challenge due to the nonlinear interactions between these components. This study aims to propose an effective methodology for establishing the ideal size of a solar photovoltaic system combined with batteries to ensure a sustainable electricity supply for the Wadi al-Shati region, an urban area located in southern Libya. Several constrained operational scenarios were studied under uncertainty to determine the ideal size of the proposed system using an iterative algorithm in a trial-and-error manner. The results showed that the proposed system consists of a 600 MW solar photovoltaic field with a battery storage capacity of 2,460 MWh, which generates enough energy to cover an estimated annual load of 590,018 MWh. The proposed system is expected to prevent the emission of approximately 611 tons of carbon dioxide per year, in addition to the possibility of exporting surplus energy. The total investment cost is estimated at $1.743 billion, while the levelized cost of energy (LCOE) is estimated with and without considering the social cost of the CO2 emission and found as $62/MWh and $135/MWh, respectively, with a payback period of 11.51 and 19.86 years, respectively.

Keywords: Renewable energy system; PV solar energy; Battery storage; sizing optimization; Libya.

تحليل أداء وحساب الحجم المثالي لمنظومة طاقة متجددة مستقلة للطاقة الشمسية الكهروضوئية والبطاريات على نطاق واسع في المناطق الحضرية

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ملخـــــــص البحـــــــث

تتطلب طبيعة الخصائص المتقطعة لمصادر الطاقة المتجددة إيجاد حلاً فعالاً لتخزين الطاقة على المدى الطويل. وقد أثبتت دمج البطاريات جدواها الاقتصادية كتقنية فعالة لتخزين الكهرباء وضمان استمرارها، وتوافقها مع أنظمة الطاقة المتجددة (RESs)، وبالأخص مع تقنيات الطاقة الشمسية الكهروضوئية (PV). وبالرغم من ذلك يبقى تحديد الحجم الأمثل لمكونات النظام يشكل تحديًا كبيرًا نتيجة التفاعلات غير الخطية بين هذه المكونات. تهدف هذه الدراسة الي اقتراح منهجية فعالة لتحديد الحجم الأمثل نظام الطاقة الشمسية الكهروضوئية المدمج مع البطاريات لضمان إمدادات مستدامة للطاقة الكهربائية لمنطقة وادي الشاطئ، وهي منطقة حضارية تقع جنوب ليبيا. تم دراسة عدة سيناريوهات تشغيلية مقيدة في ظل عدم اليقين لتحديد الحجم المثالي لنظام الهجين المقترح باستخدام خوارزمية تكرارية بطريقة التجربة والخطأ. أظهرت النتائج ان النظام المقترح يتكون من حقل طاقة شمسية كهروضوئية بقدرة 600 ميغاواط مع سعة تخزين بطارية تبلغ 2460 ميغاواط ساعة، والذي يولد طاقة كافية لتغطية حمل سنوي يُقدّر بنحو 590,018 ميغاواط ساعة. ومن المتوقع أن يساهم النظام المقترح في منع انبعاث حوالي 611 طنًا سنويًا من ثاني أكسيد الكربون، بالإضافة إلى إمكانية تصدير فائض الطاقة إلى الشبكة الوطنية. ويُقدّر إجمالي تكلفة الاستثمار بحوالي 1.743 مليار دولار، بينما بلغت تكلفة انتاج وحدة الطاقة (LCOE) مع وبدون اخذ التكلفة الاجتماعية لثاني أكسيد الكربون في الاعتبار حوالي 62 و135 دولارًا لكل ميغاواط ساعة على التوالي، مع فترة استرداد تصل إلى 11.51سنة و19.86 سنة على التوالي.

الكلمات الدالة: الطاقات المتجددة؛ الطاقة الشمسية الكهروضوئية؛ بطايات التخزين؛ امثلية حجم مكونات المنظومة، ليبيا.

1. Introduction

The global installed capacity of renewable energy increased by 50% in 2024, obsessed by concerns about climate change and global warming. By the end of 2024, the world had installed approximately 4,448.1 GW of renewable energy sources, including solar, wind, hydropower, geothermal, marine, and biogas, among others. Of this, 2,240 GW was for PV solar energy systems. While the global cumulative installed battery capacity reached 150 GW/363 GWh; this progress in the renewable energy market indicates an international shift towards the utilization of renewable and sustainable energy technologies [1,2]. Recently, the potential and feasibility of renewable energy as a reliable and sustainable source of electricity have been extensively researched by the academic community [3-20]. The world is swiftly transitioning to clean and environmentally sustainable energy sources [21,22]. Libya's economy suffers from an inability to fully cover peak loads, despite decades of reliance on fossil fuels to generate electricity. Libya is a signatory to climate change treaties and conventions. As the largest oil producer in North Africa, the country's reliance on gas and oil for the majority of its revenue and electricity generation underscores the pressing necessity to adopt hybrid renewable energy systems. This shift aims to enhance energy production and reduce its carbon footprint. Libya has great potential, as it has multiple sources of renewable energy that can contribute to energy production. Reports indicate that carbon dioxide (CO_2) emissions from energy production are responsible for 40% of environmental pollution emissions, and globally, annual CO_2 emissions from burning fossil fuels amount to 34 billion tons, with about 45% from coal, 35% from oil, and 20% from natural gas [23,24]. Fathi et al. [25] carried out a technical, financial, and environment study on a solar PV/wind/pumped hydropower storage system to compensate for the Libyan public electricity grid's power outage. The proposed system generates 762,161 MWh with 385 MW of wind and 6000 MW of PV. The load consumed 41.74% of the energy produced, while the remaining 39.26% was stored for later use in the upper reservoir. The proposed solar PV system required an investment of $19.923 billion, a total levelized cost of energy of

\$132.1/MWh, and a payback period of 7.54 years. Aqila, et al. [26] analyzed a hybrid renewable energy system to cover electrical loads based on the energy and capacity of appliances. The study was based on real-time measured data at 10-minute intervals on a house located in Semno in Sebha, Libya. The dynamic simulation results of the proposed hybrid power system reveal that the system comprises 652 W, five 500 W wind turbines, and a 2750 kWh storage battery can cover a load of 51238 kWh each year, with a levelized cost of energy of 0.0107 \$/kWh. Pujari, et al. [27] designed a hybrid renewable energy system combining solar, wind, battery storage, thermal loads, a convection controller, a boiler, and a diesel generator for a village. They used HOMER software for technical and economic analysis to meet the village's energy needs. Their optimal system included 614 kW of solar power and 850 kW of renewable energy and had a levelized cost of energy (LCOE) of 0.272 USD/kWh, supplying 92% of the daily demand of 4502.95 kWh with 70% from renewable sources. Mandal, et al. [28] explored a different hybrid energy system in northern Bangladesh, consisting of 73 kW solar PV, 57 kW wind power, and a 387kWh battery, achieving a low power cost of \$0.37/kWh and reducing carbon emissions by about 62%. In Libya, Yasser, et al. [29] proposed a hybrid energy system combining a 1000 kW solar PV field and a 5000-kW wind turbine farm, along with a pumped hydropower storage system. This setup aims to meet an annual energy load of 6,137 MWh and generates 9,342 MWh each year. The estimated investment is US\$10.5 million, with a Levelized Cost of Energy of 13.2 cents per kWh, potentially saving about 4,385 tons of CO2 annually. In Bangladesh, Das, et al. [30] compared three off-grid hybrid systems in a rural village. The system includes solar panels, wind turbines, diesel turbines, generators, and batteries, with a net cost of US\$711,943. It generates 70.8% of renewable energy and has a payback period of 3.7 years, emitting 62,075 kg of CO2 yearly. Ridha, et al. [31] presented a new method that uses iterative approaches to optimize the SAPV system based on economic and technical factors, considering different storage battery types. Their best configuration included 250 PV modules (25 in series and 10 in parallel) and 40 storage batteries, with specific values for Qi, LLP, LCC, and LCE. They also noted an optimal setup of 872 PV modules and 28 storage batteries. However, there is a lack of studies on system design for the Libyan region using detailed climate and load data.

This study aims to fill this gap by presenting a customized energy solution supported by actual data specific to the Wadi al-Shatti region. Though previous research has shown that energy will be a major feature of energy networks in the coming years, it benefits energy generation and the supply chain. The literature on system design for the Libyan region remains limited, particularly regarding the use of high-resolution hourly climate data and load data for optimizing system components, despite these developments. This study addresses this gap through multi-objective optimization tailored to local constraints. The authors claim that the current work has the following contributions:

- Analysis of a renewable energy system based on PV solar energy and batteries.
- Use of a multi-objective function to optimize the size of the components of the renewable energy system.
- Provision of an economic and environmental analysis, including the social cost of carbon dioxide..

2. Materials and Methods

The approach followed by the research to achieve the aims of the study are presented in Figure **1.**

2.1 Study Area Description

This study focuses on Wadi Al-Shati, a region located in southern Libya at coordinates 27.7351°N, 12.4381°E, approximately 700 km south of the capital, Tripoli. It is characterized by desert terrain, surrounded by mountains in the north and the Ramla al-Zalaf area in the south. The population is estimated at 78,563 (2021), and the area is sparsely populated with vast open land, making it suitable for large-scale solar energy projects. Figure **2** shows the geographic location and potential solar sites.

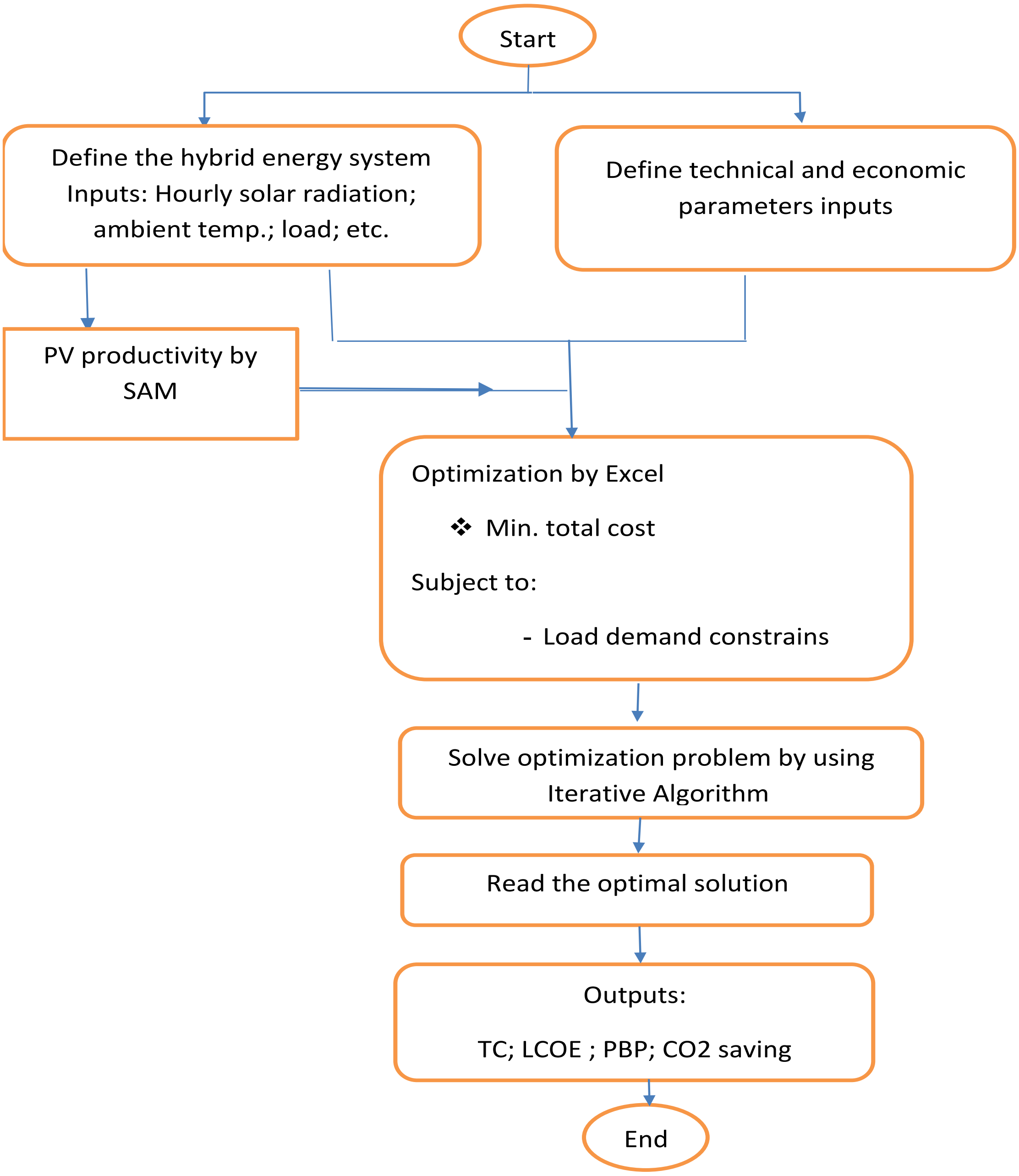

Figure 1. Flowchart for the study

Meteorological data, including Global Horizontal Irradiance (GHI) and ambient air temperature for the years 2023–2024 were gathered from Wadi Alshatti University's Renewable Energy and Sustainable Development Studies Center (RCRESDS) weather station. These parameters, shown in Figure 3 and Figure 4, are used as key inputs in modeling the solar PV performance.

2.2 Environmental Issues Related to Energy

Among the most pollution industries in Libya is the electrical sector. Libya relies solely on fossil fuels for power generation, with an average efficiency of 23%, and the distribution network suffers from energy losses of 17%.The electricity sector's CO_2 emissions factor, as determined by a life cycle assessment, is estimated at 1,037 kg CO_2/MWh [32,33]. While there is no local estimate of the social cost of CO_2, the Libyan scientific community adopts the value set by COP28, which is estimated at US$70/ton of CO_2 [34,35].

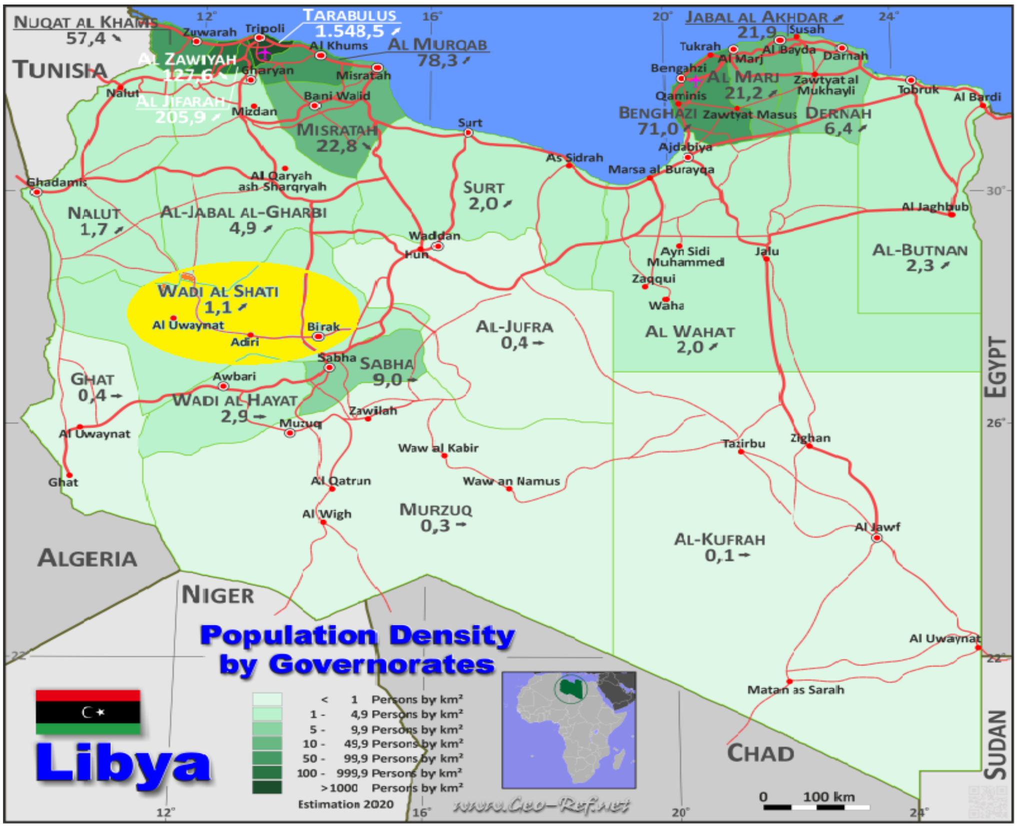

Figure 2. Map of the site under consideration [source: https://www.geo-ref.net/ph/lby.htm]

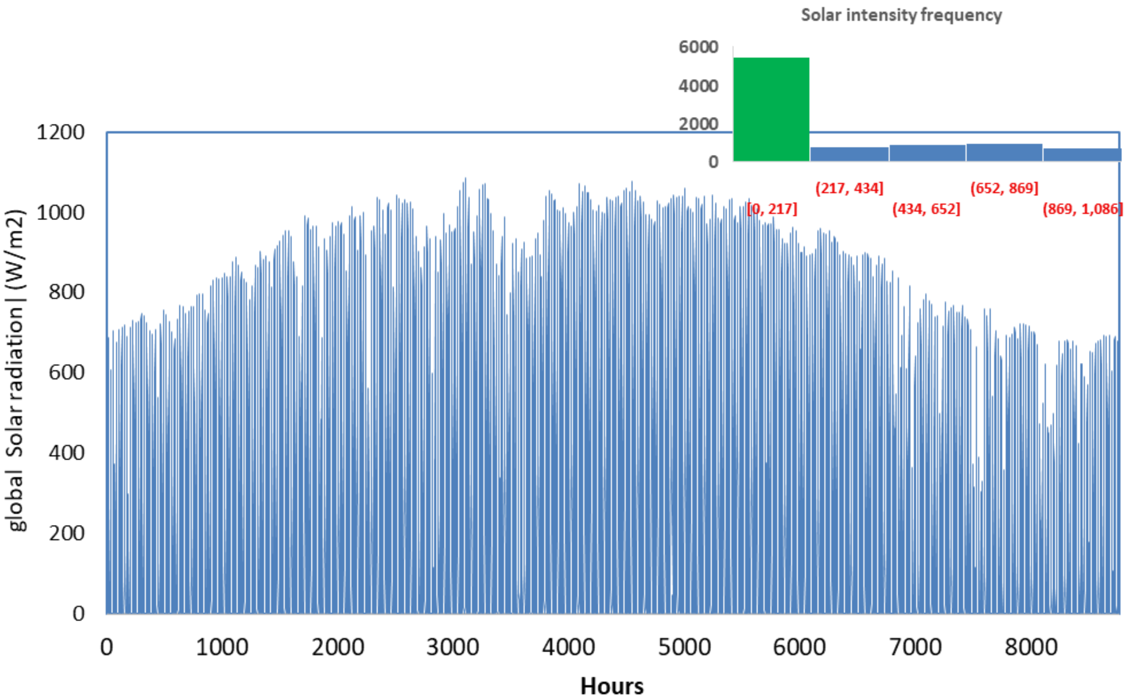

Figure 3. Hourly global horizontal solar radiation (GHI)

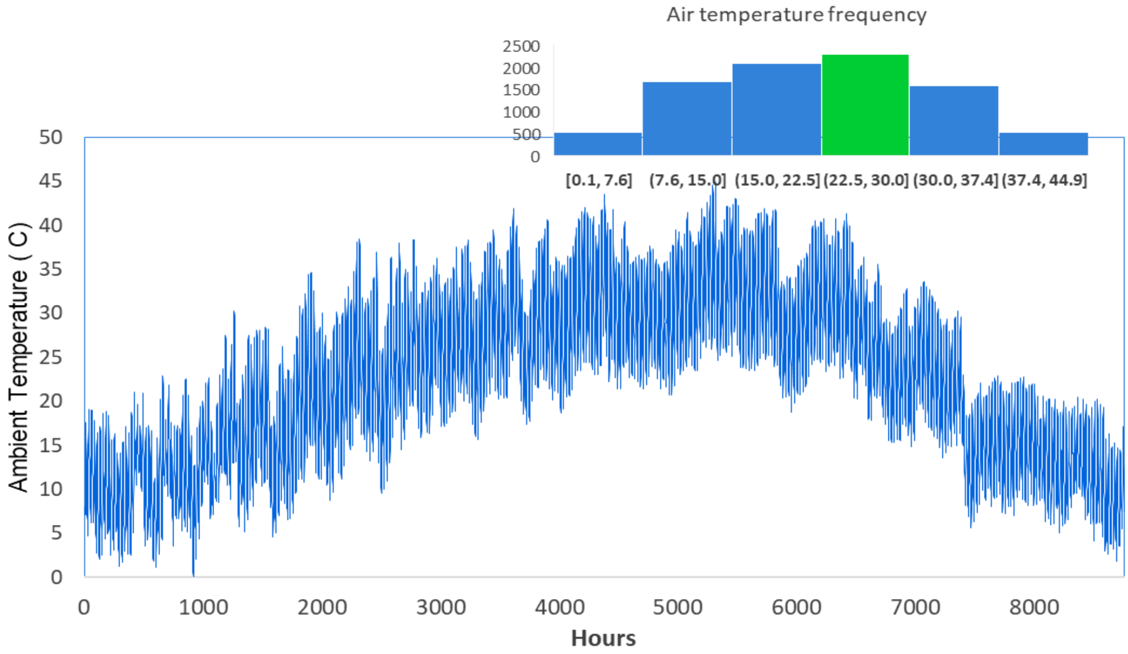

Figure 4. Hourly average ambient air temperatures

2.3 Planning and Operational Blueprint

To improve the feasibility of this work, the analysis is performed on the proposed system as it shown in Figure 5. This work simulates the real-time performance of a renewable energy system based on energy requirements and the availability of renewable energy resources.

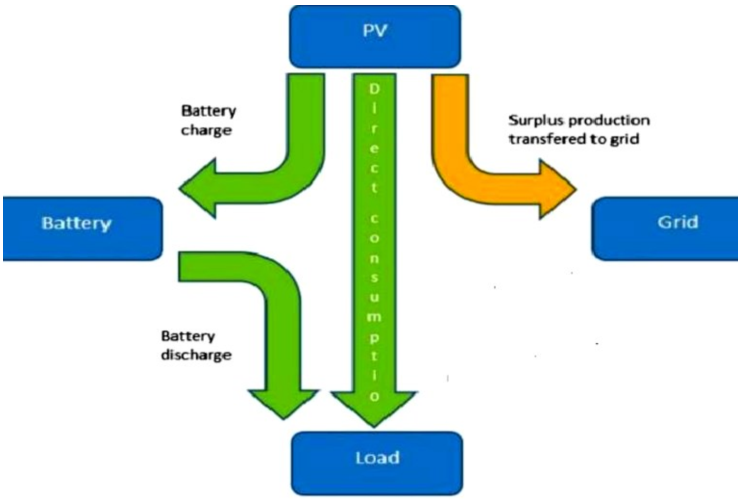

Figure 5. Proposed Renewable Energy System

2.4 PV Solar Energy

The real power ($E_{PV}(t)$) of the PV panel in actual operation and climatic conditions is estimated by [36, 37]:

$$E_{PV}(t) = P_{STC} \times \frac{H_g(t)}{H_{STC}} \times \left[1 + \beta_{p,T}(T_{cell}(t) - T_{STC})\right] \quad (1)$$

Where P_{STC} expresses for the nominal PV power at the Standard Test Condition STC; $\beta_{p,T}$ indicates to the power-temperature coefficient (%/°C); T_{STC} and H_{STC} refer to the standard test conditions of temperature (25°C) and solar radiation (1000W/m^2), respectively. The cell's temperature ($T_{cell}(t)$) is expressed as: $T_{cell}(t) = T_{\infty}(t) + 0.078H_g(t)$ [38,39]; T_{∞} and $H_g(t)$ are hourly ambient air temperature (°C) and global solar irradiance (W/m^2). The present research used the Stion SN-115 PV module (Thin film technology) as it recommended by local [40-44]. Table 1 lists the features of the PV module type Stion SN-115, thin film technology. the features of the PV module type Stion SN-115, Thin Film technology.

Table 1: Technical characteristics of the PV [41]

Metric	Value
PV modules type	Stion SN-115
Technology	Thin Film
Country of Origin	USA
Maximum Power; W	125
Temperature coefficient of power; % /°C	-0.4
Efficiency; %	11.4
Capital expenditures (C_{PV}); $/kW	876
Operational and maintenance expenditures ($C_{O,\,PV}$); $/kW/year	20
Lifespan; year	25
CO_2 life cycle emission; g CO_2/kWh	52

2.5 Inverter

According to a local researcher's recommendation, the most suitable inverter for the considered site is "AEG Power Solutions: Protect MPV. 150.01 480V(CEC2013) [40]. The efficiency of the inverter (η_{inv}) is estimated by [45,46]:

$$\eta_{inv} = \frac{E_{inv,out}}{E_{inv,in}} \quad (2)$$

Where: $E_{inv,out}$ and $E_{inv,in}$ relate to the out and in-put inverter energy.

2.6 Batteries

One crucial part of energy storage is batteries, and their application in renewable energy technologies has grown. To indicate the state of charge (SOC) of batteries in charging and discharging conditions, equations (3) and (4) are functional as [47]:

$$\boldsymbol{SoC_{ch}\,(t) = SoC(t-1)(1-\sigma) + \left[E_{pv}(t) - \frac{P_{laod\,(t)}}{\mu_{inv}}\right] * \eta_{ch}} \quad (3)$$

$$\boldsymbol{SoC_{dis}\,(t) = SoC(t-1)(1-\sigma) - \left[\frac{P_{laod\,(t)}}{\mu_{inv}} - E_{pv}(t)\right] * \eta_{dis}} \quad (4)$$

Where SOC(t) and SOC (t−1) indicate to the SOC of the battery in times of t and t−1, respectively. $P_{laod\,(t)}$, $E_{pv}(t)$, σ, η_{ch} , η_{dis}, and μ_{inv} are energy load in a particular time (MWh), produced energy (MWh), battery self-consumption (1% per day), efficiency of battery bank in charge and discharge (%), and efficiency of inverter (%), respectively.

2.7 Objective functions and constraints

This investigation aims to obtain the ideal composition of the solar PV/battery system for the Wadi Al-shatti area, Libya, while minimizing the (LCOE). According to the objective function symbolized by (OF) in the following equation:

$$OF_1 \rightarrow min(LCOE) \tag{5}$$

The suggested renewable energy system must be dependable and able of sustaining an autonomous energy supply, as it acts as the lone source for convening the location's load demand. Thence, the objective functions in Equations (5 and 6) are subject to the Loss of Power Supply Probability (LPSP) constraint [48].

$$LPSP = \frac{\sum_{t=1}^{8760}[E_L(t) - (E_{PV}(t) + (-1)^m E_{Batt}\ (t))]}{\sum_{t=1}^{8760} E_L(t)} \tag{6}$$

m=0, when discharging
m=1 when charging

Where: $E_L(t)$, $E_{pv}(t)$ and $E_{Batt}\ (t)$ are instantaneous load, PV and Battery energy respectively. LPSP of zero requires a significantly costly renewable power system. Set LPSP to 1% achieves the lowest value of LCOE and ensuring full load accomplishment [48].

2.8 Energy balance of the HRES

The balance of the HRES Stored energy occurred when the battery is managed according to the following limits:

$$SoC_{min} \leq SoC \leq SoC_{max} \tag{7}$$

Where SoC_{min} SoC_{max} are the minimum allowable discharge which represented by Depth Of Discharge (DOD) which taking as 10% and maximum storage capacities, respectively.

2.9 Environmental analysis

The environmental evaluation of the suggested system is based on the life-cycle CO_2 assessment. The proposed system's life cycle CO_2 emission can be subtracted from Libya's energy system's CO2 emissions to determine the amount of CO2 saved. (i.e. The potential amount that the proposed solar energy system could prevent from entering the atmosphere:

$$CO_{2_{savings}} = EF_{CO2,Grid} \times P_{load} - \sum_{i=PV,Battery} EF_{CO2,i} \times E_i \tag{8}$$

Where: P_{load} is the annual electrical load (MWh), E_i is the annual energy production from each energy system (i) which are: PV solar energy, and Battery energy, in MWh, $EF_{CO2,Grid}(1037\ kgCO_2/MWh)$ is the power system's CO_2 emission factor in Libya [49], and $EF_{CO2,i}$ is the CO_2 emission factor based on the life cycle assessment in (kg CO_2/MWh). CO_2 emission factors for each system component are as follows: $EF_{CO2,PV} = 52\ kg\ CO_2/MWh$, $EF_{CO2,Battery} = 187.26\ kg\ CO_2/MWh$ [34]

2.10 Economic Analysis

Levelized Cost of Energy (LCOE) is a standard for the economic evaluation of the costs related to a power generation system, covering capital, operating and maintenance costs; it also involves the social cost of carbon dioxide. LCOE is a useful metric for comparing different technologies, such as solar and battery power, which have varying lifetimes, project sizes, capital costs, risks, returns, and capabilities. LCOE is influenced by system performance, costs, and ongoing operation and maintenance, and is calculated by dividing the total electrical power output of the asset by the net present value of all costs incurred over its lifetime. By rewriting the equations, the net present cost of production can be expressed as follows:

$$LCOE = \frac{\left[\frac{r(1+r)^n}{(1+r)^n-1}(C_{PV}) + \frac{r(1+r)^{n_{Batt}}}{(1+r)^{n_{Batt}}-1}C_{Batt} + (O_{PV}+O_{Batt}) + C_{CO_2LCA} - C_{CO_2}\right]}{\sum_{t=1}^{8760} E_{Load}(t) + \sum_{t=1}^{8760} \mathrm{Grid}(t)} \tag{9}$$

$$NPV = \frac{C_{PV}}{(1+r)^n} + \frac{C_{Batt}}{(1+r)^{n_{Batt}}} \tag{10}$$

Where r is the real discount rate equals to 2.5% [17], n is the plant lifespan 25 years for PV and n_{Batt} is the lifespan 15 years for Battery. The subsequent energies of the RE sources (PV) and Battery are used to calculate the rated powers. The cost of ecological damage (C_{CO2}) caused by CO_2 can be computed by:

$$C_{CO2} = CO_{2_{savings}} \times \emptyset_{CO_2} \tag{11}$$

Where: $\emptyset_{CO2}$ denotes the carbon social cost (\$/ton CO_2), which is equivalent to \$70/ton CO_2.

The payback money period (PBP), neglected the salvage price, is estimated by:

$$PBP = \frac{C_{PV} + C_{Batt}}{\mathrm{I}_{Ele} + \mathrm{I}_{Env}} \tag{12}$$

Where I_{Ele} and I_{Env} are the annual income from electricity selling and from CO_2 emission prevention (\$/year).

2.11 Optimization Algorithm

An iterative algorithm is adopted to achieve the optimization process. Figure 6 depicts a process chart of the optimization procedure involving the proper sizing of the RES system components using SAM and Excel. The approach uses Excel to simulate hourly economic and energy performance based on data from SAM. After that, the results are compared to the stated objective functions and limitation. This process is repeated to obtain the best combination of the suggested system and determine the ideal design by achieving the lowest LCOE (cost of energy consumed) value.

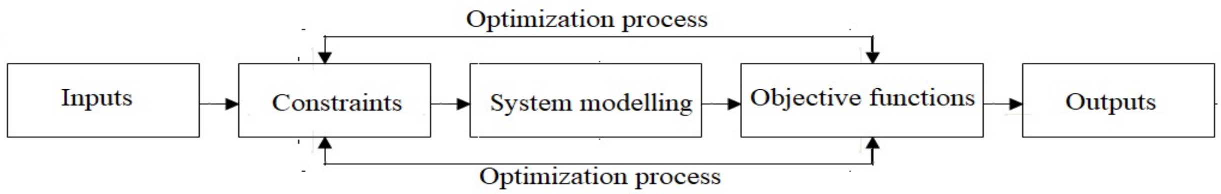

Figure 6. Optimization process

2.12 Assumptions, limitations and uncertainties in the results:

The following assumptions simplify the study analysis:

- PV & Battery system is loss-free, with no leakage or evaporation from battery.

- System salvage cost is not considered.

- There is no power loss at the terminals or controllers.

-Neglecting declinations in the performance due to age

Model selection, parameter estimation, and data availability are the primary sources of uncertainty. Climate conditions, for instance, have a big impact on the availability of renewable energy resources (like solar energy), which can have a big impact on energy production at related facilities. Another uncertainty is the cost of renewable energy project. Elnaggar, et al. [50] claim that the cost of renewable energy equipment varies by over 360 percent, with prices ranging from $980 to $4510/kW. The annual maintenance costs of solar PV facilities range from $2.12/KW to $ 5.64/KW.

3. Results and Discussion

3.1 Determination of PV/Battery system capacity

The current work investigates the effect of solution stabilization on the estimation of battery capacity. Since this issue is an unstable case with an undefined initial condition, a trial-and-error technique will be used by assigning a value to the energy level of the battery. The analysis has been performed, and the hypothesis will be accepted if the load coverage is obtained within the storage conditions indicated in the equilibrium.

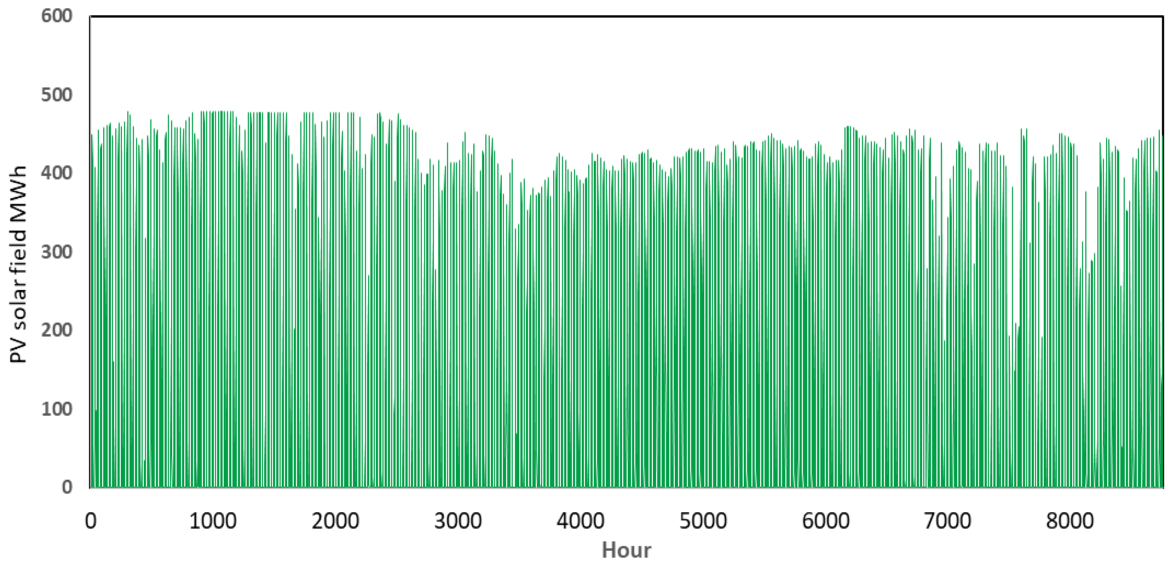

Figure 7. Hourly productivity of 1MW PV solar field (PV module type Stion SN-115, Thin Film technology)

Figure 7 displays real-time results for a 1 MW solar PV field. The figure shows that the total output of the solar field has variations throughout the year, with temporary dips at specific times. The further decrease in solar field productivity is mainly due to the hot climate affecting the performance of temperature-sensitive solar PV. Figure 7 shows the energy levels in the battery storage system according to the specific design and operating parameters. It also validates the scaling technique, proving that the system fulfills the full load of 100% of the demand. The dual direction of battery power indicates its technical feasibility, as it acts as a source as well as a sink for the load, thus ensuring continuity of supply. Compliance with the operational constraints of the design is shown in Figure 8.

3.2 Optimization of the PV/battery system size 2460 MWh

The ideal capacity of the suggested solar PV/ Battery system was ascertained by applying the objective functions within the constraints. The optimization was carried out across a board range of solar PV and battery capacities within the range of Equation (8), and the associated battery capacity. The main technical, financial, and environmental information for the system sizing procedure was tabulated in Table 2. Figure 9 shows the optimal energy sizing optimization based on the total cost of CO_2 life-cycle analysis of all power instruments and the social cost of CO_2.

The economic analysis shown in Figure 10 shows that the minimum LCOE cost is $135 per MWh. Based on this, the optimal battery capacity is 2460 MWh, and the solar PV field is 600 MWh. When considering the social cost of CO_2, the social cost of CO_2 decreased to 52 USD per MWh. These results reveal that it is worth investing in renewable energies in the Libyan market in line with the general orientation of the Libyan state and encourages investment in the energy market.

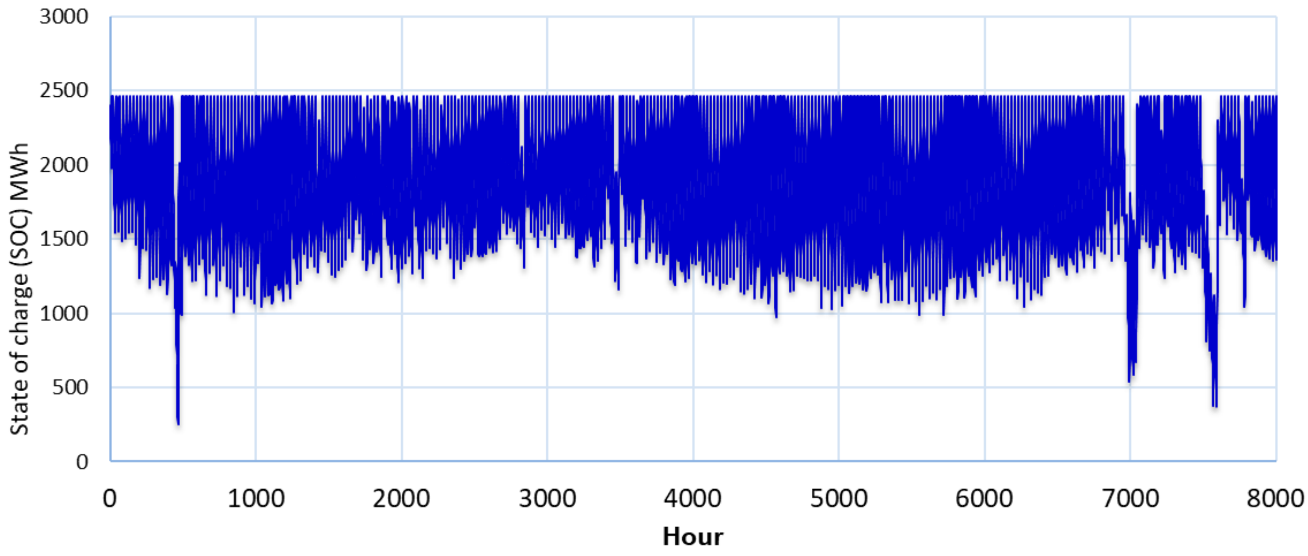

Figure 8. State of charge in the Battery system; 2460 MWh

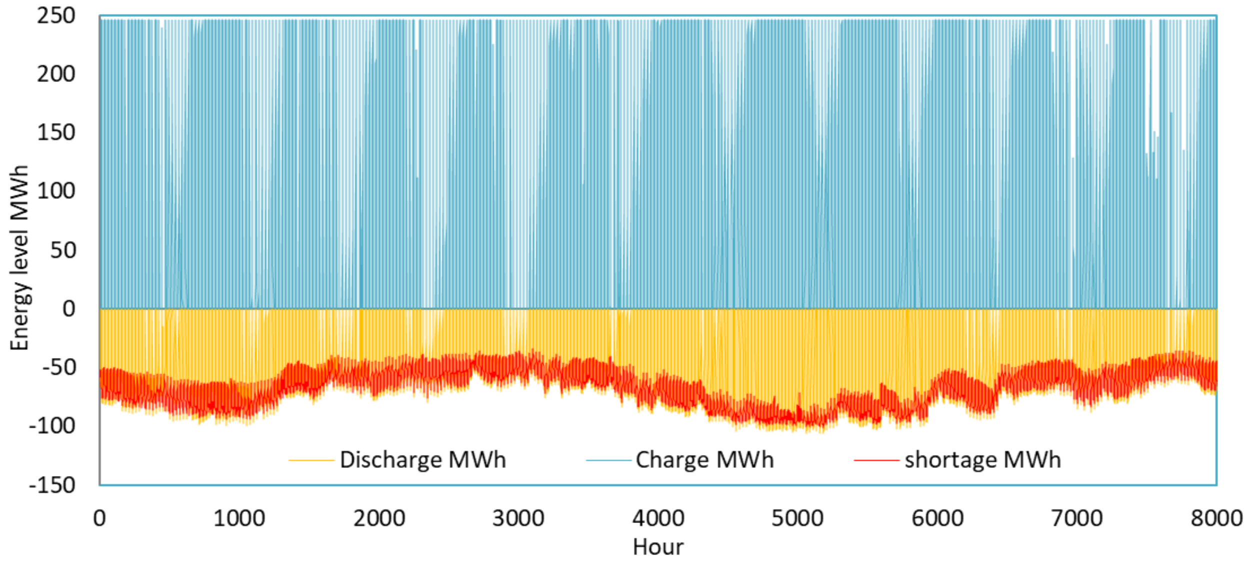

Figure 9. Energy balance of the PV/Battery max charge and discharge to covering load (shortage)

Table 2. Economic, technical and environmental data of the HRES components

Metric	**Value**
PV solar system	
Installed PV solar	$876/kW
O&M	$20/kW/year
Lifespan	25 years
Battery	
Installed Battery	$1,247/kW
O&M	$81/kW/year
Lifespan	5 years
Environmental aspects	
CO_2 life cycle emission factor for solar PV energy	52 g CO_2/kWh
Social cost of CO_2	$ 70/ton CO_2
CO_2 life cycle emission factor for Battery energy	187.26 g $CO_{2\text{-eq}}$/kWh [27]

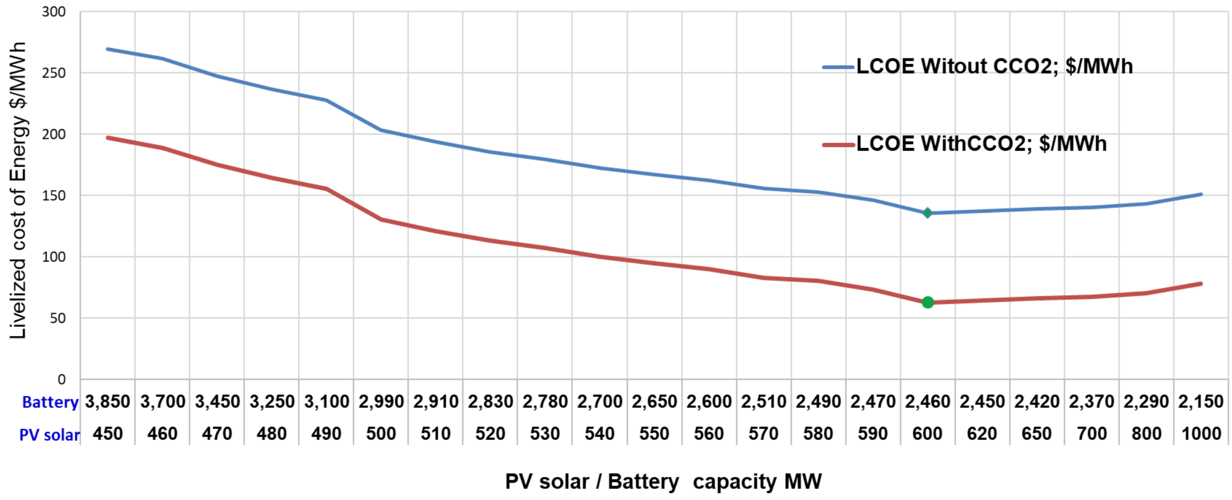

Figure 10. LCOE optimization of HRES size

3.3. Energy behavior of the proposed solar PV power plant

The energy balance of the suggested solar PV power system, which consists of 600 MW of solar PV and 2460 MWh of Battery to cover an annual electrical load of 590,018 MWh, is displayed in Figure 11. The total annual energy produced by the supply system is 600 MW of PV power (865,900, 100%), which is enough to cover an electrical load of 590,018 MWh. While 244,827 MWh (28.3%) is consumed directly by the load, about 527,222 MWh (28.9) is shipped as energy to the battery and stored for use when needed. About 93,694 MWh (8%) of the energy generated is lost in transformers, and the energy is lost in appliances. The grid receives about 286,391 MWh (4.8%) of the generated power.

4 Conclusions

This study conducted an ideal modeling to find the appropriate capacity for a solar photovoltaic system integrated with batteries to supply the local community in the Wadi al-Shati area in southern Libya with electrical energy. The ideal energy system that can meet the community's energy needs was identified. To achieve this, several constrained operational scenarios were studied and simulated under conditions of uncertainty to determine the optimal size of the proposed system. The results showed that the proposed system consists of a 600 MW solar photovoltaic field with a battery storage capacity of 2,460 MWh, generating sufficient and sustainable energy to cover the estimated annual load of 590,019 MWh. This proposed system contributes to avoiding approximately 897 tons of carbon dioxide emissions annually (according to the emission factor for the power generation system in Libya, estimated at 1,037 kg demand fluctuations, supporting the development of renewable, flexible, and independent energy systems, and helping to preserve the environment. The annual cost of carbon dioxide damage has been estimated at US$62.8 million (based on a carbon dioxide cost of US$70/ton CO_2).

The total investment cost is estimated at US$1.743 billion, while the levelized cost of energy (LCOE) are estimated with and without considering the social cost of the CO2 emission and found as $62/MWh and $135 per megawatt hour, respectively, with a payback period of 11.51 and 19.86 years, respectively. In addition, surplus energy can be exported to the national grid. This enhances economic viability and aligns with Libya's strategic vision for renewable energy.

Furthermore, this study primarily supports the United Nations Sustainable Development Goals, such as Goal 7 (Clean Energy) and Goal 13 (Climate Action) [15]. Additionally, the excess energy can be exported to the national grid. The successful implementation of these projects requires a supportive environment that includes appropriate sources of financing and legal,

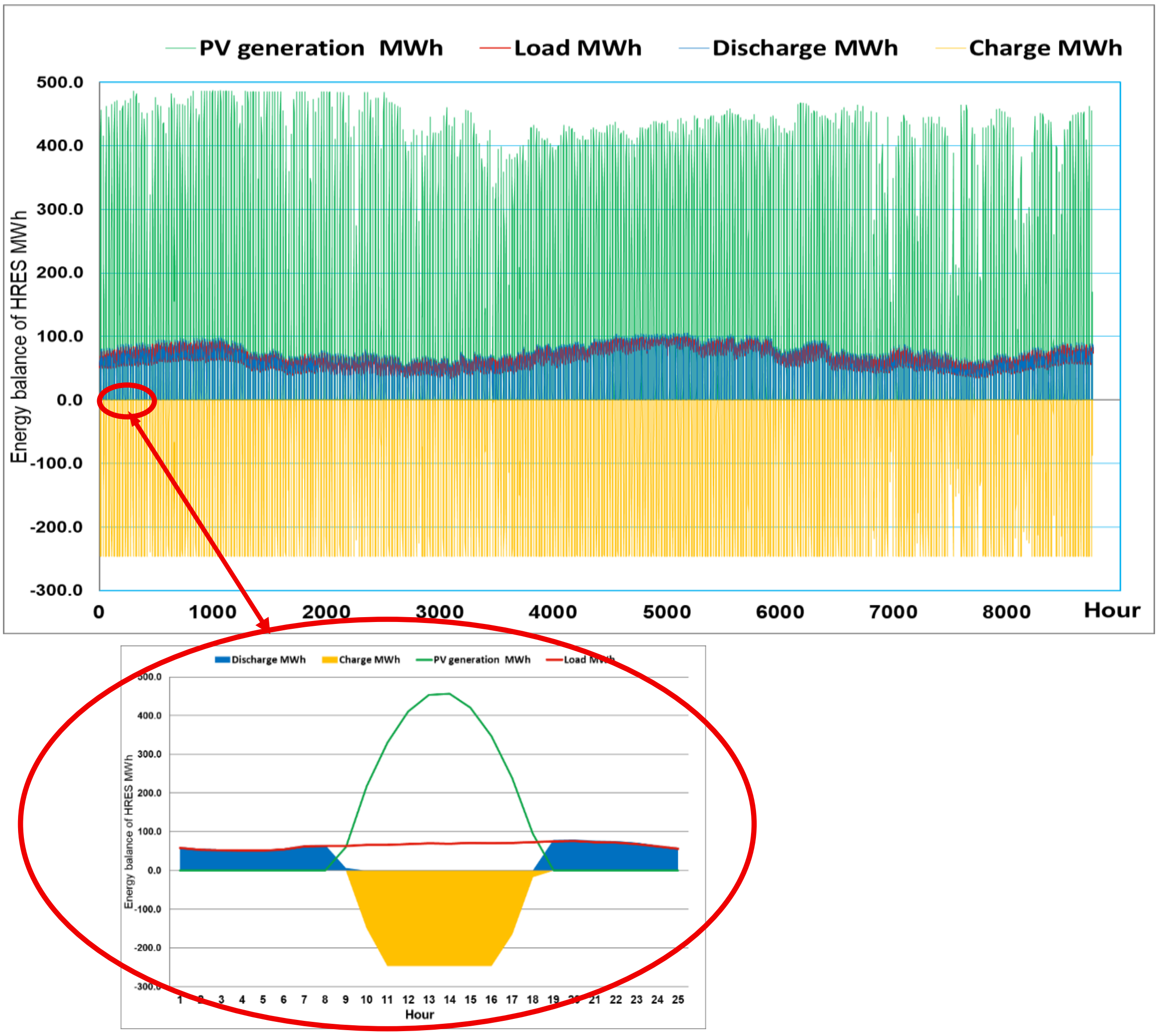

Figure 11. The energy balance of the proposed HRES consumption

regulatory, and legislative frameworks consistent with the relevant studies. Furthermore, it is essential to develop plans for the transition to renewable and environmentally friendly energy and to encourage private sector participation. CO_2/MWh), enhancing the resilience of the system design in the face of climate change and energy

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