A Case Study of Hybrid Renewable Energy System Optimization for an Island Community based on Particle Swarm Optimization

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ABSTRACT

Due to their small size and isolated energy systems, islands face a significant energy supply challenge. To develop sustainable energy systems, Hybrid Renewable Energy Systems (HRES) help in the generation of electricity in island zones, as they are a clean and inexhaustible source of energy. The purpose of this study is to optimize the allocation of Renewable Energy Sources (RES) on an island in Tunisia. To ensure efficient management between the total power generation and the total community load demand, an Energy Management System (EMS) is required. This paper presents the integration of an optimal EMS using Particle Swarm Optimization (PSO) to directly allocate and optimize the energy generated by an HRES. In addition, the PSO algorithm is applied to regulate energy production, consumption, and storage to maximize the utilization of the available renewable sources while satisfying load requirements. The results exhibit that this approach is effective for the dynamic optimization of energy management in an HRES, contributing to a more efficient and sustainable utilization of energy resources.

Keywords-modeling system; energy management system; PSO; hybrid renewable energy system

I. INTRODUCTION

Recently, the production of electricity from Renewable Energy Sources (RES) has gained global attention due to the limited nature of fossil resources, the high cost of fossil fuels, and the increasing environmental problems. As a result, there is a growing interest in the use of RES in electricity generation, particularly in remote or isolated areas. By employing various RES in conjunction with backup and conservation devices to form a Hybrid Renewable Energy System (HRES), an economical and reliable energy system can be provided [1]. Due to non-linear responses, the unpredictable nature of RES, and the variable demand profile of power plants, the utilization of an Energy Management System (EMS) is essential. The EMS adapts and effectively combines different power generation and transmission units, ensuring both efficiency and cost-effectiveness [2]. One of the main elements of recent studies is the optimization of HRES elements to satisfy load demand while minimizing costs and maximizing energy availability. Given the difficulty of HRES optimization, it was essential to obtain accurate, high-performance optimization solutions. PSO (Particle Swarm Optimization) algorithm is considered one of the most useful and interesting methods for HRES optimization [3]. In [4], better algorithms are proposed for PSO energy management distribution hybrid systems within irregular environments. In [5], the authors designed a mathematical model to calculate the electricity production which is to be achieved with RES, including solar energy, wind energy, and waves, in the Balearic Islands and Fiji. In [6-7], the authors proposed an EMS based on special features for isolated communities, exclusively supplied from RES where the extension of the grid is not feasible. In recent years, there has been a large amount of research work in the area of isolated hybrid system modeling and simulation. The PSO algorithm recommended in [8] is derived from the feeding practices of natural fish and birds (particles) and is used as an intelligent microgrid that enables the community to respond to both its current and future load profiles and to manage energy flows.

In this study, PSO algorithm has been developed to solve optimization problems in a HRES, including faster convergence of energy management units and was deployed to regulate the energy production, consumption, and storage system by maximizing the use of available RES under load requirements.

II. THE MATHEMATICAL MODEL OF THE HYBRID RENEWABLE ENERGY SYSTEM

A. HRES Configuration in the Community

Figure 1 illustrates a HRES located on the island of Djerba in Tunisia. The HRES consists of photovoltaic panels, wind turbines, tidal turbines, and biomass as RES. A diesel generator is utilized as an emergency supply and is activated when the RES production is too low. A battery park is employed as storage.

B. Photovoltaic Power Plant Model

Solar panel performance is highly dependent on ambient temperature as well as on solar radiation. The optimum performance of a solar module depends on the prevailing ambient conditions, which in turn improve energy production. Photovoltaic production is modeled in terms of linear power versus solar radiation [9]:

$$P_{pv} = \eta_{pv} A_{pv} G_t \tag{1}$$

where η_{pv} designates the fast efficiency of the photovoltaic module, A_{pv} is the position of the module employed for this system, and G_t is the total irradiance.

C. Wind Power Plant Model

The electrical power produced from a group of wind turbines at an average wind speed (v) can be formulated as [9]:

$$P_{wt}(t) = \begin{cases} 0 & v(t) < v_{in} \\ \eta_{wt} N_{wt} P_{wt\_r} \dfrac{\left(v^2(t) - v_{in}^2\right)}{\left(v_m(t) - v_{in}^2\right)} & v_{in} < v(t) < v_r \\ \eta_{wt} N_{wt} P_{wt\_r} & v_r < v(t) < v_{off} \\ 0 & v(t) > v_{off} \end{cases} \tag{2}$$

where N_{wt} represents the Wind Turbine (WT) number, η_{wt} symbilizes the WT efficiency, P_{wt_r} constitutes the rated power of a single WT operated at the rated wind speed (v_r) in (m/s), and v_{in}, v_{off} denotes the velocity in (m/s) at which the WT starts and stops, respectively.

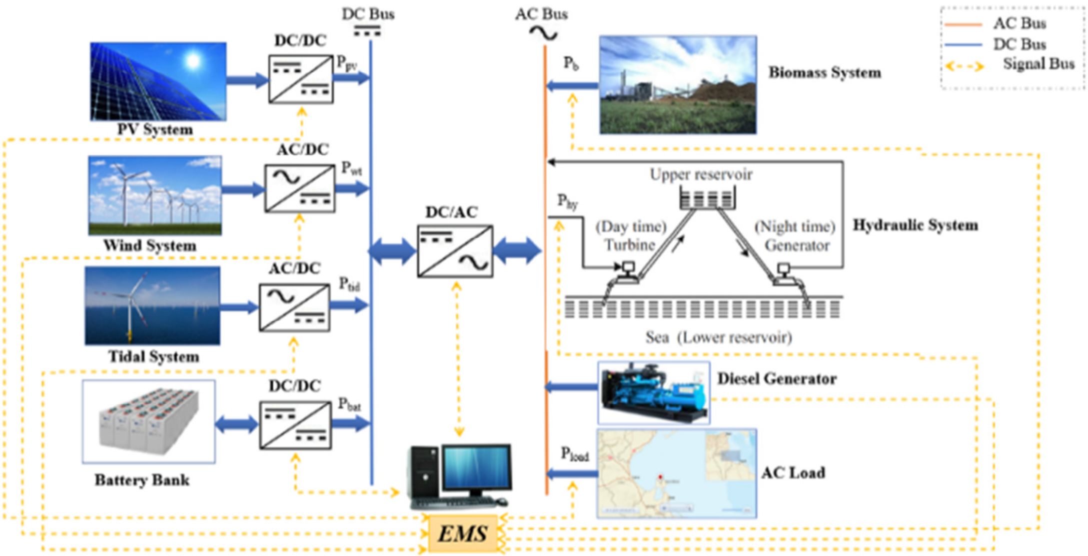

Fig. 1. Configuration of the proposed hybrid renewable energy system.

D. Tidal Power Plant Model

The tides generated from the gravitational forces between the sun, moon, and earth result in strong tidal currents in regions where the water elevation drives high flows through narrow passages carrying a significant amount of kinetic energy. The extractable mechanical power for a given current speed V_{cur} is detailed by (3) and (4) [9]:

$$P_{tid} = \frac{1}{2} \rho C_{pt}(\lambda) S V_{cur}^3 \tag{3}$$

$$\lambda = R_{tid} \frac{\omega_{tid}}{V_{cur}} \tag{4}$$

where ρ is the density of water (kg/m^3), C_{pt} is the power coefficient of the turbine, reflecting the power extraction efficiency as a function of the rotation speed ω_{tid} (rad/s), S is the section swept by the pales (m^2) and V_{cur} is the water velocity (m/s).

E. Hydroelectric Power Plant Model

Pumped storage hydropower plants constitute one of the most competitive storage technologies. Before starting the operation of the pump, the permissible upper h_{AB} and lower h_{LB} reservoir levels, as well as the actual operation of the generators are checked ($\sum P_{hyd} = 0$). This means that the pumping station can only be operated when the hydroelectric units are still. If the permissible values are not exceeded, the pump with the rated electric power P_{pumb} is operated. The amount of water (W_{pump}) obtained during pumping is:

$$W_{pump}(t) = Q_{pump} \times t \tag{5}$$

For each hydroelectric generator, the minimum electrical power (P_{hyd_min}) is defined by the technical specification parameters, and corresponds to the minimum water consumption of the turbine Q_{hyd_min} (m^3/s), determined according to [9]:

$$P_{hyd\_\min}(t) = 9.81 \times \eta_{hyd} \times H \times \frac{W_{pump}}{t} \tag{6}$$

where 9.81 is the gravitational acceleration (m/s^2), H is the water head (m), η_{hyd} denotes the efficiency of the hydroelectric units (HG) in (%). For an HG, the water head and the efficiency are known and the equation can be rearranged by:

$$P_{hyd\_\min}(t) = K_{hyd} \times \frac{W_{pump}}{t} \tag{7}$$

The pumped water volume is compared with the minimum water volume required for the operation of the hydraulic unit. The latter is activated depending on the available water volume according to:

$$P_{hyd}(t) = \begin{cases} P_{hyd\_\min}, & W_{pump}(t) = W_{gen\_\min} \\ K_{hyd} \times \frac{W_{pump}}{t}, & W_{gen\_\min} \le W_{pump}(t) \le W_{gen} \\ P_{hyd\_nom}, & W_{pump}(t) > W_{gen} \end{cases} \tag{8}$$

where $W_{gen} = Q_{gen} \times t$ is the water volume required for an one-hour operation of the hydroelectric unit at the rated capacity (m^3).

F. Biomass System Model

The transformation process employed was the biomass gasification, which is a pyrolysis process, and the Biomass Generator (BG) was taken as the base-generating unit for supplying the load demand in addition to the other sources. The electric power produced from the BG can be estimated from [9]:

$$P_b(t) = \eta_g \omega H_{hv} Q_{sr}(t) \tag{9}$$

where η_g represents the gasifier efficiency and was taken as 75%, ω is a parameter for transforming kJ to kWh (27.78 × 10^{-5}), Q_{sr} denotes the flow rate of the raw materials (kg/h), and H_{hv} symbolizes the higher heat value of the raw materials used as an input to the system.

The electric energy produced from the biomass system per year is calculated from:

$$E_b = \sum_{t=0}^{8760} N_g \times P_b \times t \tag{10}$$

where N_g represents the number of BG units.

G. Battery System Model

A storage system is a vital element in HRES. It operates in the case of an electricity blackout, and it mitigates the variability of RES. Therefore, it is usually placed between the RES and the load to help the generation match the load demand at any moment, and by doing that, it assures the stability of the system. The required battery capacity is given in by [10]:

$$C_{bat} = \frac{Days_{off} \times E_L}{\eta_T \times DoD_{\max}} \tag{11}$$

where E_L is the load that needs to be supplied during the unavailability of power in Ah, $Days_{off}$ are the storage days, DoD_{max} is the maximum depth of discharge of the battery, and η_T is the temperature corrector factor.

The charge quantity of the storage system is given by (12). This quantity is constrained by maximum and minimum charge quantities E_{Bmax} and E_{Bmin} [8], respectively.

$$E_B(t) = (1-\tau)E_B(t-1) + \frac{(E_g - E_L)}{\eta_{inv}}\eta_{bat} \tag{12}$$

where τ, η_{inv}, and η_{bat} are the hourly self-discharge factor, the efficiency of the inverter, and the efficiency of the battery, respectively. E_B (t) and E_B (t-1) represent the charge quantity of the storage system at times t and t-1, accordingly. E_g and E_L are the renewable energy power and the load demand, respectively.

H. Power Electronic Converter Model

The interface of power electronics used in the configuration of hybrid RES is a DC/AC inverter employed for providing AC power to the consumers. The output power from the inverter model is expressed by [9]:

$$P_{conv\_out} = \eta_{conv} \times P_{conv\_in} \tag{13}$$

where P_{conv_in} represents the power supplied from the RES to the load and η_{conv} symbolizes the efficiency of the inverter.

I. Location and Weather Data

The production of electricity using RES depends on the weather data and the resources available in the region where the project is located. The proposed HRES is to be installed on the island of Djerba, Tunisia. Djerba lies in the Mediterranean, with a surface of 514 km^2 (25 km by 20 km along a seaboard of 150 km), and is situated on the east coast of Tunisia at (33^{o}48' N, 10^{o}51' E). In the previous section, it was shown that the output power essentially depends on the weather parameters. The parameters of the island of Djerba were extracted by the NASA (National Aeronautics and Space Administration) databases and by implementing the HOMER (Hybrid Optimization of Multiple Energy Resources) software.

Figure 2 represents the hourly charge, with an average annual output of 6.9 kW. Figures 3 to 6 present radiation, temperature, wind, and tidal velocity for a duration of 8760 hours.

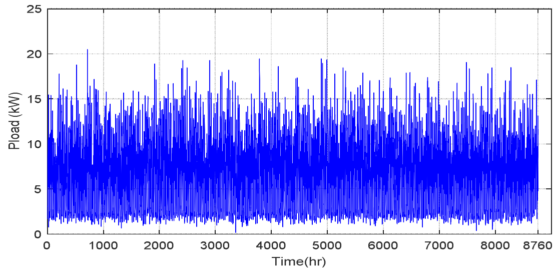

Fig. 2. Annual load demand of the studied location.

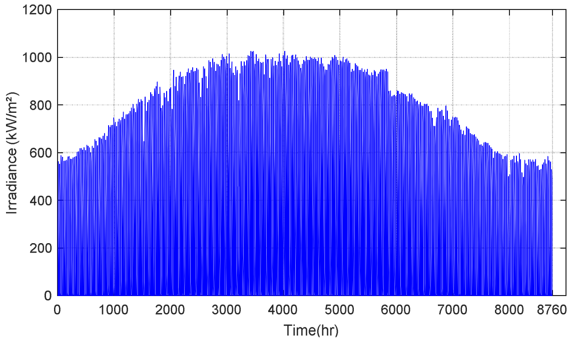

Fig. 3. Annual data of solar irradiance.

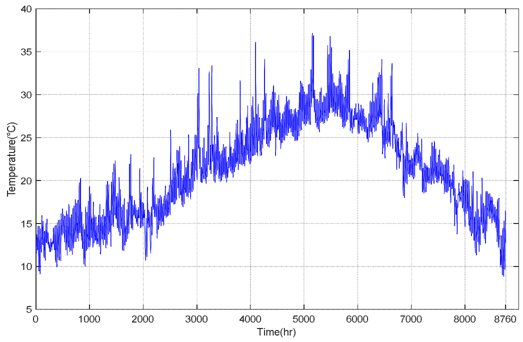

Fig. 4. Annual data of ambient temperature.

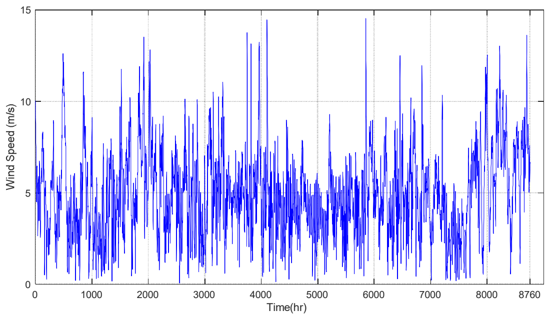

Fig. 5. Annual data of wind speed.

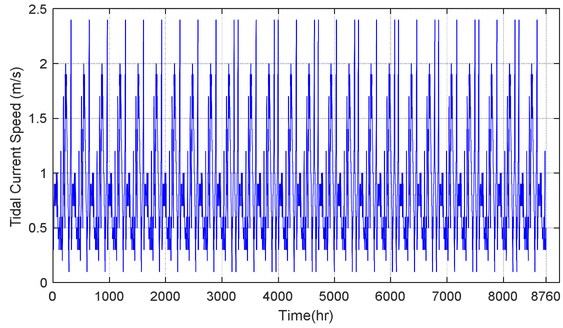

Fig. 6. Annual data of tidal current velocity.

The solar radiation power ranged between 587.5k W/m^2/day and 1016 kW/m^2/day, providing adequate electrical power for the proposed power plant. Wind velocity varies between 9.66 m/s and 36.52 m/s and Temperature varies from 0.5°C to 14.53°C. Tidal current velocity ranges from 0 m/s to 0.9 m/s.

III. ENERGY MANAGEMENT SYSTEM STRATEGY

EMS are among the key features to be aware of in the design phase or when measuring a stand-alone hybrid system. Its purpose is to guarantee energy distribution and management among the various components of the system under study. Four EMS modes are used in this analysis:

- **Mode 1:** The energy production from RES (PV, wind, tidal, hydro, biomass) is enough to satisfy the consumer demand. Surplus energy is utilized to charge the battery pack.
- **Mode 2:** The electricity produced deploying RES is over the requirements once the battery is completely charged. Too much energy is then employed for discharging.
- **Mode 3:** The energy based on RES does not meet the demand. The battery then takes over the shortfall in power generation to meet the demand.
- **Mode 4:** The power generated by RES is too low to cover user demand and, simultaneously, the battery's storage capacity is insufficient.

Figure 7 portrays the flowchart of the proposed EMS algorithm. In Figure 7, P_{ch} is the charging power, P_{disch} is the discharging power, E_{ch} is the charging energy, E_{disch} is the discharging power, P_{gen} is the generated power, and E_{dump} represents the dump energy of the battery.

IV. IMPLEMENTATION OF PSO ALGORITHM

The PSO algorithm provides a method for resolving optimization problems in power system operation. In the PSO algorithm, all individuals in the swarm correspond to vectors. Those vectors are moved to a location within a multi-dimensional search space. Each swarm member remembers its best historical position, named P_{best}. A global best position, G_{best}, is found in every iteration. When G_{best} is found, each person gets closer to its personal and global best position. After some iterations, the process can identify a suitable network for the optimal function. The velocity and the position of every swarm member can be determined from (14):

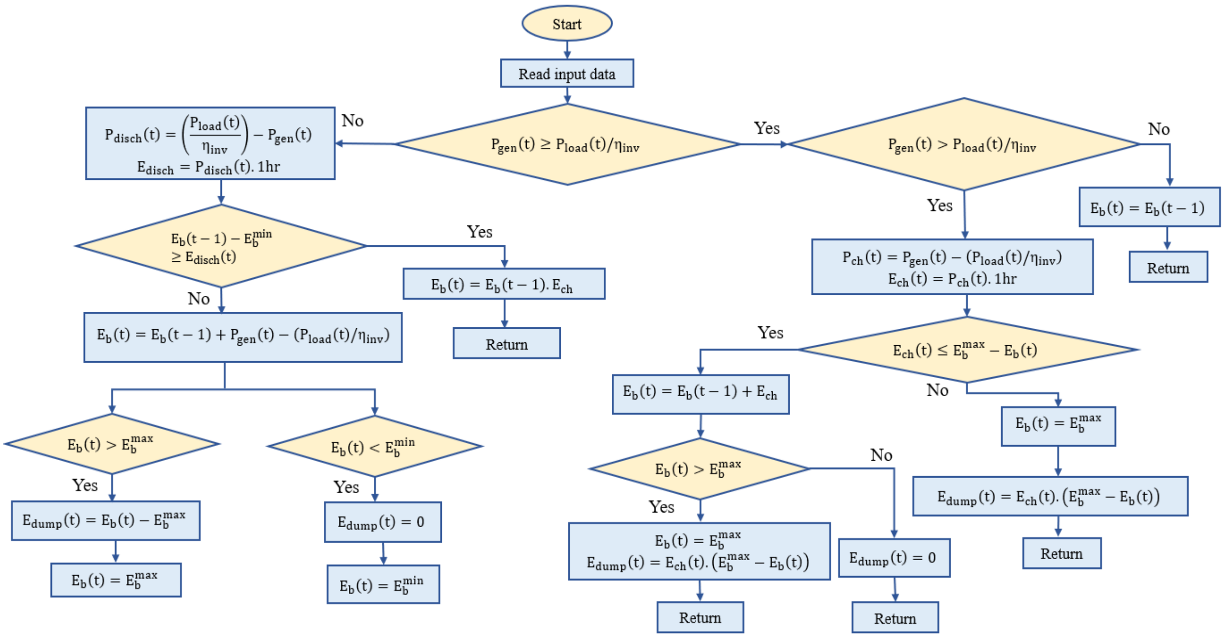

Fig. 7. The proposed energy management algorithm for the HRES.

$$v_i^{k+1} = wv_i^k + c_1r_1(P_{bestii} - x_i^k) + c_2r_2(G_{bestii} - x_i^k) \quad (14)$$

The position for each individual is updated after each iteration as in (15):

$$x_i^{k+1} = x_i + v_i^{k+1} \quad (15)$$

where w represents the weight of the inertia function, i represents the step of iteration, c_1 and c_2 symbolize the coefficients of acceleration, r_1 and r_2 denote random numbers in the range [0, 1], V_i^k represents the individual's velocity, andx_i typifies the actual position for that individual.

A. The Proposed Algorithm

The most important objective of any renewable energy electrification project is to optimize the use of the available RES while satisfying load requirements. The problem is to determine how much power will be generated from a multi-source renewable system to cover all the demand loads, including losses and storage power. In this paper, an optimization approach is followed to optimize the HRES employing the PSO algorithm to improve the contribution of RES and achieve fast convergence characteristics. The PSO algorithm was applied in the optimization problem, selecting the amount of power to be produced by the proposed HRES and achieving the optimal power output. A flowchart of the proposed optimization algorithm is depicted in Figure 8. The algorithm was implemented in MATLAB.

B. Constraints

The power generated from each source $P_{gen}(i)$ must be less than or equal to the maximum capacity of the source:

$$P_{gen}(i) \leq P_{gen\max}(i) \quad (16)$$

where i is the number of sources.

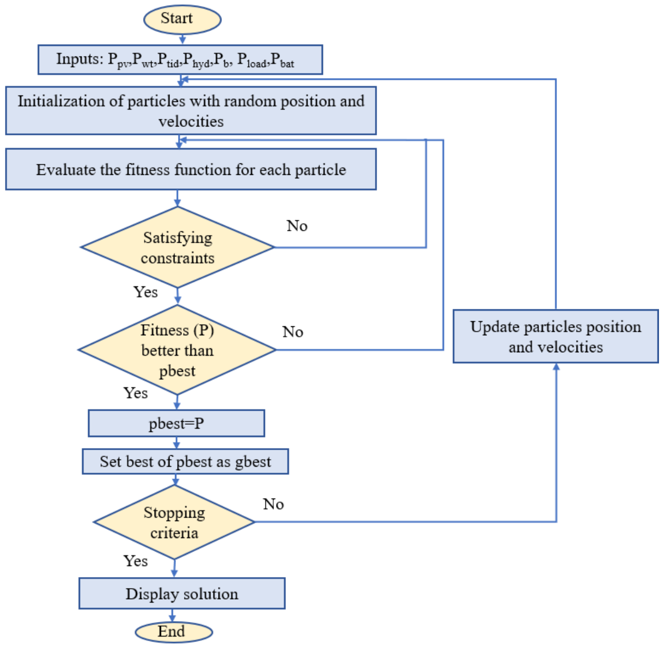

Fig. 8. Flow chart of the proposed PSO algorithm.

The energy produced by the HRES power sources $P_{gen}(i)$ must cover the total load demand P_{load} and the storage power P_{bat}, if used.

$$\sum_{i=1}^{5} P_{gen}(i) = P_{load} + P_{bat} \quad (17)$$

under the constraints illustrated by (18):

$$\begin{cases} P_{pv\,\min} \le P_{pv} \le P_{pv\,\max} \\ P_{wt\,\min} \le P_{wt} \le P_{wt\,\max} \\ P_{tid\,\min} \le P_{tid} \le P_{tid\,\max} \\ P_{hyd\,\min} \le P_{hyd} \le P_{hyd\,\max} \\ P_{b\,\min} \le P_b \le P_{b\,\max} \end{cases} \quad (18)$$

V. RESULTS AND DISCUSSION

Figure 9 presents the energy contribution cases of a HRES. One of them is using battery power and the other is exclusively utilizing the hybrid RES. Figure 9(a) indicates that the contribution from water is over 46%. The opposite case is given in Figure 9(b). The biomass source makes the largest contribution, at 62%, whereas the photovoltaic source contributes 26%.

(a)

(b)

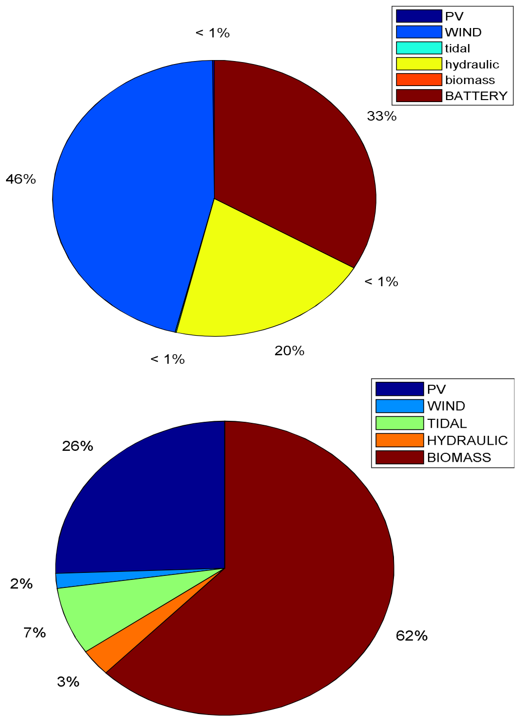

Fig. 9. Annual proportion of use of each RES of the HRES, (a) with and (b) without a storage system.

Figure 10 demonstrates the yearly energy production of the photovoltaic, wind, tidal, hydro, biomass, and battery power using the PSO algorithm.

Figure 11 manifests the load demand as well as the power generated by PV, WT, hydraulic, biomass, and battery sources for certain hours, according to the PSO method. It can be seen, that the photovoltaic energy production exceeds the load for the expansion phase, and even though the energy production by the wind turbine and the tidal turbine is low, the demand is met at all times. Wherever power produced by the PV/WT /tidal/hydraulic/biomass is greater than the load the battery is recharged. However, the battery is discharged to supply the load when the power generated by the PV/WT/tidal/hydraulic/ biomass system is lower than the load capacity.

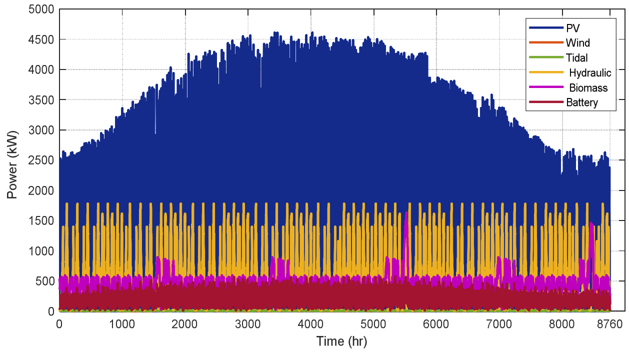

Fig. 10. Yearly energy production of the HRES by using the PSO algorithm.

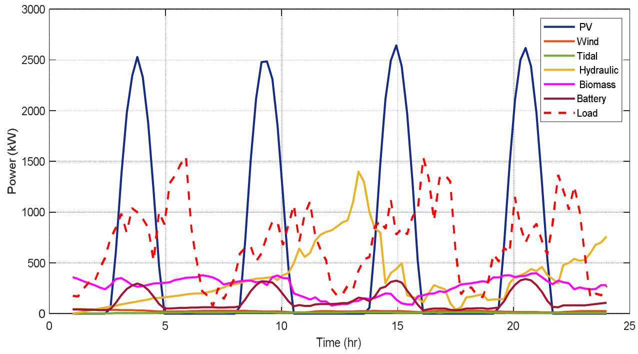

Fig. 11. Time response of the HRES over a few hours.

VI. CONCLUSION

The proposed energy management system putting into service PSO was able to optimize the energy consumption in an isolated island, and utilize the available renewable energy sources while satisfying load requirements. This approach is effective for the dynamic optimization of energy management in a HRES, contributing to more effective and sustainable utilization of energy resources. Overall, the proposed PSO algorithm determines the regulation of energy production, consumption, and storage, in order to maximize the use and distribution of the available renewable sources while responding to the load requirements throughout the island, which increases the system's stability, reliability, and sustainability.

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