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Comparison of the optimal design of PV-battery and PV-PHS off-grid energy systems-a case study in Sweden

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ABSTRACT

This study deals with the investigating of the potential of employing two energy storage technologies., i.e. battery storage and pumped hydro storage (PHS), for PV powered supply system on a small island in Sweden. The optimal design of two hybrid PV-Battery and PV-PHS systems are compared and analyzed. Genetic Algorithm (NSGA-II) is employed as the optimization algorithm. Investment cost and loss of power supply probability are considered as objective functions. Number of PV modules and battery capacity are considered as design variables for PV-Battery system and a wide range of design variables including number of PV modules, turbine capacity, pump capacity, volume, installation height and depth to diameter ratio of reservoir, pipes diameters constitute for PV-PHS system. As a result, a hybrid pareto front is proposed for case study, that means, regarding objective functions, designer can decide that which of two systems are more suitable for current case study. The results show that pareto fronts of two hybrid systems intersect each other at a point. In this case, PV-PHS led to the lower pareto front for LPSPs up to about 6.94% and for LPSPs higher than 6.94%, pareto front of PV-PHS system lies above that of PV-Battery system. This implies that under LPSPs range of 0-6.94%, the PV-PHS system resulted in the lower initial cost, therefore, it is better option for the current case study. In contrast, for LPSPs higher than 6.94%, for the same LPSP, PV-Battery system led to the lower investment cost in comparison with PV-PHS, so it can be chosen as a better option regarding designer's priorities. Also, results show that the proposed strategy can reach a design with the full satisfaction of fluctuating demand and system constraints. In this case, for the yearly average demand of 16.3 kW, the investment cost is obtained to be 2.1M$ and 1.87 M$ for the PV-battery and PV-PHS, respectively. The paper compares in detail the optimal designs and operations obtained for the two hybrid PV-Battery and PV-PHS systems.

Keywords: PV-Battery, PV-PHS, Optimal design, Sweden

1. INTRODUCTION

Currently, renewable energy systems play important role to respond to the ever-increasing global energy demand and to avoid the environmental pollution from the consumption of fossil fuels. Moreover, there are a lot of off-grid power systems in the world, and most of them are still powered by diesel generators. They are typically either remote, islanded systems or special zones designed to disconnect from the main utility grid for economic or power supply quality reasons [1]. Standalone renewable energy technologies present great potential for energy generation and supply in remote areas. One technology that has gained popularity during recent years is solar power. Due to the intermittent production characteristics of solar PV, the demand for energy storage solutions s are on the up-rise as well. There are various energy storage technologies currently in use for distributed renewable energy integration which are mentioned in [2] in details. Among these technologies, rechargeable lead-acid batteries, particularly those with deep discharge rate and high stability, are commonly employed in standalone renewable energy system [3]. Another alternative is pumped storage, which is the leading energy storage in the world, with more than 300 plants installed worldwide, which they can be employed in various scale sizes, from large-scale to small-scale pumped storage of a scale at a few hundred kW in standalone hybrid energy power generation systems for remote areas [4,5]. Several real projects on using energy storages, i.e., battery and pumped hydro storage, to service the standalone RE system in remote areas in small scale, have been presented in recent years. Ma et al presented a techno-economic analysis of the standalone hybrid solar-wind system with battery storage [5] and with pumped hydro storage [6] in a small remote island in Hong Kong. Manolakos et al. [7] reported the experiences gained from the implementation of a stand-alone PV plant in which battery storage was replaced by a hydraulic one. The plant was installed on Donoussa Island, to cover the electricity needs of the remote village of Merssini (13 houses), Greece. The combination of solar power and energy storage systems provides new opportunities for electricity consumers, particularly in small remote islands, to become independent from the grid and fulfill their demand themselves. This study compared and analyzed the potential of using of two energy storage technologies, i.e. battery and pumped hydro storage, for the PV powered microgrid power supply system on a small Island in Sweden. This study deals with an optimization approach for the multi-objective optimal design of hybrid PV-PHS and PV-battery systems for off-grid supply for a case study in Sweden. The optimal design and operation of Hybrid PV-battery and PV-PHS systems are analyzed and compared for case study.

2.System description

Two hybrid systems, i.e., PV-PHS and PV-Battery storage, are schematically shown in Fig. 1. In brief, the system is supposed to store the extra energy generated by the PV section through pumping sea water into the upper reservoir and release the stored water to pass through the turbine-generator unit to generate electricity whenever necessary. The operation of the PV-battery is identical to that of PV-PHS system except that the energy is stored electrochemically.

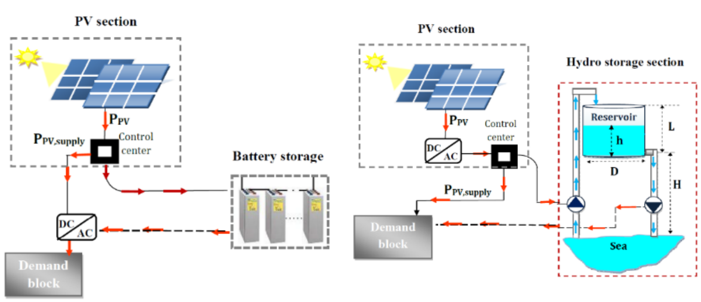

Fig.1. Schematic of Hybrid PV-PHS and PV-Battery system

2.1. Photovoltaic system

The PV modules considered in this study are of type SQ175-PC PV. The power output of PV array is simulated based on the five-parameter model of the Shockley, as shown in Eq. (1). Five unknown parameters under STC condition and real condition (dependent on solar radiation and ambient temperature) are calculated based on equations in [8,9]. Under each set of operating conditions, the operating voltage of PV modules is adjusted to attain maximum power output. Peak power of PV module is 175 W and Inverter has the efficiency of 90%.

$$P_{PV} = N_{PV}.I_A.V_A = N_{PV}.N_p I_{ph} V_A - N_{PV}.N_p I_0 V_A \left(e^{\frac{1}{V_t}\left(\frac{V_A}{N_S}+\frac{I_A R_S}{N_p}\right)} - 1 \right) - \frac{N_p}{R_p} V_A \left(\frac{V_A}{N_s} + \frac{I_A R_s}{N_p} \right) \quad (1)$$

2.2. Pump storage hydroelectric system

The pump is simulated by solving Eq. (2)

$$P_p = \frac{\rho.g.H_{tot}.Q_p}{\eta_p}; H_{tot} = L + H + H_f; \ \eta_p = 85\% \quad (2)$$

The power output and efficiency of a turbine-generator unit are computed as shown in Eqs. (3) and (4), respectively [10].

$$P_{turbine} = \eta_t.\rho.Q_t.(H_{stat} - H_f); H_{stat} = H + h \quad (3)$$

$$\eta_t = \eta_{\max} \left(1 - \left(\frac{\rho.g.H_{stat}.Q_t}{P^n_{turbine}} - 1 \right)^2 \right); \ \eta_{max} = 85\% \quad (4)$$

The head of water inside the reservoir is updated at the end of each time interval as shown in Eq. (5)

$$h_{i+1} = h_i + \frac{Q_p - Q_t}{A}.3600 \quad (5)$$

2.3. Battery storage

In this study, the employed batteries in the PV-battery system are considered to be advanced deep cycle lead acid type. Rated capacity of battery is 1.7 kWh. Maximum DOD, round trip efficiency and desired service life of battery is 75%, 75% and 5 years, respectively. The unit price of the battery is 469.82 $ [11]. The battery is set to operate above the minimal SOC (25% in this study).

2. Modeling and optimization

The operational strategy which is considered in this study, determines the steady state operation of the PV-PHS and PV-battery systems over the year for a set of input data. The input data received by the operational strategy are classified in two groups: first group is the set values of design variables, and the second group is the hourly data of global irradiance, power demand and the ambient temperature. Time interval is one hour. The number of PV modules (N_{PV}), turbine nominal power ($P^n_{turbine}$), pump nominal power (P_p) , the installation height of reservoir (H), the charge and discharge pipes diameters (d_{charge}, $d_{discharge}$), the depth to diameter ratio of reservoir (*L/D*) and the volume of reservoir ($V=A\times L$) constitute the set of design variables for a hybrid PV-PHS system. And for hybrid PV-battery system, number of PV modules and number of battery units are considered as design variables.

The Genetic Algorithm, NSGA-II, is employed to solve the present multi-objective optimization problems. The optimization and simulation of this study is carried out with own coding in MATLAB 2018 a.

The objective functions of the problem are the minimization of investment cost and the minimization of the loss of power supply probability (LPSP), as shown in Eqs. (6) and (7).

$$objective1 = C_{investment} = \begin{cases} C_{pv} + C_{reservoir} + C_{pump} + C_{turbine} + C_{pipe}\,; \text{PV\_Hydro} \\ C_{pv} + C_{battery\ bank} \qquad ; \text{ PV\_Battery} \end{cases} \quad (6)$$

$$Objective2 = LPSP = \frac{\sum_{i=1}^{total\ hours} hours[P_{supply}(i) < P_{dem}(i)]}{total\ hours} \times 100 \quad (7)$$

In addition to optimal values of objective functions and design parameters, the values of monthly and yearly supply to demand ratio (SDR) and PV supply to supply ratio (PSR) are also calculated. SDR, which mathematically defined in Eq. (8), indicates the ratio of the energy delivered to the demand block to that required by the demand block. In other words, SDR is an index of matching between the supplied and demanded energies; that means, the greatest match between power supply and power demand is occurred when SDR approaches one. PSR, which is shown in Eq. (9), shows the ratio of energy delivered to demand by the PV to that energy delivered to demand by the system. In other words, PSR is an index that show how much of energy delivered to demand is supplied by PV section.

$$SDR = \frac{\sum(P_{supply})}{\sum P_{dem}} \quad (8)$$

$$PSR = \frac{\sum(P_{PV,supply})}{\sum(P_{supply})} \times 100 \quad (9)$$

Table 1, lists cost functions of each component in hybrid system which acceptably compatible with Sweden market. The cost of PV section includes the costs of PV modules, tracking systems and accessories. PV system price is taken from the Swedish PV market report of 2018 [12] The formula presented for the calculation of the current investment cost of battery bank is originated from the fact that the batteries should be replaced with new ones every five years. In this equation 'r' shows the discount rate which is chosen as 2% considering current loan rate [13] and 'n' is the system lifetime (25 years).

Table 1. Cost functions

Cost function ($)
C_{PV}=2.5 × PV rated power (W_p)
C_{res}=170 × reservoir volume (m^3)
C_{pump}=(380.22 × pump nominal power (kW))-6360.9
$C_{turbine}$=(725.42 × turbine nominal power (kW))+7688.2
C_{pipe}=1457.14 × Pipe diameter (m) × Pipe length (m)
$C_{battery\ bank}= N_{battery}.\ C_{battery} \sum_{i=1}^{n/5} \frac{1}{(1+r)^{5(i-1)}}$

4. Case study

The current study is implemented for a small island located in Sweden. Fig.2, depicts the monthly-averaged hourly data of load profile and global irradiances received by dual axis tracking technology. The lowest and highest daily electricity consumption are in June (337.8 kWh) and January (481.4 kWh), respectively. The lowest and highest daily electrical output power of one PV module are in January (0.152kWh) and June (1.48 kWh), respectively. This implies that daily load profile in January is almost 1.5 times that in June and the average daily electricity production of one PV module in June is approximately 10 times that in January. This seasonal mismatch between summer and winter implies the importance of a suitable energy storage to balance out the mismatch between fluctuations in energy supply and the varying demand. The weather data (e.g., global solar irradiance and ambient temperature (C) in the current case study is taken from [14]. The start point for modelling and simulation is 9 A.M, April.

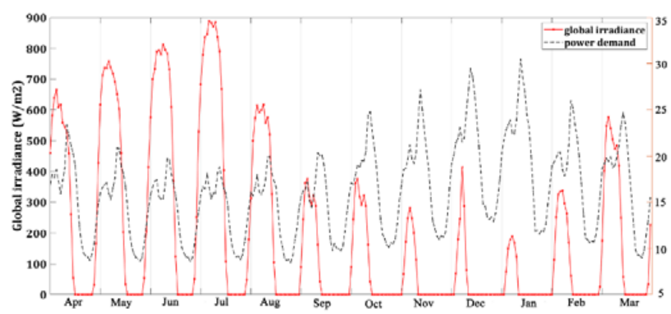

Fig.2. load profile and global irradiance, small island in Sweden

5. Results and discussion

In this section, first, simulation and optimization results of the two hybrid PV-Battery storage and PV-PHS systems are introduced and compared; then, the steady state operation of selected optimal design for two hybrid energy systems are compared and illustrated in detail.

5.1. Pareto front

In multi-objective problems, a solution is said to be better than another, if it is better at least in one objective, and it is not worse in any objective. The solutions with no better solution than them are located on Pareto front. In consequence, Pareto front is a collection of non-dominated superior solutions which each can be chosen as the optimal solution depending on the designer's priorities. The Pareto fronts obtained for two hybrid systems are shown in Fig.3. Each point on pareto fronts represents a specific design (i.e., a design with a known set of design parameters). As shown in Fig.3, for both hybrid systems, investment cost increases by the increase of power supply probability. Moreover, it is observed that two pareto fronts intersect each other at a point which is related to LPSP of 6.94%. In other words, PV-PHS system led to the lower pareto front for LPSPs up to about 6.94% and for LPSPs higher than 6.94%, pareto front of PV-PHS system lies above that of PV-Battery system. This implies that under LPSP range of 0 - 6.94%, the PV-PHS system resulted in the lower initial cost, therefore, it is better option for the current case study for this range. In contrast, for LPSPs higher than 6.94%, for the same LPSP, PV-Battery system requires a lower investment cost in comparison with PV-PHS, so it can be chosen as a better option regarding designer's priorities. Fig.4, proposed a hybrid pareto front which is composed of two parts, i.e., the best part of each pareto fronts. So, regarding objective functions (LPSP and investment cost), designer can decide that which of two systems are more suitable for current case study. Among all the solutions on a pareto front one solution is usually of special interest is solution with the full satisfaction of power demand (i.e., the solution with the LPSP of 0%). This solution is designated in Fig.3 for each of the systems. Regarding Fig4, PV-PHS system is suitable option for this design (LPSP of 0%). Trade-off solution is another solution of interest in multi-objective problems which shows a best compromise between LPSP and investment cost. Trade-off solution is the closest solution to the ideal point. The ideal point is an imaginary solution whose each objective value is considered to be equal to

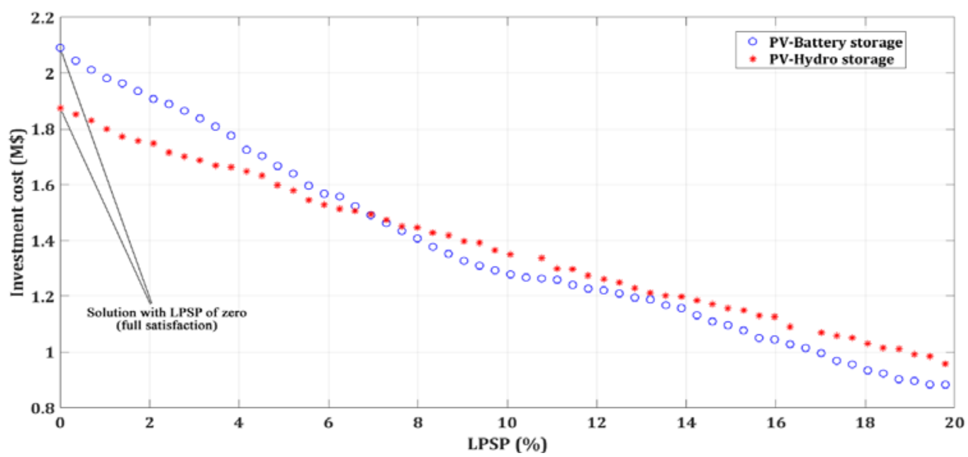

Fig.3. Pareto fronts of two hybrid PV-Battery and PV-PHS systems

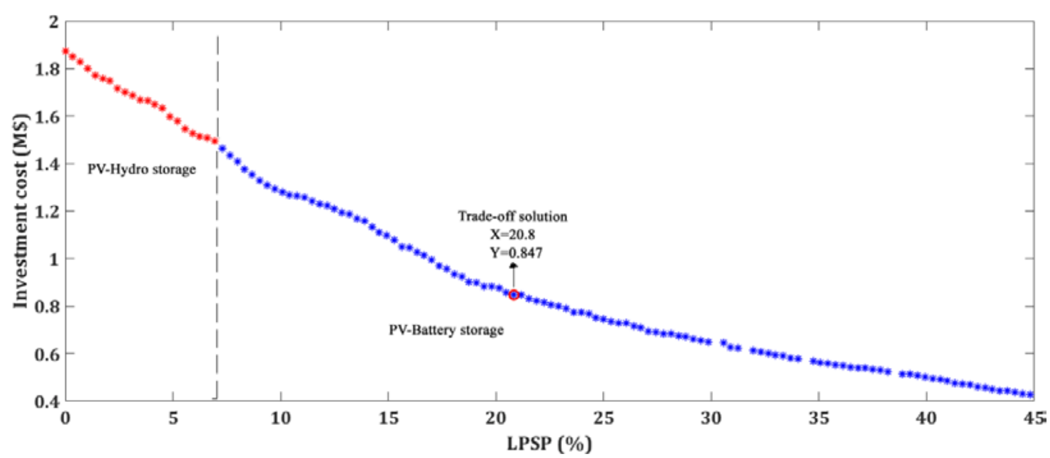

Fig.4. Hybrid pareto front (selected from the best pareto fronts of hybrid PV-Battery and PV-PHS)

the best value obtained from among all cases. Trade-off solution for hybrid pareto front is designated in Fig.4. It is observed from Fig.4, that trade-off solution is in the domain of PV-Battery design. That there is 8.3% reduction in investment cost in compare with PV-PHS system at the same LPSP of trade-off.

5.2. operation of selected optimal design for two hybrid energy systems

The detailed information of the optimal solution with LPSP of 0% relating to the both hybrid systems is quantitatively compared in Table 2. As shown in Table 2, the PV-battery resulted in a 12.3% higher investment cost compared to the PV-PH system. That about 87.8% of this higher cost relates to PV section.

Table 2. Detailed information of the optimal solution with LPSP of 0%

System type	PV-PHS	PV-Battery
LPSP (%)	0	0
Investment cost (M$)	1.87	2.1
PV system cost (M$)	0.873	1.075
Storage system cost (M$)	1	1.016
Number of batteries	-	522
Number of PV modules	1995	2457
Reservoir volume (m3)	5256.8	-
Reservoir installation height (m)	85.4	-
Reservoir diameter (m)	22.1	-
Reservoir depth (m)	13.7	-
Turbine nominal power (kW)	31.7	-
Pump nominal power (kW)	58.2	-
Charge pipe diameter (m)	0.21	-
Discharge pipe diameter (m)	0.25	-

The time variation of power supply (i.e., sum of power sent from PV and turbine to the demand block) of the optimal solution (LPSP of 0%) is shown in Fig.5 along with the demanded power profile. This figure confirms that that the total power supply is equal or greater than the demanded power always; in other words, the demand is fully satisfied. Due to the variable nature of power demand and solar irradiance, the supply and demand curves cannot be expected to match at all times. As shown in Fig.5, the matching of demand and supply mostly happened during night times when turbine generator is the only source of power supply. This is because the turbine-generator can be set to generate as much power as required. However, there are sometimes which turbine power does not match demanded power. Thus, is due to the fact that turbine is considered to work within permissible range and is not allowed to generate less power than 60% of its nominal power. Also, Fig.6, shows power supply (i.e., sum of power sent from PV and battery to the user) which confirms that the power supply is equal or greater than the demanded power always. In other words, it confirms that the demand is fully satisfied.

As shown in Figs. 5 and 6 and Table 3, it is obvious that for both system during summer, SDR values are high during summer period that implies oversupply energy in summer period. Moreover, it can be resulted that PV-Battery system led to more oversupply of energy over the year (particularly in summer period) in compare with PV-Hydro storage. Also, it is observed that during months of November, December, January and February, SDR index approaches 1, that implies greatest match between supply and power demand. Also, it is observed that during summer period PRE-values fluctuated around 90%, which this impels that demand power mostly supplied by PV section and storage system mostly is in charging and storing energy mode (except in nights) in the summer, during winter period most of demand power is supplied by storage section. This is because of the seasonal mismatch between the load and production that implies a reason for the low PV capacity in winter in current study and the importance of storage to overcome the intermittence of the PV power. For the optimal PV-PHS system with the LPSP of 0%, the time variations of PV section power production, pump power consumption, turbine power generation is shown in Fig.7, and the time variation of the reservoir state of charge (ratio of water volume to capacity of reservoir) is illustrated in Fig.8. As shown in this figure, when pump operates around the times of high irradiance the SOC of the reservoir increases and when the turbine operates,

Table 3. Monthly and yearly information of SDR and PSR related to solution with LPSP of 0%

System type		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Yearly**
PV-PHS	SDR	1.21	1.48	2.83	4.16	5.55	7.4	8.89	5.36	2.1	1.64	1.21	1.20	3.34
	PSR (%)	32	48	78	86	91	94	94	88	61	55	32	33	79
PV-Battery	SDR	1	1.17	4.4	5.46	9.50	10.7	10.8	6.9	2.8	2.4	1.27	1	4.4
	PSR (%)	29	53	91	95	97	98	97	94	81	78	47	28	89

the SOC of the reservoir decreases accordingly. Also, for the optimal PV-Battery system with LPSP of 0%, the time variations of PV section power production, rate of battery charging (which mostly occurs during periods of high solar radiation), and rate of battery discharging (which mostly occurs during nights or cloudy days) are shown in Fig. 9. Moreover, Fig.10, illustrates the time variation of the battery bank state of charge. It is observed from Figs. 8 and 10 that storage section of both systems acts as a seasonal storage, which store surplus electricity in summer and consume it in winter.

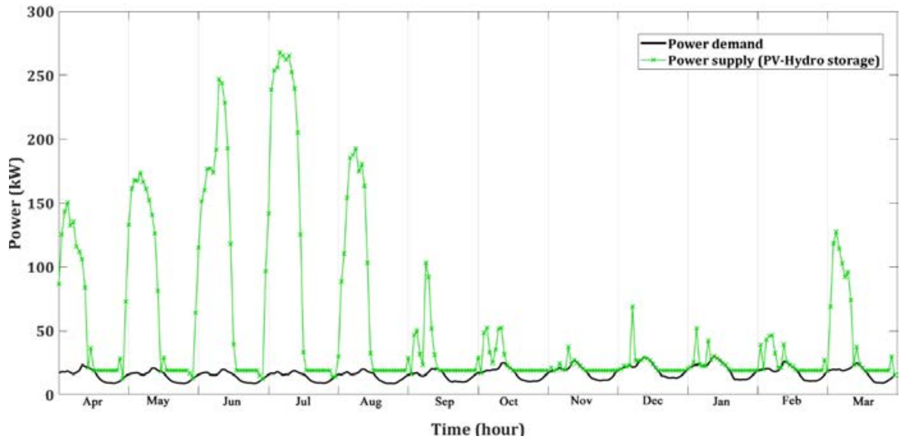

Fig.5. Time variation of power supply ($P_{pv,supply}+P_{turbine}$) and power demand, relating to the solution with LPSP 0%

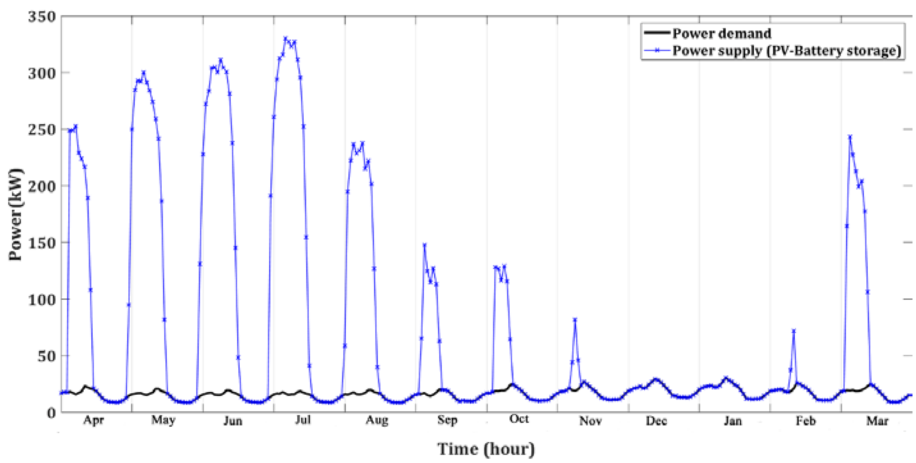

Fig.6. Time variation of power supply ($P_{pv,supply}+P_{battery,out}$) and power demand, relating to the solution with LPSP 0%

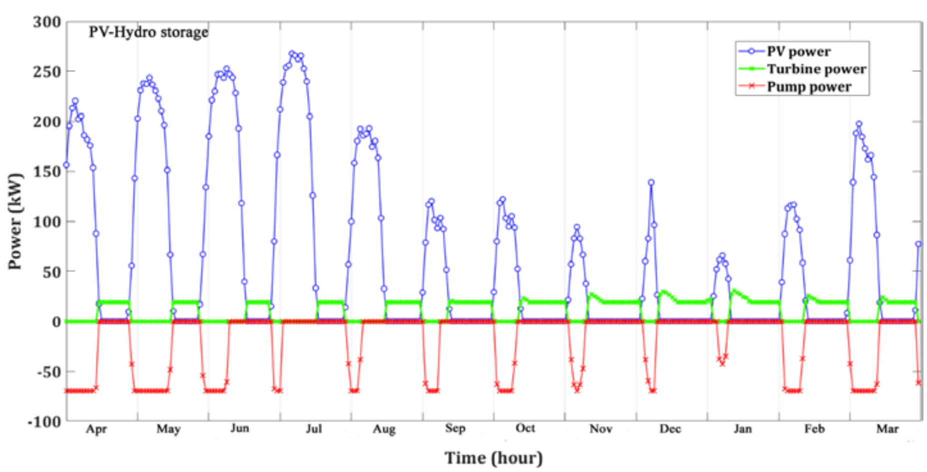

Fig. 7. Time variation of PV power (P_{PV}), Pumping power (P_{pump}), and turbine power, relating to solution with LPSP of 0%

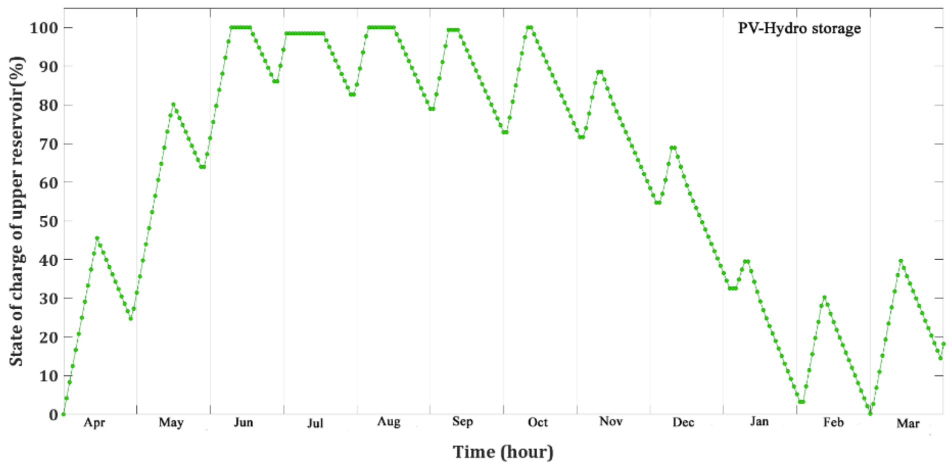

Fig.8. Time variation of reservoir state of charge, relating to solution with LPSP of 0%

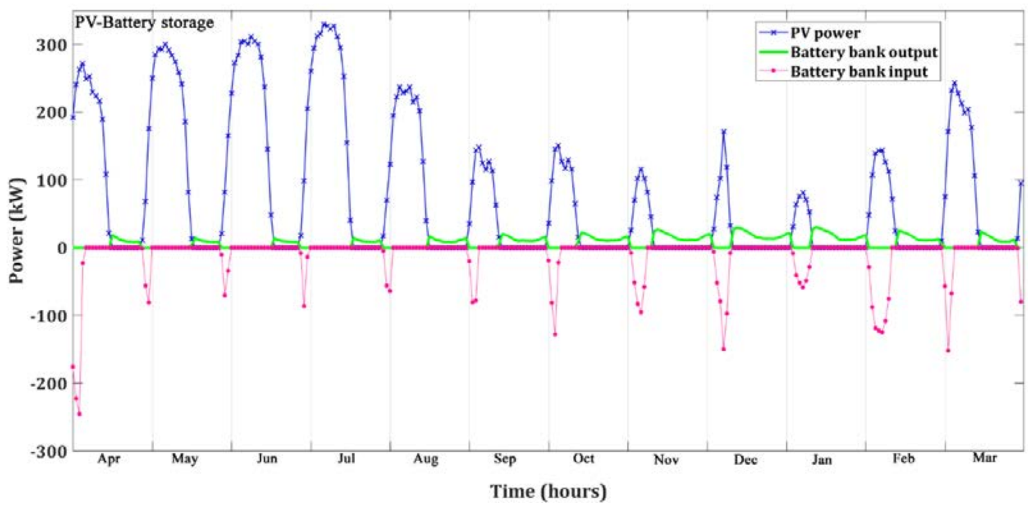

Fig.9. Time variation of PV power (P_{PV}), charge power ($P_{battery,in}$), and discharge power ($P_{battery,out}$), relating to solution with LPSP of 0%

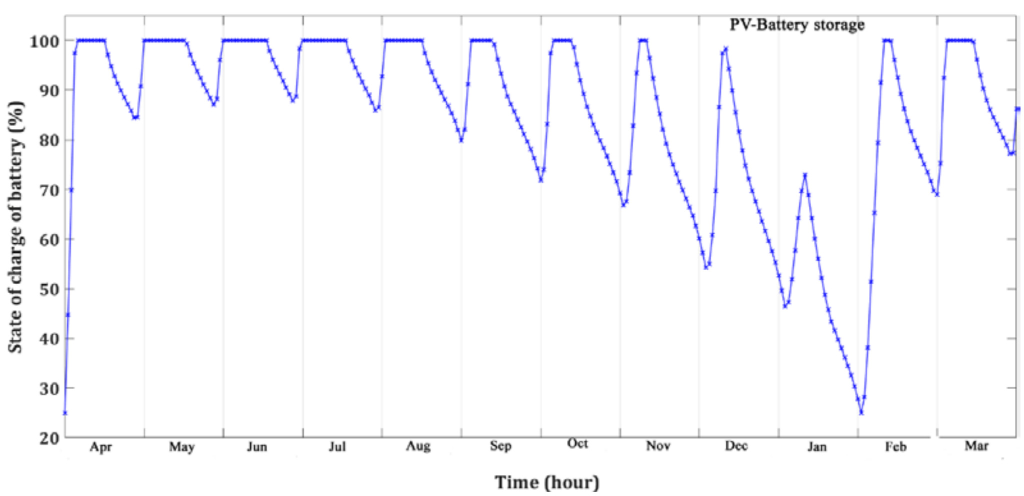

Fig.10. Time variation of battery state of charge, relating to solution with LPSP of 0%

6. Conclusions

The main aim of this study was comparing and analyzing the potential of using of the energy storage technologies, i.e., Battery storage and pumped hydro storage, in combination of PV system for power generation and power supply for a small island in Sweden. Optimal design of two hybrid PV-Battery and PV-Hydro storage systems have been done. Straightforward operational strategies in combination with Genetic Algorithm were employed to design hybrid PV-Battery and PV-Hydro storage for case study. A set of design variables were considered for both systems, and investment cost and LPSP constituted the objective functions. A hybrid pareto front is proposed for case study, that means, regarding designer's priorities, it can be decided that which of two proposed system is more suitable for case study. In this case, under LPSP range of 0-6.94%, the PV-Hydro storage system led to the lower initial cost, therefore, it is better option for the current case study. In contrast, for LPSPs higher than 6.94%, PV-Battery system resulted in a lower investment cost in compare with PV-Hydro storage, so it can be chosen as a better option. Also, results show that the proposed strategy can reach a design with the full satisfaction of fluctuating demand and system constraints. For design with LPSP of 0%, the PV-battery resulted in a 12.3% higher investment cost compared to the PV-Hydro system. Moreover, in this case (LPSP of 0%), PV-Battery system led to more oversupply energy in compare with PV-Hydro storage.

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