Application of hybrid systems in solution of low power generation at hot seasons for micro hydro systems

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Highlights

- Mashhad Sarrood powerhouse with 61 kW capacity is selected as a case study.
- The best technical and economical hybrid is introduced due to the variation in the river flow and solar energy.
- The results show that energy deficit improvement should be done using appropriate economic analysis.
- Increasing the use of renewable energy just to eliminate energy shortages may not be economically justified.

Abstract

There is potential in using water energy especially in running river systems in most rural areas, but one of the problems of using such systems is the seasonal changes. In hot and dry seasons the water flow is low and the system is confronted with low energy production. For resolving this problem and to increase the potential for renewable energy in many cities, it is possible to use these energy sources in power plant to make up the power. Mashhad Sarrood power plant with a 61 kW capacity is selected as a case study. Due to the high potential of solar and wind energies in Iran, using these energies in the season that power decreases, wind and solar energy are introduced complementary. The Homer software used to create a model of the mentioned power plant to determine the best technical and economical hybrid to account for the variations in the river flow and solar energy. The results show that energy deficit improvement should be done using appropriate economic analysis. Increasing the use of renewable energy just to eliminate energy shortages may not be economically justified.

Keywords

Hybrid systems; Photovoltaic panel; Micro hydro systems; Homer software

1. Introduction

Solar energy has been used throughout the progress of mankind. Since ancient times, humanity has used the sun for drying agricultural products, bricks, etc. Old Greek and Chinese cultures produced solar reflectors which concentrated solar radiation to generate ignition for various purposes. In the 1st century AD in Alexandria, people used the sun to create mechanical power by building solar water syphons [1,2].

Nowadays, using renewable energy (such as wind and solar energies) is the most attractive choice to optimize systems [[3], [4], [5]]. There is much research on solar energy [5]. Many of these investigations are about using solar energy collectors for heat generation [6,7]. For examples; Farshad [8] and Sheikholeslami [9] analyzed exergy and entropy by using nanofluid flow inside the solar collector.

One of the methods of using river water is by exploiting hydropower. Some power plant generate electricity without building dams and are powered directly from the river flow. This is called run-of-the-river hydropower. The required head is obtained by deflecting the river flow to collect in tanks. The water is then conducted to a turbine by a penstock. Sufficient water flow with good accessibility to the power plant to provide good head, are the required conditions for stablishing run-of-the-river power plant.

Water power plant generally are divided to six types (according to Table 1) [10].

Table 1. Water power plant types.

Large- hydro	More than 100 MW and usually feeding into a large electricity grid
Medium-hydro	10 or 20 MW–100 MW - usually feeding into a grid
Small-hydro	1 MW to 10 or 20 MW – definitions vary: Europe tends to 10 MW as maximum, China uses 20 MW and Brazil 30 MW – usually feeding into a grid
Mini-hydro	Above 100 kW, but below 1 MW; either standalone schemes or more often feeding into the grid
Micro-hydro	From 5 kW up to 100 kW; usually provided power for a small community or rural industry in remote areas away from the grid.
Pico-hydro	50 W to 5 kW usually for remote communities and individual households. Applications include battery charging or food processing.

New energies generally comprise solar heat generation, photovoltaic power, hydro power, wind power, tide power, wave power and earth thermal production. While generating of electricity by hydropower was about 5500 MW in 2009 in Iran, Iran’s wind power plants in the Manjil area and in Binalood produced 92 MW of electricity [11].

Tsalikis and Martinopoulos [12] investigated solar potential regarding photovoltaic in typical residential buildings in order to identify their impact towards nearly net zero energy buildings (NZEB). They showed that photovoltaics were able to cover the annual electricity demand of a residential building with a payback period of less than 7 years and solar energy systems are able to provide at least 76% of the primary energy demand of residential buildings, proving that they are a viable solution towards NZEB.

Hoseinzadeh and et al. investigated buildings with zero energy consumption in the north of Iran. They considered a residential building with the conventional condition as a reference and investigated energy efficiency parameters. A feasibility study for constructing such buildings in this humid mountainous area was done [13].

The impact of main factors (load being supplied, wind speed, global irradiance, ambient temperature and battery bank capacity) on the performance of a hybrid energy system was analyzed by Thapar [14]. He concluded that for a given load, with increase in battery bank capacity, the levelised cost of energy increases linearly, whereas loss of power supply probability decreases exponentially and with an increase in wind speed.

Ghasemi et al. [15] investigated solar energy for power production by considering several affecting parameters such as technical, economic, and environmental criteria for implementing solar power plants in the southeast of Iran. The solar systems considered in this study were photovoltaic (PV) collectors and concentrated solar power (CSP) generation plants. It was demonstrated that this specific location in the southeast of Iran has the technical potential to provide 8758 TWh/yr of solar electricity by installing PV technologies.

A transient simulation model of solar-assisted heating and cooling systems (SHCs) was investigated by Hoseinzadeh and Azadi [16] for a duplex house in a northern city of Iran. They designed the cooling capacity of the absorption chiller and the solar collector area on the basis of the maximum cooling load, and the auxiliary gas-fired boiler was also used in summer to feed the absorption chiller, in case of inadequate solar irradiation.

Photovoltaic panels are the best entry-level energy systems [17]. Due to high lifetime and low depreciation, photovoltaic panels are good choices to be located with fossil fuel generators for remote villages [18].

Hanna et al. [19] optimized demand charge reduction in real-time by using a battery storage dispatch strategy. The discharge of battery storage devices combined with a photovoltaic-battery storage system (PV + system) was simulated for a summer month (July) and a winter month (November). They showed that the average reduction in peak demand on weekdays was 25.6% in July and 20.5% in November. The PV array (excluding the battery array) reduced the peak demand on average 19.6% in July and 11.4% in November.

There have been many papers on using renewable energy in the last decades. Nfaha and Ngundamb [20] considered renewable energies for villages. They compared prime cost for conducting the electricity to far villages, operation cost and other parameters, with the cost of establishing small power plants. In their research they mentioned that if the cost of every kilometer of cabling from the network to its position is 5000 euro and if the replacement cost for every kilometer is 125 euro per year and the prices of every kWh is 0.1 euro, the cost of establishing photovoltaics system and battery are the same and the system generate power about 72 kWh per day with 15.2 km cabling for Cameroon city, US [20].

Using isolated electrical power generating units to electrify remote villages where grid extension is not feasible, was considered by Sreeraj et al. [21]. One of the main approaches to building isolated power systems is by hybridizing renewable power sources like wind, solar, micro-hydro, etc. with energy storage. They hybridized wind, solar photovoltaic and a battery to design an isolated power system for an Indian village. The simple methodology proposed in this paper, was based on the principles of process integration.

The main problem of continuous energy supply from photovoltaic (PV) power plant is intermittence and the inability to provide continuous energy supply. Margeta and Glasnovic [22] proposed the hybridization of photovoltaic with hydro energy. They used solar energy as primary energy source and pump storage hydroelectric (PSH) as a possible solution. They used water for energy storage and introduced hydrological and hydro-energetic indicators for the hybrid plant description. They also introduced what they called artificial rainfall, to express the hydro energy potential of the hybrid power plant.

Lee [23] estimated the energy conversions of separate and hybrid solar-wind systems under variable weather. The monthly and yearly power outputs of the separate and hybrid solar-wind systems provided with different configurations were considered by the numerical model. He used the characteristics of photovoltaic generation, wind energy conversion, energy balance, and battery bank, to integrate his model.

Hale et al. [24] modeled the Florida Reliability Coordinating Council operations in 2026 over a wide range of PV penetrations with various combinations of battery storage capacity, demand response, and increased operational flexibility.

Alsharif [25] considered heterogeneous cellular networks on the sustainability of power resources and environmental conditions. He discussed optimal criteria, system architecture, energy production, and cost analysis based on the characteristics of solar radiation exposure in South Korea. His paper compares the feasibility of using an autonomous solar power system to feed heterogeneous cellular networks versus a conventional energy source.

Photovoltaics was introduced as the best choice to combine with diesel generator by Valente and De Almeida, because fuel expended cost and overhaul cost would go down with using photovoltaics [26]. Combination of diesel generator and hydro turbine is one of the best and available system for providing power in remote regions. Kenfack et al. explained that most of the hydro power plants suffer from power shortages in warm seasons or famine years, while maximum solar energy is available in these seasons, so combining these generators with solar panels is a logical combination [27].

Williams showed that using micro hydro power as equipment to combine with diesel generator in some remote regions. This combination causes using of local potential and decreases expended fuel cost [28]. Micro hydropower plant was chosen as the best method to generate electricity in some parts far from the electrical grid in Kenia by Maher et al. [29].

For decreasing of diesel generator cost and air pollution, Kamel and Dahl [30] suggested combining wind turbine with diesel generator. They used the Homer Energy software to simulate the combination of the diesel generator and wind turbine and conduct an economic analysis. They indicated that although the primary cost of establishing the wind turbine is high, costs of operation, repair and fuel will decrease to become economically feasible.

Himri [31] compared the economy of network electricity with a combination of a diesel generator and a wind turbine. It was shown that using wind turbines and diesel was commodious when the wind speed was 5.48 m/s and the price of fuel was lower than 0.162 $/lit.

There are many researches of combination and optimization of renewable systems [[32], [33], [34]]. The combination of hydro and wind turbines was found to be an economical model for the electrification of Western Ghats in India [35].

Saheb-Koussa et al. [36] conducted a technical and economic investigation of a hybrid generator system comprising wind turbines, photovoltaic panels and a diesel generator with battery storage, to provide power in remote regions. They showed that such a combination of generators provides the optimal solution to supply power to far-off regions. One advantage of using such a hybrid system for these regions is that usually at least one of power sources is available.

Making use of micro hydro power with low flow rate and low head, as one of the best renewable energies for far-off regions, was suggested due to this being available every time and there is always the possibility of using this with one of the other renewable energy sources [37,38].

The amount of solar radiation for a country like the UK is 1050 $kWh/m^2/yr$ [39] and in very sunny countries where solar systems are highly recommended, this amounts to 2000 $kWh/m^2/yr$.

Studies of recent research have shown that there is little useful and effective research, as well as economic analysis in optimizing energy systems [40,41]. Optimizing energy for these places are very important. In the present study, a power plant system has been optimized with renewable energy production systems. The optimization criterion used in this study is the production and elimination of the required energy shortage with the lowest initial setup cost. The important point in this simulation is that although system optimization can compensate for the production deficit by increasing the number of photovoltaic panels, this is not economically justifiable and another optimization approach (wind turbine, batteries) is recommended. The results and analysis presented here can be used as useful experience and input to future projects.

2. Problem statement

In this paper, the modeling of a regional (Mashhad Sarrood) power plant which is not connected to the electricity grid, is performed. The area is water-scarce in summer (hot season) with a photovoltaic system which is then used. In winter (cold season) there is adequate water flowing and a run-of-the-river power plant is used.

The small hydroelectric power plant was built in 1987 in the village of Sarrood, 70 km from Mashhad. The plant has a flow rate of 0.5 cubic meters per second, a height of 16.6 m, and an installed capacity of 65 kW. It provides energy to the residents of Sarrood village.

During the hot season the plant flow rate is regularly checked based on the observed conditions in the plant, and power loss in the dry months can reach 26 kW.

In the geographical area under study, it is possible to solve the electrical needs of some villages by means of photovoltaic or micro-hydro cells.

The present study applies to power supply in areas that do not have much power consumption and are far from the electricity grid. When an energy source is not technically and economically insufficient, a combination of two optimization systems should be used to reduce fossil fuel consumption, transport problems to remote areas, and so on. In fact, the combination of the two renewable energies of the sun and water in this region is used to offset the power.

3. Design and simulation

The energy output of water can be calculated from the following formula:

$$P = \eta\rho gqh \tag{1}$$

where P is the attainable power (W), g the acceleration of gravity, h the height (m), q the flow rate, ρ the density of water, and η the efficiency of the power plant.

The basis for modeling is the combination of the solar system with the hydroelectric power plant, which requires other devices such as inverters and batteries. A schematic lay-out of the design is shown in the image below.

The average annual solar energy in the study area is 4.5 $\frac{kWh}{m^2\ d}$, which due to the geographical location, the effect of changes in flow rate and solar radiation energy on the combination and number of equipment required is considered.

So the annual solar energy for this case is:

$$4.5\ \frac{kWh}{m^2\ d} \times 365\frac{d}{yr}\ \ = 1642\ \frac{kWh}{m^2\ d} \tag{2}$$

Due to Given the 1.6 MW/m^2 power generation per year, the combination of hydroelectric power plants with solar power is justifiable.

According to a report of the Mashhad Water and Sewerage Center, the average river flow rate is as follows:

It can be seen from Table 2 that the water flow rate in the summer months is significantly lower than in winter. This tangible reduction reduces the hydropower generation capacity.

Table 2. Average river water flow in different months.

Month	Stream Flow (L/s)	Month	Stream Flow (L/s)
January	653	July	218
February	707	August	218
March	740	September	272
April	762	October	272
May	762	November	490
June	435	December	490

To provide a detailed economic analysis of the project, it is necessary to apply the price of the equipment used in the modeling correctly. Therefore a quote was requested for the micro-hydraulic turbine from a company in Iran, which manufactures water pumps and turbines. The turbine has an estimated capacity of 60 kW and an estimated lifetime of 30 years. The prices was USD 50,000.

The price of photovoltaic panels is another of the factors contributing to the economic analysis of the project. These can be imported in Iran for about USD 5 per Watt without a battery and inverter.

In order to model photovoltaic panels in the Homer software, in addition to knowing the exact geographical location of the project to obtain the solar energy, it is necessary to know another factor called clearness. The climate changes this factor. In general, for cloudy days it is 0.25 and for sunny days it is 0.75. This factor has a direct effect on the energy consumed on photovoltaic panels and is also called the coefficient of resolution. This coefficient has been calculated for Mashad by the Isfahan University of Technology (Table 3).

Table 3. Calculated Monthly mean clearness index [42].

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Oct	Nov	Sep	Dec
Mashhad	0.494	0.499	0.481	0.495	0.526	0.574	0.592	0.613	0.61	0.572	0.529	0.498

In order to obtain power shortage, it is necessary to obtain power demand at different hours of the night. For Sarrood village in Kalat Naderi, Mashhad, this value is assumed as per the following table (Table 4) with maximum power of 40 kW with 3% of daily variations.

Table 4. Power consumption at different times of day.

Hour	Load (kW)
00:00–01:00	15.000
01:00–02:00	15.000
02:00–03:00	15.000
03:00–04:00	15.000
04:00–05:00	15.000
05:00–06:00	15.000
06:00–07:00	20.000
07:00–08:00	20.000
08:00–09:00	20.000
09:00–10:00	25.000
10:00–11:00	25.000
11:00–12:00	30.000
12:00–13:00	30.000
13:00–14:00	35.000
14:00–15:00	35.000
15:00–16:00	35.000
16:00–17:00	35.000
17:00–18:00	35.000
18:00–19:00	35.000
19:00–20:00	40.000
20:00–21:00	40.000
21:00–22:00	40.000
22:00–23:00	40.000
23:00–00:00	35.000

4. Result

The software outputs and results for the three models are presented. The modeling was performed with 0, 5 and 10% annual production deficit and the results are as follows.

As shown in Table 2, the stream flow rate decreases in the dry months of the year, so the system experiences a decrease in power. The amount of power produced in different months of the year was calculated using equation (1).

The turbine's efficiency was estimated at 75% and according to the flow of the river in different months of the year, the amount of power produced by the hydropower is presented in Figure 1. As shown in Figure (2) the power output is drastically reduced during the low-load months. For example, in the months of July and August, when river flow reaches 218 L per second, the power output is 26.6 kW (see Figure 2).(3)

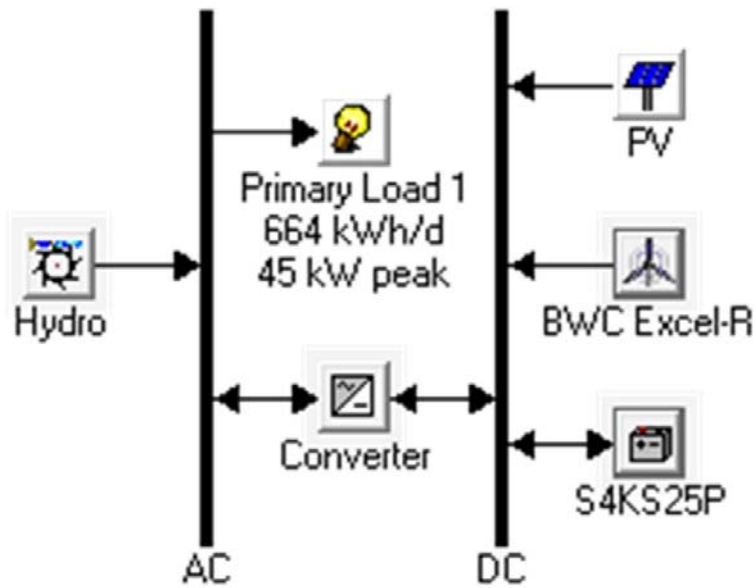

Fig. 1. Schematic lay-out for modelling.

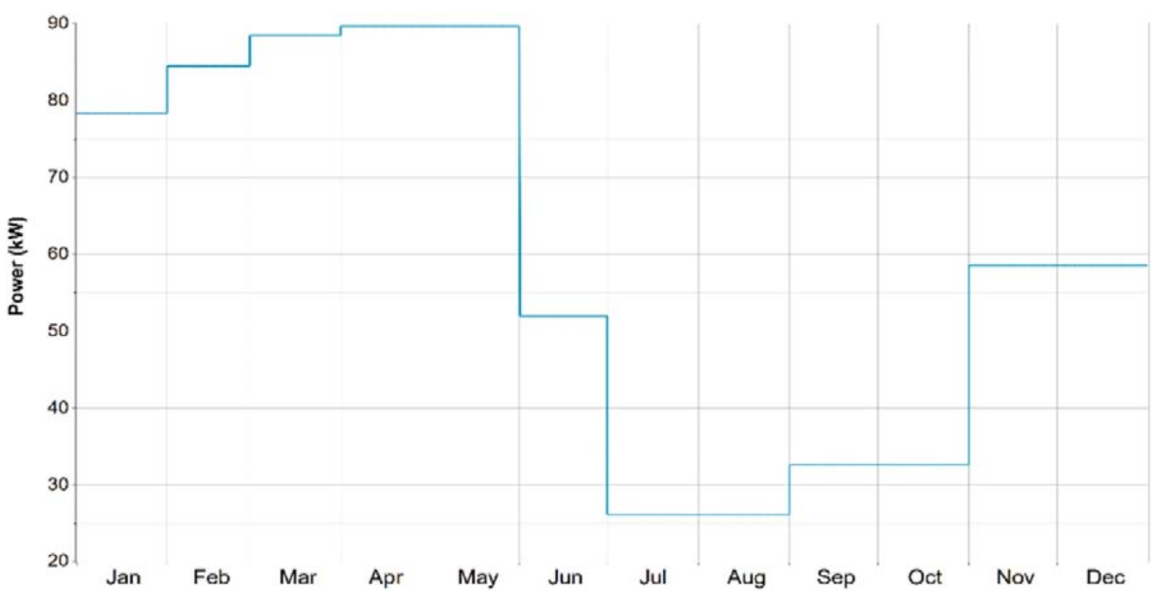

Fig. 2. Micro hydro power generation capacity at different months of the year.

Likewise, for September and October when the flow increases to 272 L per second of water, the output power is obtained as follows:

$$P = 75\% \times 1000 \times 9.81 \times 16.6 \times 272 = 33220\ W \tag{4}$$

The same approach is applied for the other months of the year.

Fig. 2 depicts the power generation for the whole year with an average water flow of 500 L/s:

Figure (3) shows a comparison of power consumption and generation capacity of the hydroelectric power plant. The amount of power produced during the low water months of the year is less than the amount of power consumed. As can be seen, in the months of July, August, September and October, which are the critical months, the power output is drastically reduced and micro hydro power alone is not capable of providing the required power.

Fig. 3. Comparison of power generation and power consumption in different months of the year.

The calculation of the energy deficit in these months shall be calculated as follows from the power consumption table (Table 4) and the power generation diagram (Figure (2)).

$$(30 - 26.1)\ kW \times 2h + (35 - 26.1)\ kW \times 6\ h + (40 - 26.1)\ kW \times 4\ h + (35 - 26.1)\ kW \times 1\ h = 125.7\ \frac{kWh}{d} \tag{5}$$

In Sep and Oct:

$$(35 - 32.5)\ kW \times 6\ h + (40 - 32.5)\ kW \times 4\ h + (35 - 32.5)\ kW \times 1\ h = 47.5 \frac{kWh}{d} \tag{6}$$

Therefore, the percentages of energy deficit in the months of July and August are as follows

$$\frac{125.7kWh/d}{665kWh/d} \times 100 = 18.9\% \quad (7)$$

The energy deficits in September and October are as follows

$$\frac{47.5kWh/d}{665kWh/d} \times 100 = 7.1\% \quad (8)$$

This happens in the season when the region receives most solar energy and there is potential to use this energy to fix the existing deficit. Figure (4) shows the solar power generated in different months in the region.

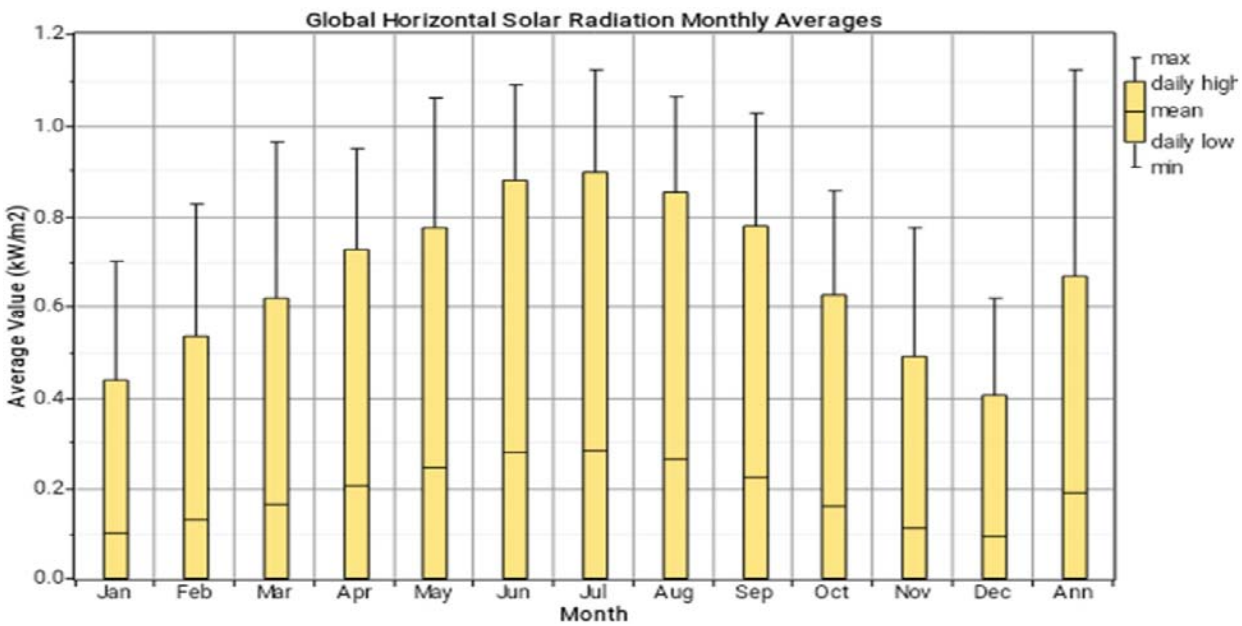

Fig. 4. Solar power available during different months of the year.

The power output during the critical and low-water months for different hours of the day is shown in Fig. 5.

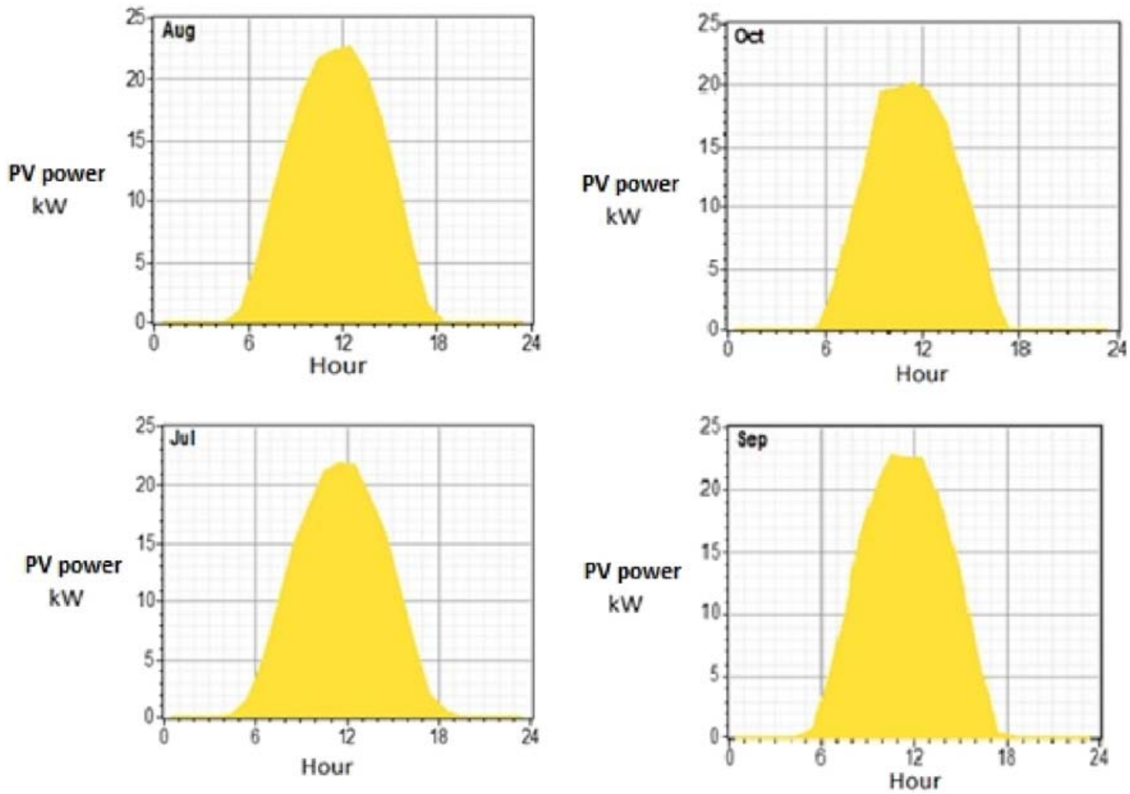

Fig. 5. Graph showing power generated during the critical months.

As can be seen, there is good potential for the sun to generate energy during these seasons. In times when the sun does not shine and given that the hydro power is diminished in these seasons, the reduction in power generation at night is noticeable. To fix this power deficit, the use of batteries for energy storage has been investigated. Batteries are charged when the power output is higher than the consumption. Fig. 6 shows the charge and discharge power of the batteries during the critical months based on daylight hours.

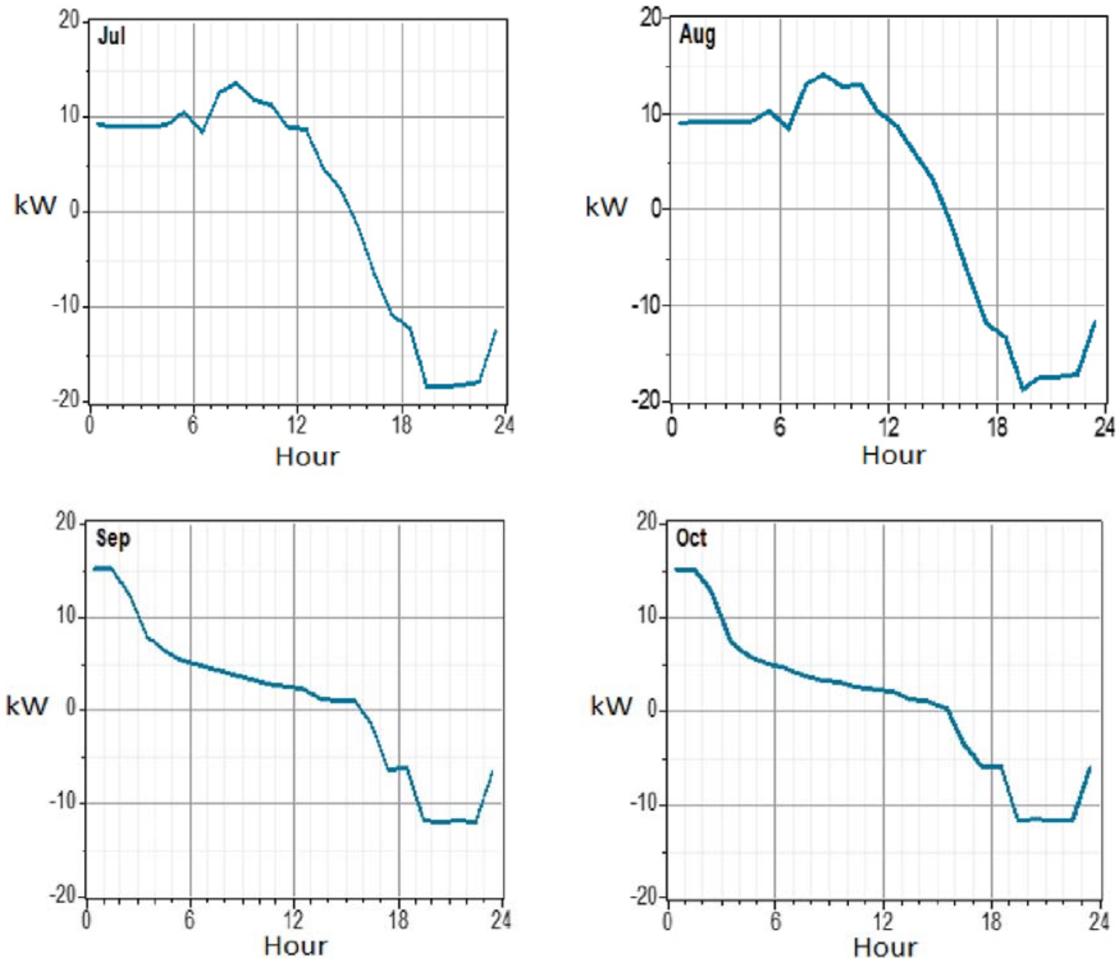

Fig. 6. Battery charge and discharge at different times of the day during critical months.

As can be seen, the batteries are recharged in less time when consuming the available sun and hydro energy from the river. And they are discharged at busy hours and when the sun's energy is no longer available.

The results of the analysis of the best combination are presented in the following form, based on the study on the output water of different months and the amount of solar radiation in different months.

Fig. 7 shows that if the water flow rate was 1000 L/s it would not be necessary to be combined with other systems. The power deficit can be improved for a 600–1000 L/s flow rate by combining the system with batteries. Solar panels and batteries must be supplied if the flow rate drops to 500–600 L/s, and a wind turbine should be added if the flow rate drops below 500 L/s. The simulation also indicates that with an average flow rate of 500 L/s, the most optimal combination for 61 kW of available hydro power is:

20 kW photovoltaic

7.5 kW BWC Excel-R wind turbine

40 Surrette 4 KS25P batteries

20 kW inverter

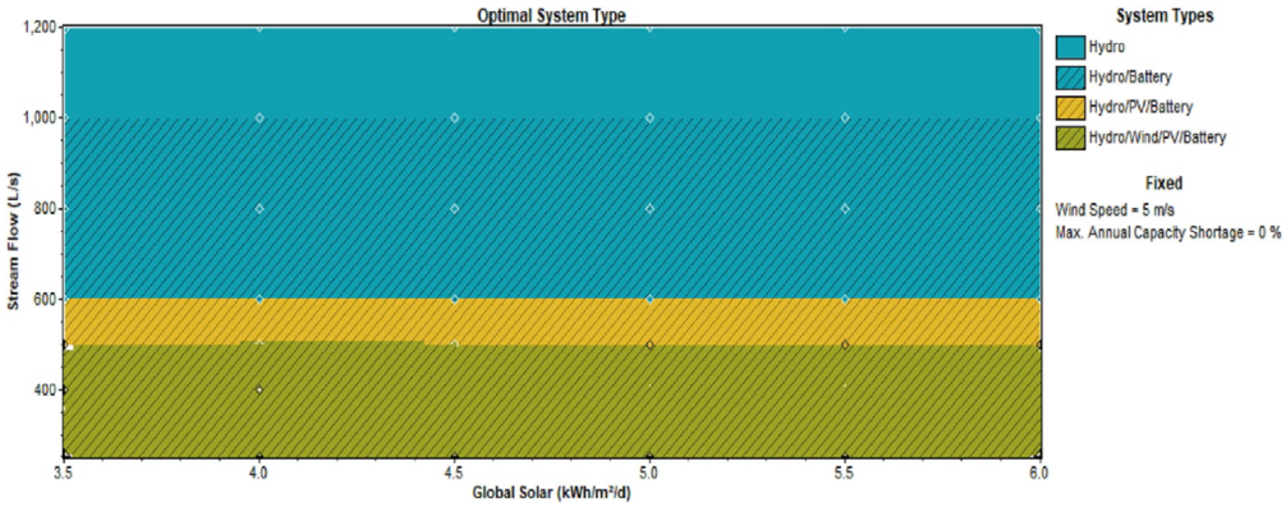

Fig. 7. Hybrid system optimization analysis.

Fig. 8 shows the monthly average graph of the electricity generated by the generators under optimal conditions. In this figure, it can be seen that during the critical months, much of the deficit is generated by photovoltaic cells.

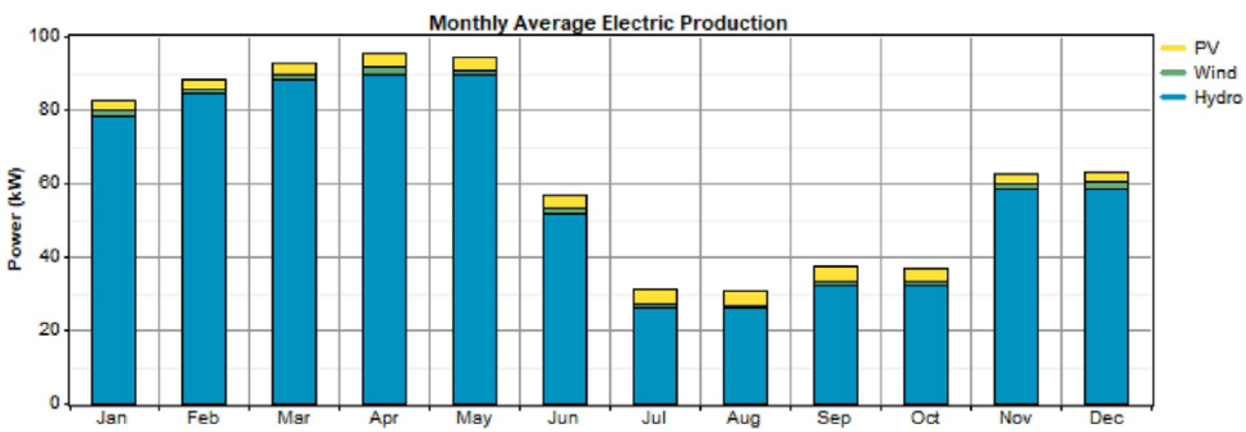

Fig. 8. Comparison of hydropower, wind power and solar panel production capacity in different months.

Table 5 shows the contribution of each generator to the overall annual power generation.

Table 5. Power Generation per Battery. The investment cost for the above power plant according to the components defined separately is presented in Table 6.

Production	kWh/year	Percentage
PV array	29,591	5
Wind Turbine	11,183	2
Hydro Turbine	521,518	93
Total	562,293	100

Table 6. Initial startup costs due to system optimization.

Component	Capital (USD)
PV	90,000
Wind Turbine	29,000
Hydro Turbine	50,000
Surrette 4 KS25P batteries	44,000
Converter	18,000
System	231,000

4.1. Effect of flow rate changes and radiation energy on generator composition

As stated, if the river flow rate rises and reaches an average 600 L/s per year, the system needs fewer photovoltaic cells than it does at this point and batteries alone will be able to meet the demand. By increasing the annual water flow average by 100 L/s to a river flow rate of 600 L/s per year, the energy requirement can be met by 10 kW of photovoltaic cells, 20 batteries and a 15 kW inverter. And the initial investment will be reduced to USD 164,500. The production and consumption chart is shown in Fig. 9. As can be seen in the figure, as the water flow increases to 600 L/s, the output power of the turbine also increases and the system's need for the solar panel decreases, so the reduction in cost is not unexpected.

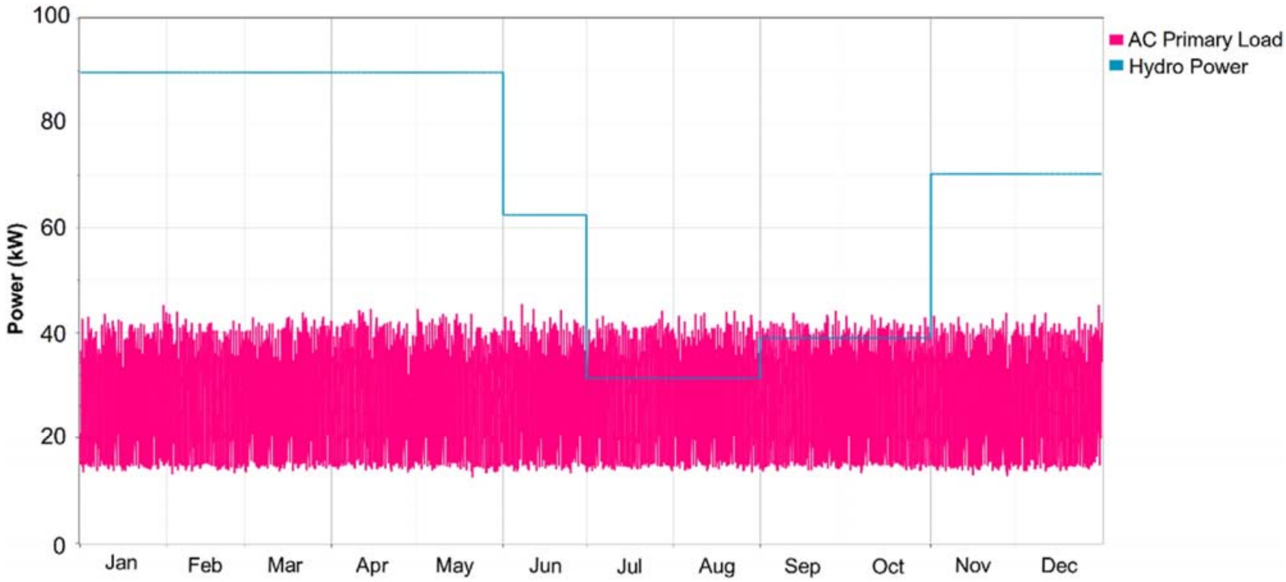

Fig. 9. Comparison of average water flow rate increase to 600 L/s with power consumption.

The contribution in of each generation unit in the annual production is given in Table 7. The total cost for the power plant based on the separate component costs is presented in Fig. 10.

Table 7. Details of power output with average discharge increased to 600 L/s.

Production	kWh/y	Percentage
PV array	14,796	2
Wind Turbine	11,183	2
Hydro Turbine	576,255	96
Total	602,234	100

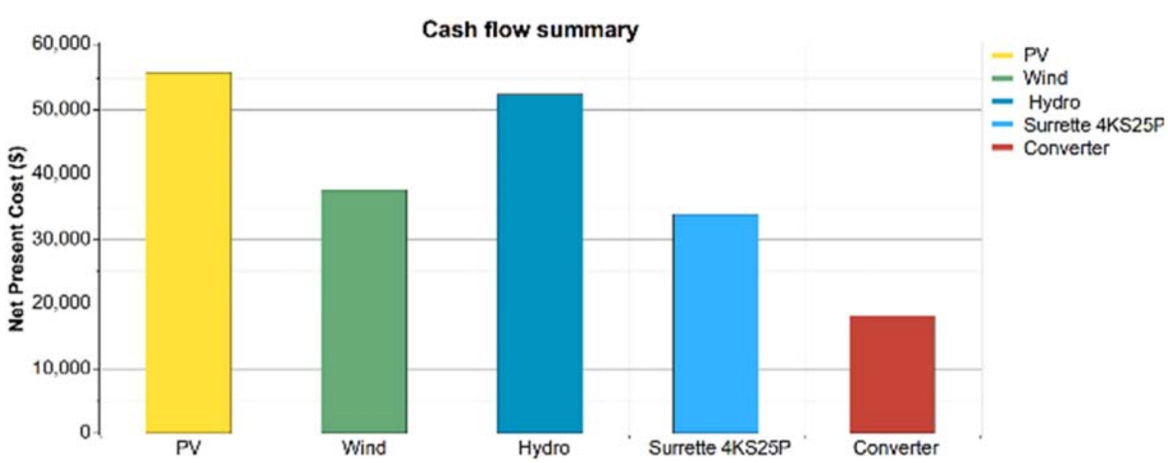

Fig. 10. Total cost (Initial startup, replacement and O&M costs) due to system optimization.

Also, if the river water flow rises to 1000 L/s, the micro-hydro turbine alone will be able to generate the required power. Further, if the daily solar radiation increased for example by 1 $kWh/m^2/d$ at the base line 500 L/s design, the number of solar panels may be reduced to 20.

4.2. Generator mix with 5% annual energy deficit

If a 5% energy deficit per annum can be allowed, which means that 5% of the energy demand on the system is not met on critical days, the fewer photovoltaic generators and batteries are required.

As can be seen in Fig. 11, the combination of generators changes at the Sarrood power plant at the 500 L/s point and 4.5 ($\frac{kWh}{m^2\ d}$). This point is a boundary point for this case and the optimization offers two combinations. The first combination is the hydropower combination with only a battery, and the second combination is the hydropower and photovoltaic combination.

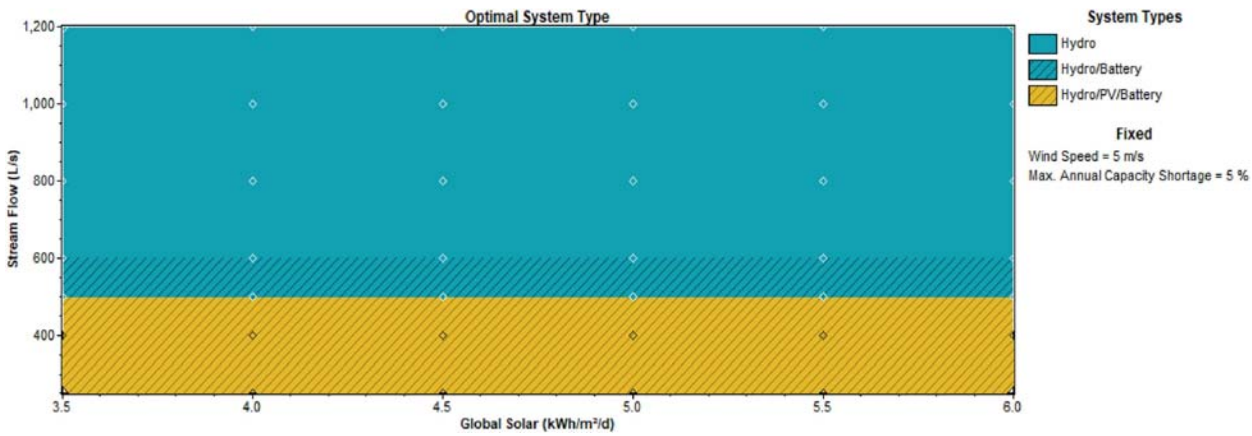

Fig. 11. Hybrid system optimization analysis with 5% power shortage.

Both combinations have the power to supply power with a 5% annual deficit, but the first combination is preferred because of the lower initial investment.

As can be seen from Fig. 11 and Table 8, for a decrease in river flow rate at the project site, the number of photovoltaic cells need to be increased. This number can be determined by the Homer software for different conditions.

Table 8. Different compounds with the same efficiency.

The first combination	The second combination
61 kW hydro power	61 kW hydro power
Without photovoltaic	10 kW photovoltaic
10 packs of 4 batteries	5 packs of 4 batteries
With 7.5 kW wind turbine	Without wind turbine
Initial Investment $ 94,500	Initial investment of $ 110,000

If the river flow rate goes up, fewer batteries are required, and at 600 L/s or higher, only micro-hydro power will be able to supply the system with 5% of shortage power.

4.3. Generator combination with 10% annual energy shortage

If 10% of energy shortages per year are allowed, fewer photovoltaic generators and batteries are required (Fig. 12).

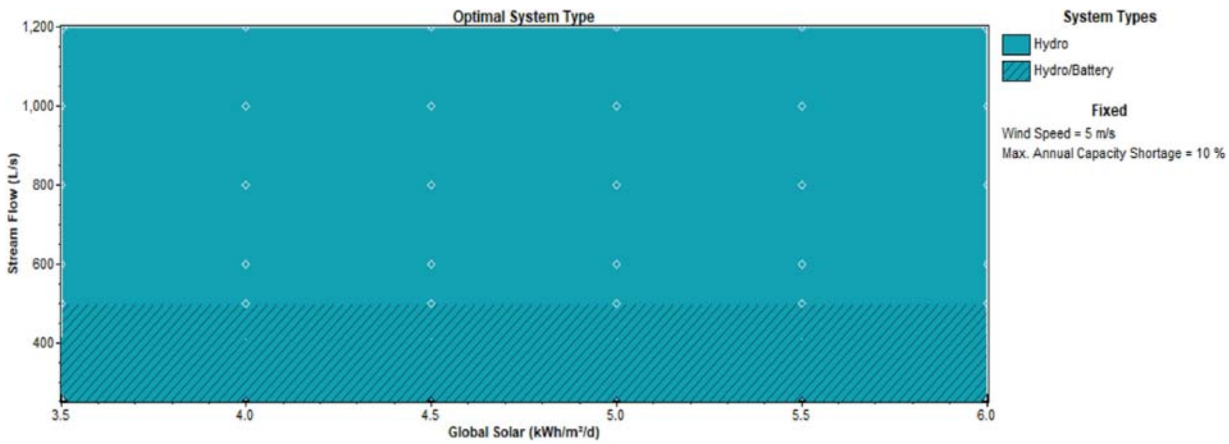

Fig. 12. Hybrid system optimization analysis with 10% power shortage.

The number of system generators may be is reduced to the point where the batteries are only introduced as a supplement to the Sarrood power plant project at the 500 L/s point and at 4.5 $\frac{kWh}{m^2\ d}$..

5. Conclusion

In the present study, a power plant system has been optimized with renewable energy production systems. The optimization criterion used in this study is the production of the required power and the elimination of energy shortages with the lowest initial setup cost. Using solar energy to compensate for the power shortage can be the best option in the studied plant (Sarrood Power Plant).

It was found that the best and the least costly combination of power plant in Sarrood geographical conditions was the following combination to offset the power shortage:

o 61 kW hydro power

o 20 kW photovoltaic

o 7.5 kW wind turbine (BWC Excel-R)

o 20 kW inverter

o And 10 4-way battery packs

This system requires an initial investment of USD 231,000.

This combination reduces the annual energy deficit to zero percent per year. If any change would occur in the energy sources (river water discharge and solar radiation), this could change. The results showed that energy deficit improvement should be done according to economic analysis. \

The use of solar energy as a complementary source for hydroelectric power plants, due to its renewability, can be a good choice for power supply throughout the year. Currently, one of the limitations of using solar energy and photovoltaic panels to generate electricity is their high cost, as these panels have a long service life and can offset their long time startup costs.

The results of this research can be the basis for the economic energy analysis of future research and can also be suitable for operationalizing projects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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