HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

TECHNICAL-ECONOMIC EVALUATION OF A HYDROELECTRIC MICRO-CENTRAL DRIVEN BY A SOLAR-POWERED WATER STORAGE SYSTEM FOR AGRICULTURAL APPLICATIONS

Alvaro F.*[a], Del Carpio H.[b], Milón J.[b] and Braga S.[a]
*Author for correspondence
Institute of Energy,
Pontifical Catholic University of Rio de Janeiro,
Rio de Janeiro, 22451-900,
Brazil.
E-mail: fiorella.alvaro@aluno.puc-rio.br

Institute of Energy,
La Salle University,
Arequipa, Peru.

ABSTRACT

The region of Arequipa, located in southern Peru, is benefited by a high solar energy resource during most part of the year: 1100 kWh/m^2, approximately. Parts of this region are located in the Andes, parts which also happen to be the ones that are isolated from the national electrical grid. The geography of these zones is considerably diverse and presents height differences all over the territory. These two characteristics: solar radiation and irregular topography, allow the use of a hybrid technology to generate electrical energy harnessing ground level variations. These two necessary features were identified in the district of Majes, Arequipa. A hydroelectric micro-central driven by a solar-powered water storage system was installed in the facilities of a winery located in this district, to supply part of its electricity demand. The micro-central was composed by three systems: the solar pumping system, the reversible pumping-power generation system and the water storage system. Performance tests were developed to evaluate the efficiency of the micro-central operating in real conditions. Parameters like the water mass flow pumped, the water mass flow through the turbine, the electricity produced through solar energy and the electricity produced by the system were studied. The hydraulic, mechanic and electric power for the maximum water mass flows tested were 1500, 500 and 400 W, respectively. The whole system attained a global efficiency of 27%, approximately. An economic evaluation was also performed, comparing two alternatives for the generation of electricity: a solar photovoltaic system feeding the electric load directly and the solar-powered hydroelectric micro-central. The aspects influencing on the economic indicators involved the availability of electrical energy produced by the systems during the day and the points of maximum performance for the operation of the micro-central determined for each month of the year according to the incident solar radiation in Majes. The study showed the feasibility of using solar energy to store water in high reservoirs as potential energy for the generation of electricity in isolated zones where geography allows the application of this technology. With the operation of the micro-central in the winery, some operational costs can be reduced, while maintaining environmental responsibility with a sustainable approach.

NOMENCLATURE

A	[m^2]	area of solar panels
E	[kWh]	produced energy
G	[J]	incident solar radiation
g	[m/s^2]	gravity force
I	[A]	electric current
$\dot{m}$	[kg/s]	water mass flow rate
P	[W]	power
TDH	[m]	Total Dynamic Head
T	[°C]	temperature
V_s	[m/s]	wind speed
V	[V]	voltage in the generator

Special characters

$\cos\theta$	[-]	offset between voltage and current
η	[-]	efficiency
$(\tau\alpha)$	[-]	transmittance-absortance product
τ	[N.m]	torque
μ	[%/°C]	temperature coefficient
ω	[rpm]	rotational speed of the turbine-generator axis

Subscripts

a	environment
c	cells
$calc$	calculated
e	electric
g	generator
h	hydraulic
m	mechanical
mp	maximum power conditions
$NOCT$	Nominal Operating Cell Temperature conditions
oc	open circuit
t	turbine

INTRODUCTION

The growing concern for climate change has promoted the subscription of energy policies that aim for a bigger share of renewable energy sources in energy supply. However, intermittency and non-controllability are inherent characteristics of the electricity generation systems based on these clean sources. Electric energy storage has a key role in providing reliability and stability to these systems; however, the majority of existent technologies allow it at high costs. This is where water storage appears as a promising strategy [1].

Among the different energy sources used to store water with potential energy, many authors have suggested wind and solar energy [2], showing that the integration of pumped hydrostorage systems could enable a 100% renewable energy penetration, but at higher costs.

Various studies have been performed to evaluate the technical and economical feasibility of the application of solar-powered hydrostorage (SPH) systems from small to big scale using photovoltaic solar energy. In them, the exploitation of watercourses with periodical-temporary water flow in existing plants has been evaluated [3] and models for the introduction of the SPH systems in conventional hydroelectric centrals have been developed [4].

The photovoltaic pumping system and the total pumping head have been determined as the parameters that determine the performance of SPH systems [5], for which mathematical models have been developed to determine the optimal sizes of the PV arrays [4,6,7,8].

Concerning the operation of the SPH systems, the optimization models consider the probability of loss of power supply and the life cycle costs, based on the water consumption profiles, the solar radiation, the morning/afternoon dissymmetry, the total head, the tank capacity and the photovoltaic array peak power [6,8,9].

SPH systems can provide continuous electric power and energy supply to its consumers and they can be successfully applied even on locations with relatively low irradiation, since the element that ensures reliability is the hydrostorage component, which could balance large summer surpluses and winter energy shortages. SPH technology has showed a wide range of implementation from relatively cold climates to those abundant in solar energy [8,10].

This energy production scheme is growingly attracting attention in the developing countries, due to its unique operational flexibility over other energy storage systems [11]. Pumped hydrostorage has proved itself more cost competitive when adjusting some parameters such as increasing energy storage capacity and days of autonomy. The availability of suitable topographies and hydro-thermal imbalances in various regions make of SPH technology an excellent opportunity to meet energy demands and practical potential for continuous power supply in remote areas [12].

A solar hydroelectric power plant using water reservoirs basically solves the problem of energy storage, which is the biggest problem for the wider use of solar energy. The solar-powered hydroelectric plant represents a permanently sustainable energy source that can continuously provide power supply to a consumer, using exclusively natural and renewable energy sources, without causing harmful effects on the environment [7].

With this background, a hydroelectric micro-central with a solar-powered water storage system was implemented in a winery in a remote district of Arequipa: Majes, to evaluate its technical performance and economical feasibility.

EXPERIMENTAL MODEL

The experimental model (Figure 1) was made up by three systems: a solar pumping system (a), a power generation system (b) and a water storage system (c).

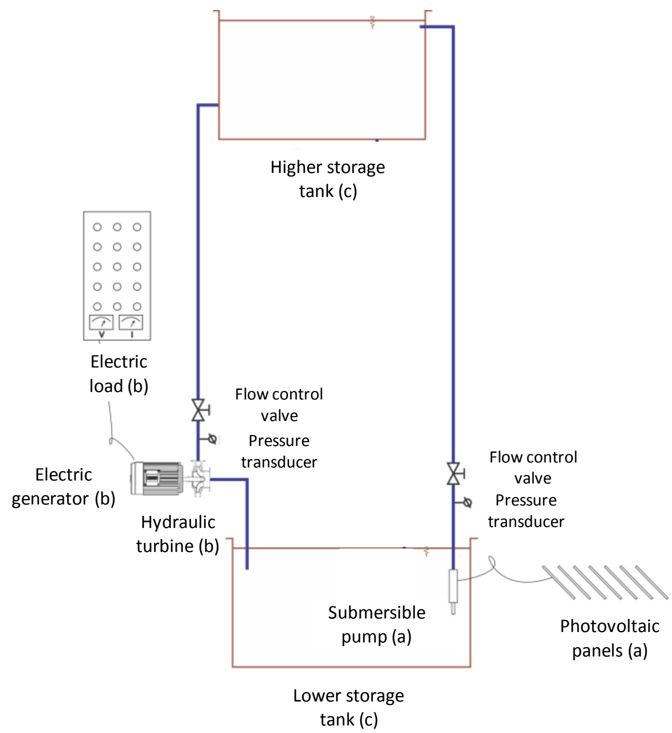

Figure 1 Experimental Model

The solar pumping system was composed by a submersible centrifugal pump (LORENTZ PS1200) powered directly by a set of 12 monocrystalline silicon solar panels (KYOCERA) with a peak power of 120 W each one. The solar radiation incident in the solar panels was measured using a pyranometer (APOGEE), to correlate the data with the performance specifications of the pump. The system pumped the water up to the higher reservoir, located 20 m above the lower one. These two reservoirs constituted the water storage system. Each tank had a capacity of 5 m^3.

The power generation system was constituted by a centrifugal pump (HIDROSTAL) that worked as a turbine and an electric generator coupled to it (Figure 2). The electric load of the generator was an array of light bulbs, which could be turned in or off to make the load variable.

Figure 2 Centrifugal pump working as a turbine.

For cases where critical conditions for layer thickness and

The water mass flow feeding the turbine was calculated from the pressure drop in that line. This last parameter was measured using a standard nozzle manufactured according to the NBR ISO 5167-1, a pressure transducer (AUTROL) and a differential pressure transducer (AUTROL).

Figure 3 Experimental device for initial tests.

The power generated by the flow of the water through the turbine was calculated from the measured voltage and current. The first parameter was measured using a voltmeter (AGILENT) and the latter, with a current shunt (FLUKE). Strain gages were used to measure the torque in the turbine shaft. The rotational speed of the shaft was measured using a laser tachometer.

All the signals emitted by the instruments were acquired by a Data Acquisition System (HP AGILENT) and sent to a computer for its later processing.

Tests were performed for five different water mass flow rates to generate electricity. Since the water mass flow rate pumped up depended on the solar radiation, the higher reservoir was filled according to this parameter. The water mass flow going through the turbine was set using restricting valves, which were installed according to the requirements of the standard NBR ISO 5167-1 to make a correct measurement of the water mass flow rate.

DATA REDUCTION

The electric power generated, the mechanical power and the hydraulic power were calculated with these formulas:

$$P_e = V \cdot I \cdot \cos\theta \quad (1)$$

$$P_m = \tau \cdot \omega \quad (2)$$

$$P_h = \dot{m} \cdot g \cdot TDH \quad (3)$$

The value of $\cos\theta$ was 1, since the current shunt is a resistive load.

The efficiency of the turbine, the generator and the global energy production efficiency were calculated:

$$\eta_t = \frac{P_m}{P_h} \quad (4)$$

$$\eta_g = \frac{P_e}{P_m} \quad (5)$$

$$\eta = \frac{P_e}{P_h} \quad (6)$$

With these values obtained for the efficiency of the system, the performance and the feasibility of a similar system in Majes, Arequipa, can be properly estimated throughout a whole year. The monthly mean efficiency of the photovoltaic system in Arequipa was estimated based on the solar radiation in the zone, the temperature, the wind speed and the characteristics of the solar panels used.

Firstly, the efficiency of the solar panels was calculated for a referential condition, in this case for NOCT standard conditions:

$$\eta_{mp,NOCT} = \frac{P_{mp,NOCT}}{G_{NOCT} \cdot A} \quad (7)$$

The value of $P_{mp,NOCT}$ was 101 W and G_{NOCT} has the standard value of 800 W/m^2. With the value obtained, the temperature of the solar cells was calculated.

$$T_c = \left\{\frac{G}{G_{NOCT}} \frac{9,5}{(5,7 + 3,8V_s)} \left[1 - \frac{\eta_C}{(\tau\alpha)}\right] \left[T_{NOCT} - T_{a,NOCT}\right]\right\} + T_a$$

Here, η_C is the efficiency of the cell, in this case, $\eta_{mp,NOCT}$. The transmittance-absortance product, $(\tau\alpha)$, has a typical value of 0.9. T_{NOCT} in those conditions attains 45 °C and $T_{a,NOCT}$ has a standard value of 20 °C. With the value of T_c, the efficiency of the cells was recalculated, and an iteration was started to find the real value of the cells efficiency, η_c.

$$\eta_c = \eta_{mp,NOCT} + \mu_{\eta,mp}\left(T_{c,calc} - T_{c,NOCT}\right) \tag{9}$$

The second parameter was calculated:

$$\mu_{\eta,mp} \approx \eta_{mp,NOCT}\frac{\mu_{V_{oc}}}{V_{mp}} \tag{10}$$

Where, $\mu_{V_{oc}}$ had a value of -0.36%/°C. Iterating, a final value for the efficiency of the cells is attained, and with it, the energy produced by them can be calculated:

$$E = \eta_c \cdot G \cdot A \tag{11}$$

RESULTS

Experimental Performance

Figure 4 shows the results for the tests made for different water mass flow rates through the turbine. Clearly, the higher powers were developed for the higher mass flows, in this case, 5.4 kg/s.

A considerable energy loss is observed between the hydraulic power and the electricity produced. This is due to the low conversion efficiency and also to the fact that a pump is being used as a turbine, i.e. not a turbine originally. The centrifugal pump used for this function had an original efficiency of 60%.

For the mechanical power, the maximum rotation speed attained was 2500 RPM, with a correspondent torque of 2 N.m.

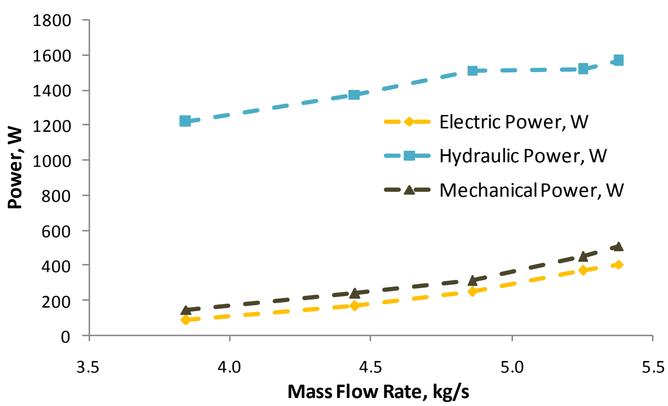

Figure 4 Hydraulic, mechanical and electric power varying with the mass flow rate.

For the same water mass flow rates, the efficiency of the turbine and the generator were analyzed (Figure 5). As expected, the generator efficiency attained values around 82% and the turbine (originally a pump) showed an acceptable efficiency 33%, around the usual efficiency for these devices. The global efficiency was slightly reduced due to the generator efficiency. Logically, also, the higher efficiencies are attained when the water mass flows are higher.

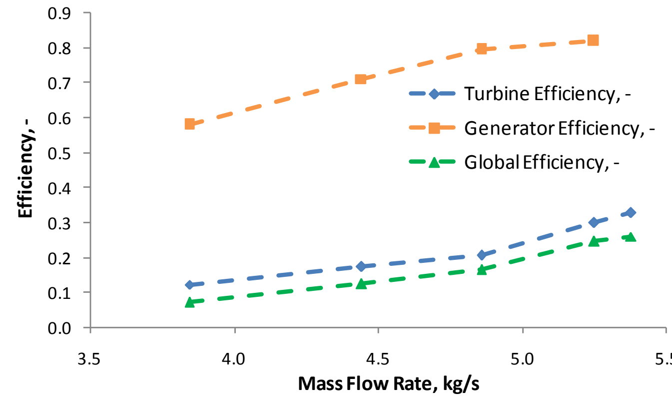

Figure 5 Turbine, generator and global efficiency according to the water mass flow rate through the turbine.

Economic Feasibility

An economic feasibility analysis was performed to evaluate the benefits of using a hydroelectric micro-central driven by a solar-powered water storage system.

To perform this evaluation, the data of solar radiation, temperature and wind speed of Majes, Arequipa, where the system was implemented, was obtained from the National Service of Meteorology and Hydrology of the Ministry of Environment of Peru (SENAMHI).

With these parameters, the efficiency of the photovoltaic system was calculated. The importance of this value lays in the fact that, whether the photovoltaic system is used directly or it is used to pump the water up to the higher reservoir, it behaves as the main source of energy, to produce electricity in the first case and to store energy in the second one.

Figure 6 shows the energy that would be produced by both systems in average per day according to the month of operation. It can be seen that for direct electricity production, the energy yielded is more variable and depends strongly on the solar radiation.

On the other hand, for the system operating with solar-powered water storage, the produced energy is less variable, nevertheless, due to the energy losses in the conversion, the amount of produced electricity is lower.

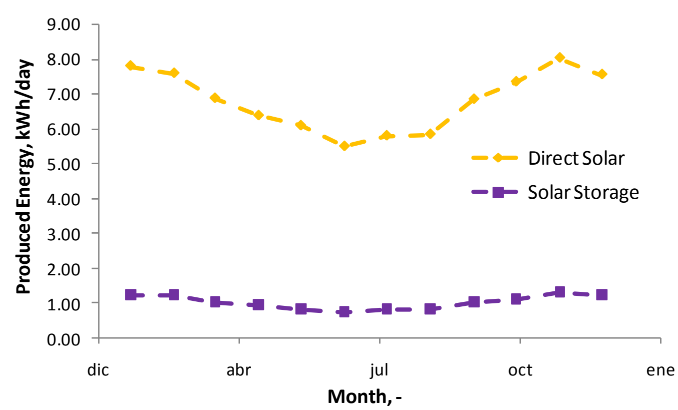

Figure 6 Energy produced using a photovoltaic system directly and storing water through solar pumping.

Once the energy both systems could produce was known, the necessary investment for both of them was calculated. Figure 7 shows the production cost of energy using the two systems.

For the solar-powered water storage system, the investment was higher, and as expected, since a levelized cost per month was found, during the months in which the radiation is lower, the amount of water stored and consequently, the amount of energy produced are lower, resulting in a higher energy production cost. The highest production cost was of USD 7.24/kWh, corresponding to the month of June.

For the direct solar photovoltaic system, the required investment was lower. Figure 7 shows a flatter curve for this parameter throughout the year, varying from 0.29 to 0.43 USD/kWh.

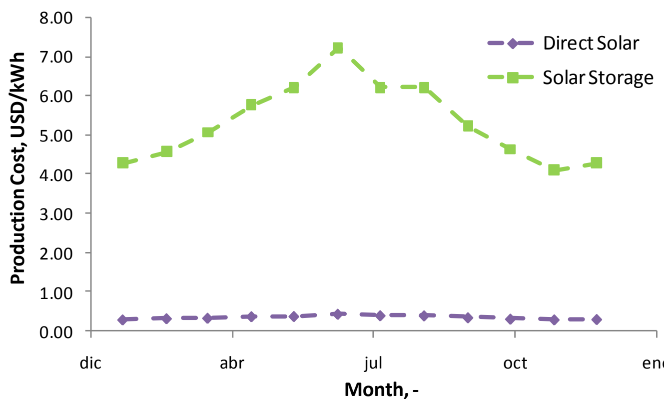

Figure 7 Production cost of energy using a photovoltaic system directly and storing water through solar pumping.

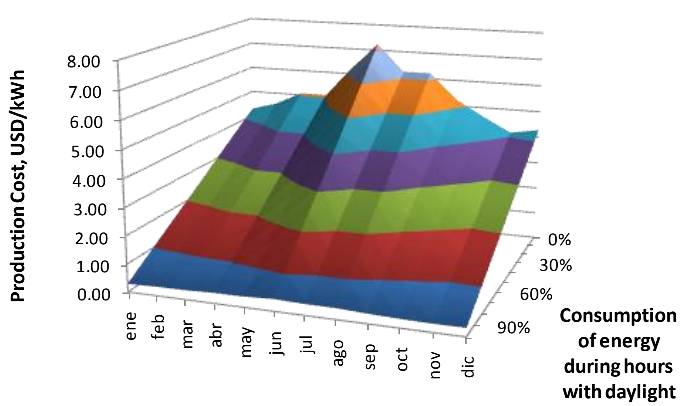

Figure 8 Production cost of energy using a photovoltaic system directly and storing water through solar pumping considering the consumption of energy through the year.

Figure 8 shows the production cost in USD/kWh for a whole year considering a new parameter: the consumption of energy during hours with daylight. It varies from 0 to 100%, 0% when there is no electricity consumption during the day and 100% corresponds to the case when all the load of the facilities where a similar system is installed occurs during hours without daylight, i.e. solar radiation. Since a system like the one presented in the experimental model is intended for rural communities, the first case, 0%, would correspond to families that work in the fields during the morning and the latter, 100%, would correspond to small scale agricultural industries that require energy for their production.

As expected, the highest energy production cost occurs for June when the 100% of the energy is consumed during the night, since the solar-powered water storage system would have to be used. The lower costs are obtained when the photovoltaic system is directly used, nevertheless, this case would not be true for all the small-scale applications.

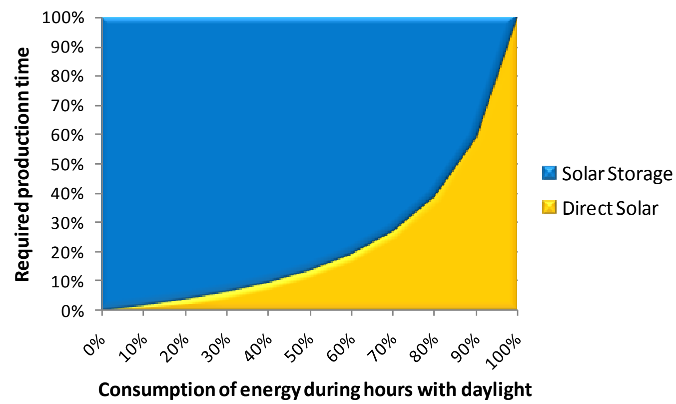

Figure 9 Required production time of energy for a photovoltaic system used directly and a storage water system with solar pumping for the month of January.

The required time for the production of energy for each of the two different systems used during the same day to attain the load of the facilities where it is implemented was calculated (Figure 9).

It can be seen that due to the higher efficiency of the photovoltaic system compared to that of the hydraulic micro-central, the time required by this system to generate the required energy is considerably lower than for the micro-central. It could be implied that the use of a micro-central would not be necessary if the consumption of energy during the day is higher than 60%. In this case, the time required for the production of the energy using the micro-central reaches 80% of the hours with insolation. The cost for this configuration would vary from USD 1.82/kWh to USD 3.15/kWh, in November and June, respectively.

However, since not all the applications have the same energy requirements, a higher energy production cost would be acceptable if the consumption of energy took place mainly during the night.

CONCLUSION

The hydroelectric micro-central with solar-powered water storage has shown itself as an adequate solution for the generation of electricity, yet, of high cost for small scale energy production.

Technically, it is feasible to produce electricity using a pump as a turbine, which lowers considerably the investment, i.e. 80% approximately. This reduction makes this solution available for small communities with low resources and for governments which want to implement plans of extension of the energetic network. Logically, as the scale increases, the efficiency will be higher and also the cost per produced kWh.

Hydrostorage allows for a more uniform production of electricity, since the variable solar irradiation determines only the quantity of water stored and not the production of energy through the hydroelectric system. In this paper, only daily production was evaluated, though, the storage of water could be performed during days or months, according to the capacity of the reservoirs, enhancing the continuity of electricity production. This feature of the hydrostorage system also allows the use of a fixed quantity of water recirculating it, this way, draughts would affect in a minor way the electricity production in the remote areas where this kind of system is implemented.

Since the system is hybrid, once the optimum amount of stored water has been determined and attained, the photovoltaic system could be used directly with the loads present during the hours with daylight.

The solar radiation in Arequipa, with 4.75 kWh/m^2as its lower value, and the topography of the area, favor the application of this technology with promising results. Since it is solar energy-powered, a hydroelectric micro-central with water storage could be implemented in any remote zone with the adequate geography and supply energy to the communities around, improving their life quality and promoting their economic and social development.

REFERENCES

[1] Margeta J., Water storage as energy storage in green power system, *Sustainable Energy Technologies and Assessments*, Vol. 5, 2014, pp. 75–83.

[2] Connolly D., Lund H., Mathiesen B.V., Pican E., Leahy M., The technical and economic implications of integrating fluctuating renewable energy using energy storage, *Renewable Energy*, Vol. 43, 2012, pp. 47–60.

[3] Margeta J., and Glasnovic Z., Exploitation of temporary water flow by hybrid PV-hydroelectric plant, *Renewable Energy*, Vol. 36, 2011, pp. 2268–2277.

[4] Anagnostopoulos J.S., and Papantonis D.E., Study of pumped storage schemes to support high RES penetration in the electric power system of Greece, *Energy*, Vol. 45, 2012, pp. 416–423.

[5] Hamidat A., and Benyoucef B., Systematic procedures for sizing photovoltaic pumping system, using water tank storage, *Energy Policy*, Vol. 37, 2009, pp. 1489–1501.

[6] Bakelli Y., Hadj Arabb A.H., and Azouic B., Optimal sizing of photovoltaic pumping system with water tank storage using LPSP concept, *Solar Energy*, Vol. 85, 2011, pp. 288–294.

[7] Glasnovic Z., and Margeta, J., The features of sustainable Solar Hydroelectric Power Plant, *Renewable Energy*, Vol. 34, 2009, pp. 1742–1751.

[8] Margeta J., Glasnovic Z., Feasibility of the green energy production by hybrid solar + hydro power system in Europe and similar climate areas, *Renewable and Sustainable Energy Reviews*, Vol. 14, 2010, pp. 1580–1590.

[9] Bennoun A., and Ijdiyaou Y., Water pumping using a photovoltaic d.c. solar pump without energy storage, *Renewable Energy*, Vol. 4, 1994, pp. 847–854.

[10] Glasnović Z., Rogošić M., and Margetab, J., A model for optimal sizing of solar thermal hydroelectric power plant, *Solar Energy*, Vol. 85, 2011, pp. 794–807.

[11] Sivakumar N., Das D., Padhy N.P., Senthil Kumar A.R., Bisoyi N., Status of pumped hydro-storage schemes and its future in India, *Renewable and Sustainable Energy Reviews*, Vol. 19, 2013, pp. 208–213.

[12] Ma T., Yang H., and Lu L., Feasibility study and economic analysis of pumped hydro storage and battery storage for a renewable energy powered island, *Energy Conversion and Management*, Vol. 79, 2014, pp. 387–397.