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Investigation of the influences of hydraulic loss and evaporation rate in a PV-pumped storage hybrid system

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ABSTRACT

To reduce heavy reliance on greenhouse gas–emitting power plants, various countries have focused on the development of renewable energy technology with the appropriate energy storage installed. Pumped hydropower energy storage (PHES) technology has been utilized for several decades for electrical ancillary benefits (e.g. spinning reserve) or linked to renewable energy sources to store excessive power and exploit it, if needed. However, several factors in hybrid renewable energy systems have been given less attention, such as hydraulic loss influences and evaporation rate, which are extremely essential parameters where a noncontinuous water sources (closed loop power plants) is used. Consequently, this study aims to investigate the impact of those factors against integration systems comprising of a photovoltaic energy system and pumped storage connected to the grid. A mathematical model is developed taking into account various monitoring variables: loss of renewable energy, amount of electricity supplied by grid, and load covered by renewable sources. It is clearly observed that hourly evaporation rate and hydraulic losses may affect the whole hybrid system performance if they are neglected. The results show that more than 10 mm of water evaporated on the first of August in Bisha, located in Saudi Arabia, which is adapted as a case study .Based on the obtained results, it is recommended that considering both essential parameters increases the accuracy of such system and raises reliability of hybrid renewable energy sources.

Keywords: renewable/green energy resources, advanced energy technologies, energy systems for power generation, environment and climate change.

NOMENCLATURE

Abbreviations	
PHES	Pumped hydropower energy storage
PV	Photovoltaic
RE	Renewable energy
Re_cap	Reservoir capacity
Symbols	
I_{pv}	Photovoltaic current
I_0	Saturation current
ΔT	Difference between actual and nominal temperature
Q_p	Pump flow rate
ET	Reference evapotranspiration
Q_t	Turbine flow rate
P_p	Pump power
R_p	Parallel resistance of the array
R_s	Series resistance of the array
V_t	Thermal voltage of the array
$P_{max,e}$	Maximum power
V_{mp}	Voltage at maximum power
I_{mp}	Current at maximum power

1. INTRODUCTION

As most generated electricity relies on fossil fuels (primary form of energy) converted through long thermodynamic processes, a considerable amount of CO_2 is emitted. This has been specified as the main global threat to the environment [1]. To reduce fossil fuel dependency, there should be rapid shifting to renewable energy sources, which remain unreliable due to fluctuating natural sources, unless an appropriate energy storage technology is installed. PHES is considered one of the most mature and reliable energy storage technologies. It exploits two reservoirs with different heights, and then water is lifted from the lower reservoir to the upper one when there is excess power and released from the upper reservoir to generate electricity during peak periods [2]. Many studies have been conducted concentrating on integration systems and their behaviour [3][4]. As the closed loop system of PHES exploits seasonal dams as lower reservoirs and the top of mountain location of upper reservoir, hourly evaporation rate and hydraulic losses are extremely vital parameters where there is no river or sufficient amount of precipitation.

2. SYSTEM DESCRIEPTION

The integration system comprises a PV system and pumped hydropower energy storage connected to the grid. Basically, thermal power plants are responsible for providing the baseload, which is the specific amount of power that should be supplied each day, while the PV and PHES systems, which are proposed in this study, are expected to provide as much power as needed.

Then, if power shortage occurs, the electricity is supplied by the grid, so it depends on power availability during the day as shown in Figure 1.

3. MATERIAL AND METHODS

Each subsystem modelling will be performed using Python software language, and then the mathematical model of the hybrid system will be created based on the results extracted from each model. Consequently, the evaporation rate and hydraulic loss influences are the main objectives of investigation in this study.

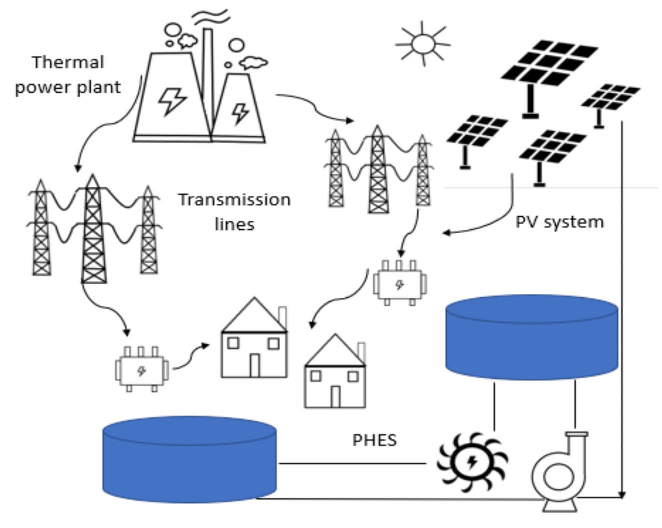

Figure 1. Proposed System diagram

3.1 Photovoltaic model

The PV system is defined as the conversion of solar radiation into power, and various types of solar panel modules have been installed around the world. In this study, a KC200GT high-efficiency multi-crystal module is picked and analysed. The power generated by PV is calculated as follows [5]:

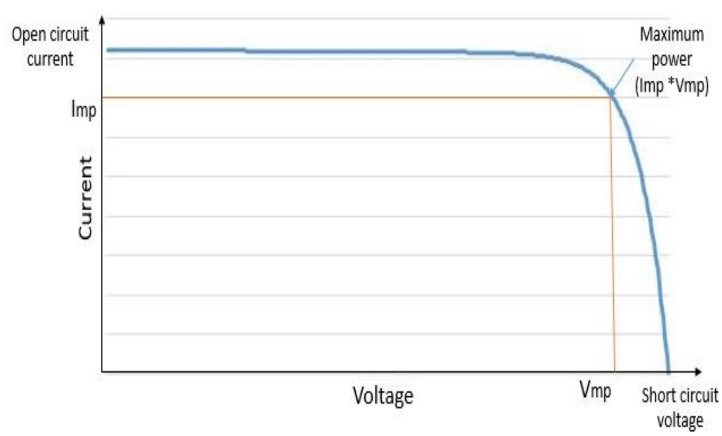

Figure. 2 I-V Characteristics of a solar cell

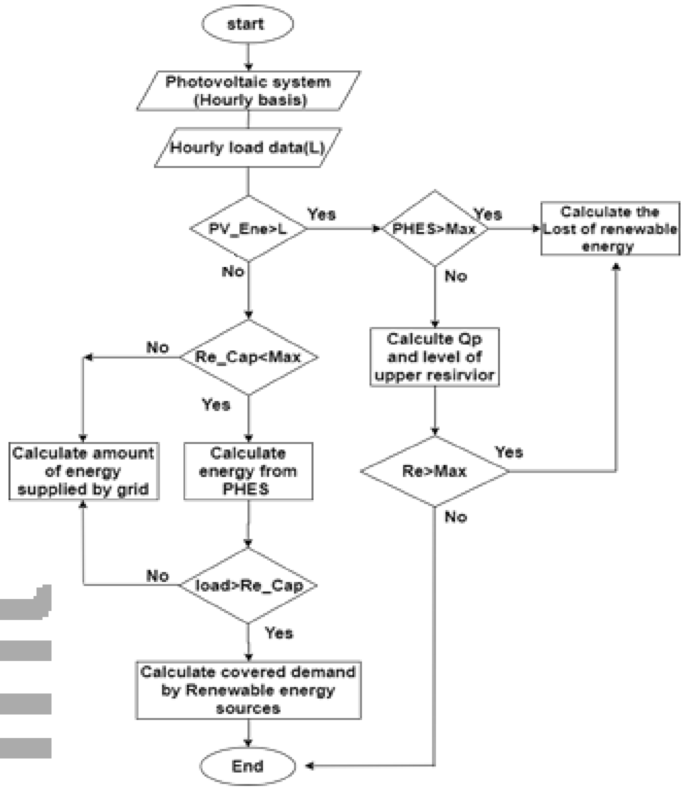

Figure 3. Flow chart of proposed system

$$Power_{Max} = Current \ * Voltage \tag{1}$$

(2)

$$I = I_{pv} - I_0 \left[Exp\left(\frac{V + R_s * I}{V_t * a}\right) - 1 \right] - \frac{V + R_s}{R_p}$$

Where:

a : Diode ideality constant

$$V_t = \frac{N_s * K * T}{q} \tag{3}$$

N_s is Cells connected in series; K is Boltzmann constant(1.3806503*10^{-23}J/K); T is Temperature of p-n junction ; q is Electron charge (1.60217646*10^{-19}C)

$$I_{pv} = \left(I_{pv,n} + K_I * \Delta T\right) * \left(\frac{G}{G_n}\right) \tag{4}$$

Where:

$I_{pv,n}$: Light generated current at the nominal condition (25 C ,1000 W/m^2)

K_I: Current coefficient

G: irradiance of device surface

G_n: Nominal irradiance

$$I_0 = \frac{I_{sc,n} + K_I * \Delta T}{Exp\left(\frac{\left(V_{oc,n} + K_v * \Delta T\right)}{a * V_t}\right) - 1} \tag{5}$$

$I_{sc,n}$ is Short circuit current at nominal condition; $V_{oc,n}$ is Open circuit voltage at nominal condition.

$$R_p = V_{mp} * \frac{\left(V_{mp} + I_{mp} * R_s\right)}{\begin{Bmatrix} V_{mp} * I_{pv} - V_{mp} + I_0 \\ * Exp\begin{pmatrix} (V_{mp} + I_{mp} * R_s/(N_s * a)) \\ * (\frac{q}{KT}) \end{pmatrix} \\ +\left(V_{mp} * I_0\right) \\ -P_{max,e} \end{Bmatrix}} \tag{6}$$

$$I_{pv,n} = \frac{R_p + R_s}{R_p} * I_{sc,n} \tag{7}$$

3.2 Pumped hydropower energy storage model

The entire system is divided into three sub-models: pump model, reservoir model, and turbine model. All calculations required to determine all values are expressed below [6]:

$$Q_p = \frac{P_p * \eta_p}{\rho * g * H_p} \tag{8}$$

Where:

η_p: Pump efficiency

ρ: Density of water

g: Gravity acceleration

H_p: Pump head

$$H_p = H_s + H_{pl} \quad (9)$$

H_s is the Static head; H_{pl} is the Head loss of pump mode

$$H_{pl} = K * \frac{v^2}{2g} \quad (10)$$

K is Resistance coefficient; v is the Water velocity

$$v = \frac{Q_p}{0.25\pi * D_p^2} \quad (11)$$

D_p^2 is Pipe dimeter between pump and reservoir

μ is Dynamic viscosity of water

$$K = K_{pipe} + K_{fittings} \quad (12)$$

$$f = \left(1.8log * \left(\begin{matrix}\left(\frac{6.9}{Re}\right) + \\ \left(\frac{\varepsilon/D_p}{3.7}\right)^{1.11}\end{matrix}\right)\right)^{-2} \quad (13)$$

$$K_{pipe} = \frac{f*L_p}{D_p} \quad (14)$$

Where:

K_{pipe}: Pipe resistance coefficient
$K_{fittings}$: Fitting resistance coefficient

$$ET = \frac{\begin{matrix}0.408\Delta(Rn-G)+ \\ \left(\gamma*\left(\frac{37}{T_{hr}+273}\right)\right)* \\ u_{2*(e^0(T_{hr})-e_a)}\end{matrix}}{\Delta+\gamma(1+0.34u_2)} \quad (15)$$

Where:

ET: Reference evapotranspiration
Rn: Net radiation
Δ: Saturation slope vapour pressure curve
G: Soil heat flux density
γ: psychometric constant
T_{hr}: Mean hourly air temperature
u: Dynamic viscosity of water
e^0: Saturation vapour pressure
e_a: Average hourly actual vapour pressure

$$\forall_{eva}(\Delta t) = \frac{ET}{3.6*10^6} * A * \Delta t \quad (16)$$

$\forall_{eva}$ is Volume of evaporated water; Δt is Time interval.

A is Reservoir surface area

$$\forall(t) = Q_p\Delta t + Q_t\Delta t + \forall_{pre}(\Delta t) - \forall_{eva}(\Delta t) + \forall(t - \Delta t) \quad (17)$$

$$\forall_{pre}(\Delta t) = \frac{I}{3.6 * 10^6} * A * \Delta t \quad (18)$$

$$H_s = H_r + H_{uwl} + H_{lr} - H_{lwl} \quad (19)$$

$$H_{uwl} = \frac{\forall}{\forall_{res}} * H_{ur} \quad (20)$$

H_r: Vertical distance between upper reservoir and lower reservoir
H_{uwl}: Water level in upper reservoir
H_{lr}: Height of lower reservoir
H_{lwl}: Water level in lower reservoir

$$P_t = Q_t H_t \rho g \eta_t \qquad (21)$$

$$\frac{P_1}{\rho g} + \frac{v_1^2}{2g} + h_1 = \frac{P_2}{\rho g} + \frac{v_2^2}{2g} + h_2 + H_{tl} \qquad (22)$$

3.3 Adopted location (case study)

This study focuses on places where there are no continuous source of water. Bisha, where King Fahad dam is located, is one of the most relevant cities in terms of solar radiation in Saudi Arabia. Relying on the open literature [7][8], a favourable opportunity to construct PHES with seasonal dams has been observed and investigated, so the dam is suitable for the proposed project.

3.4 Results and discussion

The adopted location is considered as one of the hottest cities in Saudi Arabia and the system is examined during summer period .Therefore, three days of August (1–3 August) demand as an illustration of the performance of hybrid system are picked in this study as presented in Figure 4 .To investigate how extremely significant the evaporation rate and head loss are, two different scenarios are applied to the entire integration system .Following all calculations as expressed in section 3 is the first scenarios(considering evaporation rate and head loss), and then the another one is to ignore the two parameters values(neglect evaporation rate and head loss in calculations) under the same conditions . Four PV plants capacities—300MW, 400MW, 500MW and 600MW— connected to the 150 MW PHES are proposed in this study to examine the influences of two essential parameters .The reason behind taking into account of various capacity of PV system is to take advantage of surplus power in which the behaviour of pumping and generation modes are clearly observed . Unlike the performance of 300 MW capacity as shown in Figure 4, little excess power is noticed due to small size of power plant comparing to electricity demand. As presented in Figure 5, the result shows that a critical amount of water is evaporated in three days up to 32 mm, which is considered to be a significant factor for the long term study ,and the influence of this parameter for short period study which this study is applied for might be neglected. In addition, the two scenarios study have been separately performed, and all the three monitoring variables (loss of renewable energy, amount of electricity supplied by grid, and load covered by renewable energy sources) were calculated at each interval. Then, the variation among two scenarios is determined based on disparity of load covered by renewable energy or the grid in the two cases .Finally, from Figures 6 and 7, it is noticed that a considerable amount of power is ignored due to not considering two parameters, which may negatively affect energy management and power dispatch analysis. Additionally, it is observed that when the capacity of renewable energy increases, the difference between the results raises slightly, causing more power to be neglected.

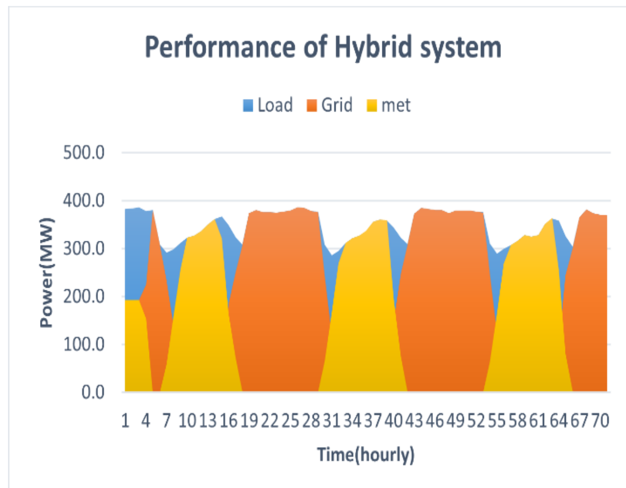

Figure 4. Performance of hybrid system

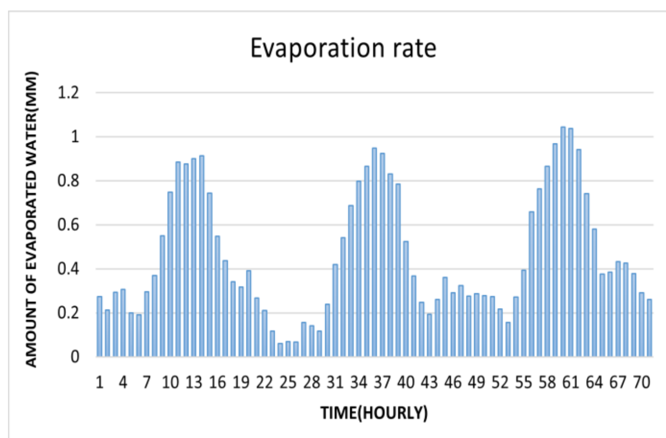

Figure 5. Evaporation rate

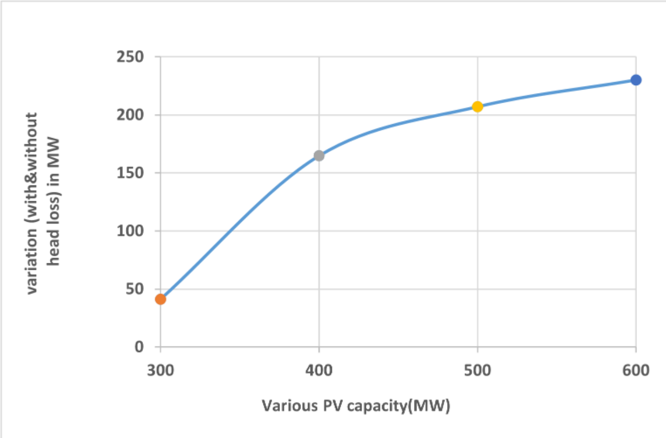

Figure 6. Variation between two scenarios results

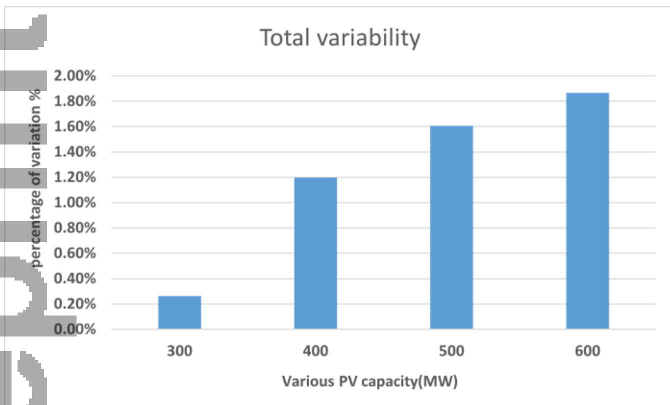

Figure 7. Percentage of variation

3.5 Conclusions

Electricity is one of the world's vital resources, but its production requires various complicated processes. These processes include the burning of natural gas, which contributes to environmental pollution. In recent years, many researchers have been attracted to the prospect of enhancing the technologies of renewable energy sources, such as solar energy, to eliminate the greenhouse gases emitted by thermal power plants. Due to the intermittent and unstable properties of natural sources, an appropriate energy storage technology should be linked to the renewable system to increase profitability. Therefore, an integrated system comprising solar energy (PV) and pumped hydropower energy storage is proposed in this study. Each subsystem is mathematically modelled based on specific factors that are neglected in some studies to investigate the influence of their parameters on the entire system. The result shows that a considerable amount of water is evaporated, which might impact the hybrid system management in the long term. In addition, taking into account the two essential factors is recommended to increase the accuracy of any study using pumped hydropower energy storage.

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