Operational Cost reduction of PV-PHS systems in farmhouses: Modelling, Design, and Experimental validation

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Abstract. This paper proposes a PV-PHS system designed for farmhouses to reduce electricity costs. This study uses existing irrigation systems to store surplus energy coming from PVs in the form of gravitation potential energy. The storage is a type of pumped hydro storage (PHS) system using a water well as the lower reservoir. A comprehensive PHS model is presented and tested with the experiment setup to accurately estimate the stored water. An energy management system (EMS) is designed to manage the stored water to reduce electricity costs without disturbing irrigation functionality. The proposed system is tested in an experimental setup to validate the performance of the system. Then the PV-PHS system is simulated in MATLAB to show the results with a high efficiency pump and turbine. The proposed PHS system reduced the operational cost of the farmhouse by 71.5%.

1. Introduction

Renewable energy sources (RESs) are popular in rural areas because they provide low cost and clean electricity for homes and irrigation systems. The major challenge of RESs is their intermittent nature. The common solution to this is storing energy in batteries when the sun is shining and discharging these batteries when the sun is not available [1, 2]. However, the manufacturing process of batteries produces a lot of carbon emissions [3], so clean energy generated by PVs is stored in a system with a high carbon footprint. In addition, batteries are the most expensive part of microgrids [4] and have a short lifespan [5], so in the long-term research batteries are not a suitable option. Therefore, this research develops an environmentally friendly storage system in order to reduce the cost of microgrids.

This study proposes a pumped hydro storage system (PHS) that can be implemented in irrigation systems. A large and growing body of literature has thus far focused on large-scale PHS for power balancing, however, the aim of this paper is to implement this clean system near demand in microgrids. There are few studies about small-scale PHS systems. Two of these studies demonstrate that the integration of a small PHS into a stand-alone microgrid including a PV, a diesel generator, and a battery can reduce the diesel fuel consumption of the microgrid by 4% [6, 7].

Agricultural lands have water wells, pumps, and reservoirs for irrigation. Adding a turbine to this system changes the existing structure to a PHS. Figure 1 is the schematic of the proposed PHS system. When there is excess energy, the surplus power is used to pump water from the well to the reservoir. Then, the stored water in the reservoir can be used for irrigation, or it can be released into the well

| Nomenclature | Variables | G | Soil heat flux density [MJ/m²/hour] |
|--------------|-----------|---|-----------------------------------|
| P_p | Pump power [W] |
| Q_p | Pump flow rate [m³/s] |
| T_hr | Mean hourly air temperature [°C] |
| RH | Relative humidity |

Nomenclature

Variables

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Pump power [W]

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Soil heat flux density [MJ/m²/hour]

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This study addresses these gaps in the literature. First, a comprehensive PHS model is presented to accurately estimate the volume of water in the reservoir. Then an EMS is designed to optimally control the pump and the turbine without interrupting the primary function of the irrigation system. Finally, the proposed system is tested in both an experimental setup and simulation to validate the performance of the system.

2. PHS model
PHS model used in the literature comprises the pump equation (1) and the turbine equation (2) [6-9]:

\[ Q_p = \frac{\eta_p \rho H_p}{\gamma g} \]  

\[ P_t = \eta_t \rho g H_t Q_t \]  

In that model [6-9], both the pump head \((H_p)\) and the turbine head \((H_t)\) are the vertical distance between the lower reservoir and the higher reservoir. However, two other parameters also affect these heads: water level \((H_{wl})\) and hydraulic losses \((H_t)\).
The pump head ($H_p$) is the sum of the hydraulic head ($H_{pl}$) and the static head ($H_s$). The static head is the vertical distance between the water surface in the upper reservoir and the lower reservoir, which can be expressed as equation (3):

$$H_s = H_{ur} + H_{wl}$$  \hspace{1cm} (3)

Water level ($H_{wl}$) depends on the volume of water in the reservoir and can be calculated by equation (4):

$$H_{wl} = \frac{\forall}{\forall_{res}} \times H_{ur}$$  \hspace{1cm} (4)

The hydraulic head of pumping is a function of water velocity ($v$), pipe absolute roughness ($\varepsilon$), pipe diameter ($D$), pipe length ($L$), and fittings resistance coefficient ($K_{fittings}$) [10, 11]:

$$H_{pl} = K \frac{Q_p^2}{0.125g\pi^2D_p^4}$$  \hspace{1cm} (5)

$$K = K_{pipe} + K_{fittings}$$  \hspace{1cm} (6)

$$K_{pipe} = \frac{f L_p}{D_p}$$  \hspace{1cm} (7)

$$f = \left[1.8 \log \left(\frac{6.9}{Re} + \frac{(\varepsilon/D_p)}{3.7}\right)^{1.11}\right]^{-2}$$  \hspace{1cm} (8)

$$Re = \frac{16 \rho Q_p^2}{\mu \pi^2 D_p^3}$$  \hspace{1cm} (9)

The water volume of the reservoir ($\forall$) depends on the pumping flow rate ($Q_p$), the turbine flow rate ($Q_t$), evaporation ($Q_{eva}$), precipitation ($Q_{pre}$), and irrigation flow rate ($Q_{IRR}$):

$$\forall(t) = Q_p \Delta t - Q_t \Delta t + Q_{pre} \Delta t - Q_{eva} \Delta t - Q_{IRR} \Delta t + \forall(t - \Delta t)$$  \hspace{1cm} (10)

where the turbine flow rate is a function of water level and the percent openness of the turbine valve ($T_v$):

$$Q_t = \frac{T_v}{100} a \sqrt{2ghS}$$  \hspace{1cm} (11)

In equation (10) evaporation ($Q_{eva}$) can be calculated by Eq. (12) [12]:

$$Q_{eva} = \left[0.408A(R_n - G) + \gamma \frac{37}{T_{hr} + 27.3} u_2 (e^{T_{hr}} - e_a) \right] \frac{A}{\Delta + \gamma(1 + 0.34u_2)} \times 3.6 \times 10^6$$  \hspace{1cm} (12)

3. Energy management system

The designed energy management system (EMS) minimises operational costs whilst not interrupting the primary function of the irrigation system. The operational cost of the microgrid is the energy cost drawn from the grid at each time interval:

$$Cost = (E_{Dt} + E_{Pt} - E_{PVt} - E_{Tr}) \lambda_t$$  \hspace{1cm} (13)

where $\lambda_t$ is the electricity tariff at interval $t$. In equation (13), Energy demand ($E_{Dt}$) is the power consumption of the farmhouse and the irrigation system. In this equation, demand and PV are not controllable; however, pump energy consumption ($E_{Pt}$) and turbine energy generation ($E_{Tr}$) are
controllable. Hence, the optimisation algorithm schedules the pump and the turbine to minimise the cost.

Figure 2 illustrates the proposed EMS. It receives needed forecast data and schedules the PHS for the next hours until the end of the day (from present time to 24 o’clock). The forecast for precipitation, temperature, irradiance, humidity, and wind are used in the PHS model for scheduling the system. Weather forecast data is collected from a weather forecast website [13].

4. Results and discussion

To schedule the PHS a genetic algorithm has been applied in this study, but any heuristic optimisation can also be applied. The objective function is given by:

$$ F = \min \sum_{t=1}^{T} (E_{Dt} + E_{Pt} - E_{PVT} - E_{Tt}) \lambda_t $$ (14)

Subjected to

Reservoir constraints: the volume of water in the reservoir is constrained due to the size of the reservoir.

$$ \forall_{\text{min}} < \forall < \forall_{\text{max}} $$ (15)

where $\forall_{\text{min}}$ is zero which happens when the reservoir is empty and $\forall_{\text{max}}$ is the size reservoir. It is assumed that at the end of each day the volume of the reservoir should be same as the beginning of the day. The volume of the reservoir at the beginning of the day ($\forall_0$) is assumed to be 40% [9].

$$ \forall_{t=0} = \forall_{t=24} = \forall_0 $$ (16)

Pump constraint: The pump power ($P_p$) is controlled by a variable speed drive. The operational limit of the pump is between zero to rated power. Thus $P_{p,\text{min}}$ is zero and $P_{p,\text{max}}$ is the pump rated power.

$$ P_{p,\text{min}} < P_p < P_{p,\text{max}} $$ (17)

Turbine constraint: The turbine flow rate ($Q_t$) can be adjusted by the turbine valve ($T_v$).

$$ T_{v,\text{min}} < T_v < T_{v,\text{max}} $$ (18)

When $T_v$ is 0% the valve is fully close and when $T_v$ is 100% the valve is fully open. Hence, $T_{v,\text{min}}$ is 0 and $T_{v,\text{max}}$ is 100.

4.1. Experimental results

The proposed system was tested for one month with an experimental setup installed at Edith Cowan University (Figure 3). Table 1 illustrates the parameters of the PHS system. The measured PV power
and PV power forecast are shown in Figure 4. PV power forecast is estimated by a trained artificial neural network (ANN) [14]. The ANN receives the forecast of clear sky irradiance, cloud cover percentage, and temperature to estimate the PV power for next hours. The demand profile is generated by a high-resolution model of household electricity [15]. Demand profile of a day is shown in Figure 5 as an example. Demand is the electricity consumption of a farmhouse with three households. The demand forecast is estimated with an ANN [16]. A time of use (TOU) tariff is used in this study; however, any other types of tariff can be adopted in this system. The Synergy Smart Home Plan presented in Table 2 is used to calculate the cost [17].

**Table 1. Parameters of the PHS system.**

| Pump Penstock          | Pump | Southern Cross, Type: MfD47A | Impeller diameter: 211 mm |
|-----------------------|------|------------------------------|--------------------------|
|                       | Turbine | Power Spout, Type: TRG | Rated: 768 w, 10 m, 15.3 L/s |
|                       | Material: carbon steel | Inside diameter: 102.3mm | ε/D :0.000049 |
|                       | Fittings resistance coefficient ($K_{\text{fittings}}$): 1 | length:13 m |

| Turbine Penstock       | Turbine | Power Spout, Type: TRG | Rated: 768 w, 10 m, 15.3 L/s |
|-----------------------|---------|------------------------|-------------------|
|                       | Material: carbon steel | Inside diameter: 102.3mm | ε/D :0.000049 |
|                       | Fittings resistance coefficient ($K_{\text{fittings}}$): 1 | length:13 m |

| Upper reservoir | $V_{res} = 600 \text{ m}^3$ |

**Table 2. Synergy TOU tariff**

| Time of use | Tariff ($/\text{kW h}$) |
|-------------|-------------------------|
| Weekdays    |                         |
| 9 PM – 7 AM | Off peak                |
| 7 AM – 3 PM | Shoulder                |
| 3 PM – 9 PM | Peak                    |
|            | 0.148405                |
|            | 0.282139                |
|            | 0.538714                |
| Weekends   |                         |
| 9 PM – 7 AM | Off peak                |
| 7 AM – 9 PM | Shoulder                |
|            | 0.148405                |
|            | 0.282139                |

**Figure 3. Experimental setup**

Figure 4 shows that the EMS has managed the water by the end of the day to return the reservoir volume to its initial level of 40%. Figure 5 illustrates the performance of the system during one day as an example. It can be seen that the EMS has reduced the cost wherever possible during the day. The
pump is working for 4 hours during the day when there is surplus energy coming from the PV. Turbine is mainly generating energy when the demand and the tariff are high.

As it can be seen the pump is not working sometimes during the day even when there is surplus energy like minute 700. The reason for this is that the PHS has losses so it is not always a right decision to use the pump when there is surplus energy. Therefore, when PHS saving is less than the money that MG earns from selling energy to the grid, the EMS has decided to not use the PHS. The EMS considers mainly the losses of PHS, tariff, and demand to decide to pump or send energy to the grid. For example, in minute 700 it was better to not use the pump and instead it has sent energy to the grid to reduce daily operational cost.

Figure 4. PV power and PHS water volume for one week during the experiment

Another parameter that makes this EMS more efficient is the high accuracy of the PHS model in estimating the water volume. This high accuracy assists the EMS to manage the water more efficiently. The result of an experiment with the experimental setup shown in Figure 3 comparing the proposed PHS model and the conventional model [8, 9] indicated that if evaporation, precipitation and hydraulic losses were neglected, the accuracy of the water volume estimation would be reduced by up to 18%.

Figure 5. Cost, PHS mode, and demand power for one day during the experiment

4.2. Simulated results
In this section, the proposed system is simulated for one year. The PV and weather data are measured from the PV system and the weather station installed at Edith Cowan University (Figure 5). The demand profile is generated same as Section 4.1. The PHS parameters are same as Section 4.1 except that the rated efficiency of the pump and the turbine are increased from 0.51% and 0.67% to 86%, and 82% respectively.

Figure 6 shows the results of the simulation for a day as an example. Results show that the PHS is used more than Section 4.1 since the efficiency of PHS is increased. The pump is working when there
is surplus energy, and turbine generates energy when there is deficit energy. The operating points of the pump and the turbine are selected optimally by the EMS to reduce the daily operational cost. The operating points of the pump and the turbine depend mainly on the amount of PV power generation, demand, and the efficiency of the turbine and pump mode at different operating points. The pump mode efficiency of the experimental setup is on its highest at 66% of its rated operating point, and the turbine highest efficiency is at 70% of its rated operating point.

Figure 6. PV power, water volume, cost, and PHS mode for one day during the simulation

Figure 7 demonstrates the operational cost of the MG for both systems with and without PHS for one year. The proposed system has reduced the annual cost of the MG by 71.5%.

Figure 7. Compare the annual electricity cost with and without PHS

5. Conclusion
This paper proposes a PHS system for farmhouses to reduce electricity costs. The proposed PHS is modelled in detail considering evaporation, precipitation, and hydraulic losses to estimate the volume of water in the reservoir accurately. An energy management system (EMS) is designed to manage the PHS operating mode and operating point. The results of the experiment illustrate that the EMS can efficiently manage the PHS to minimise the cost and keep enough water for irrigation when it is needed. The simulation results show the proposed PHS system reduced the annual electricity cost of the system by 71.5%. The improved model has helped the EMS to optimally select the operating point by providing the efficiency of the PHS at different conditions. This system is recommended for farmhouses that have water wells and reservoirs.

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