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Research paper

Hydro aeropower for sustainable electricity cost reduction in South African farming applications

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ABSTRACT

This paper develops a model which can be used to minimize the electricity cost of South African farms through the usage of a wind pump with pico hydro generator and a borehole in pumped hydro storage configuration referred to as "hydro aeropower". This model will optimally schedule the generation power flow from the pico turbine given the demand, the state of water level in the reservoir as well as the electricity pricing period. This model can be implemented to control the power flow in small farming activities where boreholes and windmill are available. Therefore, a 2kW hydro aeropower using groundwater in a farming environment and operating under the Time of Use in South Africa is used to evaluate the possible cost reduction linked to the electricity usage achievable compared to the grid.

Therefore, the problem can be seen as a minimization of the cost of energy purchased from the main electricity supplier, and the maximization of the energy used by the load directly supplied by the hydro aeropower in a dynamic pricing environment. Afterwards, the techno-economic performance of the proposed system is analysed using Matlab software. The results have revealed that up to 63.62% can be saved on the cost of energy consumed using the developed setup rather than supplying the load demand by the grid exclusively.

1. Introduction

Apart from the mining and manufacturing sectors, South Africa's economy is also depending on agriculture. The agricultural sector is one of the main pillars of South Africa's economy. This sector is the largest user of water in all regions of the country with about 62% of the annual useable runoff rainwater (Backeberg and Sanewe, 2006). It has to be noted that the country is semi-arid, therefore a significant number of the small farmers heavily rely on underground water through boroholes for irrigation as well as other farming needs (Odesola et al., 2017). Underground water is usually pumped using electricity from the grid, standalone diesel generators or renewable energy such as wind and solar pumping systems which are currently seen as promising and sustainable options, especially in regions where other alternatives are not easy to be implemented and not cost effective (Kernick, 2014).

Several farmers in South Africa draw water from boreholes and store it in the upper reservoirs for irrigation and other activities (Pinilla et al., 1984). This same arrangement can be used for the implementation of pico-hydropower system. Therefore, local renewable energy sources can be combined to pumped hydro storage facilities and pico-hydro hydropower in a hybrid system configuration.

Due to the large distances between farms and the main water supply infrastructures, supplying via conventional water distribution networks is a big challenge (Palaniappan et al., 2007). Traditionally, groundwater has been used as the preferred option compared to surface water due to various advantages such as Siebert et al. (2010):

- Groundwater can be stored in aquifers for a very long time with almost no evaporative loss.
- It can be extracted near the point of use; and it is available immediately on demand, which allows more timely applications of irrigation water.

The following alternative sources of energy to the utility grid are commonly used to extract groundwater through borehole for irrigation purposes and other farming activities:

- Diesel pumps: These pumps are very effective and operate to extract water on demand. However, they display all the disadvantages of systems powered with diesel generators such as noisy, environment pollution, high operation and maintenance costs associated with the ever increasing price of fuel. The transport and storage of fuel are also major challenges (Kusakana and Vermaak, 2014).

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- Solar pump: Consisting of a solar photovoltaic array and a controller to provide energy to an electric pump that lifts the water from the water source to the surface. However, this system requires an energy storage, as water is always needed even when there is no sun shining (Odeh et al., 2006).
- Wind pumps: These can be Mechanical Wind Pumping Systems (MWPS) where the blade turning kinetic energy of the windmill is used directly to pump water and Wind Energy Converting Systems (WECS) where the wind turbine is used to generate electricity and then used to power an electric water pump (Odesola et al., 2017).

Several research studies have analysed the performance of solar water pumping systems. In Ref. Storm et al. (2016) the research developments related to renewable energy technologies for water pumping systems are reviewed; discussing the different topologies, their advantages as well as limitations.

In Ref. Storm et al. (2013) the design, development, and performance analysis of a solar system for water pumping is presented along with its technical, environmental, and economic benefits as compared to diesel generator or power grid.

The authors of Ref. Koko et al. (2017) have compared performance of a directly connected photovoltaic pumping system and a scheme using a constant voltage maximum power point tracking algorithm. The results have demonstrated very good correlation with the numerical simulation of the systems.

The author of Ref. Kernick (2014) has concluded that in certain cases, even when connection to the grid is easily implementable, that the use of wind pumps is more viable and cost effective options compared to diesel and solar pumping. The costs include capital, installation, operating and replacement costs. The different options were compared over a period of 20 years.

As for water supply, adequate and reliable electricity supply is an absolute necessity in the farming sector. In 2016 the agricultural sector contributed 6.5% to annual South African electricity sales with pumping irrigation water being the biggest electricity demand allocation (Storm et al., 2016). Electrical power is needed to control the environment and sustain the life of livestock, poultry, and plants, and to allow proper harvesting, storing and food conservation, maximizing financial gain and security of the farm capital investments. Therefore, the proximity of electrical network as well as the type electricity source used to supply a given farm are also considered as main component of the financial returns of the farming activities.

Small farming activities in South Africa can be charged as commercial due to the shape of the load profile as well as to the size of the demand when it is less than 100 kVA (Storm et al., 2013). In general, there is a need to decrease the running cost of the electrical equipment to contribute to maximization of the total return of the farming activity. In Certain cases, Demand Side Management interventions can be applied to shift activities such as irrigation pumping from the utility peak periods. This was realized by retrofitting the irrigation pump with timers to allow automatic shutdown and start-up (Koko et al., 2017). However, this can cause some consumer discomfort or dissatisfaction because certain activities need to be performed at specific time of the day.

Renewable energy sources used in conjunction with wind pumping infrastructure can be modified to generate onsite electricity that can be used to reduce the total cost of electricity from the grid. In Ref. Kusakana (2017b), the author has described the operation principle of a novel system named Hydro Aeropower designed in Bloemfontein, South Africa. In this system, a wind pump extracts underground water via a borehole to be stored in a tank located at a reasonable height above the ground. The potential energy of the stored water is then released through a pico turbine to generate electricity.

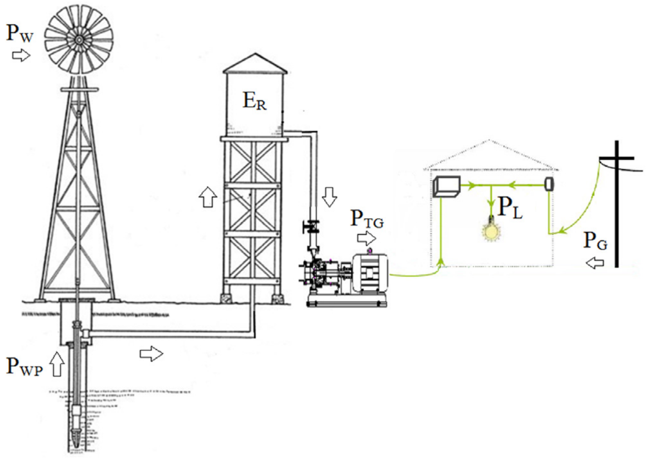

Fig. 1. Proposed grid-connected hydro aeropower.

Based on the facts discussed above, this paper develops a model which can be used to minimize the electricity cost of farm through the usage of a wind pump with pico hydro generator and a borehole in pumped hydro storage configuration. This model will optimally schedule the generation power flow from the pico turbine given the demand as well as the electricity pricing period. This model can be implemented in small farming activities where boreholes and windmill are available. Therefore, the wind and groundwater resources can be efficiently used to produce electricity and decrease the operation costs.

This study will contribute to the promotion of the use of grid-interactive PHS system in the electricity market and make the different system's owners of the potential benefit in terms of electricity bill reduction, especially in farming activities. The author hopes that this research will encourage the PHS owners and also the South African government to be drawn to this innovative technology and to adapt it as an effective strategy that will beneficial to both farmers and local utility companies. The outcomes to be considered consist of the following:

- The development of a mathematical model to optimize the net cost of energy resulting from the bi-directional power flow between the PHS and the grid;
- Promoting onsite electricity generation, storage and management;
- Increasing plant owners' benefits by taking advantage of the electricity market by implementing the developed optimal energy management strategy.

2. Proposed hydro aeropower description

The Hydro aeropower's configuration is shown in Fig. 1. This system consists of a mechanical wind pumping systems, a pumped storage unit with pico hydro turbine, an upper reservoir, and a submersible pump.

In the proposed system, the mechanical wind pumping system produces power (P_W) to extract underground water from a borehole and stores it in an upper reservoir as potential energy to be converted into electricity, though the pico hydro turbine, when needed by the electrical load. The load P_L is principally supplied by the pico hydro system through the turbine–generator unit (P_{TG}) using water stored in the upper reservoir. After the power is generated using the pico turbine P_{TG}, water is allowed to flow back underground, thereby the borehole with its reservoirs

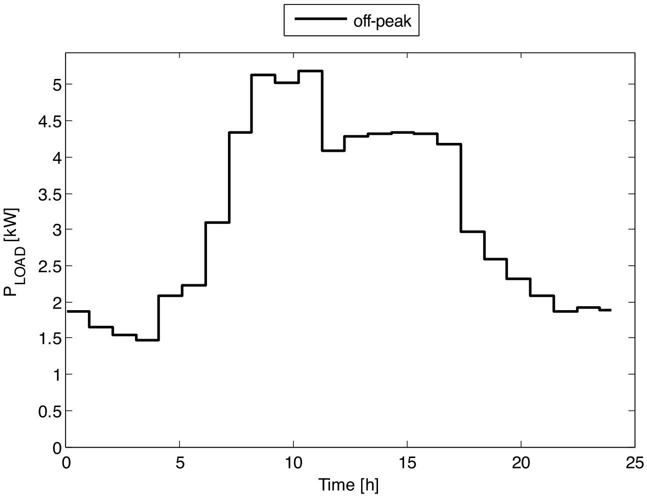

Fig. 2. Proposed domestic load profile (Pinilla et al., 1984).

is considered as an energy storage system. When there is insufficient energy from the reservoir to be supplied to the load, the power from the grid is used to balance the deficit.

It has to be noted that Fig. 1 is only one of the configurations that can be implemented. As suggested by the reviewer, the depth of the borehole can be used as useful water head in a case of a submersible borehole pump in reveres as a turbine.

2.1. Wind pump

The power output of a wind system is function of the wind speed, air density and the turbine's swept area. The wind speed at the tower height can be expressed as follows:

$$v_{hub}(t) = v_{ref}(t) \times (\frac{h_{hub}}{h_{ref}})^{\beta} \tag{1}$$

where $v_{hub}(t)$ is the hourly wind speed at the desired height h_{hub}, $v_{ref}(t)$ is the hourly wind speed at the reference height h_{ref} and β is the power law exponent that ranges from 0.14 to 0.25.

The output power from the wind speed can be expressed as:

$$P_W = \eta_W \times 0.5 \times \rho_{air} \times C_P \times A \times v^3 \tag{2}$$

where v is the wind velocity at hub height, ρ_{air} is the air density, C_p the power coefficient of the wind turbine, A is the turbine swept area, and η_w the wind generator efficiency.

Mechanical wind pumping systems are reliable, durable and reasonably efficient (up to 30%) when there is just enough wind to keep them turning, but their efficiency drops as the wind increases, and overall is typically only about 10%, but there has been some interesting work to improve that Pinilla et al. (1984), Swift (1987), Sarkis and Pinilla (2006), Phiri and Kusakana (2016) and Sarkis and Pinilla (2006).

2.2. Pumped hydro

2.2.1. Pumping system

The power required to extract water from source to the upper reservoir in kW is referred to as the hydraulic energy (P_{WP}) derived from the wind power (P_W) and is expressed as follows:

$$P_{WP} = \frac{\rho_W \times g \times h \times Q_{WP}}{\eta_{WP} \times t} \tag{3}$$

where P_W is the input power to the wind pump used to supply the load (W); Q_{WP} is the pumping flow rate (m^3/s); h is the useful pumping head (m); g is the gravity (9.8 m/s^2), η_{WP} is the total efficiency of the wind pumping system.

2.2.2. Pico hydro turbine

The electrical power generated from the pico hydro system P_{TG} is expressed as:

$$P_{TG} = \frac{\rho \times g \times h \times Q_{TG} \times \eta_{TG}}{t} \tag{4}$$

where η_{TG} is the hydro generating power efficiency; Q_{TG} is the flow rate through the turbine (m^3/s); h is the head (m).

2.2.3. Upper reservoir

The Pico turbine produces electrical power output P_{TG} with efficiency η_{TG}. Therefore, the rated output would be achieved with a water power input of:

$$P_{In-TG} = \frac{P_{TG}}{\eta_{TG}} \tag{5}$$

Water is taken from a water reservoir at height h above ground level, to the turbine located at ground level. Taking the density of water ρ and the acceleration due to gravity g, the water flow rate V needed by the turbine of power P (watts) is then:

$$V = \frac{P_{In-TG}}{h \times \rho \times g} \tag{6}$$

The available volume of water stored in the tank (V) is directly linked to the potential energy (E_R) available. This can be expressed as:

$$E_R = \rho \times V \times g \times h \tag{7}$$

where E_R is expressed in kWh and V in m^3.

Power from the utility grid

The cost of power from the grid is dependent on the Time of Use. For South Africa, this structure is shown below with peak, standard, and off-peak pricing periods (Kusakana et al., 2012).

$$\rho(t) = \begin{cases} \rho_k;\ t \in T_k,\ T_k = [7, 10) \cup [18, 20) \\ \rho_0;\ t \in T_0,\ T_0 = [0, 6) \cup [22, 24) \\ \rho_s;\ t \in T_s,\ T_s = [6, 7) \cup [10, 18) \cup [20, 22) \end{cases} \tag{8}$$

Where $\rho_k = 0.20538$ \$/kWh for peak periods;
$\rho_0 = 0.03558$ \$/kWh for off-peak periods;
$\rho_s = 0.05948$ \$/kWh for standard periods.

3. optimization model and proposed algorithm

3.1. Objective function

The main aim of the developed model is to minimize the amount of power from the grid used to supply the load demand for the considered operation horizon. This can be expresses as:

$$f_1 = \sum_{j=1}^{N} \rho_j (P_{G-L(j)}) \Delta t \tag{9}$$

3.2. Variable constraints

3.2.1. Power balance

The sum of instantaneous power from the grid as well as from the pico hydro system must always be equal to the load demand. This can be expressed as:

$$P_{TG(j)} + P_{G-L(j)} = P_{L(j)} \tag{10}$$

3.2.2. Variable boundaries

The power from the grid and from the Pico hydro are modelled as variables which can be controlled from zero to the maximum rating allowed by the designer. The volume level in the upper reservoir is modelled as a state variable. These boundary constraints linked to the variables can be expressed as:

$$0 \leq P_{G-L(j)} \leq P_{G-L}^{\max} \quad (1 \leq j \leq N) \tag{11}$$

$$0 \leq P_{T-G(j)} \leq P_{T-G}^{\max} \quad (1 \leq j \leq N) \tag{12}$$

$$V_R^{\min} \leq V_{R(j)} \leq V_R^{\max} \tag{13}$$

3.3. Dynamic of the state variable

The instantaneous value of the state variable can change due to the supply input from the pump or due to the load demand through the turbine and generator conversion. This can be expressed as:

$$V_{R(j)} = V_{R(0)} \times (1 - \delta) + t_s \times \left(\eta_{WP} \times P_{W(j)} - \frac{P_{T-G}}{\eta_{T-G}} \right) \tag{14}$$

where $V_{R(0)}$ is the initial water volume and δ is the loss in the reservoir linked to evaporation or leakage.

3.4. Solver selection

The developed objective function and constraints are linear; therefore, the optimization problem can be solved using linear programming in Matlab (Kusakana, 2017a):

$$\min\ g(x), s.t \begin{cases} Ax \leq b \\ A_{eq}x = b_{eq} \\ lb \leq x \leq ub \end{cases}, \tag{15}$$

With: $g(x)$ represents the objective function; A_{eq} and b_{eq} represent the equality constraint parameters; A and b represent the inequality constraint parameters; l_b and u_b represent the inferior and superior limits of the variables.

4. Simulation data

4.1. Load description

It has to be highlighted that a farm is a business establishment as well as a residence. These uses of electricity often occur at a time when electrical household equipment is in operation. The profile below can be used to represent a typical small sized farm in Bloemfontein such as with basic equipment such as milk cooler, milking machine, fan, water pump, freezer, electric heater, light in combination with small household equipment (Fig. 2).

The methodology for sizing the system is explained from Ref. Bokabo and Kusakana (2016). The wind resources used as input to the developed model can be accessed from Ref. Vermaak and Kusakana (2014). The main simulation data are given in Table 1.

4.2. Simulation results and discussion

4.2.1. Load exclusively supplied by the grid

Fig. 3 show the power profile when the load is exclusively supplied by the grid in a load following manner.

Table 1
Simulation parameters.

Item	Figure
Sampling time (Δt)	30 min
Simulation horizon	24 h
Wind pump rated power	2 kW
Pico hydro rated power	2.5 kW
Pumping efficiency	75%
Pico turbine efficiency	70%
Reservoir maximum volume	100%
Reservoir minimum volume	10%
Reservoir initial volume	95%
Reservoir capacity	2.5 kWh

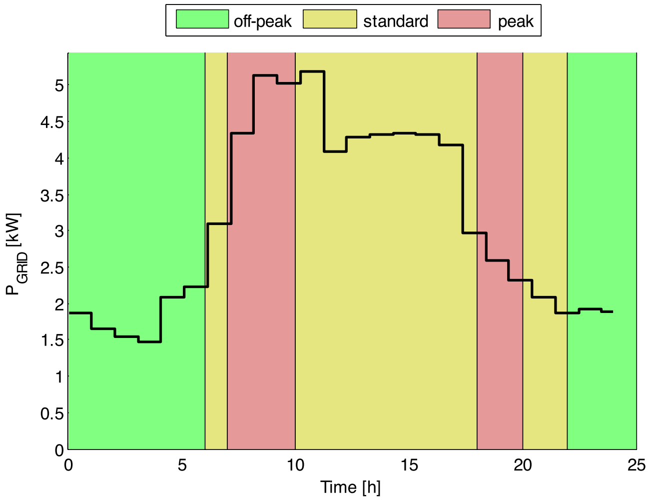

Fig. 3. Load exclusively supplied by the grid.

4.2.2. Load supplied by the hydro aeropower with the grid

In this case, the volume of water in the tank is considered to be maximum at the beginning of the simulation. It has to be noted that sensitivity analysis on this state variable can be done to study the effect of initial water level on the daily operating cost saving.

The system operation as well as power flow will be studied according to the behaviours during the different pricing periods.

- First off-peak pricing period *[0, 6)*

Given the fact that the initial water level in the tank is at its highest as shown on Fig. 4, the potential energy stored in the upper reservoir of the PHS can be used successfully responds to the load demand through the pico hydro as shown on Fig. 5. During this off-peak pricing period, there wind pump is used to extract water from the borehole and fill in the tank as shown on Fig. 6. This operation strategy results in an electricity cost saving because no power from the grid is required to supply the load as shown on Fig. 7.

- First standard pricing period *[6, 7)*

During this pricing period, the windmill is still pumping water in the tank while the pico hydro is not generating power as shown on Figs. 4, 5 and 6. This is to increase the potential energy in the tank to cater for the coming peak pricing period. Due to the reasonable price, the power from the grid is successfully responds to the load demand as shown on Fig. 7.

- First peak pricing period *[7, 10)*

During this peak pricing period, the potential energy stored in the tank is used as main supply to the load through the pico hydro turbine as shown on Figs. 5 and 6. The balance of power needed by the load is them brought in by the grid as shown on Fig. 7. This contribution from the grid is very costly because it occurs during the peak pricing period.

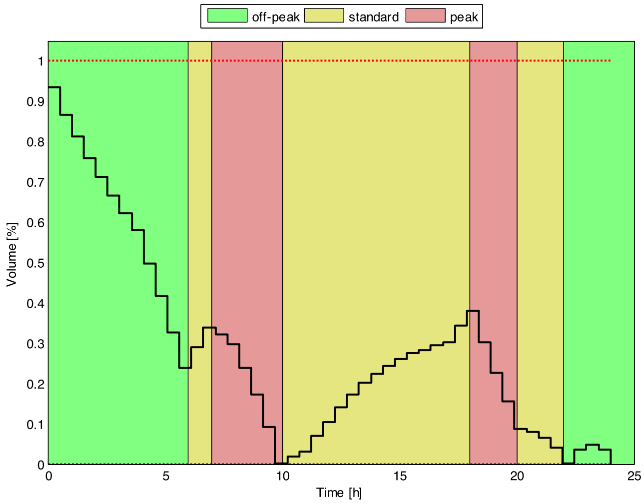

Fig. 4. Dynamic of the storage capacity (volume).

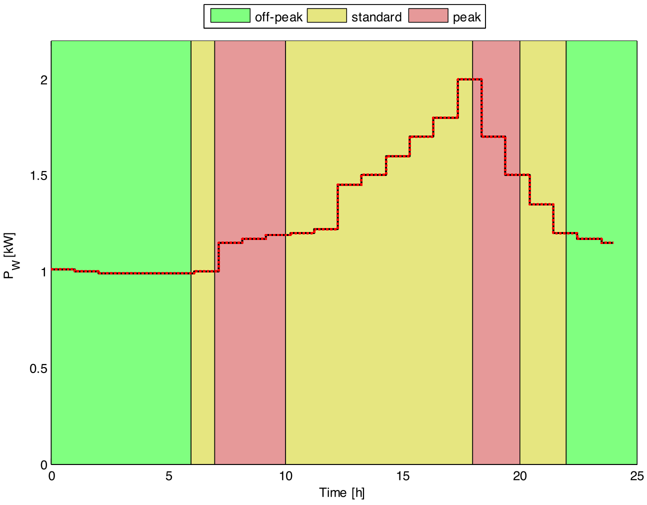

Fig. 5. Wind mill power to pump water to the storage.

- Second standard pricing period *[10, 18)*

During this standard pricing period, the windmill is extracting more water that what is used by the pico hydro to supply the load; this is translated by an increase of stored water level as shown on Fig. 5. However, the pico hydro is not able to supply the load by itself due to the low state of water stored in the tank; therefore, the grid is also used to complement the shortage of power needed by the load as shown on Fig. 7.

- Second peak pricing period *[18, 20)*

As for the first peak pricing period, the load demand is successfully supplied by the pico while there is no contribution from the grid as shown on Figs. 6 and 7 respectively. The effectiveness of the developed model is clearly demonstrated here where the high electricity cost that might occur during this peak-pricing period is avoided.

- Third standard pricing period *[20, 22)*

During this standard pricing period, the pico hydro is used in conjunction with the grid as shown on Figs. 6 and 7; this can be allowed due to the reasonable price of electricity.

- Second off-peak pricing period *(22, 24]*

In this pricing period, both the pico hydro and the grid are supplying the load due to the low potential energy stored in the reservoir as shown on Fig. 5.

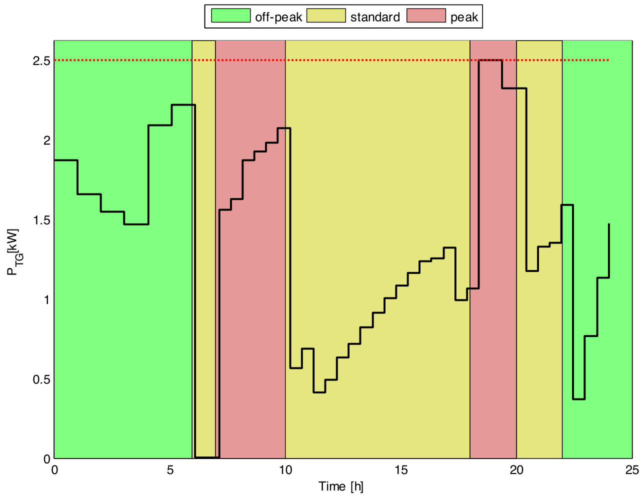

Fig. 6. Pico hydro output power to the load.

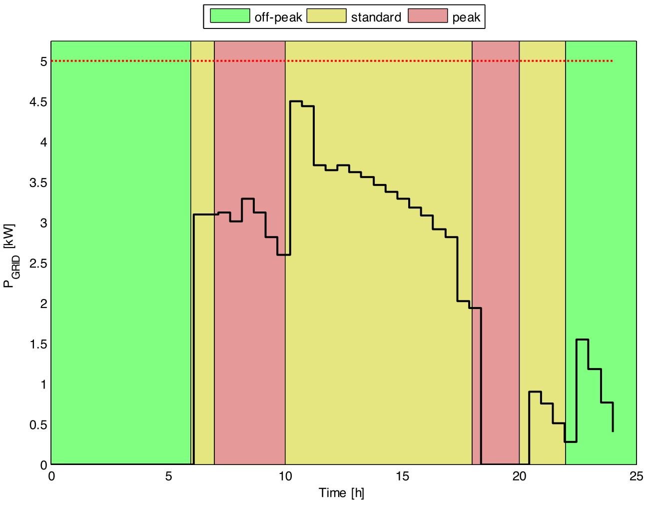

Fig. 7. Grid power to the load.

Table 2
Costs comparison.

Supply option	Daily operation cost ($)
Load exclusively supplied by the grid	$6.24
Load supplied by the grid-connected PHS (Minimal initial volume)	$2.27

4.2.3. Daily economic analysis

Table 2 gives a summary on the cost saving that can be realized by using the hydro aeropower system instead of supplying the load exclusively by the grid. It has to be noted that the results from Table 2 will depend on the sizing parameters, on the wind resource as well as on the time pricing seasons from the grid (summer or winter).

5. Conclusion

In this paper, a model for to manage the operation of the hydro aeropower system has been proposed to minimize the electricity cost of farming activities in South Africa is proposed. The system is composed of a mechanical windmill drawing water from a borehole to an upper reservoir connected to a pico hydro used to convert the potential energy into electricity. This model optimally schedules the generation power flow from the pico turbine given the demand, the state of water level in the reservoir as well as the electricity pricing period. This model can be implemented to control the power flow in small farming activities where boreholes and windmill are available.

For simulation purposes, a 2 kW hydro aeropower using groundwater in a farming environment and operating under the Time of Use is used to evaluate the possible cost reduction linked to the electricity usage achievable compared to the grid. The results have revealed that up to 63.62% can be saved on the cost of energy consumed using the developed setup rather than supplying the load demand by the grid exclusively.

From the simulation results, the following conclusion can be drawn:

- The developed model effectively utilizes the wind power as well as underground water resources available on site.
- The simulation performed using the real data shows that the daily electricity cost has been reduced for the proposed farming load profile with the use of the hydro aeropower.

It has to be noted that the aim of the paper was not to design a hydro aeropower system able to supply the load by itself but to use the available technology to reduce the cost of electricity drawn from the grid. Therefore, for future work, an electrical pump can substitute the mechanical one. In this case, the impact of supplying the electrical pump as well as the electrical load from the grid, if needed during low pricing periods, will be investigated. The potential cost saving of other renewable energy sources used to supply the pump can also be investigated.

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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