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Techno-economic analysis of hydro aeropower systems for energy cost reduction in farming activities

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Abstract

The main aim of this paper is to develop an optimal power dispatch model for grid-connected consumers who are also able to generate electricity using the innovative hydro aeropower systems. The proposed system consists of a wind pump with a hydro generator using groundwater in pumped hydro storage configuration. The developed model minimizes the consumer's energy costs by maximizing the use of the variable wind power converted and stored into potential hydropower; optimally managing the pumped hydro storage system; and minimizing the use of the electrical utility operating with the Time-of-Use rate.

Through a case study in South Africa, the results have demonstrated that, as compare to using the grid as sole power source, the selected consumer can achieve a total daily cost reduction of 49.49% and 53.5% for typical summer and winter days, respectively. The lifecycle cost analysis has projected the system to break-even after 2.6 years as compared to using the grid power exclusively. For a 20 years' project, using the grid as baseline for the comparison, the lifecycle cost analysis have projected the system to break-even after 2.6 years and save 48.4%. This model can be used to optimally dispatch the power flow in small farming activities with grid connection and where groundwater and wind pumps can be implemented.

Keywords: Cost reduction, time of use, groundwater, hydro aeropower, power dispatch, pumped hydro storage

1. Introduction

The South African agricultural sector is the country's fifth largest energy consumer; after the industrial, residential, public transport and commercial sectors [1]. In 2015, the energy demand in South Africa's agricultural sector was supplied by 66% with petroleum products, 32% electricity and 2% coal [2]. Therefore, like in any other industries, proper "Energy Efficiency" and "Demand Response" actions can benefit the sector in decreasing the amount of energy consumed and maximize the profits [3].

Most of farming activities are under dynamic tariffs programs, such as Time-of-Use Pricing (TOU). These are implemented to assist the grid reducing the stress on the supply side by forcing the consumers to shift their demand from peak toward low costing pricing intervals. The aim is to reduce peak load demands and/or shift it from peak to off-peak periods [4]. The ability of consumer to take advantage of TOU tariffs depends on the nature of the demand and the possibility to shift the different processes to a period where the energy costs from the grid are more favourable. The potential saving can be significant; however, load shifting might not always be suitable to the farming industry because some of the processes cannot be deferred or shifted.

In instances where the load demand cannot be shifted, alternative energy sources and storage systems can be used to support the demand and to reduce the reliance from the grid as well as to avoid the peak pricing periods through proper power dispatch [5].

Usually, farming activities are taking place far from the urban areas. Therefore, due to the distances between the farms and the main water distribution systems, groundwater is being extensively used as an

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alternative water supply source [6]. The advantage of using groundwater as compared to getting water from the municipal distribution network are [6]:

- Aquifers can be used to store water for a very long time with minimal evaporative loss.
- Water can be extracted near the point of use; reducing the need of long piping system for transportation .
- Water is directly available as soon as it is pumped.

As alternative to grid power, different energy sources can be used for groundwater pumping. These are

- Diesel powered water pumps.
- Solar powered water pumps.
- Wind power water pumps: Under this category, two case are available, namely the wind energy conversion system using an electric generator; and the windmill which is a purely mechanical system where the blades motion drives a pump rod, up and down inside of a pipe in the borehole.

Even though several research papers have already been published on the use of these different groundwater pumping methods; the author of Ref. [7] has concluded that in certain scenarios, even in presence of the municipal grid connection; the use of mechanical wind pumps is a more sustainable option as compared to diesel and solar pumping. This conclusion was made based on the life cycle cost analysis of these different groundwater pumping options.

One common challenge with the use of renewable energy sources, such as wind systems, is their dependence on variable resources and climatic conditions, making their power generated too unreliable to continuously meet the demand of the processes the are supplying, without having any energy excess or deficit. Generally, standalone renewable energy sources employ battery storage systems to solve the power unbalance problem between generation and supply [8]. Given their fast manufacturing time and their ability to be easily deployed in any site, batteries have been the storage system of choice for isolated RES [9]. The current trend in the energy storage system research filed has shown an increased interest in the use pumped hydro storage systems (PHSs). This energy storage system is well known, requires low maintenance, has a long lifespan, can produce high energy density, is environment friendly and has high roundtrip conversion efficiency; these characteristics makes PHS well suited to support the fluctuation of RESs such as hydropower, solar and wind energy conversion systems [10-16].

A particular type of PHS is the one that uses groundwater as resource and the aquifer as lower reservoir; and this setup has been analyzed in Ref. [17] where the author has described the general operation of the "hydro aeropower" which is an isolated system that uses a mechanical wind pump as the primary source of energy supplying a groundwater pumped hydropower system. Some of the advantages of this system are:

- The hydro turbine is added to already existing water pumping and storage infrastructures. This reduces the initial cost as compared to installing a generation system from scratch.
- The hydropower generation and the pumping system can operate simultaneously, which is usually not the case in traditional hydropower, unless the system has at least two water ways.

Based on the research works presented above, it can be seen that the use of such a system in grid-connected applications still needs to be investigated. Therefore, the current work develops a model of a grid-connected hydro aeropower which can be used to minimize the energy cost of from the grid using a Pico hydro generator in a pumped hydro storage configuration, supplied by a windmill with groundwater as resource. The model optimally dispatches the power flow from the Pico turbine and from the grid, given the variable demand as well as the applicable dynamic energy pricing structure. The developed model can be useful in the farming sector where boreholes and windmill are used, and has the potential to decrease the energy costs and the demand reliance from the grid.

2. Proposed Grid-connected System

The proposed grid-connected hydro aeropower's structure is shown in Fig. 1. It consists of a mechanical wind pump, a groundwater pumped storage system with a Pico hydro turbine and an upper reservoir.

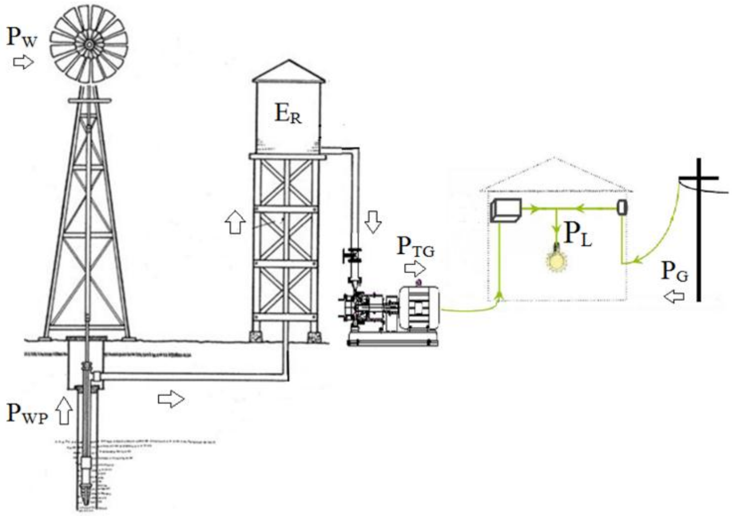

Fig. 1. Proposed grid-connected hydro aeropower

In the proposed setup, the windmill produces a power (P_W) to drive the mechanical pump that extract the groundwater and stores it in an upper reservoir situated above ground level. The potential energy stored in the upper reservoir can be converted into electricity through the Pico hydro turbine-generator unit (P_{TG}) to directly supply the load demand P_L. The power from the grid needs to be minimised, especially during the peak pricing period of the TOU. The water used to generate electrify through the hydro turbine is allowed to flow back in the lower reservoir situated underground or can be used for purposes such as irrigation.

Given the fact that the windmill is purely mechanical, the power from the grid is exclusively used to supply the load, not for pumping purposes.

2.1. Wind pump

The windmill power production is function of the wind resource velocity, air density and the blades' swept area. The wind velocity at a given tower height can be modelled 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 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.

The mechanical power supplied to the pump (P_{WP}) can be modelled as:

$$P_{WP} = \frac{\rho_W \times g \times (H_S + H_{p-loss}) \times Q_P}{\eta_P} \tag{3}$$

Where Q_P is the pumping water flow rate (m^3/s), H_S and $H_{p\text{-}loss}$ are the static head and the loss pumping water head (m), g is the gravitational acceleration and η_{MP} is the combined efficiency of the pump set.

2.2. Reservoir

The upper reservoir model indicates the dynamic of the volume stored which is a function of the input water flow, the output water flow and the volume previously strored. This can be expressed as:

$$Vol_t = Q_P \times \Delta t - Q_{TG} \times \Delta t - V_{loss(\Delta t)} + V_{press(\Delta t)} + Vol_{0(t-\Delta t)} \tag{4}$$

Where: Q_P and Q_{TG} are the flow rates of the pump and turbine/generator sets respectively; V_{loss} is the volume lost due to the evaporation and seepage, V_{press} is the volume added in case of precipitation and V_0 is the initial volume.

2.3. Turbine-generator

The turbine/generator uses the kinetic energy of the water flowing down from the upper reservoir and is mechanically coupled to the hydro generator. Therefore, the electrical power from the generator (P_{TG}) can be modelled as:

$$P_{TG} = Q_{TG} \times H_t \times \rho_W \times g \times \eta_{TG} \tag{5}$$

Where H_t is the turbine head and η_{TG} is the combined efficiency of the turbine-generator set.

3. Optimization Model and Proposed Algorithm

3.1. Objective function

Looking at the developed model, it can be clearly seen that the grid energy cost need to be decreased. Therefore, the main aim of the developed model is to minimize the resultant energy cost by maximizing the use of the hydro aeropower system for the considered operation horizon. This can be modelled as:

$$f_1 = \sum_{j=1}^{N} [\rho_j (P_{G-L(j)}) - P_{TG(j)}] \Delta t \tag{6}$$

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:

$$P_{TG(j)} + P_{G-L(j)} = P_{L(j)} \tag{7}$$

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 manufacturer. The volume level in the upper reservoir is modelled as a state variable. These boundary constraints linked to the variables can be expressed as:

$$0 \le P_{G-L(j)} \le P_{G-L}^{\max} \quad (1 \le j \le N) \tag{8}$$

$$0 \le P_{TG(j)} \le P_{TG}^{\max} \quad (1 \le j \le N) \tag{9}$$

$$V_R^{\min} \le V_{R(j)} \le V_R^{\max} \tag{10}$$

3.2.3. Dynamic of the state variable

For any considered pumped hydro storage, the state of charge (SoC) is basically the ratio of the available energy volume at a sampling time "*j*" over the maximum volume of the upper reservoir). The SoC dynamic of the PHS can be respectively modelled as:

$$SoC_{R(j)} = SoC_{R(0)} \times (1-\alpha) + \frac{\Delta t}{E_R} \times \left(\eta_P \times \sum_{i=1}^{j} P_{P(j)} - \frac{\sum_{i=1}^{j} P_{TG(j)}}{\eta_{TG}} \right) \tag{11}$$

Where $SoC_{R(j)}$ is the upper reservoir's state of charge; $SoC_{R(0)}$ is the initial state of charge; E_R is the nominal potential energy of the PHS's upper reservoir; η_P is the efficiency of the pumping process; η_{TG} is the efficiency of the generating process; and α is the upper reservoir evaporation losses.

3.2.4. Fixed-final state condition

To allow for the repeatability of the optimization algorithm; the respective SoC of the PHS at the beginning and of the simulation horizon must be equal to the one at the end. This can be modelled as:

$$\sum_{j=1}^{N} (P_{WP(j)} + P_{TG(j)}) = 0 \tag{12}$$

3.3. Solver selection

Given the fact that the modeled objective function and constraints are linear; the optimization problem can be solved using linear programming in Matlab [18].

4. Simulation Data

4.1. Demand profiles and renewable resources

As discussed in the introduction, the proposed system can be implemented anywhere in the world. South Africa extensively uses windmills to pump groundwater for irrigation and other farming activities. The case study selected is in South Africa because of the availability of data at the time of the study as well as the need and opportunity of implementing the proposed system in the farming community in need of reliable and cost effective power for the different activities. The selected farming profile, shown on Fig. 2, can be used to represent a typical small sized farm in Bloemfontein with basic farming as well as household equipment. The selected windmill's mechanical output power profile of linked to the available wind resource is shown on Fig. 4.

4.2. System components size

The present paper does not look into optimal sizing techniques; the main aim of this work is to minimize the energy cost through the optimal economic power dispatch of the grid-connected hydro aeropower system submitted to the variable wind resources and grid dynamic pricing structure.

In addition to the windmill rated power, the size of a grid-interactive hydro aeropower depends on the space available, the capital funds as well as the saving targets. The main aim of generating energy from the proposed system is not to take the farming loads off the grid but to reduce the resultant energy operation cost. The system's main simulation parameters and component size are given in Table 1.

Table 1. Simulation parameters

Item	**Figure**
Sampling time (Δt)	30 min
Simulation horizon	24h
Wind pump rated power	2 kW
Pico hydro rated power	3 kW
Pumping efficiency	75%
Pico turbine efficiency	70%
Reservoir size	136 m^3
Reservoir energy capacity	12 kWh
Reservoir maximum Volume	100%
Reservoir minimum Volume	10%
Reservoir initial Volume	55%

4.3. Grid electricity cost structure

The farming demand is supplied from the grid using the applicable Eskom Ruraflex - Local Authority tariff structure for 2019/2020 [19]. The ToU pricing periods, the rates per kWh for the different seasons as well as the flat feed-in tariff in Mangaung municipality are given in Table 2.

Table 2. Time of use pricing structure

Season	**Months**	**Period**	**Time (hour)**	**Rate (ZAR)**
High Demand (Winter)	June -August	Peak	0-6, 22-24	4.2671
		Standard	9-17, 19-22	1.2985
		Peak	6-9, 17-19	0.7085
Low Demand (Summer)	September -May	Off-peak	0-6, 22-24	1.3970
		Standard	6-7, 10-18, 20-22	0.9642
		Peak	7-10, 18-20	0.6146

5. Simulation Results and Discussion

5.1. Baseline: Load exclusively supplied by the grid

Fig. 3 represents the profile of the power exclusively supplied from the grid to the demand. In this case, the grid acts in a load following manner throughout the different pricing periods without any possibility of applying demand response strategies for reducing the operation costs, the reliance from the power grid as well as to avoid the peak pricing periods.

5.2. Load supplied by the hydro aeropower with the grid

In this case, the volume of water in the reservoir is considered to be at 55% of the total capacity, at the beginning of the simulation. The system’s operation as well as power flow will be studied according to the behaviours during the different pricing periods.

5.2.1. First off-peak pricing period [0, 6)

Fig. 4 shows the available energy from the wind system to pump water in the upper reservoir. Fig 5. shows that during this off-peak pricing period, the SoC of the reservoir is increasing due to the pumping action show on Fig. 4. At the same time, Fig. 6 shows that there is no power generated from the Pico turbine. This is to increase the potential energy in the reservoir to cater for the coming peak pricing period. Therefore, the load is exclusively supplied by the grid as shown on Fig. 7. This is allowed because the grid energy cost in this pricing period is at the lowest.

5.2.2. First standard pricing period [6, 7)

During this pricing period, Fig. 5 and 6 show that the Pico hydro start generating power to reduce the amount and cost of energy drawn from the grid. The contribution from the grid towards the load energy demand is shown on Fig. 7.

5.2.3. 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 which operates at its maximum rating as shown on Fig. 5 and Fig. 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.

5.2.4. Second standard pricing period [10, 18)

During this standard pricing period, the windmill is extracting more water to pump water in the tank and at the same time, power is generated by the Pico hydro to supply the load as shown on Fig. 5 and Fig. 6. However, the Pico hydro is not able to supply the load by itself; therefore, the grid is also used to complement the shortage of power needed by the load as shown on Fig. 7.

5.2.5. Second peak pricing period [18, 20)

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

5.2.6. Third standard pricing period [20, 22)

During this standard pricing period, water is being pumped in the reservoir while the Pico hydro is used in conjunction with the grid as shown on Fig. 5, Fig. 6 and Fig. 7 respectively. The use of the grid is allowed due to the reasonable price of electricity.

5.2.7. Second off-peak pricing period (22, 24]

Fig. 5 and Fig 6 show that the Pico hydro does not supply the load and all the water pumped by the windmill is stored in the reservoir to meet the final fixed state condition imposed on the SoC. Therefore, Fig. 7 shows that only the grid is supplying the load in this off-peak pricing period.

6. Economic Analysis

The economic analysis is conducted to compare the energy cost saving potentially achievable when the proposed hydro aeropower system is implemented. This is done in two stages; the first one is to compute the daily energy cost saving of the system and compare it with the baseline (grid only). The second step is to look at a life cycle cost (LCC) given the fact that the daily costs saving are dependant on the system initial, operation and maintenance, replacement, energy as well as salvage costs.

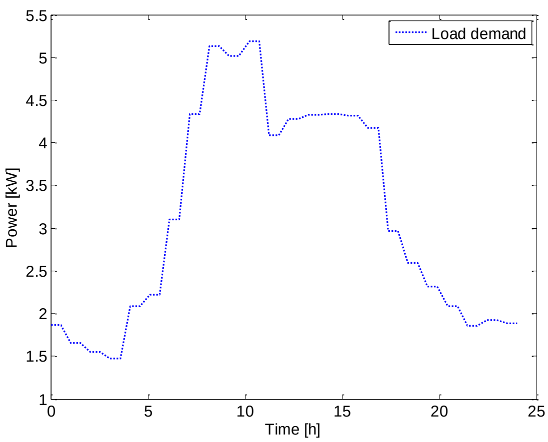

Fig. 2. Proposed farming daily load profile

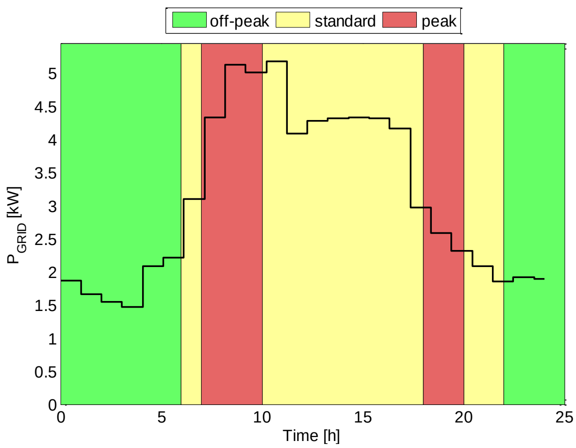

Fig. 3. Grid as exclusive power supply to the load

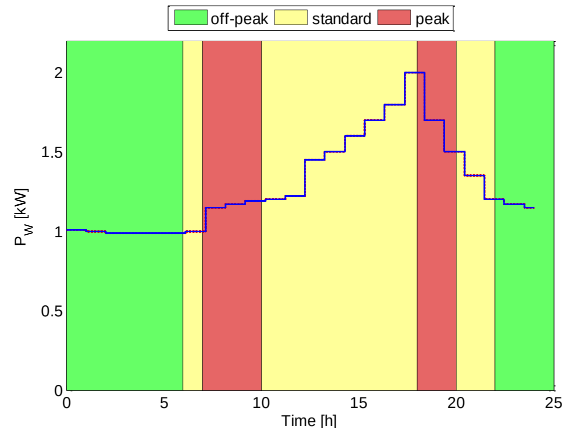

Fig. 4. Windmill output power profile

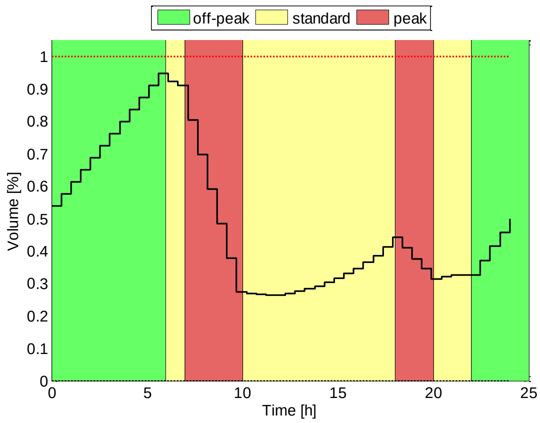

Fig. 5. SoC dynamics (volume)

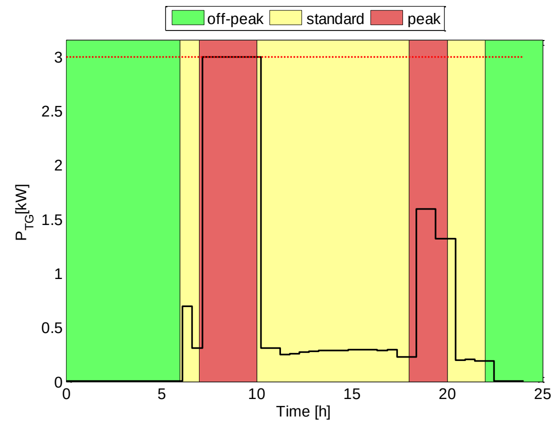

Fig. 6. Pico hydro turbine output power

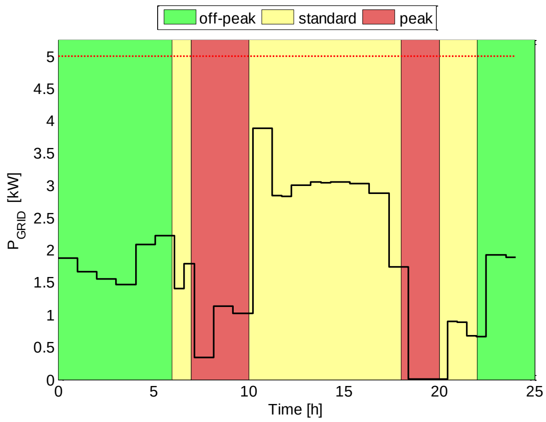

Fig. 7. Grid to load power

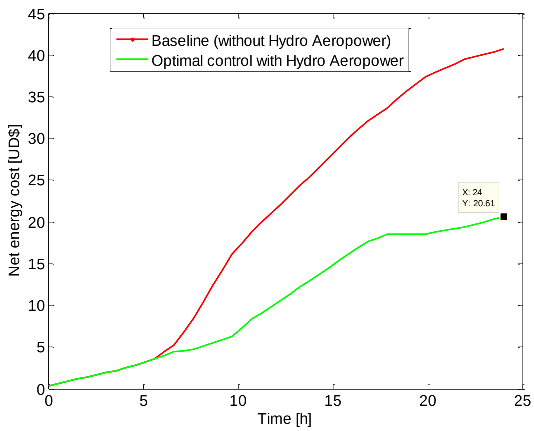

Fig. 8. Daily cumulative cost comparison (Summer)

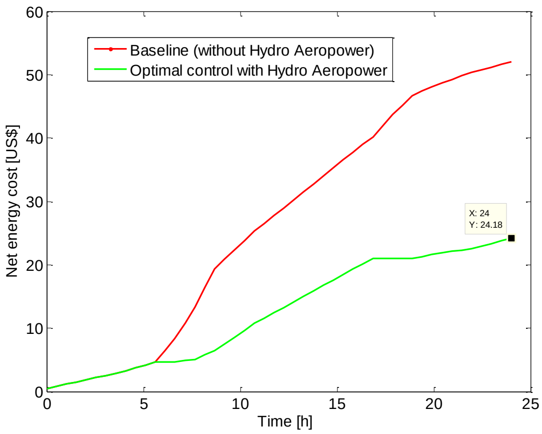

Fig. 9. Daily cumulative cost comparison (Winter)

6.1. Daily cost comparison

The daily energy cost saving of the proposed system is computed and compared with the grid only taken as baselines.

For the selected summer day, Fig. 8 shows that the consumer spends US$ 20.61 using the proposed system as compared to US$ 40.72 when using the grid as sole power source. This means that a potential saving of 49.49% is achievable in the given summer conditions.

For the selected winter day, Fig. 9 shows that the consumer spends US$ 24.18 using the proposed system as compared to US$ 52 to using the grid as sole power source. This means that a potential saving of 53.5% is achievable in the given winter conditions.

This section has shown that substantial cost savings are achievable using the proposed scheme. However, these cost savings dependent on variables such as the size of the system's component (initial cost). Therefore, further analyses, using the LLC, must be conducted to ascertain the overall economic benefit of the proposed system.

6.2. Life cycle cost analysis

The lifecycle cost (LLC) analysis is conducted to assess economic benefit of proposed system on the long run; this will assist in finding the break-even point (BEP) as compared to the proposed baseline. The LCC can be computed as:

$$LCC_{(i)} = C_{I(i)} + C_{R(i)} + C_{OM(i)} + C_{EC(i)} - C_{S(i)} \tag{13}$$

Where, for each component I, C_I is the initial cost of each component; C_S is the salvage cost linked for each component that has not reach its replacement time; C_R is the replacement cost of each component; C_{OM} is the operation and maintenance cost of each component; and C_{EC} is the applicable net energy cost.

Using the applicable daily energy cost charges from the grid, the daily variable renewable energy resources and the daily load demands; the annual energy cost is computed as the sum of the daily energy cost achieved (same methodology as for 6.1). According to the 2019 energy charges structure from the utility, the high demand season has 92 days while the low demand season has 273 days; with the corresponding flat off-peak tariff applied on the power purchased from the grid during the weekends. Therefore, the proposed system achieves a yearly energy cost US$ 7 851.09 as compared to US$ 15 900.56 using the grid as sole power source. This means that a potential saving of 50.62% is achievable yearly.

The bill of quantity applicable for the hydro aeropower is given on Table 3. A yearly increase of 10% is applicable in the case of the grid energy rates. The yearly operation and maintenance cost for each component are also given in Table 3; the applicable yearly average inflation rate is 5.3% [20].

Using the cumulative energy cost from the grid as baseline, Fig. 10 shows that the Break-even Point of the proposed grid-connected hydro aeropower can happen after 2.6 years of operation, corresponding to approximatively USD 46 000 cumulatively spent. Afterward, the proposed system start generating substantial benefits.

Table 3. Bill of quantity for prosumer 1

Component	Price (US$)	Years
Windmill with water pump	12500 [21]	25
Water Turbine-Generator (3 kW)	2180	20
Upper reservoir 136 m^3 170 m	1500	-
Water well	6600	
Connector	40	20
Cable 100m	85	20
Total capital	***22305***	

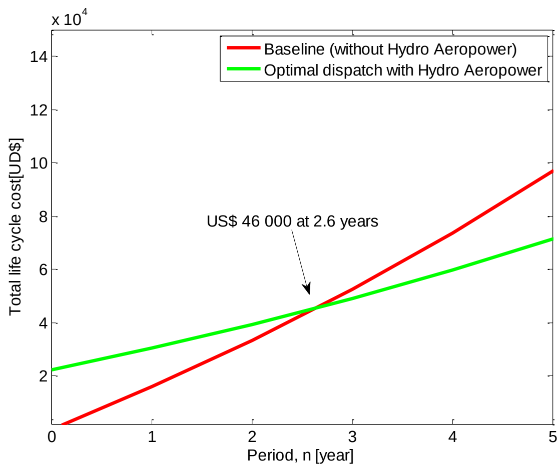

Fig. 10. LLC comparison for the two supply options and BEP

7. Conclusion

In this paper, a model for the optimal economic power dispatch of a grid-connected hydro aeropower system is developed. The developed model minimized the operation cost by maximizing the use of the power from the pumped hydro storage; and minimizing the use of the grid supplying energy under the Time-of-Use rates.

A case study was selected in South Africa where the farmers are using windmills for groundwater pumping purpose. The economic analysis has been conducted using the available wind resources, the load demand, the applicable grid tariffs as well as the system component size. The results have demonstrated that the proposed grid-connected hydro aeropower can assist the farmers to benefit from their own energy generated and substantially reduce their cost of energy as compare to using the grid as sole power source. Simulations have revealed that potential cost saving of 49.49% and 53.5% for typical summer and winter days, respectively. The lifecycle cost analysis have projected the system to break-even after 2.6 years as compared to using the grid power exclusively.

This model can be used to optimally dispatch the power flow in small farming activities with grid connection and where groundwater and wind pumps can be implemented.

Conflict of Interest

The author declares no conflict of interest.

Author Contributions

K. Kusakana is the sole author who conducted the research; analyzed the data; wrote the paper and approved the final version.

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