Techno-Economic Analysis of a Grid-Connected Photovoltaic with Groundwater Pumped Hydro Storage for Commercial Farming Activities

K. Shirinda, K. Kusakana and S.P. Koko

Department of Electrical, Electronic and Computer Engineering, Central University of Technology South Africa.

kshirinda@cut.ac.za, kkusakana@cut.ac.za, skoko@cut.ac.za

Abstract **- Underground pump hydro system is a promising innovation technology with power generation potential for remote located farms with adequate availability of underground water resource. In this paper, the techno-economic analysis of a grid-connected solar photovoltaic with groundwater pumped hydro storage for commercial farming activities in arid areas is discussed. The main objective is to reduce the grid electricity cost for farming activities under variable time-of-use electricity tariff. The results of this study indicate that the proposed system is effective in minimizing the grid consumption costs by 95% and 32.4% in winter and summer seasons, respectively. This led to a break-even point of 7 years as compared to the grid.**

Key words - Groundwater, solar photovoltaic, farming, pumped-hydro storage, techno-economic analysis.

I. INTRODUCTION

Many farms in South Africa have both challenges of electricity and water supply [1]. This results in significantly higher operation cost, which in turn reduces the return on investment of the overall farming activities. Frequent electricity blackouts and load shifting has been a common problem, to both farmers and wholesalers, who are benefiting from the farms [2]. Diesel generator (DG) has been one of the most popular power generation option used for remote rural electrification [3]. It comes with advantages such as low initial capital costs. However, DG is not a viable solution due to factors such as the long-distance fuel transportation, emission of greenhouse gases, and a rapid fuel price increase.

Therefore, renewable energy (RE) resources may offer a sustainable solution by supplying clean energy [4]. RE resources may be used in conjunction with groundwater storage and pumping infrastructures to benefit the farmers. It may be designed to generate onsite electricity that may be used to minimize the amount and cost of electricity drawn from the grid. Hence, this may result into a cost saving benefit for farmers.

In this paper a techno-economic analysis is conducted on the basis of using solar energy to pump the underground water to regenerate electricity using a hydro-turbine to supply the farming loads. Hence, the potential benefits of using underground pumped hydro storage system is analysed. This aims at maximizing the use of RE while minimizing the monthly electricity bill. Hence, the proposed system will have a positive economic and social impact on farming activities.

II. METHODOLOGY

A. System Description

The proposed system is grid-connected and consists of the solar photovoltaic (PV) system, water storage reservoir and the local grid, as shown in Fig. 1. Hence, the load demand is met by the three power sources, namely a PV system, pumped-hydro-storage (PHS) system as well as the local grid network. The main objective is to minimize the grid consumption under TOU tariffs. Hence, this will lead to a maximized RE penetration from the PV and the PHS system.

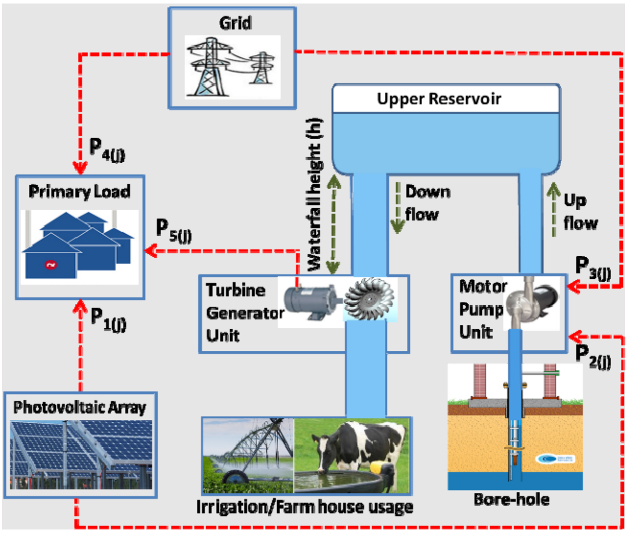

Figure 1. Proposed system layout

B. Case Study Description

The typical farming load demand has been used as shown in Fig. 2 [2]. The solar resource data used during simulation is as shown in reference [2]. The electricity tariffs as enforced by the distribution company of Bloemfontein municipality in Free State province (CENTLEC), are as shown in Table 1 [5]. The electricity price varies seasonally since the winter season proves to be costlier than the summer season.

An 8-kW solar PV system as well as the water storage reservoir that can store up to 5 kWh of energy, has been used during simulation. The bill of quantity for the project that reveals the prices of different components and project activities, is as shown in Table 2 [6-8]. These are the average prices for the year 2018. This resulted in an overall system's investment cost of ZAR 238 914.

TABLE I. TOU TARIFFS INCURRED BY LOCAL MUNICIPALITY COMPANY (CENTLEC)

Season	Period	Rate (ZAR)
High Demand (Winter)	Off-peak Standard Peak	2.101 2.182 3.557
Low Demand (Summer)	Off-peak Standard Peak	1.281 1.431 2.251

TABLE II. BILL OF QUANTITY FOR THE PROPOSED SYSTEM

Component description	Net price (ZAR)
Upper Storage tank	32 133
Tank construction labour	17 500
PV Panels	64 584
PV installations	5900
Solar tracking device	21 248
Converter	5 499
Low rpm hydrogenator	61 245
Series 5 kW submersible pump	6 805
Borehole drilling	24 000
Total initial investment cost	238 914

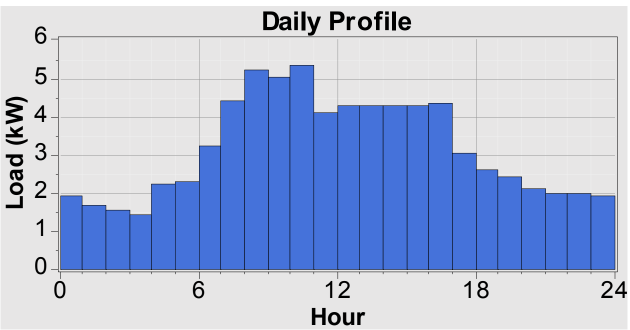

Figure 2. Load profile of a typical farm [2]

III. SIMULATION RESULTS

A. Optimum Performance of the System

The performance of the proposed grid-connected PV-PHS system has been simulated using *linprog* MATLAB solver. The optimal energy management algorithm was developed to ensure optimal power dispatch with the aim of minimizing the grid consumption costs and maximizing the renewable energy penetration. The load has been met by the three power sources, namely solar, PHS and the grid. The algorithm ensured that the commercial load demand is met at no capacity shortage.

B. Economic Analysis

To evaluate the viability of the proposed system, economic analysis of the system has been performed. Economic performance indicators such as benefits to cost ratio (BCR), initial rate of return (IRR) and lifecycle cost (LCC) analysis, has been evaluated.

The daily cumulative energy cost is calculated as follows:

$$C_{daily-EC} = t_s \cdot \sum_{K=1}^{N} (P_{grid} \cdot C_{TOU_k}) \tag{1}$$

Where: N is the number of sampling intervals, t_s is the sampling time, P_{grid} is the power allowed from the grid and C_{TOUk} is the time-based cost of electricity at each kth interval.

B1. Winter and Summer Cumulative Energy Cost

The cumulative cost of the winter period is shown in Fig. 3. This reveals the baseline cumulative grid costs if the load demand is solely supplied by the grid, as well as the cumulation cost if the load demand is met by the optimally controlled system.

The cumulative curve shows a directly proportional relationship between the baseline and optimal control strategy, after the first peak period. The cumulative costs of both baseline and optimally controlled topologies are approximately the same, at the beginning of the horizon. When comparing the operational cost curves at the end of the horizon, the baseline's total energy cost is approximately 32% higher than that of the optimal system.

The cumulative cost for summer season is as shown in Fig. 4. It behaves differently to the one of winter season. The summer electricity usage is low as compared to winter. The energy cost difference between the baseline and optimally controlled cumulative grid cost is clearly huge, as denoted by the gap between the curves. From the beginning of the first peak period, the cost of the optimal controlled system stays the same, so that its cumulative cost remains under R5.00 till the end of the of the control horizon. The difference in cumulative energy cost, at the end of the control horizon, represents the daily energy cost savings. The baseline energy cost, compared to the optimal controlled system, shows that the baseline's cost of energy is 95% higher, than that of optimally controlled system. This is way too higher, as compared to the winter case.

B2. Daily Energy Consumption and Savings

The cumulative costs and energy consumption after each simulation of the baseline and optimal control strategies, are as shown and compared in Table 3. A 32% saving of the energy in the winter season is observed, while a 90.64% saving during the summer is noted. The optimal control strategy allows most of the grid electricity consumption to be used during standard and off-peak period, in order to ensure saving. This results in a cost saving of 95% in summer season, and 32.4% in winter. This highlights the importance of avoiding grid electricity usage during expensive peak period.

B3. Annual Energy Consumption and Savings

The total cost saving for a period of a year, is calculated using the data in Table 3. Based on the utility company's tariff structure, the winter season has a total of 92 days, while the summer season consists of 273 days. The product of the number of days in the seasons and the cost saving for the respective seasons may equate to the total seasonal savings. When adding the savings of the two seasons, an approximate annual saving in electricity cost may be obtained. Using this method, the savings in 2018 were calculated as shown in Table 4.

B4. Replacement Cost

The replacement cost for each component of the system has been determined using Eq.(2). With the normal inflation rate 4.5 %, by accepting that the normal inflation rate will be equal to the interest rate [9]. The detailed data is presented in Table 5 and has amounted to a total of ZAR181 830 for a 30-year project lifespan.

$$C_{rep} = \sum_{k=1}^{N_{rep}} C_{cap}.k(1+n.r) \tag{2}$$

Where: C_{cap} is the initial capital cost for each component, N_{rep} is the number of component replacements for the 30-year lifetime, n is the lifespan for a specific component (years), and r is the average inflation rate assumed to be 4.5%.

B5. Life Cycle Cost Analysis

Since the utility grid is not to be replaced by the consumer, the total replacement costs (C_{rep}) over the 30-year lifespan is assumed to be zero. The cost at the end of year 30, equates to the total cumulative electricity cost C_{EC}, with an annual increase of 10% as shown in Eq. (3).

$$C_{EC} = \sum_{K=1}^{30} C_{initial-EC} \cdot k(1+a) \tag{3}$$

Where: $C_{initial\text{-}EC}$ is the cumulative cost of energy at the end of year one (ZAR), k represents the year at which the cumulative cost should be calculated (years) and a is the annual increase of 10%.

The operation and maintenance costs at the end of each year are calculated, using Eq. (4). However, in this case, it is assumed to be zero, since the grid does not incur the maintenance cost from the consumer:

$$C_{OM} = \sum_{k=1}^{30} C_{initial-OM} \cdot k(1+r) \tag{4}$$

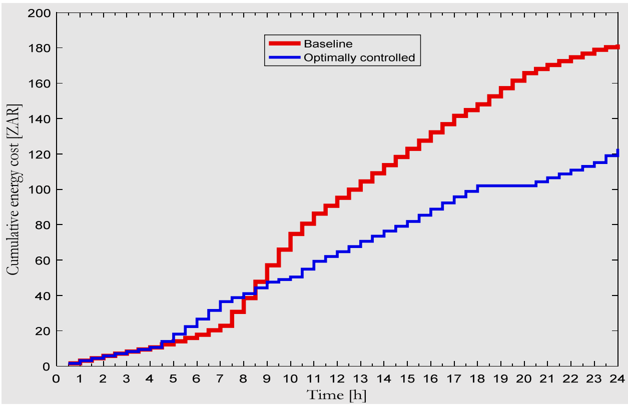

Figure 3. Winter energy cumulative cost

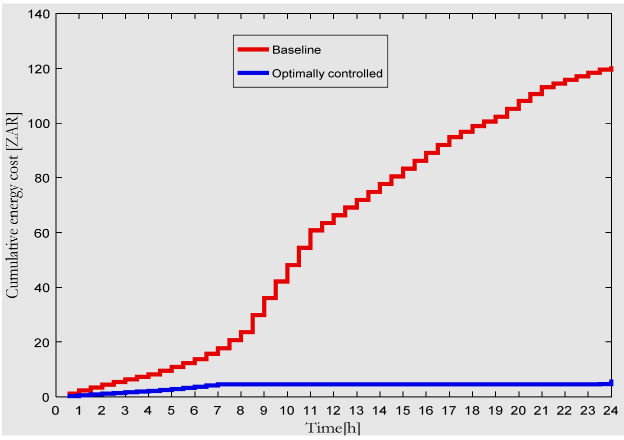

Figure 4. Summer energy cumulative cost

TABLE III. DAILY ENERGY CONSUMPTION AND SAVINGS

Strategy	**Baseline (Grid alone)**		**Optimal control (UPHS)**		**Daily Savings (ZAR)**	**Daily Savings (%)**	
Season	Energy (kWh)	Cost (ZAR)	Energy (kWh)	Cost (ZAR)	Cost	Energy	Cost
Winter	51.1	181.9	34.52	122.9	59	32.4	32.4
Summer	50.3	120.78	4.71	6.32	116.07	90.64	95

TABLE IV. ANNUAL ENERGY CONSUMPTION AND SAVINGS

Strategy	**Baseline (Grid alone)**		**Optimal control (UPHS)**		**Annual Savings (ZAR)**	**Annual Savings (%)**	
Season	Energy (kWh)	Cost (ZAR)	Energy (kWh)	Cost (ZAR)	Cost	Energy	Cost
Winter	4 701.2	16 734.8	3 175.84	11 306.8	5 428	32.4	32.4
Summer	13 731.9	32 972.94	1 285.83	1 725.36	31 247.58	90.64	95
Total	18 433.1	49 706.9	4 461.67	13 032.16	36 675.58	75.79	73.78

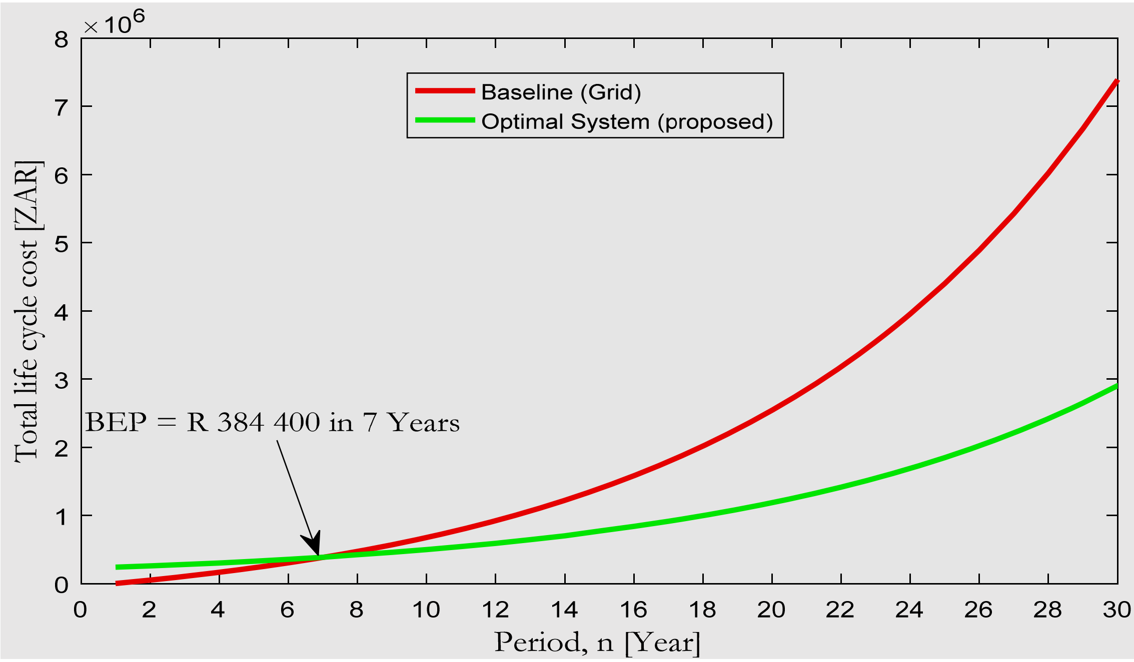

Figure 5. Break-even point analysis

For the proposed optimally controlled system, different components exist with different expected life span. Therefore, the total replacement costs (*Crep*) for each component may be obtained by applying Eq. (2) over the 30-year project lifespan. These are added, to calculate the total lifecycle replacement costs ($C_{rep\text{-}TC}$) as shown by Eq. (5).

$$C_{rep\text{-}TC} = C_{rep\text{-}US} + C_{rep\text{-}PV} + C_{rep\text{-}ST} + C_{rep\text{-}HG} + C_{rep\text{-}SP} + C_{rep\text{-}B} \quad (5)$$

For the proposed optimally controlled system, the cumulative electricity costs were also calculated using Eq. (3). The salvage cost is assumed to be 20% of the initial capital cost and the cumulative operation and maintenance costs is calculated suing Eq. (4). Hence, the total lifecycle cost (LCC) value of the proposed optimally controlled system is calculated using Eq. (6). The detailed data is presented in Table 6. Over a 30-year project lifespan, a sum amount of at least R3 042 619.19, will be spent, provided the proposed system is implemented.

$$LCC_{\text{Proposed}} = C_{initial} + C_{rep-TC} + C_{OM} + C_{EC} - C_{Salvage} \quad (6)$$

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TABLE V. TOTAL REPLACEMENT COST FOR THE PROPOSED OPTIMALLY CONTROLLED SYSTEM

Parameters	Value
Optimally controlled system lifetime (years)	30
Upper storage (US) lifetime (years)	30
N_{Rep-US} (-)	0
C_{Rep-US} (ZAR)	49 633
PV panels lifetime (years)	20
N_{Rep-PV} (-)	1
C_{Rep-PV} (ZAR)	70 484
Solar tracker (ST) lifetime (years)	10
N_{Rep-ST} (-)	2
C_{Rep-ST}(ZAR)	21 248
Hydro-generator (years)	20
N_{Rep-HG} (-)	1
C_{Rep-HG} (ZAR)	61 245
Submersible pump (years)	20
N_{Rep-SP} (-)	1
C_{Rep-SP} (ZAR)	6 805
Borehole lifetime (years)	30
N_{Rep-B} (-)	0
C_{Rep-B} (ZAR)	0
$C_{rep-TC(ZAR)}$	181 030

TABLE VI. TOTAL LIFECYCLE COST FOR THE PROPOSED OPTIMALLY CONTROLLED SYSTEM

Cumulative Cost	Value (ZAR)
$C_{initial}$	238 914
C_{rep-TC}	181 030
C_{OM}	7 274.16
C_{EC}	2 648 457.23
$C_{Salvage}$	33056.2
$LCC_{proposed}$	3 042 619.19

B6. Break-Even Point (BEP)

The break-even point is when the total implementation and operating costs of both systems incurred becomes equal at any point during the project's lifespan. In this case, the operation cost of baseline grid electricity supply is compared to the proposed optimally controlled system cost in terms of the total cumulative annual energy cost in the project's lifespan of 30 years. The cumulative cost curves are plotted on the same axis, for clear comparison. The point where these two curves intersect, shows the point in time (years), at which the two systems break even.

The overall initial capital costs of the proposed optimally controlled system and the grid-connected, are R238 914 and R0, respectively. The values are therefore considered as the starting points of the two curves, as shown in Fig. 5. After the first year has passed, the sum of total annual cost of energy and the initial investment cost, is the total present cost of energy, shown in Table 3. This equates to the total cumulative cost for the first year, after implementation. After the first year of implementation, a 10% increase in the price of electricity is considered, calculating the annual energy costs. This amount is further added to the previous total cumulative cost of the first year.

The same method is followed for the remaining years up until year 10, as shown in Fig. 5. In this curve, the replacement costs and lifespan of all the components are considered, for increased accuracy of the cumulative cost representation. It can be seen that the break-even point is achieved within 7 years after the beginning of the project. The costs incurred are equal to R 384 400 and the differences in finances used; at the end of the project's lifespan, further presents an important economic performance indicator.

IV. CONCLUSION

In this paper, economic analysis was carried out for a system with an expected operation period of 30 years. Both summer and winter seasons were considered. The initial investment cost of the proposed grid-connected PV-PHS system was R238 914. For the 30 years period, the grid cost proved to amount to a total of R8 177 578.663, if the load is solely met by the utility grid. If the optimum energy management algorithm, the incurred grid cost is reduced to R3 042 619.19.

The proposed optimized system, resulted in a cost saving of 32.4% and 95% for winter and summer seasons, respectively. Furthermore, a breakeven point of R384 400 is achievable within 7 years.

Therefore, it may be noticed that the system is economically feasible and technically viable, in South African context.

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