Lifecycle Analysis of a Grid-Interactive Photovoltaic with Battery Storage: Case of South African Residential Loads

S. Marais, K. Kusakana, S.P. Koko

Department of Electrical, Electronic and Computer Engineering, Central University of Technology South Africa
stephen.marais777@gmail.com; kkusakana@cut.ac.za; skoko@cut.ac.za

***Abstract* - In this paper, the lifecycle cost analysis of a residential grid-interactive photovoltaic system with a battery storage system is conducted. The proposed grid interactive system operates under the Time of Use (TOU) and Feed-in tariff (FIT) in the South African context. The main objective is to minimize the net electricity cost under a given period which is defined as the difference between the electricity cost, due to the power imported from the grid, and the electricity revenue, due to the power exported to the grid. Based on the simulation results relaying on the lifecycle cost analysis, it is found that the proposed system would break-even in 11.5 years as compared to the grid, with an approximate saving of 35%, translating into savings of R 270 022.83 for a 20 years' operation life.**

Keywords* - *Time of Use, feed-in tariff, grid interactive, photovoltaic, battery, economic analysis.

I. INTRODUCTION

As a result of the electricity challenge in South Africa, a few municipalities have begun revising the regulations on small scale renewable energy systems, permitting consumers, under strict regulations, to feed-back excess energy into the grid [1]. This study investigates the use of a residential PV system, combined with battery storage operating under the Time of Use and Feed-in tariff in the South African context. TOU tariff scheme has proved to be the most effective and adopted scheme in demand response program [2].

In this paper, the lifecycle cost analysis of a residential grid-interactive photovoltaic system with a battery storage system is conducted. The proposed grid interactive system operates under the Time of Use (TOU) and Feed-in tariff (FIT) in the South African context. The main objective is to minimize the net electricity cost between the power purchased from the grid and the one sold to the grid under a given period. This will assist consumers to save a significant amount if the system is implemented correctly, including the parameters of the desired system.

II. METHODOLOGY

A. System Description

The proposed system is a grid-interactive that consists of the solar photovoltaic (PV) system, battery bank and the utility grid, as shown in Fig. 1. The load demand is met by the different power sources such as PV system, Battery storage unit and the utility local grid. The objective is to maximize the energy cost saving that may be realized by consumers operating under the TOU and FIT tariff schemes. The model developed will minimize the reliance that the consumer has on the grid, whilst optimizing power flow from the battery bank and the PV.

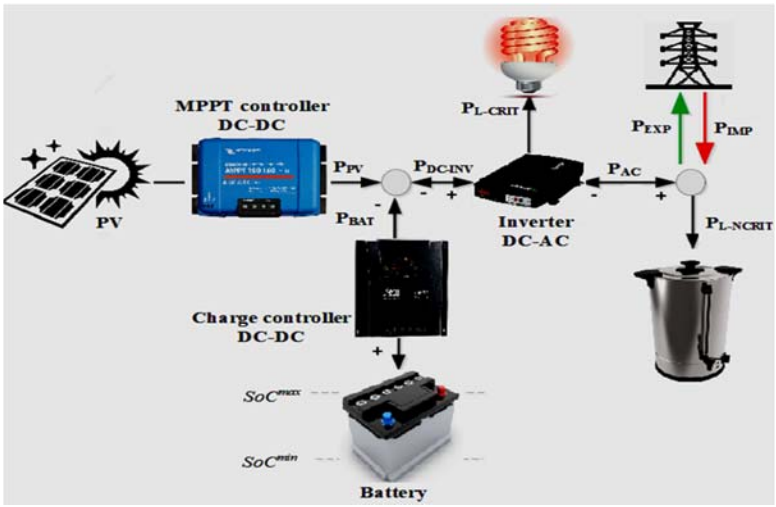

Figure 1. Proposed system layout.

B. Case Study Description

Data such as the load demand, the renewable resource, the electricity tariffs as well the size of the different components are available from reference [3]. TOU schedule rate for different times of the day and for different season, are as shown in Table I.

TABLE I. SCHEDULE RATES FOR DIFFERENT TIMES OF DAY [3]

TOU Periods	High-Demand Season (Jun-Aug)	Period Range	Low-Demand Season (Sep-May)	Period Range
Peak Periods	ZAR 3.28 /kWh	06:00-09:00 17:00-19:00	ZAR 1.07 /kWh	07:00-10:00 18:00-20:00
Standard Periods	ZAR 0.995 /kWh	09:00-17:00 19:00-22:00	ZAR 0.7374 /kWh	06:00-07:00 10:00-18:00 20:00-22:00
Off-Peak Periods	ZAR 0.54 /kWh	22:00-06:00	ZAR 0.41 /kWh	22:00-06:00

The methodology for the cost calculation adopted in this paper is available from reference [4]. The bill of quantity for the project reveals the prices of different components and installation cost, as shown in Table II. These are the average prices for the year 2017. Hence, the overall system's investment cost is ZAR 238 914. ZAR is the South African currency. During the study, 1 US$ was equivalent to ZAR 15.14.

TABLE II. BILL OF QUANTITY FOR THE PROPOSED SYSTEM

Component Description	Quantity	Net price (ZAR)
PV Panel	5	R 14 182.56
Battery	4	R15 364.44
Inverter	1	R 11 495
Charge controller	1	R5000
Installation cost		R 60000
Total initial investment cost		R 106 042

III. SIMULATION RESULTS

A. Optimum performance of the system

The performance of the proposed grid-interactive PV-Battery based system has been simulated using *fmincon* MATLAB solver. The optimal energy management algorithm was developed to ensure optimal power dispatch with the aim of minimizing the grid consumption costs by maximizing the renewable energy usage. The load has been met by the two power sources, namely solar and the utility grid. The algorithm ensured that the residential load demand is met at all time and at no capacity shortage.

B. Economic analysis

Various economic indicators may be used to evaluate the economic performance and cost effectiveness of a project. These indicators include, but are not limited to the life cycle cost (LCC) method, levelized cost of energy (LCOE) method, net present value (NPV) method, benefit/cost (or savings-to-investment) ratio (SIR) method, internal rate-of-return (IRR) method, overall rate of- return (ORR) method, discounted payback (DPB) method and simple payback period (SPP) method [5]. SPP is one of the most commonly used method to evaluate the viability of the project due to its simplicity [6]. It is used to evaluate the payback period of the project. Meaning the user can determine the years it will take to recover the initial investment through project returns.

However, using the SPP in conjunction with methods such as IRR, BCR and LCC, consider both the time value of money and the project lifetime respectively, by discounting all future worth cash flows to a present worth (PW) cash flow. Therefore, for increased accuracy, a total life cycle cost evaluation is done followed by a break-even point (BEP) analysis, in terms of the baseline and proposed hybrid system. The life cycle costs will be compared to calculate the savings over a specific project lifetime. The project lifetime for this case study was chosen to be 20 years.

The daily cumulative energy cost for both winter and summer has been calculated using Eq. (1):

$$C_{daily-EC} = t_s . \sum_{r=1}^{N} (P_{Grid} . C_{TOU_r}) \tag{1}$$

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_{TOUr} is the time-based cost of electricity at each *rth* interval.

C. Winter Cumulative Energy Cost

The cumulative curves in Fig. 2 shows that from the beginning of the control horizon, the baseline already increases at a higher rate than the grid-interactive system.

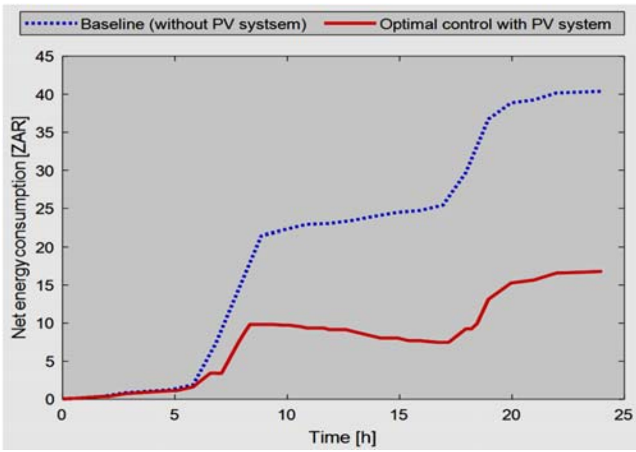

Figure 2: Winter energy cumulative cost

Based on the TOU periods, it may be seen that during the first peak period (06h00-09h00), the baseline graph, as well as the optimally controlled system increases significantly. However, the baseline graph rises at a significantly higher rate. Around 09h00, the optimally controlled system begins to decrease at a constant rate, yet the baseline continues to increase. When comparing the operational cost curves at the end of the control horizon, it may be deduced that the baseline's total net energy cost is approximately 2.4 times higher than the grid-interactive system.

D. Summer cumulative energy cost

The cumulative cost of the summer period is shown in Fig. 3. It can be seen that the electricity usage during summer is significantly less, as compared to winter season. From the beginning of the control horizon the baseline system increases at a rapid pace, with extreme increases during the peak TOU periods. The difference in cumulative energy cost at the end of the control horizon, represents the daily energy cost savings for the day.

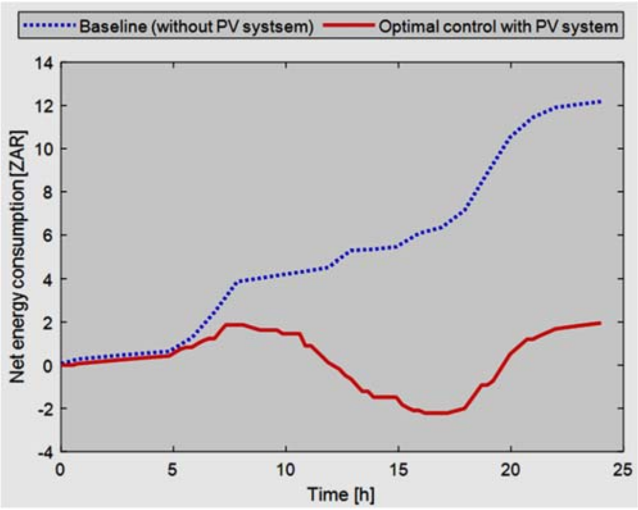

Figure 3. Summer energy cumulative cost

When comparing the baseline energy cost with the optimally controlled grid-interactive system, it can be noticed that the baseline's energy cost is 10.8 times higher. This is significantly higher, as compared to the winter case and, with this, it proves that the optimal system is more effective during the summer season.

E. Energy Consumption and Savings

The cumulative costs and energy consumed after each simulation of the baseline and optimal control strategies, are shown and compared in Table III.

TABLE III. DAILY ENERGY CONSUMPTION AND SAVINGS

Strategy / Season	**Baseline (Grid alone)**	**Optimal control (PV-Batt system)**	**Daily Savings (ZAR)**	**Daily Savings (%)**
	Cost (ZAR)	Cost (ZAR)	Cost	Cost
Winter	40.39	16.8	23.59	58.4
Summer	12.81	1.955	10.855	84.7

With grid electricity being used during standard and off-peak only for optimal control strategy, a saving of 84.7% in cost may be observed for summer season, while in winter a total savings as low as 58.4% in electricity cost is observed. The results of this comparison highlight the importance of avoiding the use of electricity during peak periods, more specially, during high demand season where the electricity tariff rates are high. The annual cost saving is determined by analyzing the recorded data. From the analysis, the most energy intensive day was selected and simulated in MATLAB.

The monthly energy cost results for the baseline consumption and for proposed optimally controlled system, are as shown in Table IV and V, respectively. During the month of June, July, and August, the baseline grid energy cost reached the peak values, as shown in Table IV.

TABLE IV: MONTHLY BASELINE ENERGY COST (ZAR)

Energy Cost/day	**Month**	**Number of Days**	**Monthly Energy Cost**
12.81	Jan	31	397.11
12.61	Feb	28	353.08
15.4	Mar	31	477.4
16.371	Apr	30	491.13
19.71	May	31	611.01
40.39	Jun	30	1211.7
39.16	Jul	31	1213.96
33.93	Aug	31	1051.83
16.34	Sep	30	490.2
15.66	Oct	31	485.46
15.21	Nov	30	456.3
14.63	Dec	31	453.53
Baseline Annual Cost			**7692.71**

TABLE V. MONTHLY ENERGY COST FOR THE PROPOSED OPTIMALLY CONTROLLED SYSTEM (ZAR)

Energy Cost/day	**Month**	**Number of Days**	**Monthly Energy Cost**
1.955	Jan	31	60.605
2.33	Feb	28	65.24
4.6	Mar	31	142.6
5.84	Apr	30	175.2
5.7	May	31	176.7
16.8	Jun	30	504
19.72	Jul	31	611.32
14.68	Aug	31	455.08
1.34	Sep	30	40.2
2.6	Oct	31	80.6
3.04	Nov	30	91.2
3.2	Dec	31	99.2
Proposed System Annual Cost			**2501.95**

The reason being that the consumer consumes large amount of electricity during high demand season, even though the tariffs are high. Hence, the annual electricity bill of ZAR7692.71 is incurred if the grid is the only source of energy for the consumer.

Similar to the baseline grid energy cost, the peak energy costs are reached during high demand season months, as shown in Table V. However, these peak costs are low when compared to the ones incurred under the baseline grid energy cost. Hence, the annual electricity bill is reduced to ZAR2501.95 if the proposed optimally controlled system is used in combination with the grid.

F. Break-Even Point

The baseline electricity cost is compared to the proposed system electricity cost over a period of 20 years in order to obtain the break-even point, as shown in Fig. 4.

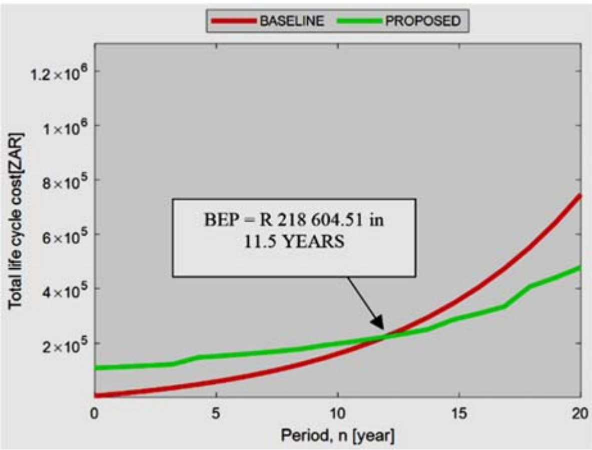

Figure 4. Break-even point analysis

The cumulative cost curves, which includes the initial investment cost and the total annual costs incurred over this period for the baseline and optimal system, is plotted on the same axis for clear comparison. The initial total cost of implementation of the proposed optimally controlled system and merely grid connection is R106 042 and R0, respectively. The values are therefore considered as the starting points of the two curves in Fig. 4.

The replacement costs and lifetimes of all the components are considered for increased accuracy of cumulative cost representation. A clear observation may be made that the break-even point occurs in 11.5 years, after the project has started. The costs incurred are equal to R 218 604.51 and the differences in total money spent at the end of the project lifetime further presents an important economic performance indicator.

IV. CONCLUSION

In this paper, a life cycle cost analysis was conducted for a period of 20 years, for both the baseline and the grid-interactive PV with battery storage system scheme. Results from the analysis indicated that the proposed system would break-even in 11.5 years, with an approximate saving of 35%, translating into savings of R 270 022.83. The results clearly illustrated that the consumer could save a significant amount if the system is implemented correctly, including the parameters of the desired system.

REFERENCES

[1] K. Kusakana: "Energy management of a grid-connected hydrokinetic system under Time of Use tariff", *Renewable Energy*, Vol. 101, pp. 1325-1333, 2017.

[2] S.P. Koko, K. Kusakana, H.J. Vermaak: "Optimal energy management of a grid-connected micro-hydrokinetic with pumped hydro storage system", *Journal of Energy Storage*, Vol. 14, pp. 8-15, 2017.

[3] S. Marais, K. Kusakana, S.P. Koko: "Techno-economic feasibility analysis of a grid-interactive solar PV system for South African residential load", *International Conference on the Domestic Use of Energy (DUE)*, *IEEE*, pp. 163-168, 2019.

[4] P.A. Hohne, K. Kusakana, and B. P. Numbi. "Optimal energy management and economic analysis of a grid-connected hybrid solar water heating system: A case of Bloemfontein, South Africa", *Sustainable Energy Technologies and Assessments*, Vol. 31, pp. 273-291, 2019.

[5] B. P. Numbi and S. J. Malinga: "Optimal energy cost and economic analysis of a residential grid-interactive solar PV system- case of eThekwini municipality in South Africa," *Applied Energy*, vol. 186, pp. 28–45, 2017.

[6] B. Capehart, W. Turner, and W. Kennedy: "Guide to Energy Management", vol. 53, no. 95, 2012.