Optimal Energy Management of a Double-Tracking Grid-Connected Photovoltaic with Battery System for a Microbrewery

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***Abstract*—Currently, the production of craft beer in microbreweries has become very popular. This craft beer production process is energy intensive due heating and cooling equipment involved. Most of these breweries are classified as commercial loads which are subjected to the applicable commercial time-of-use tariff from the utility company. Renewable energy sources can also be used to assist the breweries in reducing their reliance on the energy from the grid. However, these systems show a common disadvantage of not always meeting the energy demand during the periods where the resources are not available. In this paper, an optimal energy management model of a 5 kWp grid-connected photovoltaic, using a double tracking system with battery storage, is proposed to reduce the microbrewery's reliance on the grid. For this purpose, a mathematical model describing the system's variables, objective function, and constraints are developed. Thereafter, the performance of the developed model is simulated and analyzed using the dynamic load demand of a microbrewery brewery as a case study in the South African context. For the selected brewery, the simulation results have shown that for the solar resources as well as applicable grid tariff; up to 53.5% daily operation cost reduction can be achieved when using the proposed system as comped to the usage of the grid alone.**

***Index Terms*—Battery, cost minimization, grid-connected, microbrewery, optimal power dispatch, photovoltaic**

I. Introduction

Recent studies have demonstrated that the craft beer production process in microbreweries can be considered as energy intensive due to the fact that close to 8% of the production cost is allocated to thermal processes such as mashing, wort boiling, cooling, fermentation, maturation, and pasteurization [1]. Large breweries can consume approximately 0.43kWh to produce one liter of beer, while microbreweries will need more energy to produce the same amount of beer. Therefore, like in any other industries, proper demand side management actions such as equipment retrofits or load shifting can be very effective to decrease the cost of energy consumed and maximize the profits while avoiding the peak pricing period from the Time-of-Use (ToU) imposed by the grid [2]. However, these actions can incur high costs or disturb the production because some loads are not deferrable and their associated processes need to happen following some specific sequences [3].

In the case of non-deferrable loads, alternative energy sources such as diesel generators, renewable energy sources or battery storage systems can be generated onsite to meet the demand [4]-[6]. This can also assist in reducing the operating costs as well as the reliance from the grid to avoid the peak pricing periods. In such an instance, the energy from these sources have to be properly managed to meet the variable load demand while minimizing the cost of electricity from the grid [7]-[9]. Therefore, an optimal energy management model of a 5kWp double-tracking, a grid-connected photovoltaic system with a battery storage system is proposed to contribute to the microbrewery's operation cost reduction and minimize the reliance on the grid. As a case study, the load profile, solar resources as well as the applicable electricity tariff, where an actual microbrewery is operated, have been recorded and used as input to the optimal energy management model developed.

The model aims to minimize the operation costs subjected to the ToU while maximizing the use of the photovoltaic system and battery. The simulations are performed with MATLAB to assess and analyze the performance of the proposed model used to manage the hybrid system under the given operation constraints. The simulation results have shown that a substantial operation cost reduction can be achieved when using the proposed system as comped to the usage of the grid alone.

II. Proposed Double Tracking Grid-Connected PV with Battery, Description and Modelling

A. Proposed Scheme Description

The proposed double-tracking grid-connected PV system with battery is shown in Fig. 1, where the Maximum Power Point Tracking (MPPT) is done through the DC-DC converter which extracts the optimum from the variable solar resource. This power extracted is then used to recharge the battery through the charge controller or to supply the load through the DC-AC inverter.

If the PV system is generating more power than what is needed by the load demand, the maximum power (P_{PV})

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from the MPPT converter is shared between the inverter input ($P_{DC\text{-}INV}$) and the battery charging process ($P_{BAT\text{-}in}$). The AC power coming out of the inverter output can be used to supply the critical load ($P_{L\text{-}CRIT}$) and also to supply the non-critical load ($P_{L\text{-}NCRIT}$).

When there is not enough power generated from the PV to supply the load, the following operation strategies can be adopted:

- The battery power $P_{BAT\text{-}out}$ can be used, through the inverter, to supplement the deficit of power required;
- The imported power from the grid P_{IMP}, subjected to the ToU, can be used to supply the load but not recharge the battery storage system because the inverter does not allow bidirectional power flow.

The variable power P_{AC} can be positive when flowing from the inverter to the non-critical load or negative when flowing from the grid to the critical load.

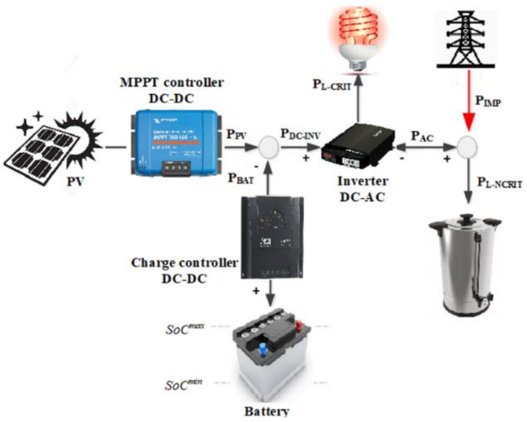

Fig. 1. Proposed hybrid system power flow.

B. Optimal Energy Management Model of the Grid-Connected PV System

The main objective function f of the developed model is to minimize the operation cost for the optimization horizon. In this case, the power imported (P_{IMP}), subjected to the ToU, is the variable that needs to be minimized. This can be mathematically formulated as

$$f = \sum_{j=1}^{N} \rho_j \times P_{IMP(j)} \times \Delta t \tag{1}$$

where j is the j^{th} sampling interval, N is the number of sampling intervals, Δt is the sampling time and ρ is the variable ToU electricity tariff. Based on the objective function, the power from the grid will be minimized based on the PV generation, the load demand as well as the State of Charge (SoC) in the battery at the considered sampling interval j.

C. Variable Constraints

1) Load balance

The power balances to be met at main nodes of the system are expressed as follows:

$$P_{PV(j)} = P_{BAT-in(j)} + P_{DC-INV(j)} \tag{2}$$

$$P_{DC-INV(j)} - P_{IMP(j)} = P_{L-CRIT(j)} + P_{L-NCRIT(j)} \tag{3}$$

Equation (2) means that at any considered sampling period j, the power from the PV can be used to supply the demand or/and to charge the battery. Equation (3) means that at any considered sampling period j, the load can be supplied by a combination of the output power from the inverter (PV and battery) and the power from the grid.

2) Dynamics of the battery state of charge

The state SoC can be expressed in the discrete-time domain as follows:

$$SoC_{(j)} = SoC_{(0)} \times (1-\delta) + \frac{\Delta t}{E_n} \times \left(\eta_{ch} \times \sum_{i=1}^{j} P_{BAT-in(j)} - \frac{\sum_{i=1}^{j} P_{BAT-out(j)}}{\eta_{disc}} \right) \tag{4}$$

where $SoC_{(j)}$ is the SoC at the considered sampling interval, j; $SoC_{(0)}$ is the SoC at the initial or previous sampling interval; E_n is the nominal potential energy of the battery in kWh; η_{ch} is the efficiency of the battery charging process; η_{disch} is the efficiency of the battery discharging process, and δ is the battery self-discharging factor.

For proper operation, all the variables linked to the different components must be kept within their size and rating limits according to the manufacturer's specifications. These constraints can be expressed as:

$$P_i^{\min} \le P_{i(j)} \le P_i^{\max} \tag{5}$$

where i represents the different control variables. This is also applicable for the SoC which must be kept within a maximum and a minimum (SoC^{min} and SoC^{max}) depending on the type of battery used.

3) Exclusive power flows

The battery cannot be charged and discharged at the same time. This can be mathematically expressed as follows:

$$P_{BAT-in(j)} \times P_{BAT-out(j)} = 0 \tag{6}$$

4) Fixed-final state condition

To allow for the repeated implementation of the control algorithm, for a given optimization window, the SoC at the beginning should be equal to the one at the end. This constraint can be mathematically expressed as:

$$\sum_{j=1}^{N} (P_{BAT-in(j)} + P_{BAT-out(j)}) = 0 \tag{7}$$

III. Case Study Description

A. Daily Load Profile and Solar Resources

The total load on Fig. 2 can be subdivided into two parts, the critical or continuous or baseload (cold storage and fermentation system) and the non-critical or deferrable load (water heating, mashing, wort boiling, cooling and packaging). The power rating, as well as the sequence in which the different processes occur, can be seen on Fig. 2. The solar data was collected from the weather station located in Bloemfontein (latitude: -29.11074, longitude: 26.18503 and elevation: 1491m) [10]-[11].

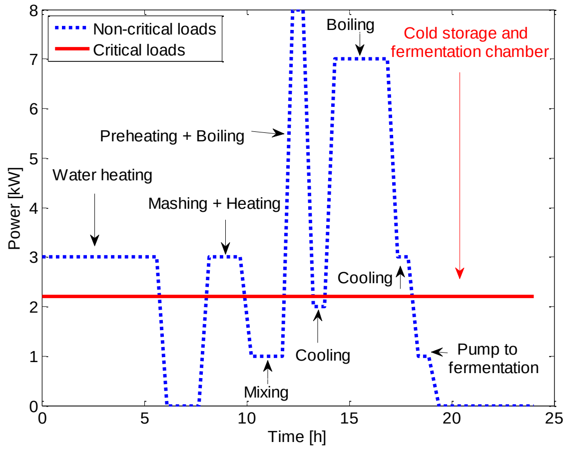

Fig. 2. Snapshot of the 24-hour demand profile.

TABLE I: SIMULATION PARAMETERS

Parameter	Unit/Figure
Sample period duration (Δt)	30 min
PV power rating	5kWp
Battery storage capacity	9.6kWh
ρ_k (peak period price)	0.20538 \$/kWh
ρ_0 (off-peak period price)	0.03558 \$/kWh
ρ_s (standard period price)	0.05948 \$/kWh
SoC_0	80%
SoC^{max}	100%
SoC^{min}	30%
η_{Ch}	85%
η_{Disc}	95%

B. Component Size

The Size of the PV system depends on the available space, capital funds, the energy saving target as well as on the amount of energy planned to be produced. The 5kW SMA Sunny Tripower 5000TL is proposed used for a PV array with peak power of 5kWp [12]. The battery used is the AGM deep cycle battery from CB solar with a total capacity of 9.6 kWh [13].

C. Other Simulation Parameters

For the studied system, the parameters used for simulation the operation are given on Table I.

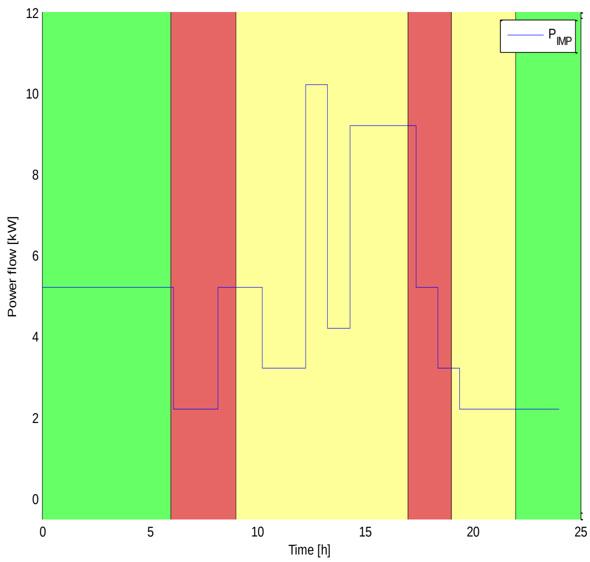

Fig. 3. Grid alone.

IV. RESULTS AND DISCUSSION

In order to evaluate the effectiveness of the proposed model, the daily costs achieved using the proposed system and optimal control is compared to the cost achieved when the microbrewery is supplied by the grid exclusively. The developed nonlinear problem can be solved by using “*fmincon*” in MATLAB [14].

A. Baseline: Load Exclusively Supplied by the Power Imported from the Grid

Fig. 3 shows the simulation results in the case where the microbrewery’s demand is supplied by the grid. There is no optimal power flow in this scenario because the grid will act in a load following manner and the profile of the power drawn will be the resultant of the critical added to the non-critical demands.

B. Load Supplied by the Grid-Connected PV with Battery

Fig. 4 shows the output power profile of the PV system which depends on the available double-tracking abilities as well as on the variable solar resources. The behaviour of the hybrid system is explained according to the different pricing periods in the sections below.

1) Optimal power flow during first off-peak pricing period (green)

Fig. 2 shows that the combined load demand is more than 5kW while Fig. 4 shows that there is no power from the PV during this pricing period. Therefore, the demand is met by the grid (Fig. 5) and battery power (through the inverted) as respectively shown on Fig. 6 and Fig. 7 for the corresponding SoC. Fig. 8 show that P_{AC} is negative; this means that during this time, the critical load is supplied by both the battery and the grid.

2) Optimal power flow during first peak pricing period (red)

From 06h00 to 07h00, Fig. 2 shows that only the critical load needs to be supplied while there is no non-critical load. It can also be noticed that the energy price from the grid is quite high, and the PV system is starting to produce energy as shown on Fig. 4.

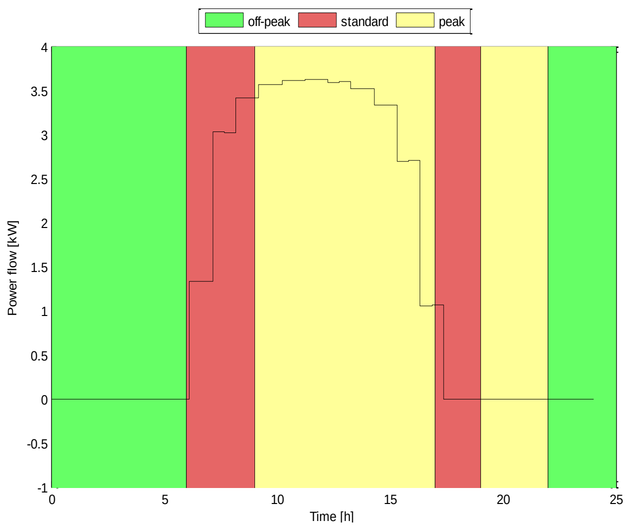

Fig. 4. PV output.

Fig. 5 show that there is no power used from the grid, as modelled in the objective function; the critical load is supplied by the PV and the battery as shown on Fig. 6 with the corresponding SoC shown on Fig. 7. It can be noticed from the power flow in Fig. 8 and the SoC on Fig. 7, that there is a positive power flow, from 07h00 to 08h00, which means that the PV is also used to recharge the battery because there is more power produce by the PV than what the load requires.

Between 08h00 and 09h00, it can be seen on Fig. 8 that P_{DC} and P_{AC} are both positive, this means that the power through the inverter, from the PV and the battery, is used to supply both the critical and non-critical load. This can also be explained by the negative power flow from the battery which can be seen from Fig. 6 corresponding to a decrease SoC seen from Fig. 7.

3) Optimal power flow during first standard pricing period (yellow)

From 09h00 to 17h00, the combined load demand is high and the PV output power is at its peak as seen from Fig. 4. Therefore, the PV is used to supply both the critical load and a portion of the non-critical load's demand as well as to recharge the battery as shown on Fig. 6, Fig. 7 and Fig. 8 (seen on the positive power flow of P_{AC}) respectively.

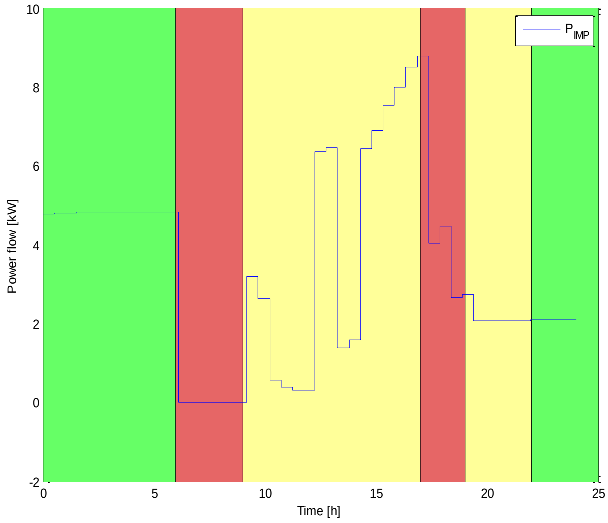

Fig.5. Grid power profile in hybrid system.

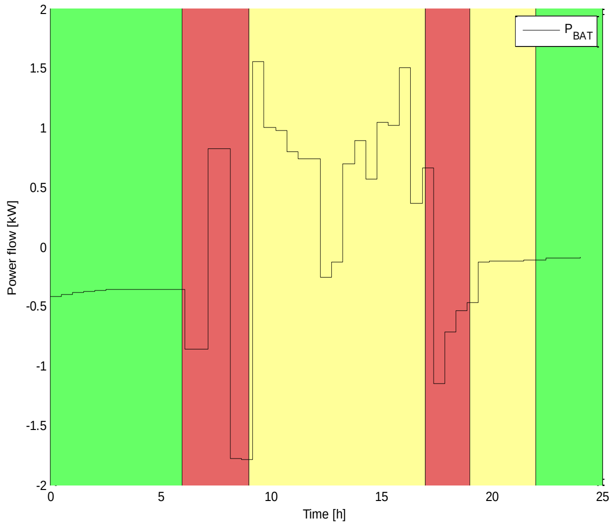

Fig. 6. Battery power profile.

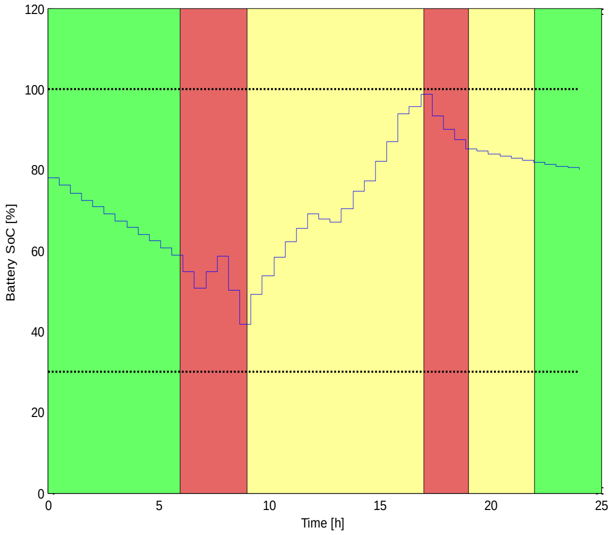

Fig. 7. Battery state of charge.

However, from 15h00 to 17h00, Fig. 5 shows that there is more power imported from the grid because the output power from the PV is being reduced due to the decreasing solar resource (Fig. 4), therefore, the main strategy adopted is to recharge the battery as shown on Fig. 6 and Fig. 7 (to prepare for the upcoming peak pricing period) and partially meet the critical load at the same time. The grid power is used to supply the non-critical load as well as to supplement the deficit of power from the PV to the critical load as shown by the negative power flow of P_{AC} on Fig. 8.

4) Optimal power flow during second Peak pricing period (red)

During this peak pricing period, there is no power produced by the PV system as shown on Fig. 4. The combined load is supplied by the power imported from the grid as well as a contribution from the battery as shown on Fig. 5 and Fig. 6 respectively.

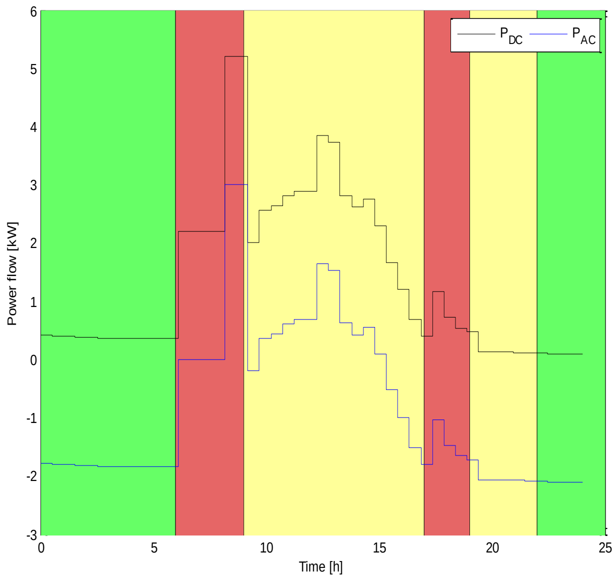

Fig. 8. AC and DC power flows from the inverter to loads.

Fig. 6 show shows that the battery is used to supply the load through the inverter and this results in a decrease of the corresponding SoC (Fig. 7). However, when analyzing Fig. 8, it can be seen that the power flow P_{AC} is negative, which means that the grid is used to supply the non-critical load as well as the part of the critical load which is not totally supplied by the battery.

5) Optimal power flow during second standard pricing period (yellow) and second off-peak pricing period (green)

The system's operation behaviour is the same for these two last pricing periods lapsing from 19h00 to 24h00, where Fig. 2 shows that only the critical load or baseload (cold storage and fermentation chamber) is running. Given that the electricity price is low, this baseload demand is mainly supplied by the grid as shown in Fig. 7 as well as from the negative power flow of P_{AC} on Fig 8.

To meet to a condition imposed on the battery SoC's fixed-final state condition given by (7), a small contribution of the battery's power is also used to supply the baseload as shown on Fig. 6 and Fig. 7.

C. Economic Analysis for the Selected Day

Fig. 9 shows the total cumulative costs for the case where the load is exclusively supplied by the power imported from the grid and the case where the load is supplied by the grid-connected PV with the battery. Table II shows the potential cost saving achievable when the hybrid system is selected to supply the brewery instead of the grid alone.

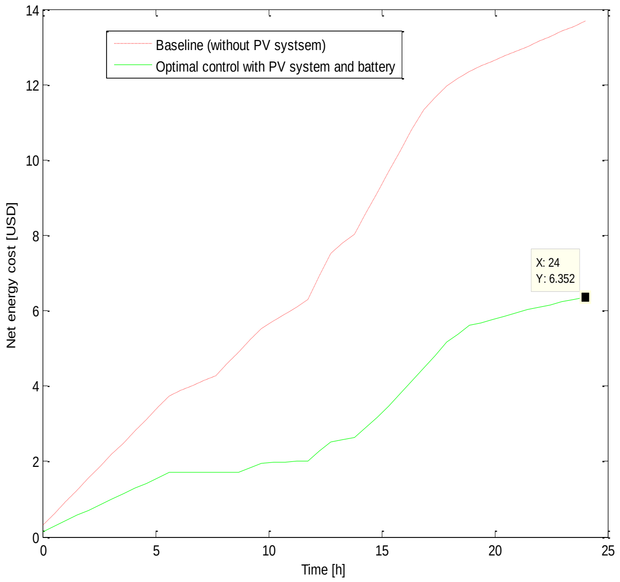

Fig. 9. Cumulative cost for both supply option

TABLE II: COSTS COMPARISON

Supply scheme	Cost achieved ($)
Load exclusively supplied by the power imported from the grid	$13.67
Load supplied by the grid-connected PV with battery	$6.35
savings	$7.32

V. CONCLUSION AND SCOPE FOR FUTURE WORK

In this paper, an optimal energy management model of a 5kWp double-tracking, grid-connected Photovoltaic System with battery storage has been proposed to reduce the microbrewery's reliance on the grid. For this purpose, a mathematical model describing the system's variables, objective function and constraints developed. Thereafter, the performance of the developed model is analyzed using the dynamic load demand of the brewery as a case study in the South African context. For the selected brewery, the simulation results have shown that for the proposed daily load, solar resources as well as applicable grid tariff; up to 53.5% daily operation cost reduction can be achieved.

In this work, only the ToU has been considered as a cost component. A need to be developed to include the peak demand charges which is currently being introduced by the power utility at the municipality level.

Further research studies have to be conducted on the viability of the system using economic factors such as payback period, life cycle cost or breakeven analysis.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHOR CONTRIBUTIONS

K. Kusakana conducted the research; analyzed the data; wrote the paper and approved the final version.

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