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Optimal energy management of a grid-connected dual-tracking photovoltaic system with battery storage: Case of a microbrewery under demand response

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ABSTRACT

Nowadays, the production of craft beer in microbreweries has become very popular all over the world. However, recent studies have demonstrated that the craft beer production process in microbreweries can be considered as energy intensive due to the fact that more to 8% of the production cost is allocated to thermal processes such as heating and cooling. Therefore, most microbreweries have been applying some Energy Efficiency actions to their production processes to decrease the amount of energy consumed and maximize the profits.

In cases where the amount of energy consumed cannot be reduced using Energy Efficiency actions, Demand Response measures are implemented to reduce the cost of energy needed to supply the different processes involved. From the available literature, most of the studies based on Demand Response in the microbrewery sector have focused on the use of heating resources for the onsite energy generation to directly support the thermal processes. Very few published studies looked at the onsite “electricity” generation with small scale renewable energy sources and onsite energy storage to assist with energy cost reduction strategies.

Therefore, this paper develops an optimal energy management model to minimize the energy cost of a microbrewery, under demand response, supplied with a grid-connected photovoltaic system with battery storage system. As a case study, a microbrewery in South Africa has been selected for simulation purposes. The detailed brewing process’s load profile, the solar resource, the system components’ specifications as well as the Time of Use energy cost structure has been used as input to the developed model with the aim of assessing and analyzing the technical and economic performance of the proposed system under the given operation conditions and constraints. The simulation results have shown that, as compared to supplying the microbrewery exclusively by the grid, the break-even point of the proposed supply option happens after 9.5 years of operation, corresponding to ZAR 398583.18 (USD 22592,09) cumulatively spent. For the considered 20 years’ operation lifetime, the projected savings on the lifecycle cost is ZAR 603490.49 (USD 34206,44) or 40.8%. The result of the discounted payback period analysis indicated that the total investment cost may be recovered in 13.8 years.

The microbrewery is selected as a case study just to highlight the fact that some processes are critical and cannot be shifted without compromising the quality of the final product. Therefore, the proposed hybrid system, the developed model and the optimization methodology can be applied to any load in different demand sectors (residential, commercial and industrial) implementing demand response measures in order to reduce their operation energy costs.

1. Introduction

The size, the different processes and the machineries a company has are some of the main factors influencing the amount of energy consumed. Based on their respective energy usage, companies are classified either as energy intensive or energy non-intensive. The portion of the total production cost allocated to energy in non-intensive industries goes up 3%; while this can go from 5% to 20% for some energy intensive companies [1]. These important share of

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Nomenclature

ρj	Cost of energy linked to the applicable residential ToU
AC	Alternative current
BEP	Break-even point
C_{EC}	Net energy cost
C_I	Initial cost of each component
C_{OM}	Operation and maintenance cost of each component
C_R	Replacement cost of each component
C_S	Salvage cost linked for each component
DC	Direct current
DC	Direct current
f	Objective function
HLT	Hot liquor tank
I_t	Solar irradiance
j	jth optimization sample interval
LLC	Life cycle cost
MPPT	Maximum power point tracking
N	Number of sampling intervals
NOCT	Nominal operating cell temperature
$N_{PV,S}$ and $N_{PV,P}$	Series and parallel numbers of PV modules connected
P_{AC}	AC power to the critical or non-critical loads
P_{BAT}	Battery charging power
P_{BAT+}	Battery output power
$P_{DC\text{-}INV}$	Input power to the inverter
P_{IMP}	Power imported (purchased) from the grid
$P_{L\text{-}CRIT}$	Power demand from the critical load
$P_{L\text{-}NCRIT}$	Power demand from the non-critical load
P_{PV}	Power from the PV system
PV	Photovoltaic
STC	Standard test condition
T_a	Ambient temperature
T_c	Cell temperature
TOU	Time of Use
ZAR	South African Rand
α	Power temperature coefficient
Δt	Sampling time
η_{ch}	Battery charging efficiency
η_{disch}	Battery charging efficiency

production costs allocated to the energy consumption of the different processes have led to the introduction different energy efficiency techniques. However, "Energy Efficiency" is a valuable tool for any company aiming to reduce its total production cost, irrespective of its size [2].

The South African agricultural sector, comprising food and beverage, is the fifth largest energy consumer sector; after the industrial, residential, public transport and commercial sectors [3]. In 2015, the energy demand in the South African agriculture sector was supplied by 66% with petroleum products, 32% electricity and 2% coal [4].

A particular trend in the South African industry is the increasing number of small capacity production. In 2018 there were 211 active microbreweries, including for craft beer production [5]. 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 [6]. Large breweries can consume approximately 0.43 kWh to produce 1 L of beer, while microbreweries will need more energy to produce the same amount of beer [7]. Therefore, like in any other industries, proper "*Energy Efficiency*" actions can be very effective to decrease the amount of energy consumed and maximize the profits [8].

Several Energy Efficiency researches applied to the brewery industry focused on the thermal aspect, but other also looked at the electrical efficiency of the main processes involved. Some of the recommended energy efficiency actions consist of improving the power factor correction of the installation [9]; refrigeration load management [10]; saving compressed air and steam [11]; automating the boiler [12]; using of waste biogas [13]; using heat recovery systems [14], using thermal energy storage [15]; and improving thermal insulation of process tanks [8]. While these energy efficiency actions focus on reducing the amount of energy needed for the brewing processes, there is still a need for reducing the cost of energy consumed.

Considering all the energy consumed in microbreweries, approximately 40% is needed for the electrical processes and 60% used for thermal processes [7]. It has to be noted that, in some cases, most of the equipment that are using energy for thermal processes like mashing, boiling, cooling, fermenting or maturing; are primarily supplied with electricity. Therefore, on top of Energy Efficiency tools, it is imperative to also look at "*Demand Response*" measures that can reduce the total cost of electrical energy consumed [16]. Dynamic tariffs programs, such as Time-of-Use Pricing (TOU), are designed to lower system the demand and reduce the users' energy costs by increasing the rates during peak hours and reducing them during off-peak hours. This assists in decreasing the peak load demands and/or shift the different activities from peak to off-peak pricing periods [17]. The ability of microbreweries to take advantage of TOU tariffs depends on the nature of the production process and the ability to shift electrical loads to a period where the tariffs are more favorable. The potential saving can however be significant; however, load shifting might not be suitable to the microbrewery industry because some of the processes are not deferrable and must happen in a specific sequence [7].

In case of non-deferrable loads, renewable energy sources and energy storage systems can assist in reducing the operation costs as well as the reliance from the grid to avoid the peak pricing periods. In such instances, the energy from these sources have to be optimally controlled to meet the variable load demand while minimizing the cost of electricity from the grid, usually operating under the time-varying pricing structure [18].

Some authors have looked at Demand Responses strategies for microbreweries using alternative energies to support the different thermal processes.

A comprehensive study on thermal energy production from renewable sources is available in Ref. [19] where the authors have analyzed the use of different heating resources such as biogas system, biomass system, solar thermal system, district heat system, geothermal energy system and heat pumps for supporting the different thermal processes in the brewery industry. Among all the renewable energy sources considered in the study, the use of solar energy to support the brewery thermal processes has been identified as the best option to be used on a long term basis.

The authors of Ref. [20] have modelled the integration of a hybrid solar system for heat and electricity generation using a 14.6 m^2 flat-plate collectors (with a 1.4 m^3 storage tank) and a 2.86-kWp grid-connected photovoltaic (PV) system. Using two case studies in Spain, the simulations have demonstrated that the project earnings are more substantial in the case of the PV system as compared to the solar heating system. The simulation results showed that the discounted payback period (with 3% annual interest) is 10.7 years. Therefore, the authors concluded that there are potential benefits in integrating solar energy sources in microbreweries. However, for this specific study, it has to be noted that these results are influenced by the fact that this payback period was achieved under a direct incentive of 50% reduction in the investment cost; in addition, a Net-metering scheme was considered for the PV system, i.e. the price of the energy injected to the grid is equal to the purchase price. Additionally, no optimal control approach, applied to the energy management or power dispatch strategy, was developed or implemented.

Most of the studies based on "Demand Response" in the brewery sector have focused on the use of heating resources for the onsite thermal energy generation. Very few published studies looked at the onsite "electricity" generation with small scale renewable energy sources such as PV; and none of them have looked at the application in Africa with countries such as South Africa experiencing high solar radiation [21].

Given the fact that the production of craft beer in microbreweries has become very popular, and the energy cost in the production need to be reduced; there is an opportunity to look at the use of alternative energy sources such as PV system which is suitable for small scale systems. Therefore, using an optimal control approach, this paper develops an optimal energy management model for a microbrewery under demand response in the presence of a grid-connected photovoltaic system with battery storage system. The aim of the model is to contribute to the microbrewery's operation cost reduction by maximizing the use of the PV/battery system and minimize the reliance on the grid supplying energy with the TOU tariff. As a case study, a microbrewery in South Africa has been selected, from which the load profile is recorded, and the solar resource has been collected to assist with analyzing the operation pattern as well as with renewable energy system sizing. The simulations are performed to assess and analyze the techno-economic performances of the proposed model in managing the hybrid system under the given operation conditions. The simulation results have shown that a substantial energy cost reduction can be achieved when using the proposed system as compared to the scenario where the grid is used as sole energy supply option. The daily energy cost savings as well as lifecycle cost analysis are used to assess the economic benefit of the proposed system.

Compared with the available studies based on demand responses applied to microbreweries, the main differences and contributions of this study are highlighted as follows:

1. Most demand response studies in the brewery sector have focused on the use of heating resources such as biogas system, biomass system and solar thermal system to support the different thermal processes. However, this paper looks at the "Demand Response" combined to an "Optimal Control" approach applied to the energy management of a PV with a battery storage system used for onsite electricity generation and energy cost reduction. For some small scale microbreweries, electricity may be the only primary source of energy supplying all the different processes.
2. For microbreweries operating under dynamic electricity pricing structure such as the TOU tariff; available studies only look at basic operation strategies such as load shifting of non-critical processes. The current study is applying the optimal power dispatch approach to reduce the microbrewery's total energy cost in the presence of a grid-connected photovoltaic system with battery storage.

The rest of this manuscript is structured as follows. A description of the load demand resulting from the different processes is presented in Section 2. The system description, solar resource, components sizing and specific of the model developed are presented in Section 3. The power flows linked the system's optimal operation are discussed in Section 4. Section 5 presents the economic analysis and assesses the economic viability of the proposed system. Finally, concluding remarks are given in Section 6.

2. Case study description

The case study is a microbrewery in Bloemfontein which can produce seven types of craft beers. Electricity is provided from the national grid, for both the electrical and thermal processes. The microbrewery has a capacity of producing one batch of 800 L of beer per week. Therefore, the yearly demand is basically made on average of 52 brewing days while the cold storage and the fermentation chamber run as the critical, or baseload, throughout the year. It has to be noted that the demands from all the thermal processes involved are highly depend on the location of the microbrewery due to the ambient temperature and the supplied inlet water temperature. Additionally, according to the Basic Conditions of Employment Act, the maximum normal working time allowed for employees is 5 days per week; therefore, the "brewing day" can be any of the week days, not during the weekend.

The load demand has been recorded in real-time using the three-phase energy monitoring device "PEL103" [22] for the year 2019. The first brewing day is the most energy intensive one, with the different processes shown in Fig. 1 for the worst operating conditions happening in the winter season where the brewery's load demand is the high.

The process begins with heating up water in a hot liquor tank (HLT), using a 3 kW element, from 22 °C (in summer or 15 °C in winter) to 85 °C for approximately 5.5 h. This is done during the off-peak pricing period to reduce the cost of energy consumed and prepare for the mashing process. A base load of 2.2 kW is constituted by the cold storage and the fermentation chamber running continuously.

As a demand response strategy to save on the energy cost, the heating element is switched off to avoid the peak pricing period occurring from 06h00–08h00.

During the standard pricing period, starting at 08h00, the hot

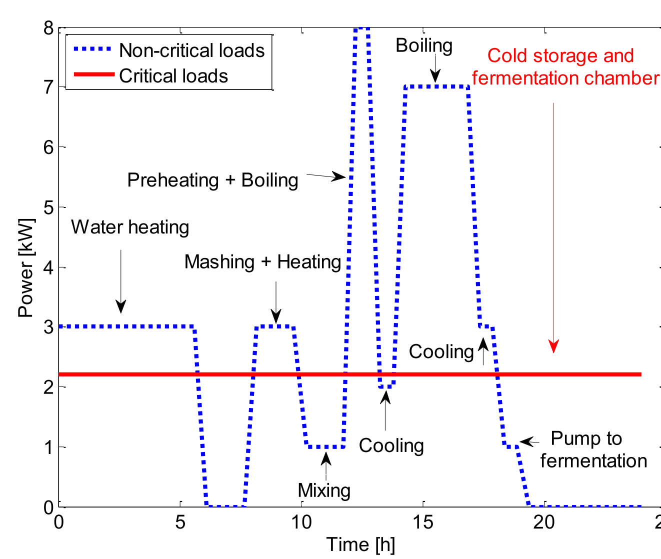

Fig. 1. Brewing day demand profile.

water is discharged from the HLT into an insulated mash tank (mixer). Malted barley and specialty grains are conveyed into the mash tank; the 3 kW heating element is switched on again for 2 h during this stage. The mixing stage starts from 10h00 where the mixture is constantly churned with a stirrer (rake) by means of a 1 kW pump/motor for about 1 h.

At 13h00, the mixture is then heated from 65 °C to 78 °C for 1 h. In this process, hot water from the HLT is trickled added to the mash tank over a period of about 1 h. Simultaneously, using a 1 kW pump, the dissolved sugars in water (wort) extracted from the grain husks is slowly drained from the bottom and pumped into a boiler where the hops are added and the mixture (wort) heated by means of a 7 kW resistive element system (heating jacket) for 30 min.

From 15h00–17h00, the hop is then introduced. The wort is further boiled to a temperature of 97 °C for 2 h by means of a 7 kW resistive element system in order to separate coagulated proteins and other suspended particles. Thereafter, the boiling wort is given a heat shock via heat exchanger to reach a temperature of 18 °C, desirable for the required fermentation.

The whole preparation process ends at 20h00; the beer wort in moved to the fermentation (for 3 weeks or more) which constitutes the 2.2 kW base load together with the cold storage.

3. Methodology

After analysing Fig. 1, it can be noticed that most of the peak power demand is occurring during the day; matching the solar resource daily profile. Given that the study location experiences an average solar radiation ranging between 4.5 and 6.5 kWh/m^2 a day [21]; the implementation of dual-tracking photovoltaic system can be of great advantage in maximizing the electrical energy that can be generated from the panels while minimizing the cost and amount of energy acquired from the grid. A battery storage system can be added to the supply system to store some energy during excess generation times and can also be used in the event the PV system cannot supply the demand; or during high pricing periods to shift the supply from the grid. This will also increase the availability of energy supply as well as provide an opportunity of applying demand response strategies through optimal power dispatch [23].

This section will describe the proposed system's operation modeling; the selected size and the basis of the economic analysis to be performed.

3.1. Proposed grid-connected PV system description

The proposed double-tracking grid-connected PV system with battery is shown in Fig. 2, where the maximum power point tracking (MPPT) is done through the DC-DC converter which extracts the optimum power from the variable solar resource. This power extracted can then be used to recharge the battery, through the charge controller, or to supply the microbrewery's demand through the DC-AC inverter.

The PV system generated power, (P_{PV}), from the MPPT converter can be shared between the inverter input ($P_{DC\text{-}INV}$) and the battery charging process (P_{BAT}-). The AC power from the inverter output can be used to supply both the critical load ($P_{L\text{-}CRIT}$) and the non-critical load ($P_{L\text{-}NCRIT}$).

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

- The battery power, (P_{BAT}+), can be used, through the inverter, to supplement the deficit of power required;

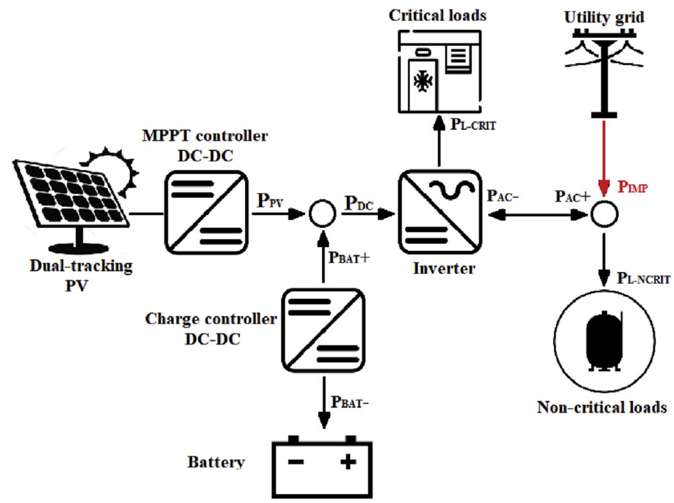

Fig. 2. Power flows in the proposed grid-connected PV with battery system power flow.

- The imported power from the grid (P_{IMP}), subjected to the TOU pricing structure, can be used to supply the demand 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.

3.2. System components sizing and resource

3.2.1. Solar resources

The microbrewery is located in Bloemfontein, an arid city in South Africa with high solar resources. Therefore, the PV system is one of the renewable energy sources best suited to be implemented in the region [21]. The 2019 solar irradiance data, for a summer and winter day, collected from a SAURAN weather station at the Central University of Technology, are given on Fig. 3 and Fig. 4 respectively [24,25]. Data are available at 1-min, hourly and daily time averaged intervals.

The available solar resource is one of the factor that influence the size and the investment cost of the PV system to be implemented. Regarding the sizing, latest advances in metaheuristic optimization techniques have assisted solving the problem of optimal sizing of hybrid energy systems. Many studies have analyzed and demonstrated their performances in providing accurate solutions. Therefore, the present paper does not look into optimal sizing techniques; the main aim of this work is to minimize

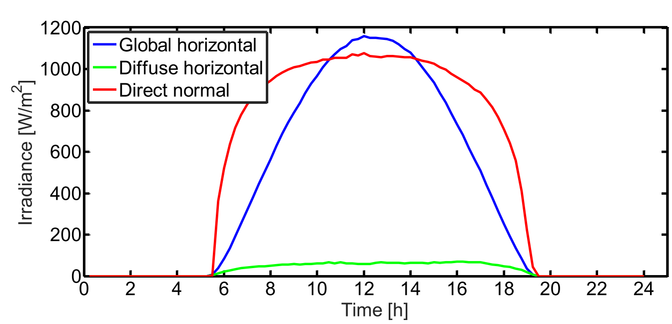

Fig. 3. Summer solar irradiance (January 2019).

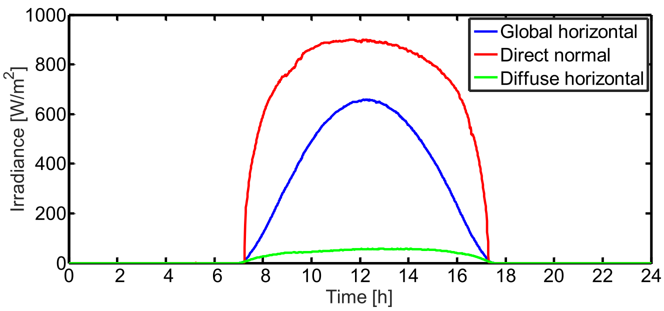

Fig. 4. Winter solar irradiance (July 2019).

the energy cost through the optimal economic power dispatch of the different components in the system submitted to the dynamic resources and pricing structure. The multi-objective optimal sizing and operation of the different components of such system is part of the scope of future work.

3.2.2. Photovoltaic system

The power produced by a PV system can be calculated as [26]:

$$P_{PV} = P_{PV,STC} \times N_{PV,S} \times N_{PV,P} \times \frac{I_t}{1000}[1 - \alpha \times (T_C - 25)] \tag{1}$$

With:

$$T_C = T_a + \frac{I_t}{800} \times (NOCT - 20) \tag{2}$$

Where P_{PV} is the instantaneous power generated; $P_{PV,STC}$ is the power at standard test condition; $N_{PV,S}$ and $N_{PV,P}$ are the series and parallel numbers of modules connected; I_t is the solar irradiance; α (0.0045 °C) is the power temperature coefficient; T_C is the cell temperature; T_a is the temperature of the air around the cell; and $NOCT$ (45 °C) is the nominal operating cell temperature.

The size of a PV system to be implemented on the microbrewery premises depends on the space available, the capital funds as well as the saving targets. The main aim of implementing the proposed system is not to take the microbrewery off the grid but to reduce the energy operation cost. Therefore, based on the load demand and available solar resources, a 4.34 kWp PV system with dual-tracking capabilities is proposed be installed on the microbrewery premise. The system is made of 14 monocrystalline panels (Peimar) of 310 W each [27].

With this, a 5 kVA 48 V inverter (Lynx Axpert), having a maximum power on the Maximum Power Point Tracking, is proposed [28].

3.2.3. Battery bank sizing

The Pylon US2000B Plus 9.6 kWh Lithium Battery Package is proposed. The system as 80% depth of discharge and a 48 V system. The maximum charge and discharge rate are both 4.8 kW [29].

3.2.4. Grid maximum demand and electricity cost structure

The microbrewery is supplied from the grid using the applicable Eskom Megaflex (Local Authority) tariff structure for 2019/2020 [30]. The time pricing periods as well as the rates per kWh for the different seasons are given in Table 1 (at the time of the study, $1 United States Dollar equals ZAR 17.64 South African Rand).

3.3. Optimal energy management model of the grid-connected PV system

3.3.1. Objective function

The main objective "*f*" of the developed model is to minimize the total energy cost supplied from the grid to the brewing process. Looking at Fig. 2, the cost linked to the power imported (P_{IMP}), is the variable that needs to be minimized, while the use of the power generated from the PV system needs to be maximised. This can be modelled as:

$$f = \min \sum_{j=1}^{N} (\rho_j \times P_{IMP(j)} \times \Delta t) + \min \sum_{j=1}^{N} (\delta_j \times P_{IMP}) + \max \sum_{j=1}^{N} (P_{PV(j)} \times \Delta t) \tag{3}$$

Where ρ is the grid energy cost linked to the applicable TOU; δ_j is the maximum demand cost over the considered sampling interval; j is the selected jth sample interval where the optimization is taking place; N is the overall number of sample intervals; Δt is the duration of each sampling interval.

The first part of the objective function ensures the minimization of the energy cost imported from the grid subjected to the TOU. The second part ensures the minimization of the maximum demand cost linked to the power imported from the grid. The third component ensures that the use of the power generated from the PV is maximised.

3.3.2. Equality constraints: load and supply balances

Using the system power flows given on Fig. 2, the power balances to be met at main nodes of the system are expressed as follows:

$$P_{PV(j)} = P_{BAT-in(j)} + P_{DC-INV(j)} \tag{4}$$

$$P_{DC-INV(j)} - P_{IMP(j)} = P_{L-CRIT(j)} + P_{L-NCRIT(j)} \tag{5}$$

Equation (4) means that at any considered sampling period "*j*", the power from the PV can be used to supply the demand through the inverter, or/and to charge the battery.

Equation (5) means that at any considered sampling period "*j*", the critical and the non-critical loads can be supplied by a combination of the power from the inverter (PV and battery) and the power from the grid.

3.3.3. State variable: dynamics of the battery SoC

The dynamic of the *SoC* is a function of the power flows in and out of the battery. For any given optimization interval "*j*" the SoC can be modelled as:

$$SoC_{(j)} = SoC_{(0)} \times (1 - \delta) + \frac{\Delta t}{E_n} \times \left(\eta_{ch} \times \sum_{i=1}^{j} P_{BAT-in(j)} - \frac{\sum_{i=1}^{j} P_{BAT-out(j)}}{\eta_{disc}} \right) \tag{6}$$

Where $SoC_{(j)}$ is the state of charge at the current sampling interval, j; $SoC_{(0)}$ is the state of charge at the end of the 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

Table 1
Eskom Megaflex tariff structure.

Season	Months	Period	Time (hour)	Rate (ZAR)
High Demand (Winter)	June–August	Peak	0-6, 22-24	4.2671 (USD 0.24)
		Standard	9-17, 19-22	1.2985 (USD 0.073)
		Peak	6-9, 17-19	0.7085 (USD 0.040)
Low Demand (Summer)	September–May	Off-peak	0-6, 22-24	1.3970 (USD 0.079)
		Standard	6-7, 10–18, 20-22	0.9642 (USD 0.054)
		Peak	7-10, 18-20	0.6146 (USD 0.035)
Maximum demand	–	–	–	125.76 (USD 7.10)/kVA

self-discharging factor depending on the type of battery used as well as the storage conditions.

3.3.4. Inequality constraints: power sources operation constraints

For any optimization sample interval (j), the sum of powers supplied by the PV, battery or the grid should be less or equal to the power generated by the considered power source. For the PV, this maximum value depends on the system's rating as well as the instantaneous resource available. For the grid, this is limited by a maximum demand imposed to the consumer. All these constraints can be modelled as:

$$P_{BAT(j)} + P_{DC-INV} \leq P^{\max}_{PV(j)} \tag{7}$$

$$P_{AC(j)} + P_{L\_NCRIT} \leq P^{\max}_{IMP} \tag{8}$$

3.3.5. Variables boundaries: power flows maximum and minimum limits

For proper operation, each power source must not be operated above its rated or maximum limit according to the manufacturer's specifications. As explained in the section above, it is only the maximum power of the PV that varies depending on the available solar resource. The minimum limit of the control variables can be considered as the case where the power source is not used. These can be modelled as:

$$P^{\min}_{PV} \leq P_{PV(j)} \leq P^{\max}_{PV(j)} \tag{9}$$

$$P^{\min}_{BAT} \leq P_{BAT(j)} \leq P^{\max}_{BAT} \tag{10}$$

$$P^{\min}_{IMP} \leq P_{IMP(j)} \leq P^{\max}_{IMP} \tag{11}$$

$$P^{\min}_{DC-INV} \leq P_{DC-INV(j)} \leq P^{\max}_{DC-INV} \tag{12}$$

$$P^{\min}_{AC} \leq P_{AC(j)} \leq P^{\max}_{AC(j)} \tag{13}$$

The state variable also has boundaries where the minimum depends on the type of battery used. This is modelled as:

$$SoC^{\min} \leq SoC_{(j)} \leq SoC^{\max} \tag{14}$$

3.3.6. Exclusive power flows

This condition is applied to power flows that are mutually exclusive and cannot take place simultaneously in the same considered sampling interval. Looking at Fig. 2, this condition is applied to the branches and components experiencing bidirectional power flows. In the case of the battery, the charging and discharging processes cannot take place at the same time. In the case of P_{AC}, the power cannot flow in the positive and negative direction at the same time. This means that the inverter cannot supply the non-critical load at the same time the grid power is used to supply the critical load.

There are several ways of modeling this type of constraint. One option is to introduce a switch as control variable with two state [0,1] which multiply each of the mutually exclusive variables, and the model becomes a mix-integer linear programming problem. The second option is more generic, considering that the product of the involved variable will always be equal to zero, and the model becomes non-linear optimization problem [31]. The second option is modelled as:

$$P_{BAT-in(j)} \times P_{BAT-out(j)} = 0 \tag{15}$$

$$P_{AC-(j)} \times P_{AC+(j)} = 0 \tag{16}$$

3.3.7. 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:

$$\sum_{j=1}^{N} \left(P_{BAT-in(j)} + P_{BAT-out(j)}\right) = 0 \tag{17}$$

3.3.8. Solver selection

Looking at the developed optimization model, it can be noticed that the objective function and all the constraints are linear, except equations (15) and (16) which are non-linear. Therefore; the optimization problem can be solved using "*fmincon*" solver from MATLAB (R2019) optimization toolbox [31].

3.3.9. Other simulation parameters

For the studied system, other parameters related to the PV, battery, and grid are given on Table 2.

Table 2
Simulation parameters.

Parameter	Unit/Figure
Sample period duration (Δt)	15 min
PV power rating	4.34 kWp
Battery storage capacity	9.6 kWh
SoC_0	80%
SoC^{max}	100%
$SoC^{\min}$	30%
η_{Ch}	85%
η_{Disc}	95%

3.4. Economic analysis

A lifecycle cost (LLC) analysis can be performed to assess the economic viability of supplying the microbrewery with the proposed grid-connected PV with battery system. The scenario where the power grid is used alone to supply the entire microbrewery's demand will be used as the baseline for comparison with the proposed system. Using the utility energy rates, the renewable resource and well as the load demand; the daily cost comparisons will be done for different days to assess the economic performance of the grid-connected system in both high and low demand seasons. The daily energy costs can be computed by executing the objective function for the simulation horizon. The same methodology can be used for each day to compute the monthly and annual potential energy cost savings.

Given the fact that the daily energy cost savings are generally dependent on the initial capital cost determining the size of the system's components to be used; a LLC analysis is needed to determine the overall economic benefit of the grid-connected PV with battery storage system supplying the microbrewery. This analysis can assist to determine break-even point (BEP) where total expenses and total savings are equal. The LCC can be calculated as:

$$LCC = C_{I(i)} + C_{R(i)} + C_{OM(i)} + C_{EC(i)} - C_{S(i)} \tag{18}$$

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.

Given to its ability to assess the economic benefit of a system, the "true" payback period (PBP) method is used to assess the economic performance of the proposed system, [32]. The true PBP may be calculated as the ratio of the present worth of the total costs (PW_{TC}) and the annual average of the present worth of the total benefits ($PW_{TB\text{-}av}$).

$$''True''PBP = \frac{PW_{TC}}{PW_{TB-av}} \tag{19}$$

The PW_{TB} is calculated as:

$$PW_{TB} = AB\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right] \tag{20}$$

Where AB is the annual benefit and r is the discount or interest (inflation) rate.

4. Simulation results: Optimal power flows analysis

Simulations are performed to assess the effectiveness of the developed grid-connected system optimal operation model to minimize the daily energy cost of power purchased from the grid. Using the week from Monday the 1st July to Sunday the July 7, 2019; all the possible day scenarios (based on the demand, resource and the TOU) in winter, are discussed. These are:

1. The brewing day demand supplied by the grid-connected PV with battery (week day only);
2. The baseload supplied by the grid-connected PV with battery (week day);
3. The baseload supplied by the grid-connected PV with battery (weekend).

The exclusive supply of the microbrewery's load demand by the utility grid is used as the baseline for comparison with the proposed grid-connected system. As exclusive supply option, the grid will act in a load following manner and the energy cost incurred using this supply option will be discussed in the economic analysis.

The same methodology adopted for simulating and reporting the results for the winter season, can be applied for any other day in the summer season (using the corresponding data input data).

4.1. Brewing day demand supplied by the grid-connected PV with battery (winter)

The simulations reported in the sections below explain in detail the system's behavior for a brewing day in the worst case scenario (in winter); where the brewery's load demand as well as the utility charges are high while the renewable resource is low. The resultant optimal power flows from the different sources to the load are explained.

Fig. 5 shows the output power profile of the PV system which depends on the variable solar resources and maximised by the double-tracking abilities. The behavior of the hybrid system is explained according to the different energy pricing periods in the sections below.

4.1.1. Optimal power flow during first off-peak pricing period 00h00-06h00 (green)

Fig. 1 shows that the combined load demand, due to the water heating and the critical load demand or baseload (cold storage and fermentation chamber), is around 5.2 kW while Fig. 5 show that there is no power generated from the PV during this pricing period. Therefore, Fig. 6 shows that the combined load is met by a large contribution from the power imported from the grid (P_{IMP}). It can be seen that P_{AC} is negative while P_{DC} is positive; this means that during this time, the water heating system (non-critical load) is fully supplied by the grid while the baseload is supplied by both the grid and the battery. This is due to the low energy charge attributed to this pricing period.

Fig. 7 also shows that the battery power (P_{BAT}) is used through the inverter, and the corresponding decrease in its SoC is also shown.

4.1.2. Optimal power flow during first peak pricing period 06h00-09h00 (red)

In this period, the energy cost of the grid is at the highest. From

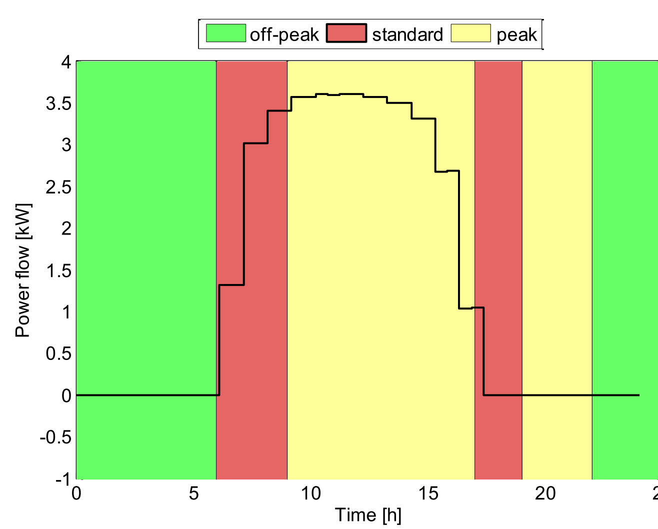

Fig. 5. PV power output profile.

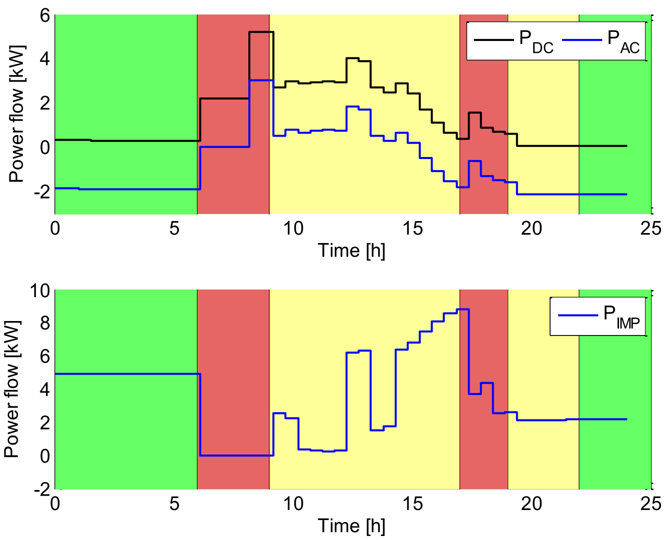

Fig. 6. Inverter input/output and grid imported power profiles.

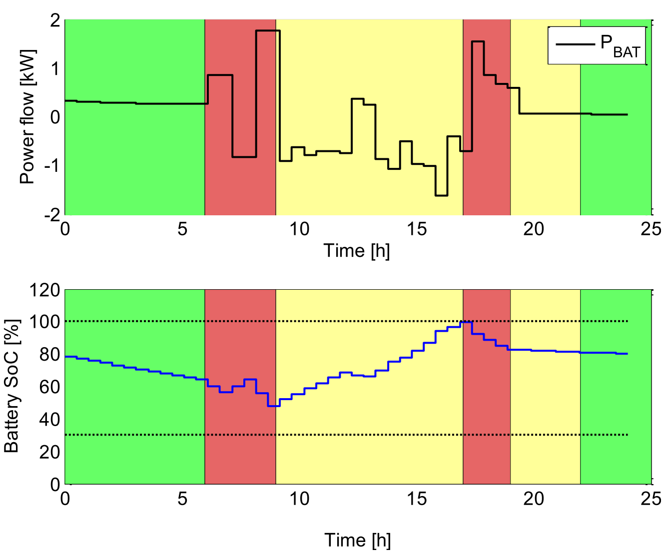

Fig. 7. Battery input/output power and SoC dynamic.

06h00–07h00, Fig. 1 shows that the water heating system is switched off; therefore, only the critical load needs to be supplied. It can also be noticed that the dual-tracking PV system is starting to produce power (around 1.3 kW) as shown on Fig. 5.

Fig. 6 shows that P_{DC} increases to a value around 2.2 kW and there is no power imported from the grid (P_{IMP}) during this time interval. The operation strategy selected is to supply the critical load by P_{DC} from the PV and the battery through the inverter as shown on Fig. 6. Fig. 7 shows that the contribution from the battery to the critical load is a bit less than 1 kW; with the corresponding decrease in the SoC also shown on the same figure.

From 07h00–08h00, Fig. 6 shows that there is still no power imported from the grid, while the power input to the inverter P_{DC} is maintained at 2.2 kW to supply the critical load. Fig. 5 shows that the amount of power generated by the PV system has increased to almost 3 kWp; the balance of power not used by the critical load is used to charge the battery. Therefore, Fig. 7 shows that the battery power (P_{BAT}) is negative, which means that the PV is also used to recharge the battery; and the corresponding increase in the SoC is also shown.

Between 08h00 and 09h00, towards the end of the pricing period, both the critical and non-critical (heating and mashing processes) loads need to be supplied. Therefore, it can be seen on Fig. 6, 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. Fig. 6 also shows that there is no power imported from the grid (P_{IMP}) during this pricing period. Fig. 7 shows a positive output power flow from the battery and the corresponding and reduction in the SoC.

4.1.3. Optimal power flow during first standard pricing period 09h00-17h00 (yellow)

From 09h00–10h00, power is needed for the heating and mashing processes running in conjunction with the critical load. Therefore, the power from the PV is used to supply the 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 (seen by the magnitude of P_{DC} and the positive power flow of P_{AC}). The balance of power needed for the heating and mashing processes is imported from the grid (P_{IMP}) as shown on Fig. 6. Fig. 7 shows that there is a negative power flow associated to the battery charging process (P_{BAT}); the associated SoC is also increasing.

From 10h00–12h00, the mixing process takes place together with the critical load. Fig. 6 shows, that the total demand is successfully met by the power from the PV, through the inverter (P_{DC}), with a small contribution from the grid (P_{IMP}) while the battery is still being charged by the PV power.

From 13h00–14h00, a peak power demand is occurring due to the boiling process that is taking place. It can be seen on Fig. 6 that to make up for this combined peak demand, the power from the PV and a contribution from the battery (P_{DC}) through the inverter is used to supply the critical load and part of the non-critical load (P_{AC} positive). Additionally, power is imported from the grid (P_{IMP}) to balance the deficit power needed by the boiling process. Fig. 7 shows that there is a small contribution from the battery to the input power of the inverter (P_{DC}); a slight reduction in the SoC can be also noticed.

From 14h00–15h00, the cooling and pumping processes are taking place. The PV is used in conjunction with the grid (P_{IMP}) to supply these processes and the baseload as shown on Fig. 6 (P_{DC} and positive P_{AC}). The battery is being recharged by the PV as shown Fig. 7 by the negative power linked to P_{BAT} as well as by the increase in the SoC.

However, from 15h00–17h00, the load demand is high due to the boiling process, and the output power from the PV is decreasing due to the solar resource profile (Fig. 5). Fig. 6 shows that there is more power imported from the grid (P_{IMP}), and the power flow P_{AC} is negative because the grid is used to supply the power needed for the boiling as well as a part of the critical load's demand. Fig. 7 shows that the P_{BAT} is negative and the SoC is increasing which indicates that the battery is being recharged to prepare for the upcoming peak pricing period.

4.1.4. Optimal power flow during second peak pricing period 17h00-19h00 (red)

During this peak pricing period, the output power from the PV is further reduced until there is no power produced at around 17h30 as shown on Fig. 5. Therefore, the combined load is supplied by the power from the battery (P_{BAT}) as shown on Fig. 7; in conjunction with the power imported from the grid (P_{IMP}) as shown on Fig. 6. It can be seen from Fig. 6 that P_{AC} is negative, this means that the grid is used to supply the non-critical as well as a part of the critical load's demand which is not totally met by the battery.

4.1.5. Optimal power flow during second standard pricing period (yellow) and second off-peak pricing period (green) 19h00- 23h59

The system's operation behavior is the same for these two last pricing periods lapsing from 19h00—23h59, where Fig. 1 shows that only the cold storage and fermentation chamber are running as the baseload. Given that the utility energy charge is low, this baseload demand is mainly supplied by the grid; as shown on Fig. 7 as well as from the negative power flow of P_{AC} on Fig. 6.

To meet to condition imposed on the battery SoC's fixed-final state condition given by Eq. (17), a minimal contribution of the battery's power is also used to supply the baseload as shown on Fig. 7.

4.2. Baseload supplied by the grid-connected PV with battery (week day)

The simulations reported in the sections explain the proposed system's behavior for a non-brewing day in winter where only the baseload (cold storage and fermentation chamber) is running with a continuous demand of 2.2 kW. The PV output power of the subsequent non-brewing day is almost similar to the one given on Fig. 5.

4.2.1. Optimal power flow during first off-peak pricing period 00h00-06h00 (green)

As there is no power from the PV during this pricing period, Fig. 8 shows that the baseload or critical load demand is supplied by the combination of the grid power (P_{IMP}), with P_{AC} being negative, and part of the battery power through the inverter (P_{DC}). Fig. 9 shows that the power from the battery (P_{BAT}) is positive and the SoC is decreasing.

4.2.2. Optimal power flow during first peak pricing period 06h00-09h00 (red) and first standard pricing period 09h00-17h00 (yellow)

The peak pricing period start from 06h00 and ends at 09h00. It can be seen on Fig. 5 that from 06h00 the PV starts producing power which is directed to the inverter. Fig. 8 shows that there is no power imported from the grid (P_{IMP}) and the load is supplied by the PV and a contribution from the battery up until 07h00 as shows on Fig. 9.

From 07h00, up until 16h30, in the standard pricing period, there is enough power from the PV, as shown on Fig. 5. Therefore,

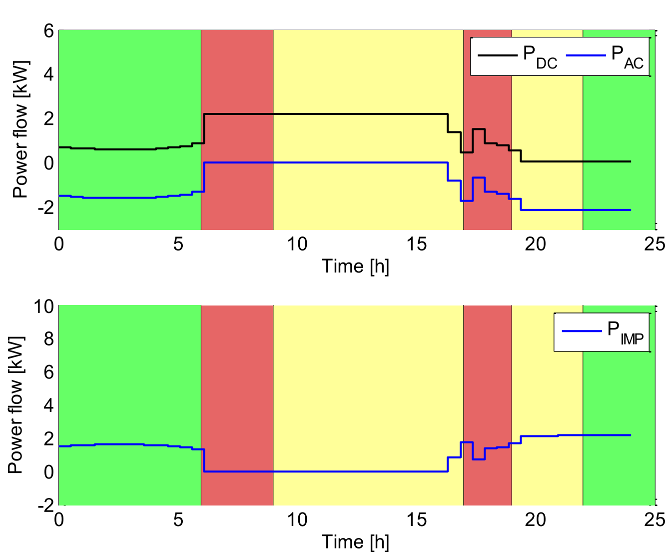

Fig. 8. Inverter input/output and grid imported power profiles.

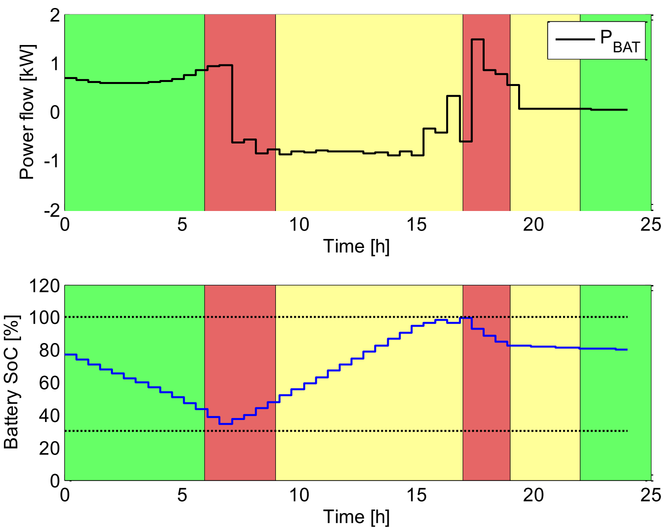

Fig. 9. Battery input/output power and SoC dynamic.

the load is exclusively supplied by the PV through the inverter power (P_{DC}), with no power imported from the grid, as shown on Fig. 8. Fig. 9 shows that the battery power (P_{BAT}) is negative and the SoC is increasing while the charging process is taking place.

From 16h30 to 17h00, Fig. 5 shows that the PV output is decreasing. Therefore, Fig. 8 shows that the critical load is met by power (P_{DC}) from the PV and the battery (positive P_{BAT}) as well as by a small contribution from the power imported from the grid (P_{IMP}). This is also interpreted by the negative power flow of P_{AC}.

4.2.3. Optimal power flow during second peak pricing period 17h00-19h00 (red)

From 17h00—17h30, Fig. 5 shows that the power production from the PV is further decreasing. It is used to supply the critical load through P_{DC}, supplemented by the power imported from the grid (P_{IMP}). The battery is also charged from part of the PV production as shown by the negative power from P_{BAT} and the corresponding SoC as shown on Fig. 9.

From 17h30 to 19h00, there is no power produced from the PV. Therefore, the load is met by the battery power as shown by the negative P_{BAT} and the associated decrease in SoC shown on Fig. 9. The balance of power needed by the load is supplied from the grid (P_{IMP}) as shown on Fig. 8.

4.2.4. Optimal power flow during second standard pricing period (yellow) and second off-peak pricing period (green) 19h00- 23h59

Fig. 9 shows that the battery is close to reaching the final fixed SoC condition, and only a minimal amount of power (P_{BAT}) can get out of it. Therefore, Fig. 9 shows that the load is supplemented by the grid power (P_{IMP}), this can also be interpreted by the negative power flow P_{AC}.

4.3. Baseload supplied by the grid-connected PV with battery (weekend)

As per the applicable Eskom Megaflex (Local Authority) ToU tariff structure; weekends are charged with a flat off-peak tariff. This tariff is applied to the brewery's baseload supplied by the proposed grid-connected PV system. Therefore, a similar operating strategy, as for the case in section "*4.2*" is observed; where the grid power need to be minimized while maximizing the PV power. The power imported profile as well as the one from the inverter are given on Fig. 10, while the battery charging/discharging power and the corresponding SoC are given on Fig. 11.

In summary, the battery and the grid are used at night until the PV starts generating in the morning. As soon as there is enough power from the PV, no power is imported anymore and the battery is recharged. In the evening, the battery is used, within the operation constraints, to minimize the power imported from the grid.

5. Simulation results: Economic analysis

As stated in the methodology section, the lifecycle cost analysis and the payback period analysis are performed to assess the economic viability of supplying the microbrewery with the proposed grid-connected PV with battery system. The total cost of energy incurred when the grid is used as exclusive supply option, is considered as the baseline for the comparison. This section will start by analyzing the daily energy cost corresponding to the power flows of section 4. The same methodology can be used to find the energy cost of any other day.

5.1. Daily energy cost saving

Fig. 12, Fig. 13 and Fig. 14 show the progression of the winter daily cumulative costs, for the case where the load is exclusively supplied by the power imported from the grid as compared to the case where the load is supplied by the optimally controlled grid-connected PV with the battery. It can clearly be seen from the figure that there is a substantial saving achieved by using the dual-tracking PV with the battery storage system.

The daily economic analysis is further substantiated on Table 3, where the cumulative cost is also computed for a summer day where the PV resources, air and water temperature are high, while the loads and grid charges are low. From this Table, it can be seen that the system can potentially save 42.9% for the selected winter brewing day and 57.7% for the selected summer brewing day.

Table 4 shows that in the case of a non-brewing day during the week, where only the baseload is running to supply the cold storage and the fermentation chamber; the proposed system can potentially save 66.27% for the winter day and 59.3% for the summer day.

Table 5 shows that in the case of a non-brewing day during the weekend, where a flat off-peak tariff is applicable and only the baseload is running to supply the cold storage and the fermentation chamber. The proposed system can potentially save 56.32% for the winter day and 52.8% for the summer day.

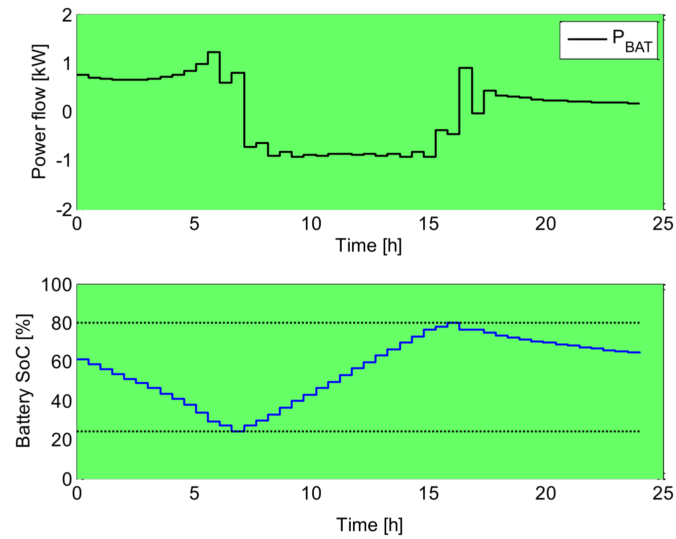

Fig. 11. Battery input/output power and SoC dynamic.

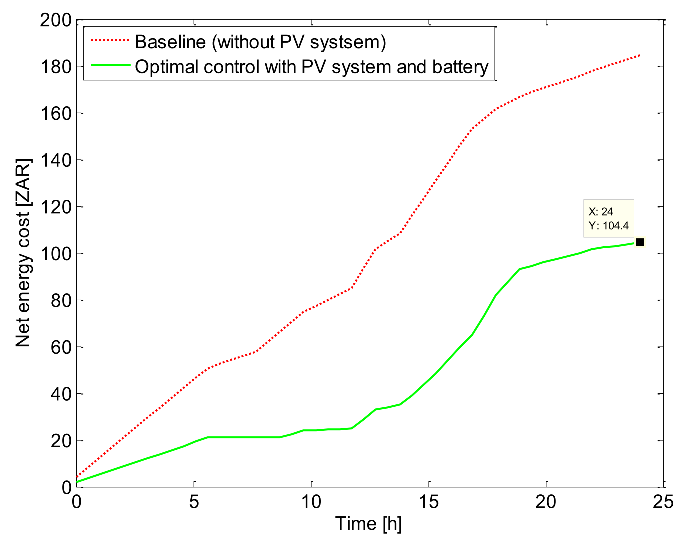

Fig. 12. Cumulative cost for both supply options on the selected winter brewing day.

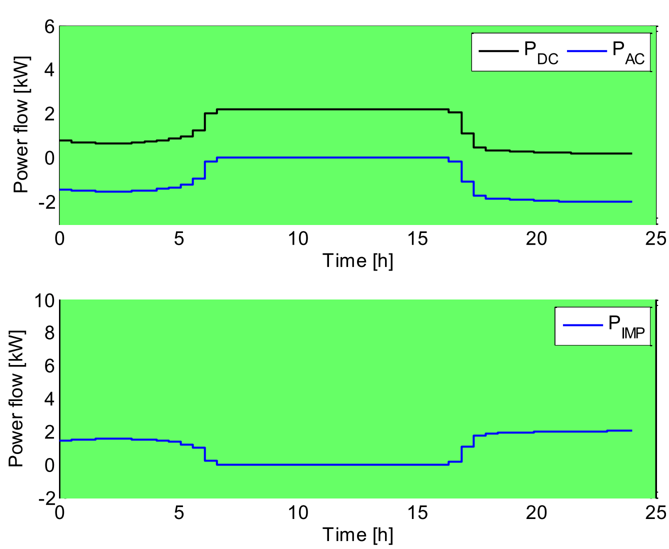

Fig. 10. Inverter input/output and grid imported power profiles.

5.2. Annual energy cost saving

The total annual energy cost can be calculated by adding the daily energy cost achieved for each day. As explained in the load description section, the microbrewery has a production capacity of one batch per week which makes an average of 52 brewing days a year. 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. Basically, each week will have 1 brewing day, 4 week days with the baseload only and 2 weekend days with a flat off-peak tariff.

Table 6 shows the energy cost results for each supply option, per seasons as well as for the whole year. It can be seen that, under the considered variable demands, resources as well as well as electricity charges; the proposed system can achieve a reduction in the

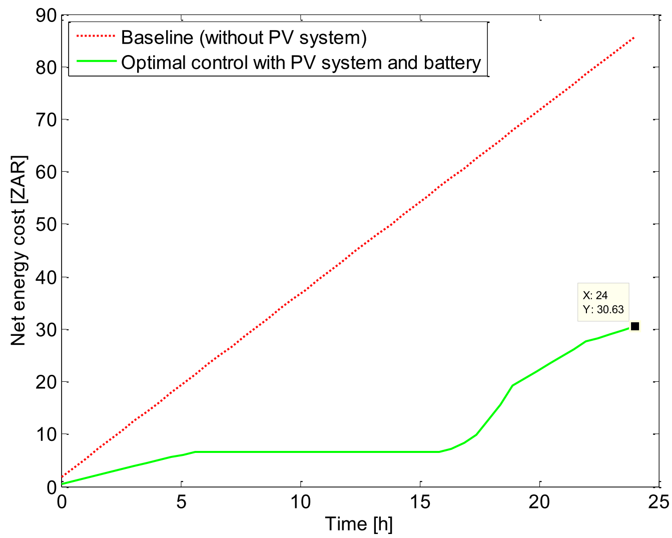

Fig. 13. Cumulative cost for both supply options on the non-brewing day (winter weekday).

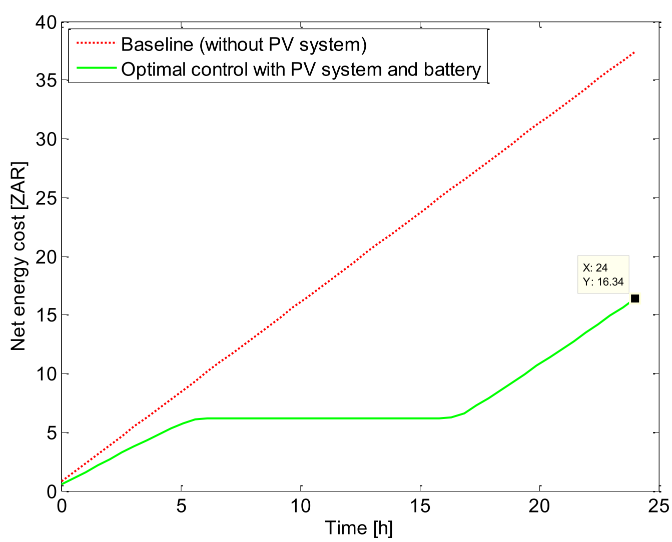

Fig. 14. Cumulative cost for both supply options on the non-brewing day (winter weekend).

Table 3
Energy costs comparison for brewing days.

Supply option	Daily cost (ZAR)	
	Winter	Summer
Utility grid exclusive (Baseline)	*182.9*	*162.39*
Grid-connected PV with battery	*104.43*	*68.68*
Daily savings	***78.47 (USD 4.45)***	***93.71 (USD 5.31)***

Table 4
Energy costs comparison for baseload only (week day).

Supply option	Daily cost (ZAR)	
	Winter	Summer
Utility grid exclusive (Baseline)	*90.83*	*49.51*
Grid-connected PV with battery	*30.63*	*20.15*
Daily savings	***60.20 (USD 3.41)***	***29.36 (USD 1.66)***

Table 5
Energy costs comparison for baseload only (weekend).

Supply option	Daily cost (ZAR)	
	Winter	Summer
Utility grid exclusive (Baseline)	*37.41*	*32.42*
Grid-connected PV with battery	*16.34*	*15.3*
Daily savings	***21.07 (USD 1.99)***	***17.12 (USD 0.97)***

total annual energy cost of 59.3% for the considered year of operation.

5.3. Lifecycle cost analysis

The annual energy savings depend on the capital cost invested in the PV and battery sizes. Therefore, in this section, the LLC analysis, which includes all the cost flows occurring during the system's operation lifetime, is performed to provide a better indication of the value of the investment over the project lifetime. This analysis can also assist in determining the break-even point (BEP) of the proposed system's both fixed and variable costs as compared to the grid used as baseline.

For each year, an increase of 10% is applicable in electricity price supplied by the grid. The yearly operation and maintenance cost is considered to be 1% of the capital cost initially invested; this increases using a yearly average inflation rate of 5.3% [33]. The bill of quantity for the proposed grid-connected PV with battery storage system is available from Table 7.

The annual energy cost saving, the proposed system's bill of quantity as well as the different interests and increments are used in Eq. (18) to compute the LCC for a projected operation lifetime of 20 years.

Using the cumulative energy cost from the grid as baseline, Fig. 15 shows that the break-even point of the proposed grid-connected PV with battery can happen after 9.5 years of operation, corresponding to ZAR 398583.18 cumulatively spent. Afterward, the proposed system starts generating benefits for the brewery.

For the considered 20 years' operation lifetime, the projected LCC incurred by the microbrewery, when using the proposed grid-connected PV with battery storage system is ZAR 875489.74 (USD 49623.62). However, when using the grid exclusively, the projected LCC is ZAR 1478980.23 (USD 83830.06). Therefore, the projected savings on the LCC, when using the proposed system as compared to the baseline, is ZAR 603490.49 (USD 34206.44) or 40.8%.

5.4. Payback period

The annual benefit or cost savings achieved are calculated, using the results in section 5.3 (Table 6), as the difference between the grid energy cost and the proposed optimally controlled system's resultant energy cost; minus the annual operation and maintenance costs (Table 7); which gives ZAR 12524.37/year (USD 705.15). The true payback period is calculated, using the different parameters in Table 8 and the results show that the total investment cost will be recovered in 13.8 years.

The economic performance of the proposed system can be compared to the one from the system studied in Ref. [20], which aimed to provide from solar 50% of the annual electricity consumption and has a discounted payback period of 10.7 years. This payback period was achieved under a direct incentive of 50% reduction in the investment cost; in addition, a Net-metering

Table 6
Annual energy costs analysis.

Supply option	Energy cost per seasons (ZAR)		Year (ZAR)
	Winter (days)	Summer (days)	
Utility grid exclusive (brewing days)	*182.9 X 14 = 2560.6*	*162.39 X 39 = 6333.21*	*8893.81*
Utility grid exclusive non-brewing days (baseload week day)	*90.83 X 55 = 4995.65*	*49.51 x 156 = 7723.56*	*12719.21*
Utility grid exclusive non-brewing days (baseload weekend days)	*37.41 X 23 = 860.43*	*32.42 X 78 = 2528.76*	*3389.19*
Total baseline	***8416.68***	***16585.53***	***25002.21***
Grid-connected PV with battery (brewing days)	*104.43 X 14 = 1462.02*	*68.68 X 39 = 2678.52*	*4140.54*
Grid-connected PV with battery (week day)	*30.63 X 55 = 1684.65*	*20.15 X 156 = 3143.4*	*4828.05*
Grid-connected PV with battery (weekend day)	*16.34 X 23 = 375.82*	*15.3 X 78 = 1193.4*	*1569.22*
Total proposed system	***3522.49***	***7015.32***	***10537.81***
Total savings	***4894.22 (USD 277.41)***	***9570.21 (USD 542.45)***	***14464.4 (USD 819.86)***

Table 7
Bill of quantity for the solar PV with battery system.

Component	Price (ZAR)	Life (years)
4.34 kWp, dual axis solar tracking (14 Panels Peimar Monocrystalline 310 W PV)	112 000	20
Pylon 9.6 kWh Lithium battery	68 046.72	20
Lynx Axpert 5 kVA 48 V inverter	11923.51	10
Connector	606.97	20
Solar Cable 100 m	1425.71	20
Total capital	***194002.91 (USD 10996.28)***	

scheme was considered for the PV system, i.e. the price of the energy injected to the grid is equal to the purchase price. This means that without these incentives, the system in Refs. [20] would not have performed better than the proposed optimally controlled system in this study.

6. Conclusion and scope for future work

In order to become more competitive, microbreweries need to reduce their energy costs without compromising the quality of their processes as well as of their final product. To achieve this goal, energy efficiency and demand response measure are put in place. The aim of this work is to assess the techno-economic benefits of using a grid-connected photovoltaic system to directly assist the electrical needs in a microbrewery; and currently, there is a lack of such studies in the available literature linked to small scale microbreweries.

In this paper, optimal energy management model for a microbrewery under demand response in the presence of a grid-connected photovoltaic system with battery storage system is developed using an optimal control approach. The aim of the model is to minimize the energy cost by maximizing the use of the renewable energy generated on site and minimize the reliance on

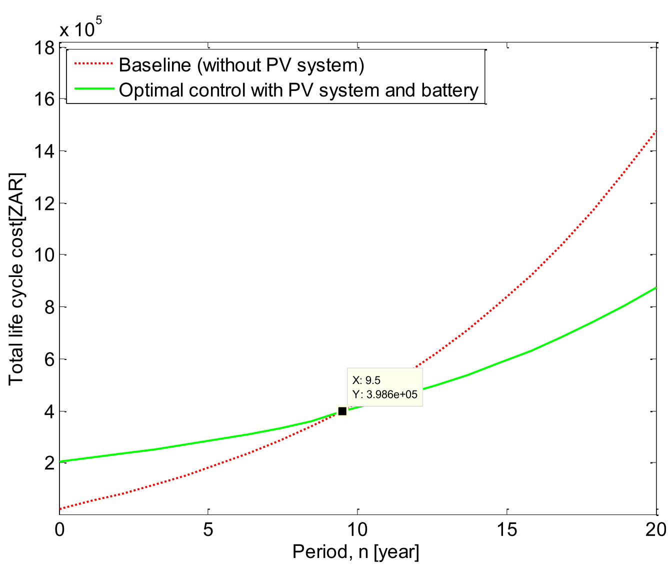

Fig. 15. LLC comparison for the two supply options and BEP.

Table 8
Payback period for the proposed system.

Parameters	Figure
Total initial investment cost	ZAR 194002.91 (USD 10996.28)
Project lifetime, n (years)	20
PV lifetime (years)	20
$N_{Rep\text{-}PV}$	–
$C_{Rep\text{-}PV}$	–
Inverter lifetime, n (years)	10
$N_{Rep\text{-}Inverter}$	1
$C_{Rep\text{-}Inverter}$	ZAR 11923.51 (USD 671.87)
Connectors and cables	20
$N_{Connectors\ and\ cables}$	0
$C_{Connectors\ and\ cables}$	0
Lithium battery life, n (years)	0
$N_{Rep\text{-}Battery}$	0
$C_{Rep\text{-}Battery}$	0
AB	ZAR 12524.37 (USD 705.72)
PW_{TC}	ZAR 205926,42 (USD 11603.55)
PW_{TB}	ZAR 179049.52 (USD 10089.09)
$PW_{TB\text{-}av}$	ZAR 14920.63 (USD 840.75)
"True" PBP (years)	***13.8***

the grid energy subjected to the TOU tariff.

As a case study, a microbrewery in South Africa has been selected. The corresponding demand profile was recorded, the TOU tariff structure was provided, the available solar was evaluated, and then sizing of PV and storage system was presented. All the different daily operating scenarios of the microbrewery (based on the demand, resource and the TOU) have been simulated using MATLAB R2019b.

The detailed analyses of the simulation results have revealed that the model can effectively optimise the power flows between the power sources, the storage and the load; to minimize the resultant energy cost as well as the reliance of the grid supply during peak pricing periods.

The simulation results have shown that a substantial energy cost reduction can be achieved when using the proposed system as compared to the scenario where the grid is used as sole energy supply option. For the different type of operating day scenarios, the following saving has been achieved:

- A potential energy cost saving of 42.9%, for a winter brewing day and 57.7% for a summer brewing day, is possible when the optimal energy management model is applied to the proposed system, under the applicable operating condition as well as TOU tariff.
- In the case of a non-brewing day during the week, the proposed system can potentially save 66.27% energy cost for the winter day and 59.3% energy cost for the summer day.
- In the case of a non-brewing day during the weekend, where a flat off-peak energy tariff is applicable, the proposed system can potentially save 56.32% energy cost for the winter day and 52.8% energy cost for the summer day.

The results have also revealed that under the considered variable demands, resources as well as well as electricity charges; the proposed system can achieve a reduction in the total annual energy cost of 59.3% for the considered year of operation. The proposed system's the projected savings on the LCC, when using the proposed system as compared to the baseline, is 40.8% with a break-even cost happening after 9.5 years of operation. The result of the discounted payback period analysis indicated that the total investment cost will be recovered in 13.8 years.

The satisfactory results obtained in this study demonstrate the potential techno-economic benefits of solar PV integration in the small-scale microbreweries. For future work, the following will be considered:

- The performance analysis of the system may be conducted through sensitivity analysis under different operating conditions i.e. varying PV and battery type and size, and to validate the system through experimentation.
- The optimal energy management of a load under demand response in the presence of a grid-connected photovoltaic/ Thermal hybrid solar collector, to simultaneously support both the electrical and thermal processes, may be investigated.
- A multi-objective optimal sizing and operation control model may be developed.

Even if the microbrewery is selected as a case study, the proposed hybrid system, developed model and optimization methodology can be applied to any load in different demand sectors (residential, commercial and industrial) implementing demand response measures to reduce their operation energy costs.

Credit to author

K. Kusakana, Resources, Data curation, Writing - original draft.

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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