Impact of demand profiles on grid-interactive photovoltaic systems in Bloemfontein: A case study

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***Abstract*— In this paper the impact brought by different demand sector profiles on the daily operational cost and optimal scheduling of grid connected photovoltaic system with bidirectional power flow is analysed for the specific case of Bloemfontein in South Africa. For this purpose, residential, commercial and industrial daily load curves are used to estimate daily load demands. For comparison purposes, three load profiles representing the demands from the residential, commercial and industrial sectors, have been used and normalized to display the same daily energy consumption level with different demand patterns. The results of the simulations, obtained using Matlab 2016, have revealed that for the same energy consumption and renewable resources, the running expenses of any proposed scheme are mainly dependent on the demand sector. Consequently, it can be recommended that in Bloemfontein and South Africa in general more focus should be on implementing grid-connected renewable hybrid energy with storage system in the commercial and industrial sectors instead of in the residential sector.**

***Index Terms*-- Distributed generation; Grid-connected; Time-of-Use; demand sectors; optimal scheduling**

I. Introduction

The South African electric power system was designed in times when adequate energy storage systems where not in use, forcing its instantaneous consumption. Recent developments in energy storage systems have changed all that, and this has facilitated the introduction of distributed power sources such as solar or wind systems [1].

Providing an electricity supply which continuously matches the consumer demand is one of the most challenging tasks of any power generation system. Therefore, any power generation entity needs to fulfil two exclusive tasks:

- The necessity to maintain a continuous power balance between power production and consumption [2],
- The necessity to manage power flows between the generation, load and storage [3].

To adequately meet the consumers' demands, fast power sources optimized to respond to the needs of the variable demand, such as battery storage systems, can be incorporated as part of the supply [4]. In real time applications, the rapid response to fluctuation load exhibited by batteries is constrained by the size of the storage needed to back up unavailability in renewable power sources. This size can be much higher, if not used in conjunction with a conventional generator or is connected to the grid [5].

The new scheme of the South African government to promote the use solar energy systems is favouring the development and implementation of small domestic and other power producers dispersed throughout the local grid [6]. This support from the government usually comes with an obligation for the main electricity supplier to purchase the exceeding power produced [7].

Grid-connected photovoltaic (PV) with battery storage systems are currently gaining considerably more attention. Studies have exposed the potential benefits of using this technology in rural electrification. It has proved to offer reliable and cost effective power which can be produced as opposed to systems without storage or where traditional diesel generators are used as back-up systems [8]. Several researchers have analysed the sizing and scheduling of macro grid-tie PV systems. However, it has been noticed that the impact of different load types of users or sectors on the daily operation cost of grid-connected PV system has not been investigated. For this reason, the current paper evaluates the impact brought about by different daily demand sectors in terms of the resulting operation scheduling and corresponding operation costs of the proposed grid-connected photovoltaic system in Bloemfontein. The optimal scheduling of the proposed system has been modeled and simulated using Matlab Simulink. For comparison purpose, the three load profiles, respectively from residential, commercial and industrial sectors, have been depicted and normalized to have the same daily energy consumption level with different peak demand patterns. The results have shown that for the same daily energy consumption, the type of a load profile affects the grid-connected PV system's operation, resulting in different daily operational costs achieved. Consequently, it can be

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recommended that in Bloemfontein and South Africa in general, more focus should be on implementing grid-connected systems with storage on the commercial and industrial instead of residential sector.

II. Methodology

A. Schematic diagram of the system

The Photovoltaic generator is used as main supply to consumers. In cases in which there is excess of energy from the PV generator, the surplus power can either be stored or fed into to the grid, depending on the pricing period. For periods during which customer power requirements are higher than the PV generation, the stored energy is released to top up the balance from the demand. This stored energy can also be fed into the grid when the demand is entirely satisfied. Depending on the pricing period, the grid can be used to feed the consumer or to store energy for future use. From Fig.1, the following control variables can be identified: P_1 is the power from the PV system for battery charging; P_2 is the power from the storage used to feed the consumer; P_3 is the power from the grid for battery charging; P_4 is the power from the grid for load demand; P_5 is the power from the PV system for load demand supply, and P_6 is the power from the hybrid system sold to the grid.

These power flows will be the control variables to be optimized.

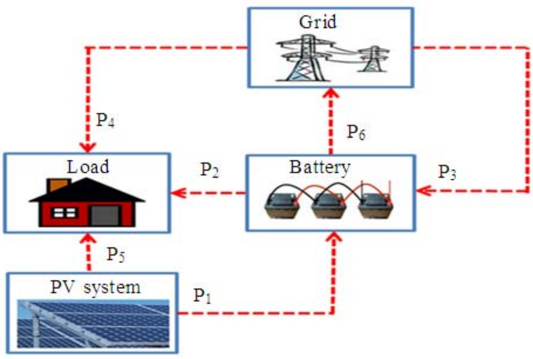

Figure 1. Set-up of the studied microgrid

B. Simplified photovoltaic model

A simplified expression of the PV output power can be found in ref. [9]. For a given size, the output power can be expressed as:

$$P_{PV} = A \times \eta_{PV} \times I \quad (1)$$

Where: A_{PV} is the surface size of the PV array (m^2); η_{PV} is the efficiency PV system; and I is the solar irradiation (kWh/m^2).

C. Battery bank model

The power balance between the generation and the varying consumer's power requirements influences the charge level in the battery (SoC) which can increase, decrease or stay constant. This dynamic can be expressed as [10]:

$$SoC_{(j+1)} = SoC_{(j)} + P_{in(j)} \frac{\Delta t \times \eta_C}{E_{rat}} - P_{out(j)} \frac{\Delta t}{E_{rat} \times \eta_D} \quad (2)$$

Where: SoC is the percentage energy level of the storage at any given time; η_C is efficiency linked to the charging process of the battery; P_{In} is the power used to charge the battery (P_1 and P_3); P_{Out} is the power used from the battery (P_2 and P_6); $\eta_{D:}$ is efficiency linked to the discharging process of the storage; E_{rat} is the rated energy or size of the storing system, and J is the considered sampling interval ($1 \le j \le N$).

Equation 2 can be further developed by induction to introduce the initial state of charge as:

$$SoC_{(j)} = SoC_{(0)} + \sum_{i=0}^{j-1} P_{in(j)} \frac{\Delta t \times \eta_C}{E_{rat}} - \sum_{i=0}^{j-1} P_{out(j)} \frac{\Delta t}{E_{rat} \times \eta_D} \quad (3)$$

III. Optimization Model

The purpose of the model to be developed is to realize minimal running expenses of the proposed system by finding its optimal schedule of operation that will allow for minimum energy obtained from the utility and maximum injected to the grid given the Time of Use tariff imposed by the grid. Mode details on the price structure used in this work can be obtained from ref [11]. The price of electricity for Bloemfontein in South Africa is presented below:

$$\rho(t) = \begin{cases} \rho_k; t \in T_k, T_k = [7,10) \cup [18,20) \\ \rho_0; t \in T_0, T_0 = [0,6) \cup [22,24) \\ \rho_s; t \in T_{s,} T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \quad (4)$$

With: ρ_k = 2.2225 R/kWh (electricity rate in peak pricing time interval); ρ_0 = 0.3656 R/kWh (in off-peak pricing time interval); and ρ_s = 0.6733 R/kWh (in standard pricing time interval).

In the rates above, "R" represents the South African currency (Rand).

A. Objective function

The objective function is given as equation 4 where the first part represents the charge of buying power from the utility (to be minimized); the second part is the income realized from feeding power to the utility (to be maximized); the third part is the wearing component cost of the whole scheme [12].

$$g = \sum_{j=1}^{N} \rho_j (P_{3j} + P_{4j}) \Delta t - r_k \rho_k \sum_{j=1}^{N} P_{6j} + \sum_{j=1}^{N} a (P_{2j} + P_{6j}) \Delta t + 24b \quad (5)$$

With: r_k as a fraction of the rate for the peak pricing time interval ρ_k for selling power during the peak pricing period.

B. Constraints

The control variables to be optimized were presented in section 2.1; they have to meet the constraints below:

1) PV generator:

As stated in section 2, the PV system can deliver power to the consumers and/or feed the storage system. Therefore, at any instant, the power from the PV feeding the demand and/or the storage system must be less than the instantaneous power from the PV generator. This is expressed in the equation below:

$$P_{1(j)} + P_{5(j)} \le P_{PV(j)}^{\max} \tag{6}$$

2) Power balance constraint:

The power required to satisfy the consumer must be equal to the linear combination of the powers from the PV, the utility and from the storage system as formulated in the equation below:

$$P_{L(j)} = P_{2(j)} + P_{4(j)} + P_{5(j)} \tag{7}$$

3) Control variable boundaries

Each control variable can take a set of values between a minimum and a maximum limit for the proposed simulation horizon time as formulated in the equation below:

$$P_i^{\min} \le P_{i(j)} \le P_i^{\max} \tag{8}$$

With: "*i*" (P_1..., P_6).

C. State variable

The different power flows as well as the variable load requirements at any selected sample period *j*, influence the charge level in the battery. As for the control variables, the battery SOC can vary between a maximum and a minimum set value. This is given by the expression:

$$SoC^{\min} \le SoC_j \le SoC^{\max} \tag{9}$$

D. Algorithm formulation in Matlab

Given the linear nature of the optimization problem developed using the objective function and constraints given from equations (5) to equation (9) it can be resolved by using the linear programming solver in Matlab with the following syntax [13]:

$$\min g(x), s.t \begin{cases} Ax \le b \\ A_{eq}x = b_{eq}, \\ lb \le x \le ub \end{cases} \tag{10}$$

With: $g(x)$ represents the objective function; A_{eq} and b_{eq} represent the equality constraint parameters; A and b represent the inequality constraint parameters; l_b and u_b represent the inferior and superior limits of the variables.

IV. APPLICATION RELATIVE TO BLOEMFONTEIN CASE (SOUTH AFRICA)

A. Load profile description

As stated in the introduction, this study focuses on analysing the impact brought about by residential, commercial, and industrial demand on the daily running expenses and schedule of the considered microgrid working under TOU. For this purpose, the impact of different load profiles on the optimal power scheduling of the considered microgrid has determined using three different load profiles having the same energy consumption of 75kWh/day.

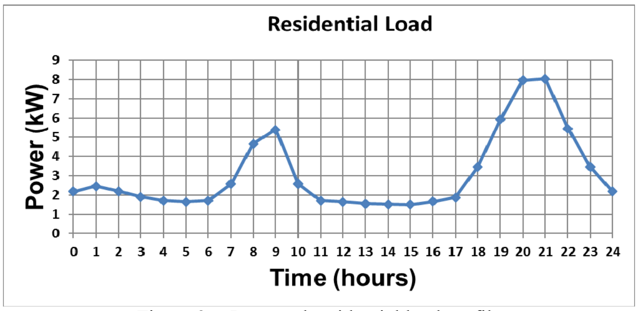

Figure 2. Proposed residential load profile

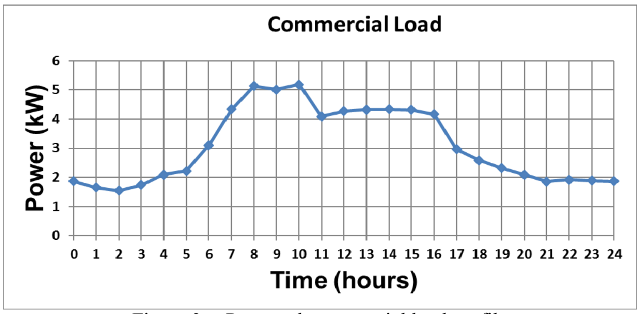

Figure 3. Proposed commercial load profile

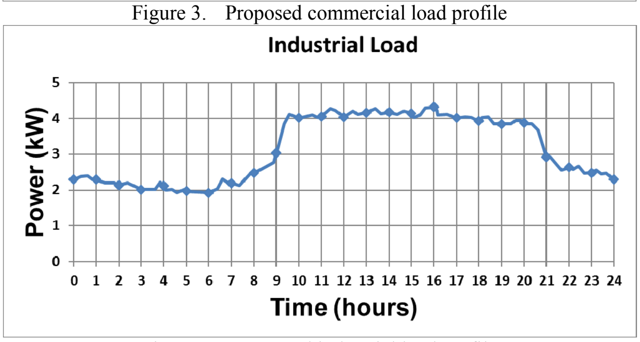

Figure 4. Proposed industrial load profile

Fig. 2, representing a residential load profile, shows that the power demand has a low peak of 5.5kW in the morning at around 09:00, a variable demand throughout the daytime between 11:00 and 17:00, and a maximum demand of 8kW. Industrial and commercial demand profiles are represented in Fig.3 and Fig.4 respectively. They increase in the morning to a to reach a peak of 5.2kW for commercial and 4.3kW for industrial, then dropping in the evening to reach their minimum during night-time.

B. Component characteristics

The size of the hybrid system's components used in this study can be found in our previous work, available in ref. [14], in which all the parameters and specifications necessary for the simulation are explained in detail.

V. Discussion

As described in the introduction, the current analysis is based on the daily operational behaviour of the considered microgrid. The performance of the system supplying the three different types of load under TOU will be discussed and categorized to find out which of the demand sectors are more likely to accrue more income when the hybrid system supplying its demand is connected to the grid. It is important to highlight that the hybrid system size, architecture, control settings, PV resources as well as energy requirements are the same for the three cases, and only the load profiles (power demands) are different.

A. Residential demand supplied by the proposed system

1) System performance during off-peak pricing time interval [00:00, 06:00)

Fig. 6 (A) shows how the battery is discharged within its operational limits while supplying the load. Form Fig. 6 (B) and Fig. 6 (C) it can be seen that during this off-peak pricing time interval, neither the utility and the PV supply the battery. Fig. 6 (D) reveals that there is no power fed into the utility during this off-peak pricing time interval.

2) System performance during standard pricing time interval [06:00, 07:00)

All through the first standard pricing time interval taking place between 06:00 and 07:00, the consumer's power requirement is exclusively met by the utility, as revealed in Fig. 5 (D). The Photovoltaic systems and battery storage system are not used to feed the consumer, as illustrated in Fig. 5 (B) and Fig. 5 (C).

From Fig. 6(C) it can be noticed that the storage system is being recharged by the utility, and this is reflected in Fig. 6 (A) where an increase in the storage's SoC is observed. Fig. 6 (D), reveals that there is no income generated because the utility does not receive any power from the renewable source or from the storage system during this time interval.

3) System performance during peak pricing time interval [07:00, 10:00)

During this peak pricing time interval, the consumer is supplied with power from the photovoltaic combined with the storage system (Fig. 5 (B), Fig. 5(C)) with a small contribution from the utility. The SoC is decreasing because of the power flowing from the storage to the consumer, as shown in Fig. 6 (A). The model has been developed to maximize the power fed into the grid with the aim of generating income at the consumer side. However, it can be seen from Fig. 6 (D), that no profit is generated during this peak pricing time interval due to the priority given to the consumer's demand.

4) System performance during standard pricing time interval [10:00, 18:00)

During this standard pricing time interval, the consumer's power requirements and the rate imposed on the electricity by the utility are reasonable. Therefore, consumer demand is exclusively met by the utility which is simultaneously used to increase the SoC of the storage system: this is noticeable from Fig. 5(D) and Fig. 6(C). Fig. 5(B) and Fig. 5(C) corroborate the fact that the photovoltaic and the battery systems do not provide any power to the consumer; this power is fed to the utility to generate income as pointed out in Fig. 6 (D).

5) System performance during peak pricing time interval [18:00, 20:00)

In this pricing time interval, the consumer is mainly supplied by the photovoltaic in conjunction with storage system as illustrated in Fig. 5 (B) and Fig. 5 (C). Fig. 6 (D) highlights the fact that the available energy stored and not used by the customer is fed into the utility grid to generate substantial income during this peak pricing time interval.

6) System performance during standard pricing time interval [20:00, 22:00)

During this standard pricing time interval, it can be seen in Fig. 5 (A) that the load is high, reaching a peak of 8kW. The photovoltaic system does not produce any power at night-time; therefore, the customer's demand is supplied by the battery with a contribution from the battery when, needed as illustrated in Fig. 5 (C) and Fig. 5 (D). The balance of energy from the storage system not used by the customer is injected into the utility grid, as shown of Fig. 6 (D).

7) System performance during off-peak pricing time interval (22:00, 24:00]

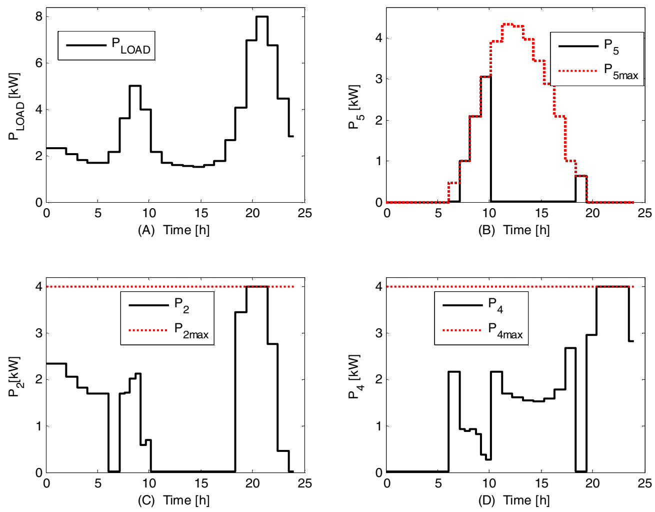

Figure 5. Residential case: Demand side power scheduling

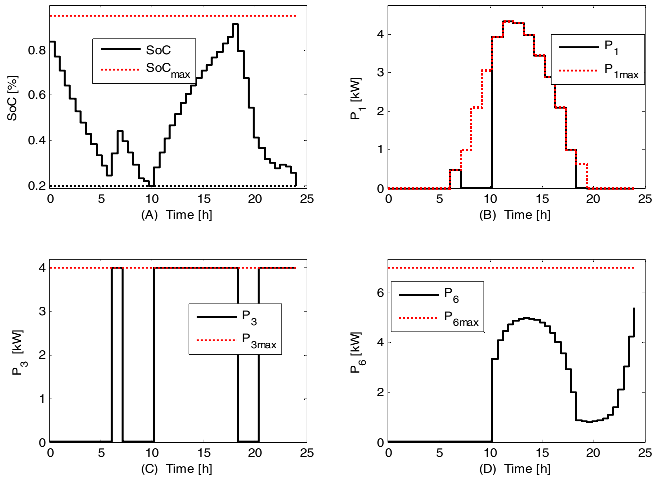

Figure 6. Residential case: Storage side power scheduling

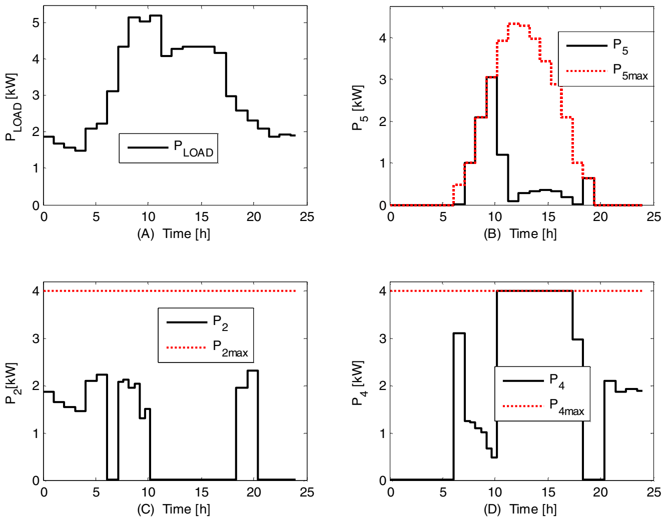

Figure 7. Commercial case: Demand side power scheduling

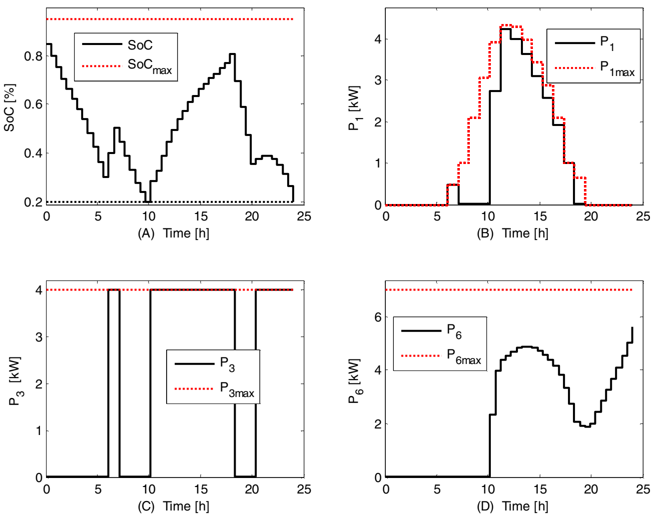

Figure 8. Commercial case: Storage side power scheduling

Fig. 6 (C) illustrates that during this off-peak pricing time interval, the utility principally supplies the required energy; however, a minimal output from the storage system to the consumer is also noticeable as illustrated in Fig. 5 (D). Fig. 6 (D) shows the profile of power injected into the grid during this off-peak pricing time interval.

B. Commercial demand supplied by the proposed system

Even though the commercial load profile is different from the residential one, the behaviour and power flow of the hybrid system during the first off-peak pricing period [00:00, 06:00); during the standard pricing period [06:00, 07:00) and during the peak pricing period [07:00, 10:00), are similar for both sectors.

The behaviour and power flow of the hybrid system supplying the commercial load during the standard pricing period [10:00, 18:00) is characterized by the fact that the load demand is high; the grid is used as the main supply to the demand together with the storage system as illustrated in Fig. 7 (D) and Fig. 8 (C). However, the photovoltaic system also contributes to supplying the demand to a minor instance as illustrated in Fig. 7(B) which was not needed in the residential case. The battery doesn't provide any power to the consumer, as illustrated in Fig. 7 (C); Fig. 7(D) reveals that there is no power fed into the utility.

The performance of the hybrid system supplying the commercial load during peak pricing period [18:00, 20:00), during the standard pricing period [20:00, 22:00) and during the off-peak pricing period (22:00, 24:00] are similar for the residential ones.

C. Industrial demand supplied by the proposed system

The behaviour and power flow of the hybrid system supplying the industrial load are very similar to that of the commercial case. However, the main difference is that under peak pricing period [07:00, 10:00), the photovoltaic system is used as main source to respond to the demand requirement in conjunction with a minor output from the storage system (Fig. 9 (B), Fig. 9 (C)). Specifically, in this case, the surplus of energy available from the storage system not used to feed the consumer is injected into the grid, as illustrated in Fig. 10 (D).

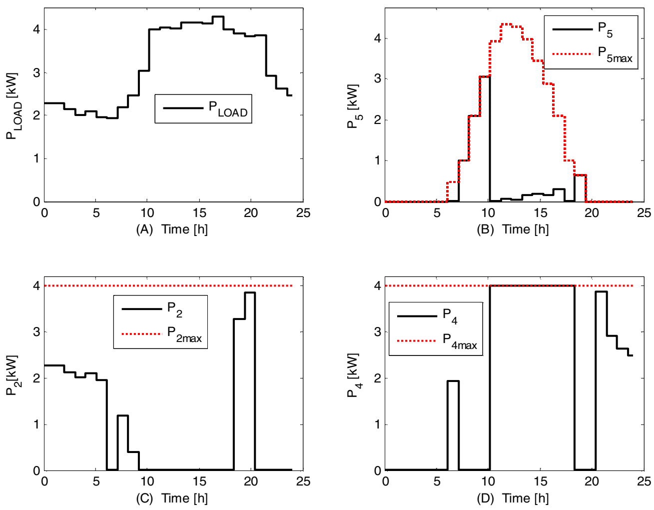

Figure 9. Industrial case: Demand side power scheduling

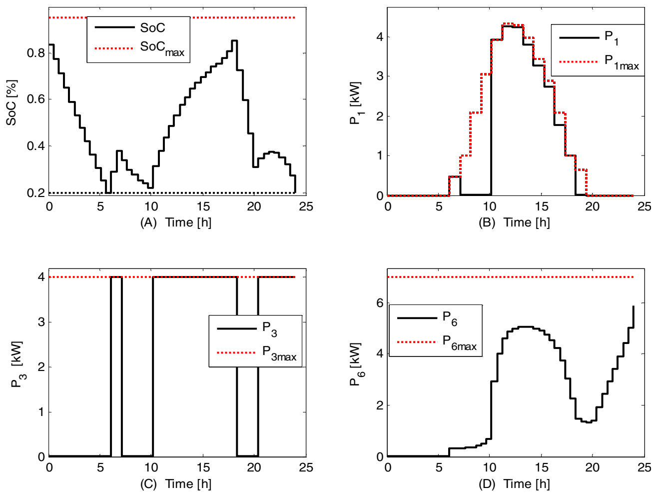

Figure 10. Industrial case: Storage side power scheduling

D. Daily economic analysis

A summary of the system's daily running expenses in given in Table 1 below. The second column gives the daily cost of electricity when the utility exclusively supplies the consumer. The monetary value of the daily power sold to the utility when the system is optimally scheduled is given in the third column; the fourth column displays the net revenue generated by the consumer.

Table 1: Daily operation cost comparison.

Sector	Power used: Grid only (R)	Sold: Grid connected hybrid system (R)	Saving (R)
Residential	67.4	-73	-5.6
Commercial	62.4	-85.2	-22.8
Industrial	62.3	-93.9	-31.6

Even though the energy consumption is the same for the three cases, the results show that the difference in the income generated is mainly a function of the daily load profile. The results show that more savings and income are generated in the industrial and commercial sectors than in the residential sector.

VI. CONCLUSION

This study focuses on analysing the impact brought about by residential, commercial, and industrial load profiles on the daily operational cost and scheduling of grid-connected hybrid systems with time-of-use tariff in Bloemfontein, South African. Therefore, three profiles from the main demand sectors, namely residential, commercial, and industrial load profiles having the same daily energy consumption of 75 kWh were considered, and techno-economic behaviours of the system have been conducted during the different hourly pricing periods.

The simulation results have revealed that for the same energy consumption and renewable resources, the daily operational cost of a proposed system is mainly dependent on the demand's profile. It has been shown, using the proposed set-up in this work, that more saving or income is generated from the industrial and commercial sectors than from the residential sector. Therefore, from the results obtained, it can be recommended that in South Africa more focus should be directed on grid-connected renewable hybrid with storage system in the commercial and industrial sectors rather than that in the domestic one.

For future work, the stochastic nature of the solar resource, the variation of the load profile with seasons as well as a closed loop optimisation method such as Model Predictive Control (MPC) will be considered.

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