Optimal Power Flow of a Battery/Wind/PV/Grid Hybrid System: Case of South Africa

K. Kusakana

Abstract Photovoltaic and wind systems have been demonstrated to be sustainable alternatives of producing electricity in rural electrification, particularly in islanded applications. Currently, the advancement of research in the area of power electronics has allowed the connection of these renewable resources to the grid with bidirectional power flow. In this work, the optimal power scheduling for a grid-connected photovoltaic–wind–battery hybrid system is proposed to maximize the use of solar and wind resources to assist customers at demand side. The developed model for the hybrid system's optimal power flow management aims to minimize electricity purchased from the grid while maximizing the energy sold to the grid as well as the production of the renewable sources subject to the power balance, photovoltaic, wind, and battery storage outputs as well as other operational constraints. Relating to demand-side management, a control technique is developed to optimally schedule the power flow from the different components of the hybrid system over 24-h horizon. Simulations are performed using MATLAB, and the results demonstrate that operating the proposed hybrid system under the developed optimal energy management model can reduce the operation cost and allow consumers to generate substantial income by selling power to the grid.

Keywords Photovoltaic energy · Wind · Hybrid system · Optimal scheduling

1 Introduction

Renewable energy (RE) sources have become attractive choices of generating electricity in comparison to traditional fossil fuels due to different characteristics such as low cost, no pollutant emission, energy security as well as their modularity [1].

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Renewable energy sources can be used in islanded or as grid-connected mode where bidirectional power flow can be implemented to buy or sell power to the utility company [2]. Because of the intermittent nature of their resources, renewable power systems are regularly coupled with storage systems such as batteries [3]. Energy storage systems can be used to ensure that the variable load demand is continuously met irrespective of the intermittency of the renewable resources [4].

Generally, grid-connected renewable systems do not necessitate battery storage systems. Therefore, advanced energy management systems are also not needed [5]. Maximizing the use of the power from the renewable sources is the only operation strategy implemented when the power generated is less than the instantaneous load power demand [6]. For grid-connected renewable with battery storage systems, the energy management becomes more difficult, as more complicated operation strategies must be taken into account, such as charging the battery from the grid or renewable source and discharging into the grid or to the load when necessary [7]. As a result, controllers are required for hybrid renewable-battery systems, such that the use of the renewable system can be considerably improved and the grid regulation can be enhanced in terms of safety, reliability, and efficiency [8].

For grid-connected hybrid renewable-battery systems, the changing electricity price imposed by the utility, the period of power transaction, and the balance between the instantaneous renewable power produced and the instantaneous load demand are main challenges encountered while implementing any suitable energy management strategy [9]. Several demand-side management (DSM) programs can be implemented when renewable energy systems are connected to the grid:

- Peak shaving: Where consumers can shift the usage of their electrical appliances to reduce the peak power demand [10].
- Direct load control: In which a utility operator remotely shuts down or cycles a customer's electrical equipment at short notice to address system or local reliability [11].
- Capacity market programs: In which customers commit to respond pre-specified load reduction when system contingencies arise and are subject to penalties if they do not curtail power consumption when directed [12].
- Time-of-use (TOU): Where the electricity price is high in the peak load time and low in the off-peak time [13].

From DSM approach, the energy from the renewable sources or from the grid can be stored when the generation is higher than the demand or when the electricity price from the grid is very low. The stored energy can then be used to supply the load during peak power demand; to be sold to the grid when the electricity price from the utility is high or even when the power from the renewable resources is unavailable [14]. Well-managed grid-connected hybrid system with DSM program can assist customers in substantially reducing their electricity cost, and also can assist utility companies to control the grid in terms of security and efficiency issues while increasing the reliability.

Therefore, at both supply and demand side, grid-connected systems can bring in new opportunities to smart grid but also induce several challenges in the following DSM programs. For the specific case of grid-connected renewable sources with battery storage systems operation under TOU scheme, challenges such as determining how to optimally schedule the hybrid system in peak, standard and off-peak periods with the aim of minimizing the total electricity cost and satisfying the consumer demand as well.

Research works have already been conducted on grid-connected renewable systems. However, most of these studies have focused on energy management for large-scale integration of renewable energy at the utility side [15, 16]. Currently, there are very few studies reporting on the optimal energy management and DSM for small-scale grid-connected hybrid systems at the demand side, because hybrid systems are installed for stand-alone or backup usage without any contribution of DSM program.

Wolisz et al. [17] have analyzed the feasibility and the resulting potential of coupling the electricity grid with the thermal supply of residential buildings. In this paper the technical and economical key impact factors for such thermal DSM approach are elaborated. The practicability and possible magnitude of the intended DSM is then analyzed based on the identified scenarios. It is found that especially the strong dissemination of smart metering and smart control infrastructure is crucial to incorporate these capacities into DSM activities.

Dufo-Lopez and Bernal-Agustin [18] have presented a methodology to evaluate the technical and economic performance of a grid-connected system with storage under a time-of-use electricity tariff. The storage can help smooth demand, reducing peak demand from the grid and, in some cases, also reducing the electricity bill for the consumer.

Dufo-Lopez [19] has considered a storage system to be added to a private electricity facility in order to reduce the electricity bill. This kind of system could make sense with a time-of-use tariff (with two or three periods of different electricity price) or a real-time pricing tariff, where each day, electricity is bought from the AC grid during off-peak hours to store energy, and during on-peak hours, the storage supplies the whole load or a part, avoiding the purchase of expensive electricity from the AC grid.

Sichilalu and Xia [20] have developed an optimal scheduling strategy model for a grid-tied photovoltaic (PV) system to power a heat pump water heater (HPWH). The system is composed of PV modules that are grid-tied and a backup battery. The PV is capable of supplying power simultaneously to the HPWH and domestic load, while the grid and the battery are complementary sources. The objective function of this model is energy cost. The time-of-use (TOU) electricity tariff is taken into account in the optimal scheduling model. The control variables are the power flows within the branches of the system. This model has shown to have more economic benefits than solar thermal heaters, because of the possibility to turn the dwelling into net-zero energy or positive-energy buildings with the attractiveness of the feed-in tariff.

Unlike the above-mentioned papers, the focus of this chapter will be on analyzing a more comprehensive grid-connected PV-WT-battery system under the Time-of-Use (TOU) program with contracted selling as an example using the specific South African context. An optimal power flow management algorithm of the proposed hybrid system is developed aiming to minimize the electricity purchased from the grid, maximize the energy sold to the grid as well as the renewable production within the DSM framework while satisfying the load demand. It will be shown how the developed system can assist consumers to optimally schedule the system's operation to earn cost savings with changing prices in the TOU program, and how they can manage their generation, consumption, and storage to sell surplus power to the grid over peak period.

2 Description of Hybrid System and Proposed Methodology

The hybrid system analyzed in this work is composed of a PV system, wind system, and battery bank that are connected to the grid. The output power of the renewable systems feeds the load demand directly. If the demand is less than the renewable output, the surplus power will be stored into the battery bank. If the load power requirement is larger than the renewable output, the deficit of power will be supplied by the battery or the grid. The grid plays a preponderant role in the hybrid system for charging the battery and directly supplying the load demand depending on the price of electricity in the considered time interval. The battery can be charged by the grid in the off-peak period, and then discharged in the peak period either to the load or to the grid to save electricity cost. The grid provides electricity directly when the load cannot be entirely met by the renewable sources and the battery storage system. The schematic of this hybrid system is shown in Fig. 1, in which arrows represent directions of power flows in the hybrid system. $P_{\text{PV-B}}$ and $P_{\text{WT-B}}$ are the renewable powers used for charging the battery; $P_{\text{B-L}}$ is the discharging power of battery for load demand; $P_{\text{G-B}}$ is the grid power for charging the battery; $P_{\text{G-L}}$ is the grid power for load demand; $P_{\text{PV-L}}$ and $P_{\text{WT-L}}$ are the renewable powers directly supplying load demand; P_{SOLD} is the battery discharge for selling power to the grid.

2.1 Photovoltaic System

When light strikes a silicon, gallium arsenide, or cadmium sulfide cell, an electric current is generated through the photovoltaic effect. The power rating of a PV panel is expressed in peak Watts (Wp) indicated at "standard test conditions" conducted

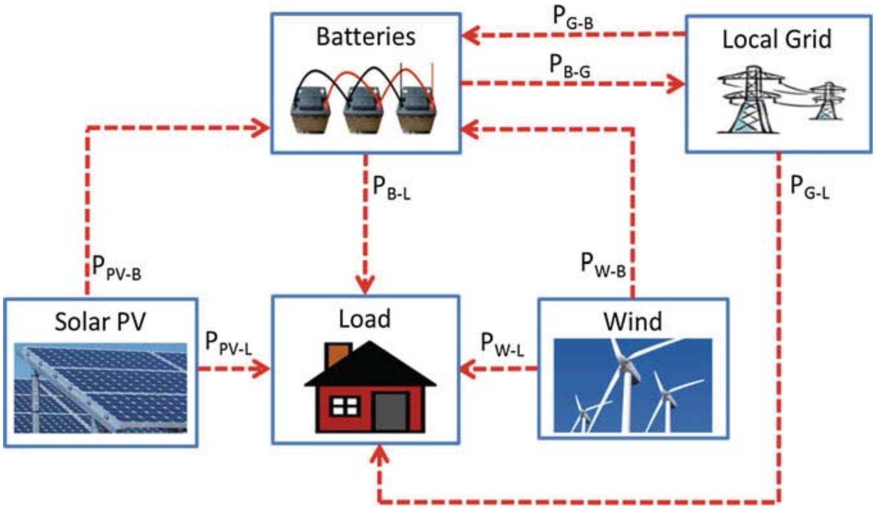

Fig. 1 Hybrid system layout (power flow)

at a temperature of 25 °C and irradiance of 1000 W/m^2. The output power of the solar PV system can be expressed as follows [21]:

$$P_{\text{PV}} = A_{\text{PV}} \times \eta_{\text{PV}} \times I(t) \times f(t) \times \text{d}t \tag{1}$$

where A_{PV} is the total area of the photovoltaic generator (m^2); η_{PV} is the module efficiency; I is the hourly irradiance (kWh/m^2); and $f(t)$ is the radiance density.

2.2 *Wind Energy System*

Wind energy systems convert the kinetic energy of moving air into mechanical and then electrical energy [21]. The power output (P_{WT}) of the wind system within a sampling time interval can be expressed as

$$P_{\text{WT}} = \frac{1}{2} \times \rho_{\text{a}} \times A_{\text{WT}} \times C_{\text{p,WT}} \times \eta_{\text{WT}} \times v_a^3(t) \times f(t) \times \text{d}t \tag{2}$$

where ρ_{a} is the air of water (1225 kg/m^3); $C_{\text{p,WT}}$ is the coefficient of the wind turbine performance; η_{WT} is the combined efficiency of the wind turbine and the generator; A_{WT} is the wind turbine swept area (m^2); v_a is the wind velocity (m/s); and $f(t)$ is the wind probability density function.

2.3 Battery Storage System

The power flows from the PV, the grid, and the load demand at any given sampling interval j, determine whether the battery is charging or discharging. The dynamics of the battery state of charge (SOC) can be expressed in discrete-time domain by a first-order difference equation as follows [22, 23]:

$$\mathrm{SOC}_{(j+1)} = (1 - d_{\mathrm{b}}) \times \mathrm{SOC}_{(j)} + \frac{\Delta t \times \eta_{\mathrm{C}}}{E_{\mathrm{nom}}} \times (P_{\text{PV-B}(j)} + P_{\text{G-B}(j)} - \frac{\Delta t}{E_{\mathrm{nom}}\eta_{\mathrm{D}}} \\ \times (P_{\text{B-L}(j)} + P_{\mathrm{SOLD}(j)}) \tag{3}$$

where SOC is the state of charge of the battery; d_{b} is the self-discharging rate of the battery storage system; η_{C} is the battery charging efficiency; η_{D} is the battery discharging efficiency; and E_{nom} is the battery system nominal energy.

By induction reasoning, the dynamics of the battery state of charge at jth sampling interval can be expressed in terms of its initial value $\mathrm{SOC}_{(0)}$ of a day as follows:

$$\mathrm{SOC}_{(j)} = (1 - d_{\mathrm{b}}) \times \mathrm{SOC}_{(0)} + \frac{\Delta t \times \eta_{\mathrm{C}}}{E_{\mathrm{nom}}} \times \sum_{i=0}^{j-1} (P_{\text{PV-B}(j)} + P_{\text{G-B}(j)}) - \frac{\Delta t}{E_{\mathrm{nom}}\eta_{\mathrm{D}}} \\ \times \sum_{i=0}^{j-1} (P_{\text{B-L}(j)} + P_{\mathrm{SOLD}(j)}) \tag{4}$$

2.4 Flowchart of the Proposed Optimization Methodology

The simplified flowchart of the proposed methodology is presented in Fig. 2. The main optimization variables are described below:

- Independent variables: Load demand, solar and wind resources, Time-of-Use.
- Dependent variables are all variables which are affected by any change or variation in the input variables. In this case it is mainly the battery state of charge (SOC).
- Controlled variable: The powers related to the renewable sources, storage, and the grid are considered as controlled variables.

3 Optimization Model and Proposed Optimal Control Algorithm

As stated in the introduction, the optimization problem addressed in this work aims to minimize the electricity cost within the framework of TOU in which the electricity price changes over different time intervals according to cost imposed by the

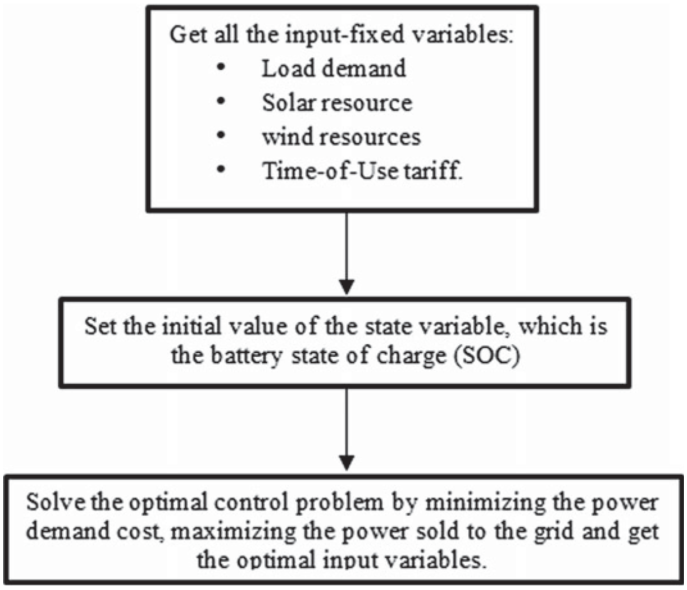

Fig. 2 Flowchart of the proposed optimization methodology

utility company, for instance a high price for peak load periods, medium price for standard periods, and low price for off-peak periods. In this study, the daily electricity price at the selected region of South Africa can be given as [24]

$$\rho(t) = \begin{cases} \rho_k; t \in T_k, T_k = [7,10) \cup [18,20) \\ \rho_0; t \in T_0, T_0 = [0,6) \cup [22,24) \\ \rho_s; t \in T_s, T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \quad (5)$$

where

ρ_k 0.20538 \$ = kWh is the price for the peak load period;
ρ_0 0.03558 \$ = kWh is the price for the off-peak period;
ρ_s 0.05948 \$ = kWh is the price for the standard period.

3.1 Objective Function

The proposed cost function has three main components. The first component is the cost of purchasing electricity from the grid, which is used to supply the load demand and charge the battery. The component is the revenue generated from selling electricity to the grid. The third part is the wearing cost of hybrid system. The total function can be expressed as

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$$f = \sum_{j=1}^{N} \rho_j (P_{\text{G-B}(j)} + P_{\text{G-L}(j)}) \Delta t \\ - r_k \rho_k \sum_{j=1}^{N} P_{\text{B-G}(j)} \Delta t + \sum_{j=1}^{N} a(P_{\text{B-L}(j)} + P_{\text{B-G}(j)}) \Delta t + 24b \tag{6}$$

where r_k = 0.65 is the contracted ratio of the peak price ρ_k for selling power during the peak load period; a is the coefficient of battery wearing cost; and b is the hourly wearing cost of other components [24].

3.2 Constraints

The control variables in the objective function above have to satisfy the following constraints:

- Renewable output constraints:

The sum of instantaneous PV or WT power for charging the battery and for supplying the load must be less than the PV or WT output power generated:

$$P_{\text{PV-B}(j)} + P_{\text{PV-L}(j)} \leq P_{\text{PV}(j)} \tag{7}$$

$$P_{\text{WT-B}(j)} + P_{\text{WT-L}(j)} \leq P_{\text{WT}(j)} \tag{8}$$

- Power balance constraint:

The required load demand must be exactly satisfied by the total power of PV, WT, grid, and the battery. This can be expressed as

$$P_{\text{B-L}(j)} + P_{\text{G-L}(j)} + P_{\text{PV-L}(j)} + P_{\text{WT}(j)} \leq P_{\text{L}(j)} \tag{9}$$

Each power source is modeled to be controllable in the range of zero to their rated power for the 24-h period. Therefore, the variable limits are the output limits of these different power sources at any sampling interval j. These can be expressed as

- Control variables limits:

$$0 \leq P_{\text{PV-B}(j)} \leq P_{\text{PV-B}}^{\max} (1 \leq j \leq N) \tag{10}$$

$$0 \leq P_{\text{WT-B}(j)} \leq P_{\text{WT-B}}^{\max} (1 \leq j \leq N) \tag{11}$$

$$0 \le P_{\text{B-L}(j)} \le P_{\text{B-L}}^{\max} (1 \le j \le N) \tag{12}$$

$$0 \le P_{\text{G-B}(j)} \le P_{\text{G-B}}^{\max} (1 \le j \le N) \tag{13}$$

$$0 \le P_{\text{G-L}(j)} \le P_{\text{G-L}}^{\max} (1 \le j \le N) \tag{14}$$

$$0 \le P_{\text{PV-L}(j)} \le P_{\text{PV-L}}^{\max} (1 \le j \le N) \tag{15}$$

$$0 \le P_{\text{WT-L}(j)} \le P_{\text{WT-L}}^{\max} (1 \le j \le N) \tag{16}$$

$$0 \le P_{\text{B-G}(j)} \le P_{\text{B-G}}^{\max} (1 \le j \le N) \tag{17}$$

The available battery bank state of charge in any sampling internal must not be less than the minimum allowable and must not be higher than the maximum allowable state of charge. This can be expressed as

$$\text{SOC}^{\min} \le \text{SOC}_{(j)} \le \text{SOC}^{\max} \tag{18}$$

3.3 Optimal Control Method

An optimal control method is used to manage the power flows P_i in all the sampling periods over a 24-h period to minimize the daily electricity cost, Eq. (4), subject to constraints, Eqs. (6)–(18). Because the objective function and constraints are linear, this power flow control problem can be expressed as a linear programming problem as [25]

$$\min f(x), \text{s.t.} \begin{cases} Ax \le b \\ A_{\text{eq}} X = b_{\text{eq}} \\ l_{\text{b}} \le x \le u_{\text{b}} \end{cases} \tag{19}$$

where $f(x)$ represents the objective function; A_{eq} and b_{eq} are the coefficients associated with equality constraints; A and b are the coefficients associated with inequality constraints; l_{b} and u_{b} are the lower and upper bounds of variables.

4 Case Studies

4.1 Control System Settings

In this work, real daily load data and water velocity have been used as input to evaluate the performance of the system submitted to the developed optimal energy management system. These hourly data are available from Ref. [21].

The sizing of PV, WT, and battery bank is based on a sizing model in [26]. The parameters (size, initial costs) of this hybrid system are available from Ref. [21]. The simulation results will be discussed and categorized according to the behavior of the proposed grid-connected hybrid system under the different pricing periods in South Africa.

4.2 Household's Results of Optimal Control

A 24-h detailed load data, given in Fig. 3, is obtained from a typical household situated in the KwaZulu Natal Province at 30.6° latitude south and 29.4° longitude east. The hybrid system is designed in such a way to provide electricity for low consumption electrical appliances such as lights, TV, radio, laptop, fridge, kettle, cell phone chargers, iron, toaster, etc. When scrutinizing this load profile, one can notice a general pattern arising from the daily activities of the users which changes depending on different seasons of the year. The selected load demand from Ref. [21] reaches a peak demand of 8 kW in winter; therefore, the hybrid system must be able to adequately respond to this demand.

4.2.1 Power Flow Under Off-Peak Load Period

Figure 3 shows the load profile for the selected winter day. It can be observed that the demand is highly nonlinear; low during the night with high peaks in the morning and in the evening. The power flow on the battery and load side are provided in Figs. 4 and 5 respectively.

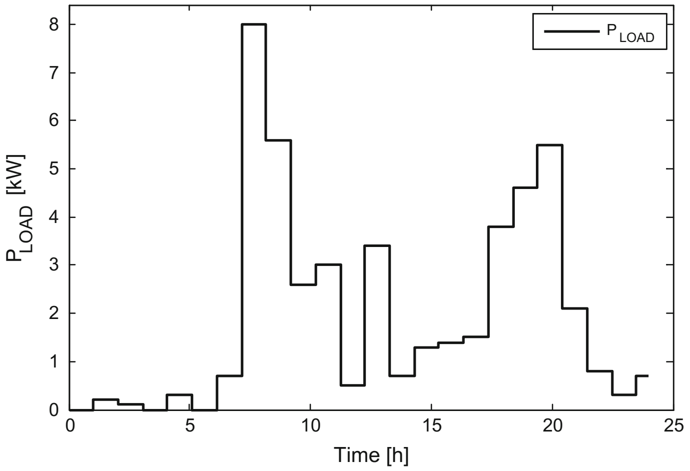

Fig. 3 Load profile (household case)

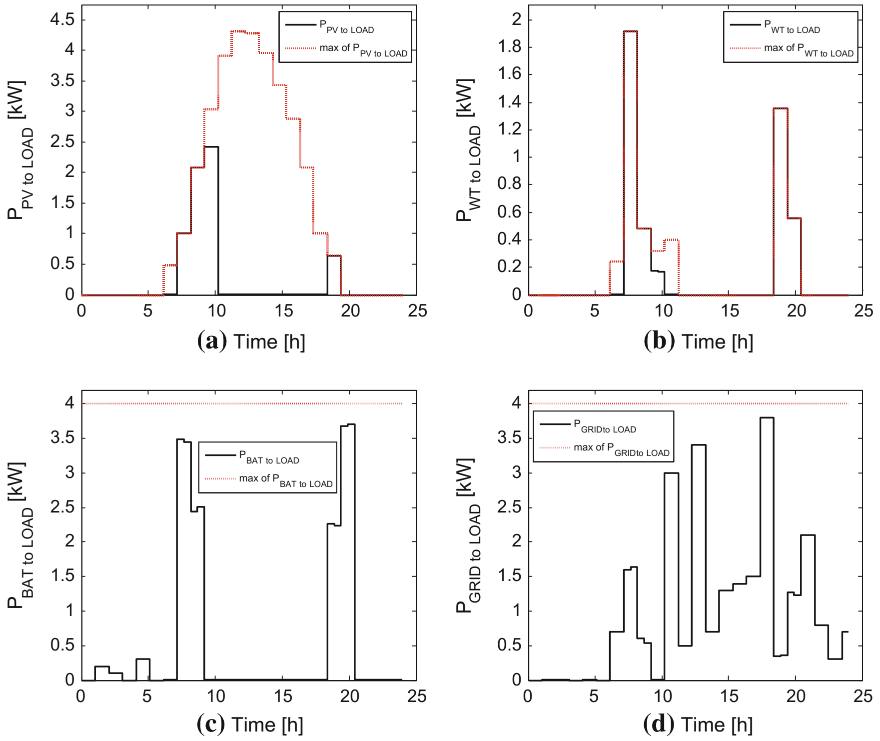

Fig. 4 Load-side power flow (household case)

The power provided to the load includes the batteries $P_{\text{B-L}}$, $P_{\text{G-L}}$, $P_{\text{PV-L}}$, and $P_{\text{WT-L}}$. During the off-peak period, only the battery system provides power to the load as illustrated in Fig. 4c; its corresponding state of charge decreases as shown in Fig. 5d. The PV, the WT, and the grid do not supply the load during that period as shown in Fig. 4a, b, d respectively.

There is enough power from the battery to supply the load and to be sold to the grid to generate revenue. Even if the price is low during this period, excess power not used to supply the load is sold to the grid as shown in Fig. 6.

4.2.2 Power Flow Under Standard Load Period

During the standard price period, although the battery system can fully satisfy the load demand, the grid power has been used as main supply to the load as well as to recharge the battery, which can be seen from Fig. 4c, d, respectively. There is a very small output from the PV and WT; these are used to recharge the battery as shown in Fig. 5a, b.

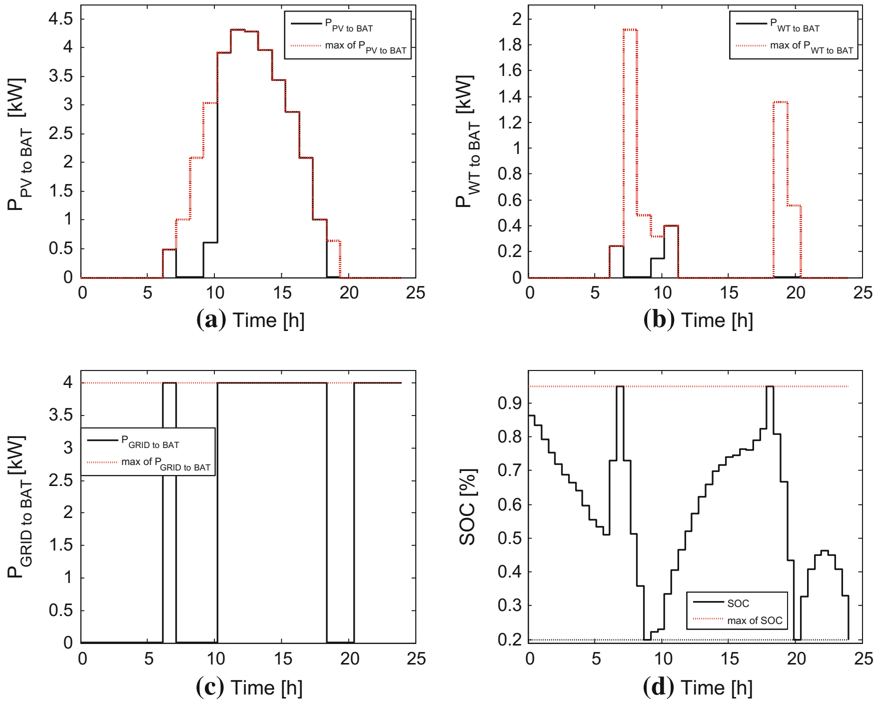

Fig. 5 Battery-side power flow (household case)

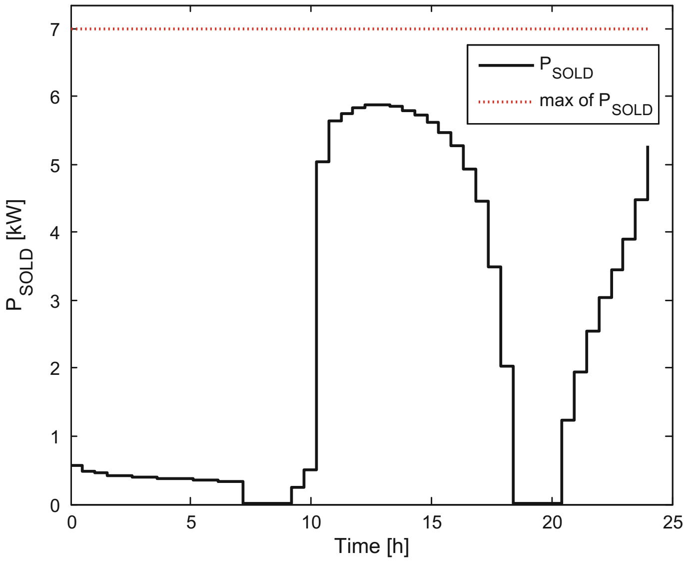

Fig. 6 Profile of power sold (household case)

4.2.3 Power Flow Under Peak Load Period

During the peak load period, the load is principally met by the power from the PV and WT, if there is any shortage in supply; the battery can be used in conjunction with the PV and WT (Fig. 4a–c). It can be seen from Fig. 5d how the state of charge decreases when the battery is giving power to the load. If the PV, WT, and battery cannot adequately respond to the demand, the grid can be used to balance the power needed to satisfy the load demand as shown in Fig. 4d. The power stored in the battery could have been sold to the grid during this period but because of the proposed hybrid system's size and the priority given to the load demand, there is almost no excess power to be sold during this peak power demand. Therefore, it can be seen from Fig. 6 that the power sold the grid at the end of this period is minimum.

4.2.4 Power Flow Under Off-Peak Load Period

During this off-peak load period, both the load demand and the price of electricity are low. Therefore, the power from the grid is used to principally supply the load and recharge the battery at the same time. This can be seen when looking at Fig. 4d and Fig. 5c respectively. Figure 4b, c confirms that no power from the PV or the battery is used to supply the load; this power is sold to the grid as illustrated in Fig. 5d.

4.2.5 Power Flow Under Peak Load Period

During this second peak load period, there is a very small amount of power generated by the PV. Most of the power consumed by the load is coming from the WT battery and the grid is shown in Fig. 5b–d. There is no power sold to the grid during this high-demand pricing period as illustrated in Fig. 6.

4.2.6 Daily Income Generated

On the selected day, if the load demand is supplied by the grid only without the PV, WT, and battery storage system, the daily electricity cost would be $4.32. When optimally operating the grid-connected hybrid system, the daily income generated by selling electricity to the grid is $20.79. In other words, when making the balance between what is purchased from the grid and what is sold to the grid, the customer can earn $16.47. This income is a function of the size of the hybrid system's components, the battery initial state of charge, as well as on the load profile.

4.3 *Base Transceiver Station's Results of Optimal Control*

The base transceiver station selected for this study is situated in the Western Cape region at 32.8° latitude south and 17.9° longitude east. The energies needed by the BTS communication equipment and the cooling system used to remove heat from the cabin are given in Ref. [27]. The load profile resulting from the daily power demand of the radio, power conversion, antenna, transmission, security lights, and cooling equipment at the base station site is given in [28]. It is noticeable from this table that except for the auxiliary equipment such as air conditioning which is running during the day for only 6 h (11:00–17:00 h), and the security lights for 11 h throughout the night (19:00–6:00 h), the rest of the BTS communication equipment is running for 24 h non-stop. However, during winter, the air conditioning is running for only 2 h (13:00–15:00 h) and the security lights for 13 h (18:00–7:00 h). This load (Fig. 7) has been selected because of its pattern which is different than the one from the household; this will induce a different response of the hybrid system operation energy scheduling. The power flows on the battery and load side are provided in Figs. 8 and 9, respectively.

4.3.1 Power Flow Under Off-Peak Load Period

During this off-peak period, the battery system and the grid provide power to the load as illustrated in Fig. 8c–d, respectively. Therefore, there is no excess of energy from the renewable components to be sold to the grid during this period as shown in

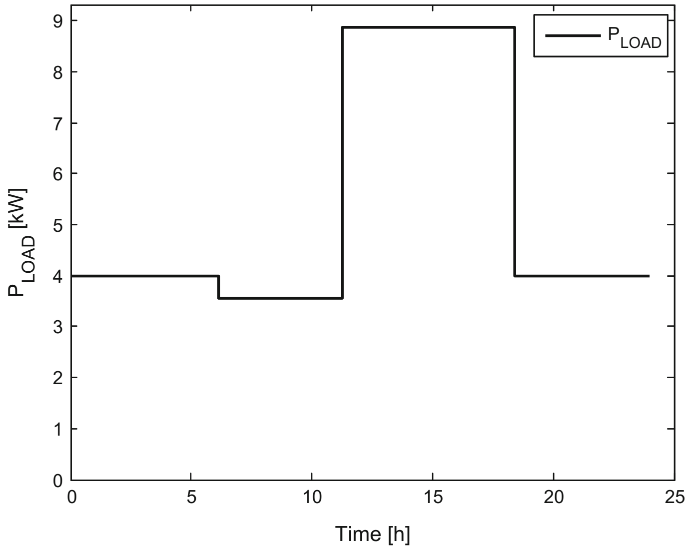

Fig. 7 Load profile (BTS case)

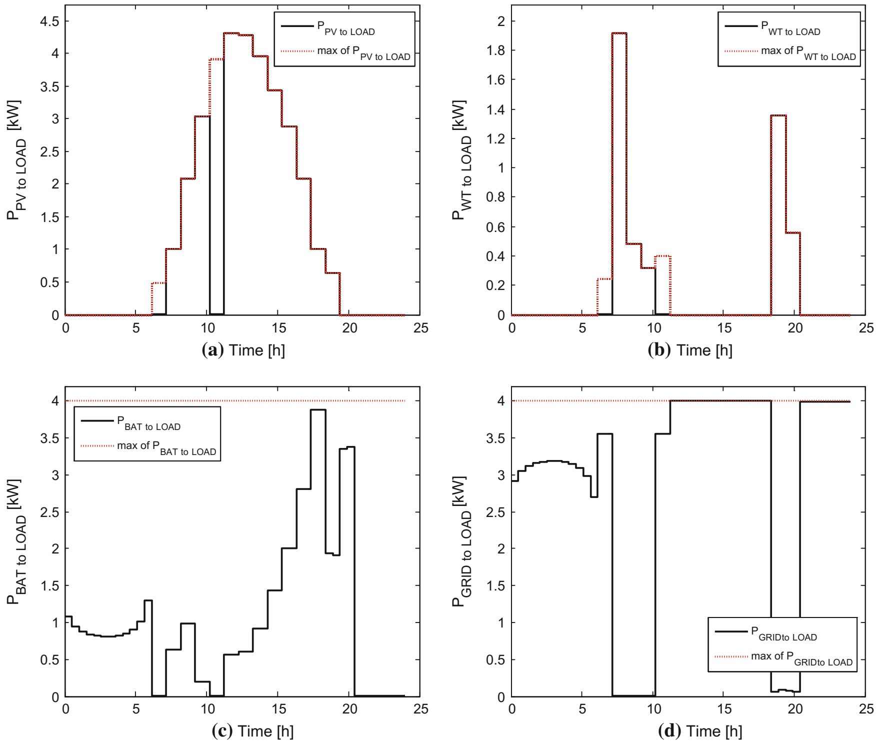

Fig. 8 Load-side power flow (BTS case)

Fig. 10. There is no power generated from the PV and WT because of the lack of resources as shown in Fig. 8a–b.

4.3.2 Power Flow Under Standard Load Period

During the standard price period, the powers from the PV, WT, and the grid are used to recharge the battery as shown in Fig. 9a–c; this is done so that there can be enough power stored to be for sold during the coming peak period. The load is exclusively supplied by the grid as shown in Fig. 8d.

4.3.3 Power Flow Under Peak Load Period

During the peak load period, the demand is primarily satisfied by the PV and WT as shown in Fig. 8a–b; any deficit of power demand is then balanced by the battery and the grid. There is no power sold to the grid because there is no excess of energy and because of the priority given to supply the load by the PV, WT, and the battery;

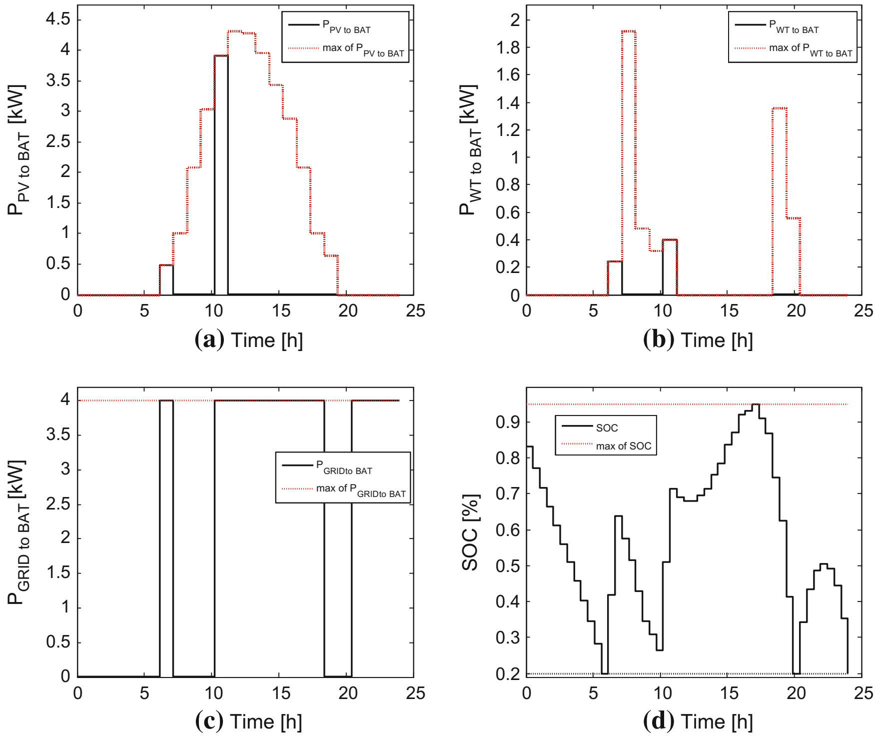

Fig. 9 Battery-side power flow (BTS case)

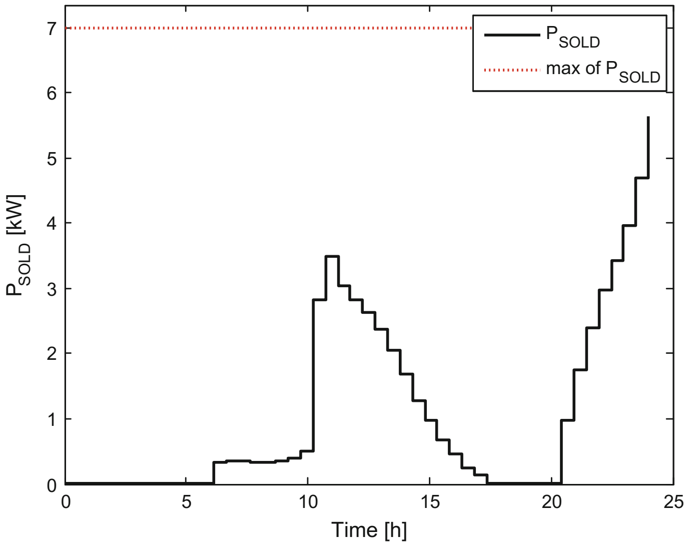

Fig. 10 Profile of power sold (BTS case)

the excess of energy from the hybrid system to be sold to the grid during this period is minimal as shown in Fig. 10.

4.3.4 Power Flow Under off-Peak Load Period

During this period the cost of electricity from the grid is low; therefore, the PV, WT, and the grid are used to supply the load demand as shown in Fig. 8a, b, d, respectively, and the excess of power from the PV and WT is sold to the grid through the battery as shown in Fig. 10. This load demand is supplemented by an increasing contribution from the battery in the afternoon toward the evening, due to the shortage of the output power of the PV and WT; this can be seen from Fig. 8a, b.

The battery is being recharged by the grid only and its corresponding state of charge increases as shown in Fig. 9c–d, respectively.

4.3.5 Power Flow Under Peak Load Period

During this second peak price period, all the power generated by the PV, WT system, and battery with as small contribution of the grid is used to supply the load as shown in Fig. 8a–d. There is no power used to either recharge the battery or supply the load as shown in Fig. 9a–c.

4.3.6 Daily Income Generated

If the BTS demand is supplied by the grid only without the PV, WT, and battery storage system, the daily electricity cost would be \$12.69. When optimally operating the grid-connected PV, WT hybrid system, the daily electricity cost is reduced to 5.29\$. In other words, when making the balance between what is purchased from the grid and what is sold to the grid, the income generated by selling electricity to the grid is \$7.

5 Chapter Summary

In this chapter, demand-side management has been applied in the optimal energy management of grid-connected PV–WT–battery hybrid system. The Time-of-Use operating tariff with power selling to the grid has been studied for energy management in this work. A model for decreasing electricity charge at the consumer's side has been developed. The simulation results of two case studies in South Africa have demonstrated that the developed optimal operation model for the hybrid system results in the maximal use of PV, WT, and battery storage system. The simulation results highlight the important role played by the battery which is storing power from the utility during off-peak periods and providing power to the load during peak periods. Consequently, by optimally operating the hybrid system, the load consumes nominal amount of power from the utility and the consumers can generate income by selling electricity to the grid. This income is a function of the size of the hybrid system's components, the battery initial state of charge, as well as on the load profile. It has also been demonstrated that optimal control is a powerful control method for power flow management in DSM.

For future work, Model Predictive Control will be developed to handle the control when the hybrid system experiences disturbances in PV output and load demand. Also different load patterns as well as different renewable energy sources will be considered.

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