Demand Side Management of a grid connected PV-WT-Battery hybrid system

S.F Phiri and K. Kusakana

Abstract— Due to technological developments, some isolated areas, where consumers were supplied with electricity using standalone hybrid systems, are currently being connected to the grid. The new problem induced by these advancements is to find how to efficiently operate these grid-connected systems.
The present paper proposes a multi-objective energy management model in order to optimize the short-term operation of a grid-connected hybrid system supplying an industrial load while participating to the Time of Use Demand Side Management program.
The main purpose of the developed model is to minimize the operation cost of a proposed grid-connected hybrid energy system consisting of a photovoltaic unit, a wind unit and a battery storage system while optimizing the system's power flow considering the different component's operational constraints. The simulations have been performed using "linear programming" implemented in Matlab. The simulation results demonstrate that the developed model can assist the hybrid system in reducing the operation cost and allow consumers to generate substantial income by selling power to the grid.

***Index Terms*— Renewable energy, grid connected, Time of Use, energy management, Demand Side Management**

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]. 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 such as Peak shaving [10], Direct load control [11], Capacity market programs [12] or Time-of-use (TOU) [13] can be implemented when renewable energy systems are connected to the grid.

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 back-up usage without any contribution of DSM program [17-20].

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Unlike the above-mentioned papers, the focus of this paper 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 THE GRID CONNECTED PV-WIND-BATTERY HYBRID SYSTEM

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 feed 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_{PV-B} and P_{WT-B} are the renewable powers used for charging the battery; P_{B-L} is the discharging power of battery for load demand; P_{G-B} is the grid power for charging the battery; P_{G-L} is the grid power for load demand; P_{PV-L} and P_{WT-L} the renewable powers directly supplying load demand; P_{SOLD} is the battery discharge for selling power to the grid.

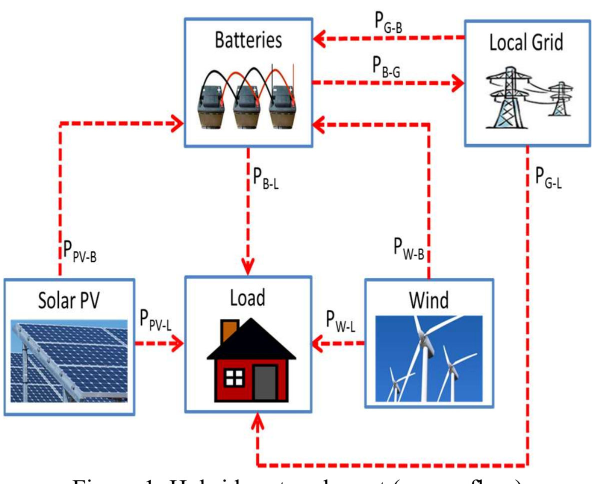

Figure 1: Hybrid system layout (power flow)

2.1 Photovoltaic system

When light strikes a silicon, gallium arsenide or cadmium sulphide 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 at a temperature of 25°C and irradiance of 1000W/m^2. The output power of the solar PV system can be expressed as follows [21]:

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

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 then electrical energy [21]. The power output (P_{WT}) of the wind system within a sampling time interval can be expressed as is expressed as:

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

Where: ρ_a is the air of water (1,225kg/m^3); $C_{p,W}$ 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 WT, 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]:

$$SOC_{(j+1)} = (1-d_b) \times SOC_{(j)} + \frac{\Delta t \times \eta_C}{E_{nom}} \times (P_{PV-B(j)} + P_{WT-B(j)} + P_{G-B(j)} - \frac{\Delta t}{E_{nom}\eta_D} \times (P_{B-L(j)} + P_{SOLD(j)}) \tag{3}$$

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.

3 OPTIMIZATION MODEL AND PROPOSED OPTIMAL CONTROL METHOD

3.1 DSM model of the grid connected PV-WT-Battery hybrid system

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 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]:

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

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

3.2 Objective function

The operation costs of the proposed system are the costs experienced after the system has been designed and installed. These costs are typically calculated a specific daily, monthly or yearly time interval and then discounted for the project life. The long-term running costs of the system is composed of maintenance, component overhaul and replacement costs. These costs are basically estimated and are therefore more difficult to determine than the initial capital costs. In the concept of smart-grid, the focus is on the best decision to be taken for given short-term operating condition. Therefore; the operation costs of the battery and PV, WT are negligible during the daily time interval considered.

The proposed cost function aims to minimize the cost of purchasing electricity from the grid, which is used to supply the load demand and charge the battery; while maximizing the revenue generated from selling electricity to the grid. This multi-objective function be expressed as:

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

Where r_k is the contracted ratio of the peak price ρ_k (between the seller and the utility company) for selling power during the peak load period [24].

3.3 Constraints

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

3.3.1. 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 total PV or WT output power generated.

$$P_{PV-B(j)}+P_{PV-L(j)}\le P_{PV(j)} \quad (7)$$

$$P_{WT-B(j)}+P_{WT-L(j)}\le P_{WT(j)} \quad (8)$$

3.3.2. 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:

$$P_{B-L(j)}+P_{G-L(j)}+P_{PV-L(j)}+P_{WT(j)}\le P_{L(j)} \quad (9)$$

3.3.3. Variables limits

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

$$0\le P_{PV-B(j)}\le P_{PV-B}^{\max}\quad(1\le j\le N) \quad (10)$$

$$0\le P_{WT-B(j)}\le P_{WT-B}^{\max}(1\le j\le N) \quad (11)$$

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

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

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

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

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

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

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:

$$SOC^{\min}\le SOC_{(j)}\le SOC^{\max} \quad (18)$$

3.4 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, Eq. (6) to (18). Because the objective function and constraints are linear, this power flow control problem can be expressed as a linear programming problem as [25]:

$$\min\ f(x), s.t.\begin{cases}Ax\le b\\ A_{eq}X=b_{eq}\\ lb\le x\le ub\end{cases} \quad (19)$$

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 STUDY

4.1 Input data and control system settings

In this work, a representative industrial daily load profile (Fig.2) and renewable energy resources have been used as input to evaluate the performance of the system submitted to the developed optimal energy management system. When scrutinizing this load profile, one can notice a general pattern arising from the daily activities of the users which can change depending on different seasons of the year. 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 of this hybrid system are available from our previous work [21]. The diesel

generator is now replaced by the grid, from greener and cheaper power production.
The simulation results will be discussed and categorized according to the behavior of the proposed grid-connected hybrid system under the different pricing periods.

Table 1: Simulation parameters

Item	Figure
Sampling time (Δt)	30 min
Battery nominal capacity	5.6 kWh
Battery maximum SOC	95%
Battery minimum SOC	20%
Battery initial SOC	90%
Battery charging efficiency	85%
Battery discharging efficiency	95%
PV system rating	4.5 kW
Wind system rating	2 kW

4.2 Simulation results and discussion

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 9kW; therefore, the hybrid system must be sized to adequately respond to this demand.

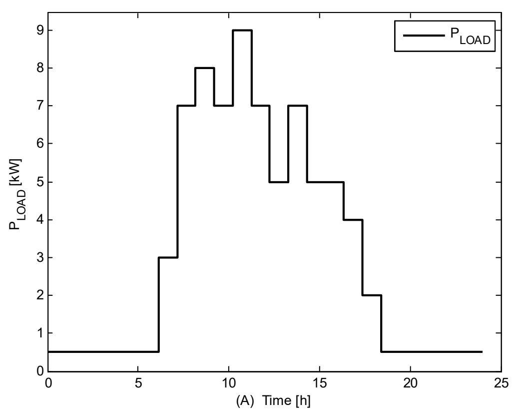

Figure 2: representative industrial daily load profile

i. Power flow under off-peak price period [0, 6) U (22, 24]

The power provided to the load includes the battery P_{B-L}, P_{G-L}, P_{PV-L} and P_{PWT-L}. During this off-peak period, only the battery system provides power to the load as illustrated in Fig. 3(C); its corresponding state of charge decreases as shown in Fig. 4(D). The PV, the WT and the grid do not supply the load during that period as shown in Fig. 3(A), Fig. 3(B) and Fig. 3(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. 5.

ii. Power flow under standard price period [6, 7)

During this 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. These can be seen from Fig.3 (C) and Fig.3 (D) respectively. There is a very small output from the PV and WT; these are used to recharge the battery as shown in Fig. 4(A) and Fig. 4(B).

iii. Power flow under peak price period [7, 10)

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. 3(A), Fig. 3(B), Fig. 3(C)). It can be seen from Fig. 4(D) 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. 3(D). 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 for Fig. 5 that the power sold the grid at the end of this period is minimum.

iv. Power flow under off-peak price period [10, 18)

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. 3(D) and Fig.4(C) respectively. Fig. 3(B) and Fig. 3(C) confirm that no power from the PV or the battery is used to supply the load; this power is sold to the grid as illustrated from Fig. 4(D).

v. Power flow under peak price period [18, 20)

During this second peak load period, the load demand is low and 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, the battery and the grid as shown in Fig. 3(B) and Fig. 3(C). Most of the power sold to the grid during this high demand pricing period come from the battery as illustrated from Fig. 4(D).

vi. Power flow under standard price period [20, 22)

During this second standard price period, the grid power is used as main supply to the load as well as to recharge the battery. These can be seen from Fig.3 (D) and Fig. 4(C) respectively. There is no output from the PV and WT.

vii. Power flow under off-peak price period (22, 24]

During this second peak price period, the load is supplied by the power from the grid. All the power from the battery is sold to the grid as shown in Fig. 3(D), Fig. 4(D) and Fig. 5.

viii. Daily income generated

On the selected day, if the proposed industrial 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 power sold to the grid add up to electricity to the grid is \$16.41. 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 \$12.09. This income is function of the size of the hybrid system's components, the battery initial state of charge as well as on the load profile.

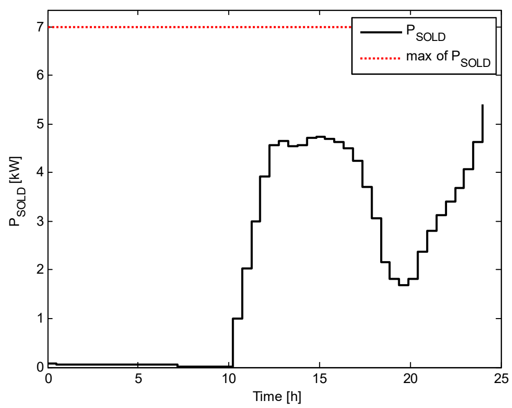

Figure 5: Profile of power sold to the grid

5 CONCLUSION

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 based on a representative industrial daily load profile 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 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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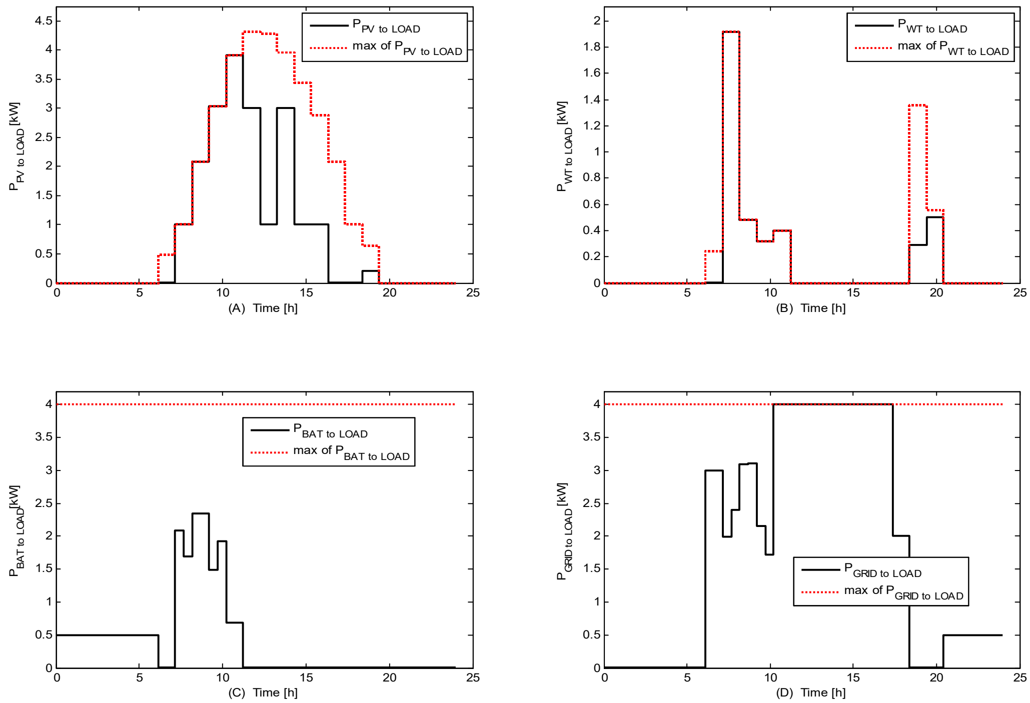

Figure 3: Load side power flow

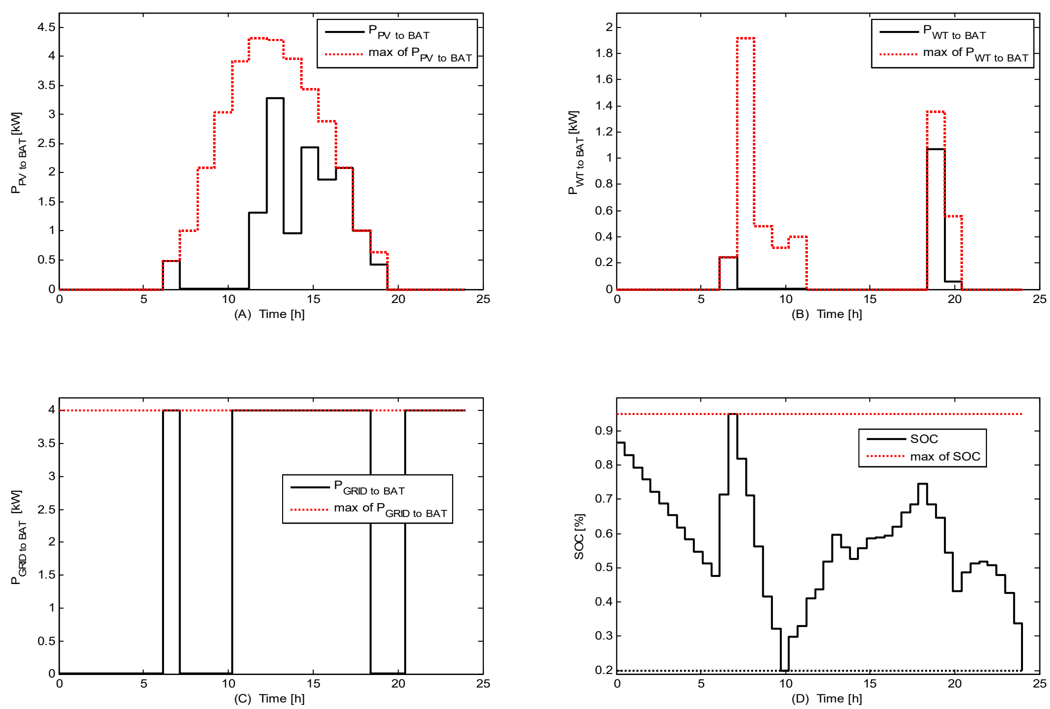

Figure 4: Battery side power flow (Household case)

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