# Optimal energy control of a grid-connected solar-wind-based electric power plant applying the time of use tariff

By

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# Declaration

I, Sibongile Florina Phiri (student number: [redacted]) hereby declare that this research project which has been submitted to the Central University of Technology, Free State for the degree of MASTER OF ENGINEERING IN ELECTRICAL ENGINEERING, is my own independent work; complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State, and has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

Student Signature:

Date: 2016-10-01

# Dedication

I dedicate this research to my family, friends and my son as the source of inspiration in my life and to God because I would never have got this far without Him MY Almighty GOD.

# Acknowledgements

I owe a debt of gratitude to my supervisor, Dr K Kusakana and co-supervisor, Mr. SP Koko for their continuous support in this study. They made this research possible through the provision of a continuous and indispensable guidance during my research and writing processes and along the ever changing road in research.

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# Abstract

Further combination of renewable sources is needed for improving grid economical management. Therefore, a good energy management of the hybrid renewable plant is more important to make the system more economically feasible. This study will promote to an optimal operational efficiency of a hybrid renewable energy plant. The initial objective will be minimizing the system operation and maintenance costs. Secondly maximizing the sales of energy to the grid based on the time-of-use tariffs scheme.

Both wind and solar have tremendous potential for fulfilling the world's energy needs. Renewable generation, especially from wind and solar concepts are critical technologies needed to address global warming and related issues. Solar and wind power plants exhibit changing dynamics, nonlinearities, and uncertainties challenges that require advanced control strategies to solve effectively. The use of more efficient control strategies would not only increase the performance of these systems, but would also increase the number of operational hours of solar and wind plants and therefore reduce the cost per kilowatt-hour (KWh) produced.

The key challenge is to reduce the cost of renewable energies to reasonably priced levels. Control and related technologies will be necessary for solving these complex problems.

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# Abbreviations

| | |
|---|---|
| BCS | Battery charging station |
| BESS | Battery energy storage system |
| BMS | Battery management system |
| COE | Cost of energy |
| $CO_2$ | Carbon dioxide |
| DSM | Demand side management |
| EMS | Energy management system |
| EPBT | Energy payback time |
| EBB | Electricity buy-back |
| FIT | Feed-in Tariff |
| FC | Fuel cell |
| HRES | Hybrid renewable energy system |
| HOMER | Hybrid optimisation modelling software |
| HOGA | Hybrid Optimization by Genetic Algorithms |
| KWh | Kilowatt-hour |
| LEC | Levelized Electricity Cost |
| NPV | Net Present Values |
| MATLAB | Matrix laboratory |
| PCC | Point of common coupling |
| PMS | Power management system |
| PV | Photovoltaic |
| RE | Renewable energy |
| REB | Reduce electricity bill |

| | |
|---|---|
| SOC | State of charge |
| TOU | Time of use |
| RTP | Real-time pricing |
| WT | Wind turbine |
| WP | Peak Watts |

# CHAPTER 1: INTRODUCTION

## 1.1. Background

Renewable energy is now seen as an effective alternative source of energy in order to meet the exponential growth of the world's energy demand. With the increase of the price of fossil fuel due to its shortage and emission costs, more integration of renewable sources is needed for better grid economical management [1]. The load demands of the consumers will generally vary according to their needs. This variation is independent from the intermittency characteristics of renewable power generation. The hybrid renewable systems are becoming important energy source by improving the operational efficiency reliability of the whole system and increase the availability of energy supplied to a remote load.

The hybrid renewable system can be connected to the grid to improve the reliability of the network or some time to improve its power in the peak time. The presence of wind source, photovoltaic source and the storage in a hybrid system can lead to a complex system energy management process in the renewable energy plant since its dynamics (charging and discharging states) needs to be carefully taken into account during the system operation [2] and [3]. It is known that the initial cost of renewable energy systems is generally relatively high if the optimal sizing of the system is not taken into account during the design period. Optimization for both operation control and design must be carefully considered to minimize the life cycle cost of the hybrid renewable system. If the optimal operation is not considered, this becomes also another challenge due to the variability of the energy sources that the hybrid system depends on.

In case where the hybrid system is connected to the national grid, some restrictions may be imposed by the grid operators. Hence, a good energy management of the hybrid renewable plant is of great importance to make the system more economically feasible. Based on the aforesaid, this research is dedicated to an optimal operational control of the hybrid renewable energy plant after its optimal configuration (sizing) has been obtained. A multi-objective problem will then be considered. The first objective of this study is to minimize the system's operational cost while the second objective is to maximize the sales of energy to the grid during peak demand based on time-of-use (TOU) tariffs scheme. Constraints related to the power quality, continuity of the plant power supply, grid connection restriction and equipment safety will be taken into consideration.

## 1.2. Problem Statement

Hybrid renewable energy systems containing wind, solar, and battery bank can provide a variety of benefits including low operation cost if they are properly managed when connected to the grid. The load and the renewable resources (solar and wind) are varying continuously. However, the variable load demand must always be met by the supply and the excess of energy generated by the hybrid system has to be sold to the grid using the TOU tariff which is also variable (imposed by the grid).

Therefore, an optimal management action must be continuously taken so that the operation of the grid connected hybrid system may not lead to poor economic performance (High operation cost and low income from selling to the grid).

## 1.3. Objectives of the Study

The present work focuses on the optimal operation control of a solar photovoltaic-wind turbine-battery based (PV-WT-Battery) hybrid power plant connected to the national grid. The objectives of this study are as follows:

- To develop a mathematical model that can minimize the operation cost of the proposed grid connected system by using energy management concepts to maximize the energy sold while minimizing the power purchased from the grid based on the TOU tariff.
- Assess the financial impact of different demand sectors (residential, commercial and industrial) on the grid-connected hybrid system`s optimal energy management under Time of Use Tariff using the developed model.
- To assess that in which of the South Africa demand sectors (domestic, commercial, and industrial) can more income be generated when using grid-connected hybrid system for the same daily load energy consumption.

## 1.4. Research Methodology

To achieve the above-mentioned objectives, the following methodology will be adopted:

### *1.4.1. Literature Review*

A thorough review on literatures related to wind, solar, battery storage system based on optimal control will be carried. The emphasis will be on grid connected renewable energy systems and TOU pricing tariff scheme.

### *1.4.2. Resources and load assessment*

The residential, commercial and industrial load curves will be used to estimate the daily energy consumptions. The three load profiles will be standardised to have the same energy daily demand for proper comparison purpose.

### *1.4.3. System Modelling*

The mathematical model for the optimal operation control of the proposed grid connected hybrid system will be developed. The linear programming method will be used to solve different constraints.

### 1.4.4 *Simulation*

MATLAB software was used to apply the developed model to minimize the cost and to maximum the energy sales to the grid.

### *1.4.5 Result discussion*

The proposed PV-WT-battery based hybrid system will be used to supply residential, commercial and industrial load profiles, respectively. Hence, the results will be used to compare the energy sales to the grid for each load profile when applying the TOU tariff.

## 1.5. Hypothesis

The development of the optimization model will control the operation of the proposed PV-WT-battery hybrid system:

- To enable the consumer to achieve energy cost savings and to maximize the renewable energy sales to the grid.
- For the same energy, different demand sector will have different influence of the hybrid system cost savings.

## 1.6. Limitation of the Study

The study has been conducted with the following limitations:

- This study focuses only on the development of an optimal energy control model and simulation for a grid-connected PV-WT-Battery based electric power plant applying the TOU pricing tariff scheme.
- The study will focus on residential, commercial and industrial load demand profiles only.
- The work will be limited to mathematical modeling as well as simulation.

## 1.7. Contribution to Knowledge

The development of a model to optimally control the operation of the PV-WT-battery based hybrid system to minimize the hybrid system's operation costs and to maximize the renewable energy sales to the grid.

The analysis of which demand sector can be more promoted in terms of selling power to the grid for the South African case.

## 1.8. Publication and Presentation during the study

During the course of this research work, the following paper was presented and published: S.F. Phiri, K. Kusakana, "Demand Side Management of a Grid Connected PV-WT-Battery Hybrid System" International Conference on the Industrial and Commercial Use of Energy (ICUE 2016), pp. 45-51, 15 – 17 August 2016, Cape Town South Africa.

## 1.9. Outline of the Dissertation

This dissertation has been arranged into chapters as follows:

Chapter 1 presents an introduction to the dissertation which includes background, problem statement, objectives, methodology, hypothesis, delimitation of the study, as well as the research outputs.

Chapter 2 reviews the literature related to wind, solar, battery storage and also on grid connected systems and TOU tariff.

Chapter 3 discusses different system components of the proposed grid-connected PV-WT-battery based hybrid system and their operations. It also covers the development of the proposed optimal energy management model for controlling the operation of the proposed grid-connected hybrid system using MATLAB software.

Chapter 4 presents the simulation results of the developed optimal energy management model in order to show the technical advantage/benefit of the proposed model.

Chapter 5 presents the conclusion and also suggests future areas of research to be carried.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Introduction

Renewable energy is generally defined as energy that is generated from resources which are naturally replenished on a human timescale such as sunlight, wind and rain. These resources often generate power during off-peak periods or when demand for energy is low. They can be used to help with the reduction of greenhouse gases leading to global warming around the world. However, the use of a single technology based renewable energy system does not guarantee a reliable power supply due to the intermittent nature of renewable energy sources. Hybrid renewable energy system is a solution to enhance the reliability. It is a guaranteed clean and reliable source of energy especially when combined with energy storage device.

A hybrid power system can provide a variety of benefits including improved reliability if they are properly operated in the electrical distribution system. Loads and hybrid energy sources can be disconnected or reconnected to a grid system with minimal disruption. Proper planning is always required when a grid-connected hybrid system is to be implemented in an electrical distribution system. Grid-connected hybrid power plant minimizes the chances load shedding by injecting more power into the grid.

This study considers the hybrid system consisting of the combination of a PV system, wind turbine system and battery bank connected to the grid. The load demand will be met by the output power from the hybrid system and/or by the grid power. This chapter gives a brief review on renewable energy sources such as wind and solar as well as battery storage technologies. It also presents various studies that concentrated on optimal energy control of different hybrid systems as well as the demand side management (DSM) using TOU tariff scheme as imposed by the utility.

## 2.2. Solar PV as a Renewable Energy Source

### *2.2.1. Introduction*

According to Warner [4], solar energy can be regarded as provision of cost-effective related benefits to both the customers and electric utility as well as the environmental benefits in South Africa. The photovoltaic generation system is one of the most promising renewable energy sources, as it has the advantages of being safe, inexhaustible, pollution free and can also require little maintenance. The photovoltaic (PV) systems are used today in many applications which can be classified into two main categories: the stand alone PV system and the grid connected PV system. In remote rural areas where the grid connection is impossible, the stand-alone PV systems are used with a battery bank for the energy storage. On the other hand, to answer the need for alternative energy, the grid connected PV systems are used. Mellit et al. [5] have reviewed various techniques for sizing PV systems, i.e. stand-alone, hybrid off-grid and grid-connected systems. They concluded that when all required data is available, the conventional sizing methods (empirical, analytical, and numerical) present good solutions.

Solar systems are accessible as long as there is sunlight and they can be connected in all areas [6-7]. The solar cell units convert solar energy into electric power during the day. Some of the energy can be used to supply the DC/AC load when the energy is accessible and the remainder is used to charge the battery packs. So that the battery packs will supply power to the dc/ac load when the sun is inaccessible, or when the cells require maintenance the battery packs will be able to provide a large momentary current in order to start equipment such as electric motors. It has ability to meet the summer peak demand when the utility company applies a tariff structure that has seasonal TOU tar periods.

### *2.2.2. Description of solar PV system*

The output power of the PV array feeds customers' demand directly. If the demand is less than the PV's output, the surplus PV power will be charged into the battery bank. If the demand is larger than the PV's output, the deficient power will be covered by the battery or the grid.

When light strikes a silicon, gallium arsenide or cadmium sulphide cell an electric current is generated through the photovoltaic effect [8]. 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 [9]:

$$P_{pv} = A_{pv} \times \eta_{pv} \times I \times f(t) \tag{2.1}$$

where:

$A_{pv}$ is the total area of the photovoltaic generator (m$^2$),

$\eta_{pv}$ is the module efficiency,

$I$ is the hourly irradiance (kwh/m$^2$) and

$f(t)$ is the radiance density.

## 2.3. Wind as a Renewable Energy Source

### *2.3.1. Introduction*

South Africa has improved from zero to hero in increasing the share of RE in the country's energy mix. The achievement of the national objective of 30% clean energy by 2025 has been created, and South Africa is well on its path towards this risky goal. Enos stated that wind energy is another renewable source of energy which is generated by the action of moving wind or breeze here in South Africa [10]. Although wind energy is also used to generate mechanical energy in wind mills, wind pumps, ships with sails and similar, the main utility of wind energy is generation of electricity via special wheels known as wind turbines. In spite of the fact that it is a renewable source of energy and apparently appears to be "greener" than other more conventional forms of energy, there are actually several disadvantages of wind energy discussed in ref [10]. Wind turbines have proved to require low maintenance; they also have low pollution [10].

### *2.3.2. Description of a wind energy system*

Wind energy systems convert the kinetic energy of moving air into mechanical then electrical energy [11]. The power output (PWT) of the wind system within a sampling time interval can be expressed as is expressed as:

$$P_{WT} = \frac{1}{2} \times \rho_a \times A_{WT} \times C_{P^{WT}} \times \eta_{WT} \times V_a^3 \times f(t) \tag{2.2}$$

Where:

$p_a$ is the air velocity (1.225kg/m$^3$);

$A_{WT}$ is the wind turbine swept area ($m^2$);

$C_{PwT}$ is the coefficient of the wind turbine performance;

$\eta_{WT}$ is the combined efficiency of the wind turbine and the generator;

$V_a$ is the wind velocity (m/s); and

$f(t)$ is the wind probability density function.

For wind power plants, using ESS for energy time shifting may result in higher profits thus making wind integration more attractive [12 - 13]. This is done by storing the energy when the price of the utility energy is less and then discharge the stored energy during peak demand. Hence, this become beneficial since the wind energy is stored during low price periods and used during high price periods. This will increase the profit due to energy sales to the grid and can also reduce the power loss and increase the level of the voltage in different bus of the grid network.

## 2.4. Battery Storage Devices

### *2.4.1. Introduction*

Battery storage ensures the smooth operation of a grid by acting as an energy reserve to cater to scenarios leading to abrupt power shortage. Several different battery technologies are being used for today's grid installations which include sodium sulphur batteries, redox flow batteries, lithium ion and lead acid batteries [14-16]. The addition of batteries to grid-connected domestic PV systems has been examined for its ability to maximise the financial return of the system. The purpose of the battery is to charge during the day using cheap surplus PV generation, and to discharge during the evening to avoid expensive imports from the grid.

Different kinds of batteries that are mostly required for hybrid system and their advantages and disadvantages as well as their applications have been discussed in ref [17-18]. Battery ageing is the phenomenon which causes the capacity of the battery to decrease most and the internal resistance to increase. Battery ageing is a complex process and it is influenced by many external parameters such as:

- Sulphatation that takes place when a battery is kept in a state of low charge for a longtime [17].
- Overcharging can also cause capacity reduction [14].
- Corrosion of the electrodes, which increases the internal electric resistance of the battery [15].

### *2.4.2. Description of a 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 using first order difference equation as show below [19-20]:

$$SOC_{(j)} = SOC_{(0)} + P_{in(j)} \frac{\Delta t \times \eta_C}{En} - P_{out(j)} \frac{\Delta t}{En \times \eta_D} \tag{2.3}$$

Where:

$P_{in(j)}$: is the power entering the battery at any sampling interval $j$,

$P_{out(j)}$: is the power going out of the battery at any sampling interval $j$,

$E_n$ is the minimal energy from the battery system, and

$\eta_c$ and $\eta_D$ are the coefficient of charging and discharging efficiency of the battery.

Therefore, the battery storage will play an important role not only to enhance the demand response, but it can also respond effectively to time-varying electricity prices by charging battery during low price periods and discharging it during peak hours. The battery state of charge (SOC) changes dynamically due to possible charge process injected by the availability of renewable energy resources and / or utility grid. It changes also due to the discharge process caused by customer usage.

Some of the parameters used to determine the optimized solution for the economic analysis are the capitalized cost, net present value, market rates and tax credits. Table 2.1 shows the capital cost analysis of different battery energy storage systems (BESS) as well as their efficiencies and cycles. The project life of these batteries considered in this research is estimated to be 20 years [21]. Table 2.2 shows the comparison of other major parameters.

Table 2.1: capital cost analysis based on battery technology [21]

| *Battery technology* | *Power sub-system cost($/kW)* | *Energy storage sub-system cost($/kWh)* | *Round-trip efficiency (%)* | *Cycles* |
|---|---|---|---|---|
| Advanced lead-acid | 400 | 330 | 80 | 2000 |
| Sodium/Sulphur | 350 | 350 | 75 | 3000 |
| Lead-Acid battery with carbon enhanced electrode | 400 | 330 | 75 | 20000 |
| Zinc/Bromine | 400 | 400 | 70 | 3000 |
| Vanadium redox | 400 | 600 | 65 | 5000 |
| Lithium ion | 400 | 600 | 85 | 4000 |

Table 2.2: Comparison of the major parameters for battery energy storage [21]

| *Battery parameter* | *Lead-acid* | *Nickel-Iron* | *Zinc-Chlorine* | *Sodium sulphur* | *Lithium-ion* |
|---|---|---|---|---|---|
| Nominal cell voltage(V) | 2 | 1.4 | 2.12 | 1.7 | 3.7 |
| Specific energy(Wh/kg) | 30–50 | 30–55 | 25 | 150–240 | 110–160 |
| Energy density(Wh/L) | 100 | 60–110 | NA | 150–250 | 245–430 |
| Round trip efficiency (%) | 70–80 | 65–85 | 75–86 | 85–90 | 95–98 |
| Cycle Life depth of discharge (DoD) | 200–300[a] | 3000–4000[b] | 1500[c] | 2500[d] | 3000[e] |
| Self-discharge (%/month) | 5 | 20-40 | Negligible | Negligible | 2-10 |

(a) Cyclelifeat80%DOD, (b) Cyclelifeat100%DOD, (c) Cyclelifeat100%DOD, (d) Cyclelifeat90%DOD, (e) Cyclelifeat100%DOD.

## 2.5. Grid

### *2.5.1. Grid connected renewable systems*

Research studies have already been conducted on grid connected renewable systems. Though, most of these studies have concentrated on energy management for large scale integration of renewable energy at the utility side [22]. 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 [23-26].

The investigations on an optimization framework for designing a grid-connected PV-based renewable energy system and proposed model in which the excess energy can be sold to the grid and the deficit energy can be purchased from the grid has been done in ref. [27]. The 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. The grid in this system will feed the load while the resources fails to generate the energy due to weather conditions and also the energy will be sold to the grid by taking advantage of the TOU electricity tariff.

As a result, the proposed model will consider purchasing of electricity from the grid when lower electricity prices are low instead of using storage system to supply deficit energy. Therefore, the strategies will be purchasing all the deficit energy from the grid and supplying the load from the grid and the storage system.

Grid-connected photovoltaic-battery systems under TOU or RTP (real-time pricing) conditions have been studied in [28 - 29]. The authors reviewed the system under a TOU tariff scheme and assumed that the electricity price is the same for each hour of the period (peak, mid-peak, and off-peak). Such control strategy is very simple: during off-peak hours (low price), supply the whole load and fully charge the battery bank; during on-peak hours, discharge the battery bank to supply the load.

Whereas under a RTP hourly pricing tariff (the electricity price, based on day-ahead electricity spot market, is different from one hour to the next), the control strategy is much more complex. It is also assumed that private electricity facility can only purchase electricity from the AC grid but not sell it back to the AC grid [30-31].

### *2.5.2. TOU pricing tariff scheme*

TOU pricing is a form of dynamic pricing that is being adopted in many areas, in which electricity prices are set for a fixed period. Energy providers use TOU pricing to drive down demand at peak periods by using high prices to influence customers' consumption rather than more invasive controls such as dynamic or passive demand response mechanisms, or even power cuts TOU tariff is likely to have two or three price levels (e.g., "off-peak", "mid-peak", and "on-peak") where the price is determined by the time of a day. Customers can be expected to vary their usage in response to this price information and manage their energy costs by shifting their usage to a lower cost period. ESSs will play an important role in residential areas with a dynamic pricing policy. By storing energy during low off-peak price periods and using the stored energy when the price is high, consumers can avoid paying high rates.

In Malaysia the FIT (feed-in tariff) scheme for grid-connected electricity generated using renewable is being introduced for encouraging the general public and business enterprises to invest in PV systems [32- 34]. The purpose of this scheme was to allow locally produced electricity to be sold to power utilities at a fixed premium over a specified period

In the case of Brazil, its being considered that the combination of high residential tariffs with superior solar radiation availability suggests that PV electricity might reach economic feasibility for grid-connected rooftop installations within the near future [35]. They announced grid parity which is the moment when PV electricity costs are equal to retail electricity prices.

Therefore, in grid parity conditions they would enable private house owners to install small scale PV systems on their roofs. This would enable them to produce electricity they can consume or sell back to the utility at no additional cost as to evaluate the economics of the investment. They defined the cost of PV-generated electricity and the overall financial performance of the project considering both expense and revenue cash flows. Their work analyses the indicators using simple and widely used metrics of levelized electricity cost (LEC), and net present values (NPV).

The study based on the development of an optimization model for the design of optimal operation and management strategy for the grid-connected PV/fuel cell/battery energy system has been carried [36]. The model was developed from economic and environmental viewpoints for delivering surplus PV electricity back to the grid with the aim of creating profit for the users.

## 2.6. Recent Studies on Solar-Wind Hybrid Optimal Energy Control

Some of the authors have performed more comprehensive analyses on purpose of solving different problems related to the implementation of renewable energy. Fadaeinedjad et al. [37] analysed the power quality of the wind plant based on the power and the voltage variations at the Point of common coupling (PCC).

Kuhn et al. [10] and Wolisz et al. [38] discussed the reliability of the wind plant compared to the thermal plant and its investment in the electricity market. They concluded that the growth of renewable sources can affect other infrastructures into the network such as transmission lines, generation and loads. With a need to have a continuity supply when the renewable energy sources have been implemented, the hybrid sources may be more reliability compare to a stand-alone source because a stand-alone solar energy system can be reliable in the summer but in the winter with a non- sun; the system will be affected by the low availability of the sun which means the system become disadvantages.

The latest advances in wind, PV and diesel hybrid systems with batteries, using data from hybrid systems in various locations in the world is been discussed [23-24]. In [25] Hybrid Optimization by Genetic Algorithms (HOGA) program was developed to determine the optimal configuration of the hybrid PV and diesel system.

Bakos et al. [26] presented the hybrid system with three sources PV, Wind and hydro, where the PV and the wind will be the backup source to the hydro system. Amau et al [27] design an optimal sizing method for grid-connected PV-Wind hybrid power system using the hourly average data of wind speed, solar radiation and consumer power demand.

Elhadidy [39] and Shaahid [40] developed the idea where they discussed an economic analysis based on hybrid system between a solar and a wind, the output of his work as shown that the combination of the PV and wind provides higher system performances than either of the single systems for the same system cost and for a given battery storage capacity .The idea was extended in [41-42], where the economic analysis and environmental impact model of a PV - diesel–battery based hybrid system was carried. The fuel cost is calculated over a one-year period and simple payback is worked out for the PV module. The electric power sources in the hybrid system consist of a PV array, a battery bank and a wind generator. The model calculates the annual cost of electricity for different systems and also the annual cost of fuel.

Ghada and Krichen [43] proposed a modified simulated strengthening approach for finding optimal control strategies for energy management in grid-connected PV supply. The authors optimized a control system by having task to improve user comfort and energy savings.

Masoud and Alireza [44] recommended an approach that gives a possibility of selecting the optimum control scheme and also to generate cost effective hybrid systems for power supply of grid connected residential application. Their management strategy was based on peak and load shedding.

Maleki and Pourfayaz [45] focused on modeling, sizing and cost analysis of a photovoltaic (PV)/wind generator (WG)/diesel hybrid system considering two storage devices, namely: battery and fuel cell (FC). The aim was to compare the traditional PV/WG/diesel/battery systems in which battery banks are used as the storage system to the method of using PV/WG/diesel/FC system. For cost analysis, a mathematical model was introduced for each system's component and then, in order to satisfy the load demand in the most cost-effective way, one discrete version of harmony search (HS) algorithm was developed to optimally size the systems components.

Belfkira et al. [46] and Tahani et al [47] presented an optimal sizing study of a wind-diesel generator hybrid. The model was implemented to make use of a deterministic algorithm to suggest, among a list of commercially available system devices, the optimal number and types of units ensuring that the total cost of the system is minimized while guaranteeing the availability of the energy. The optimization problem has also been extended with the use of the energy storage system (ESS) apply to wind power plant. For wind power plants, using ESS for energy time shifting may result in higher profits thus making wind integration more attractive. This is done by storing the energy in the night where the price of the energy is less and used the discharge energy during the day to meet the load demand which mean the peak time, this become beneficial if the wind energy is stored during low price periods and benefit of discharging back during peak time will make profit to wind plant company as connected to the grid, and also it can reduce the power loss in the network and increase the level of the voltage in different bus into a networks.

With the same consideration presented in [18] we take advantage of the utility tariff (Eskom) to maximise the sale of the electricity generated by renewable sources which are made by three sub sources.

In some of the papers discussed above they did take the consideration to maximise the sale of energy to grid during the peak period. The advantage of the system will be to reduce the network stress, and losses. Different system constraints such as power limitations, state of charge of the battery, etc. will be taken into account. The objective function will be a multi-objective where the first term of the objective function is electricity cost. While the second term is the sales of energy to the grid using the TOU tariff, which will be an input to the proposed optimal control strategies. The TOU tariff is an important parameter in this model to be developed. The maximization of energy sales will be achieved by selling more energy to the national grid during peak period where the energy cost is higher than off-peak and standard periods. A multi-objective function will be formed after the combination of these two terms. The simulation results will be presented.

## 2.7. Conclusion

Lithium-ion batteries are the best batteries due to their advantageous characteristics. Therefore, they can play a significant role in grid-connected residential PV battery systems and in quarter-storage applications by offering high efficiencies, high depth of discharge values, high cycling stability and high calendar lifetimes [48]. Furthermore, their lifetimes cannot be affected by typical operating conditions in such PV applications, e.g. long winter periods without any full charges and partial cycling at low and medium state of charge values [30].

Development of safe, long-life, high-efficiency, low-priced energy storage systems is therefore a high priority hence Lead-acid batteries (LAB) with their advantages of low price compared to other battery types, high-unit voltage, stable performance, a wide operating temperature range, and its wide availability, face an exciting challenge as major components in the development of the PV/wind power industry [49-50], and also because they are commonly used in hybrid renewable energy systems.

Investigations of previous papers described the problem of minimization of the operation cost of the hybrid system was faced in the design stage, but costs were not taken into account during their operation since they were not included in their Energy Management Side (EMS). The proposal of including the operation cost in an EMS that solves for each sample time an optimization problem (to minimize the costs or maximize the profit of selling energy to the grid) is less common.

Several papers based on different hybrid system have been carried by taking into account of the economic parameters. On the one hand, the papers with costs optimization objective have only focused on the sizing of the components subject to a defined EMS which in the majority of the cases is usually a conventional rule based control strategy. Therefore, this study is carried to maximize the energy sales to the grid by taking advantage of the time-of-use (TOU) electricity tariff in order to minimize the energy cost of the consumer. Different system constraints such as power limitations, state of charge of the battery, etc. will be taken into account for that reason the TOU tariff is an important parameter in the developed model.

# CHAPTER 3: OPTIMIZATION MODEL FORMULATION AND PROPOSED ALGORITHM

## 3.1. Introduction

In this chapter, the mathematical expression of the hybrid system's optimal operation control problem will be derived. On the other side an objective function is being formulated for minimization the operation costs in a hybrid system with renewable resources using the time of use tariff. Finally, the different constraints about the system's components' proposal and operating limits are also expressed.

The hybrid system considered in this dissertation consists of solar PV system, wind turbine system and the battery bank. The proposed hybrid system is connected to the grid to enable the energy sale to the grid and to use grid energy during renewable power deficit. Therefore, this chapter briefly discusses the basic operation of the components used in the proposed grid-connected PV-WT-battery based hybrid system.

### *3.1.1. Schematic layout of the hybrid system*

The schematic diagram that shows the power flow of the proposed grid-connected hybrid system is shown in Fig. 3.1 below. The arrows reveal the direction of the power flows in the system. In this system the battery will be recharged using power from the PV system, wind turbine system and/or grid. The battery can be recharged using grid power especially during off-peak period, and then discharged during peak period to save electricity cost. $P_1$ is the solar PV generation power supplying the load; $P_2$ is the wind turbine system power supplying the load; $P_3$ is the discharging power of the battery bank for the load demand; $P_4$ is the grid power supplying the load demand; $P_5$ is the solar PV generation power for recharging the battery; $P_6$ is the wind turbine power for recharging the battery; $P_7$ is the grid power for recharging the battery; and $P_8$ is the battery discharging power for selling power to the grid.

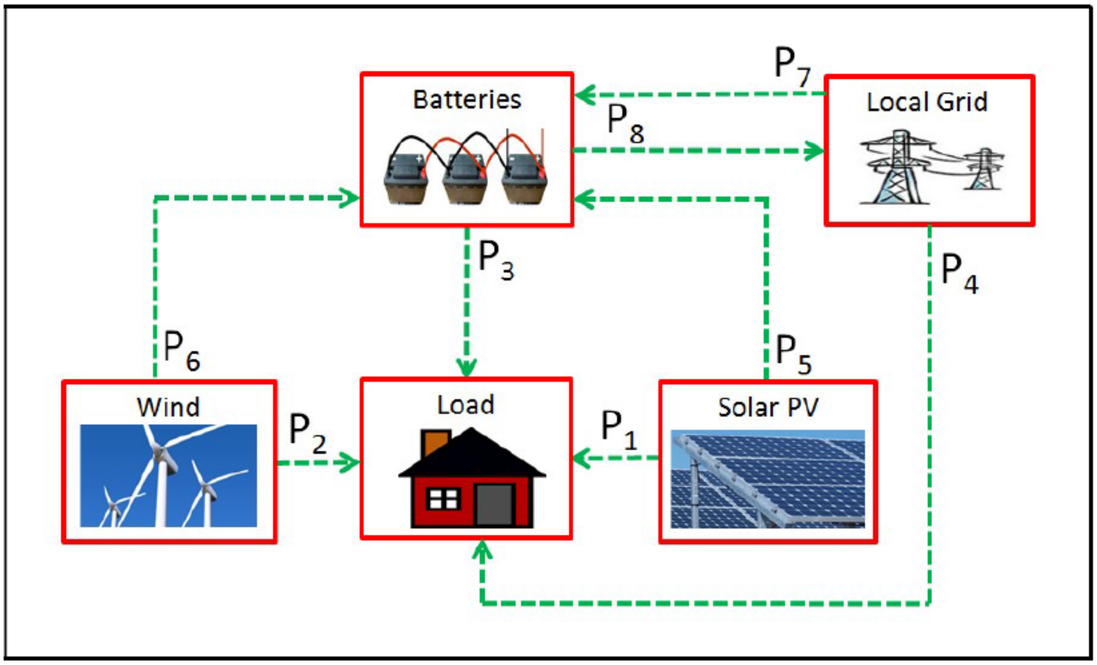


Figure 3.1: Proposed grid-connected PV-WT-Battery based hybrid system power flow

### *3.1.2. System Operation*

The main purpose of the proposed hybrid system is to generate power that continuously matches the load demand. As a result, the power generated by the renewable energy system (Wind turbine and solar PV) will be used to meet the load demand. When the power generated by the renewable energy system is more than the load demand, the excess power will then be stored in the battery bank until the maximum capacity is reached. When the battery is fully charge, the excess power is sold to the grid. In other condition, whereby the PV and the wind system cannot satisfy the load demand, the shortage will be supplied by the battery bank. If the load demand is still not fully met, the grid will therefore supply the unmet load demand. This will also depend on the price of electricity during the considered time interval. The battery can be recharged by the grid during the off-peak period, and then discharged during peak period to supply the load and/or to sell energy to the grid as a means of saving electricity cost.

## 3.2. Model Formulation

### *3.2.1. Objective Function*

The objective is to minimize the operation cost by minimizing the power purchased from the grid and using the renewable energy sources as priority supply to the load; and maximize the power sold to the grid using the TOU tariff... The proposed hybrid system model consists of three amounts. Initial part is the cost of purchasing electricity from the grid during the off-peak period. Secondly will be the income part of selling electricity to the grid. And the last part is the total wearing cost of the hybrid system during the control period. Therefore, the total cost will be formulated as shown in Eq. 3.1 below:

$$F = \sum_{j=1}^{N}(P_{4_j} + P_{7_j})\Delta t - r_k.\rho_k \sum_{j=1}^{N} P_{8_j} + \sum_{j=1}^{N} a(P_{3_j} + P_{8_j})\Delta t + 24b \tag{3.1}$$

Where:

$r_k$ is the contracted ratio of the peak price and is $0.65P_k$ in our case used when selling power to the grid during peak hours [49],

$a$ is the coefficient of battery wearing cost,

$b$ is the hourly wearing cost of other components and,

$F$ is the total cost function of the whole system.

### 3.2.2. DSM model of the PV-WT-Battery based hybrid system

Optimal scheduling of the modelled hybrid system aims to minimize electricity cost within the outline of DSM. Therefore, the TOU program is a typical program of DSM for concern, because the electricity price changes over different periods according to the electricity supply cost, for instance we have a high price for peak load periods, medium price for standard periods and also low price for off-peak periods. In this study, the daily electricity price at the target expanse can be given as [51]

$$p(t) = \begin{cases} \rho_k, t \in T_k T_K = [7,10) \cup [18,20) \\ \rho_o, t \in T_o T_o = [0,6) \cup [22,24) \\ \rho_s, t \in T_s, T_s = [6,7) \cup [10,18) \cup [20,22) \end{cases} \tag{3.2}$$

Where:

$\rho_k$ is the price during the peak load period (0.20538$/KWh);

$\rho_o$ is the price during the off-peak period e.g. 0.03558$/KWh;

$\rho_s$ is the price during the standard period that is 0.05948$/KWh.

### 3.2.3. Constraints

The different constraints on the system operation are as follows:

#### 3.2.3.1. Linear equality constraints of the system

The load power demand of the system can be expressed as follows:

$$P_{Lj} = P_{1j} + P_{2j} + P_{3j} + P_{4j} \tag{3. 3}$$

Where:

$j$ is the sampling interval Equation 3.3 simply means that the load demand should be equal to the total amount of the power supplied by the different sources.

#### 3.2.3.2. Control variable limits

The power from the PV system, the power generated by WT, the power from the battery modules and the power from the grid are modelled as adaptable power sources manageable in the range of zero to their maximum accessible power, or their rated power for the 24 hours' period. Therefore, the variable limits will be the output limits of these different power sources and also of the battery storage system at any time.

These constraints can be determined by the characteristics of each power source and can be stated as:

$$P_1^{\min} \le P_{1j} \le P_1^{\max} \tag{3.4}$$

$$P_2^{\min} \le P_{2j} \le P_2^{\max} \tag{3.5}$$

$$P_3^{\min} \le P_{3j} \le P_3^{\max} \tag{3.6}$$

$$P_4^{\min} \le P_{4j} \le P_4^{\max} \tag{3.7}$$

$$P_5^{\min} \le P_{5j} \le P_5^{\max} \tag{3.8}$$

$$P_6^{\min} \le P_{6j} \le P_6^{\max} \tag{3.9}$$

$$P_7^{\min} \le P_{7j} \le P_7^{\max} \quad (3.10)$$

$$P_8^{\min} \le P_{8j} \le P_8^{\max} \quad (3.11)$$

Where:

$P_1^{max}$, $P_2^{max}$, $P_3^{max}$, $P_4^{max}$, $P_5^{max}$, $P_6^{max}$, $P_7^{max}$ and $P_8^{max}$ stand for the maximum values of the given power sources at any sampling interval (*j*),

$P_1^{min}$, $P_2^{min}$, $P_3^{min}$, $P_4^{min}$, $P_5^{min}$, $P_6^{min}$, $P_7^{min}$ and $P_8^{min}$ are the minimum values of the given power sources at any sampling interval (*j*).

3.2.3.3. Linear inequality constraints

- State of charge of battery

Depending on the conditions in the considered sampling interval j the battery can be recharged (by the renewable sources or the grid) or can be used to supply the load or feed the excess power to the grid., this can be indicated by the following equation:

$$SOC^{\min} \le SOC(0) + \sum_{j=1}^{N}(P_{5j} + P_{6j} + P_{7j})\frac{\Delta t.\eta c}{E_n} - \sum_{j=1}^{N}(P_{3j} + P_{8j})\frac{\Delta t}{E_n.\eta_D} \le SOC^{\max} \quad (3.12)$$

Where:

$SOC^{max}$ is the maximum capacity of the battery,

$SOC^{min}$ is the minimum acceptable battery state of charge;

$N$ is the number of sampling intervals.

$\eta_C$ and $\eta_D$ are the coefficient of charging and discharging efficiency of the battery;

- PV constraints

The power generated by the PV system is used to supply the load ($P_1$) and to recharge the battery bank ($P_5$) and for both cases, the power must not exceed the maximum power generated by the PV system and this constraint can be expressed as:

$$P_{1j} + P_{5j} \leq P_{PV}^{\max} \tag{3.13}$$

- Wind constraints

This is whereby the power generated by the wind turbine system is used to supply the load ($P_2$) and to recharge the battery bank ($P_6$) and for both cases, the power must not exceed the maximum power generated by the wind system and this constraint can be expressed as:

$$P_{2j} + P_{6j} \leq PW^{\max} \tag{3.14}$$

## 3.3. Description of the model in linear programming

The optimal control method will be used in the system and therefore if the objective function and the constraints are linear the control problem of the power flow can be expressed as a linear programming problem, so this will be shown as [52]:

$$\min g(x), s.t \begin{cases} Ax \leq b \\ A_{eq}x = b_{eq}, \\ Ib \leq x \leq ub \end{cases} \tag{3.15}$$

Where:

$g(x)$ represents the objective function;

$A_{eq}$ and $b_{eq}$ will be related to the equality constrains coefficients;

$A$ and $b$ are the inequality constraint coefficients;

$lb$ and $ub$ are the lower and upper bounds of variables.

For modelling purpose, MATLAB code will be developed, therefore the output powers from the different sources have to be expressed in functions of the variable "x". The following preparation has been completed

$$P_1 = x(1:N) = [x_1, x_2] \quad (3.16)$$

$$P_2 = x(N+1:2N) = [x_3, x_4] \quad (3.17)$$

$$P_3 = x(2N+1:3N) = [x_5, x_6] \quad (3.18)$$

$$P_4 = x(3N+1:4N) = [x_7, x_8] \quad (3.19)$$

$$P_5 = x(4N+1:5N) = [x_9, x_{10}] \quad (3.20)$$

$$P_6 = x(5N+1:6N) = [x_{11}, x_{12}] \quad (3.21)$$

$$P_7 = x(6N+1:7N) = [x_{13}, x_{14}] \quad (3.22)$$

$$P_8 = x(7N+1:8N) = [x_{15}, x_{16}] \quad (3.23)$$

### 3.3.1. *Objective function definition in linear programming*

It can be noted that the main objective of this project is to maximize the sale, minimize the power purchased and minimize the operation cost for the suggested time horizon, knowing that in Eq. 3.1 we have an equation for maximizing and minimizing and therefore the process of this system using linear programming can be written as follows:

When N=1

$$F = \rho_1 (X_7 + X_{13}) \Delta t - r_k \rho_k (X_{15}) + a(X_5 + X_{15}) \Delta t + 24b \tag{3.24}$$

When N=2

$$F = \rho_2 (X_8 + X_{14}) \Delta t - r_k \rho_k (X_{16}) + a(X_6 + X_{16}) \Delta t + 24b \tag{3.25}$$

Finally, the sum of the two equations can be simplified as follows:

$$F = \Delta t (e_1 e_2 e_3 e_4) \begin{bmatrix} X_7 \\ X_8 \\ X_{13} \\ X_{14} \end{bmatrix} + (-r_k \rho_{kj} - r_k \rho_k) \begin{bmatrix} X_{15} \\ X_{16} \end{bmatrix} + (a, a, a, a) \begin{bmatrix} X_5 \\ X_6 \\ X_{15} \\ X_{16} \end{bmatrix} \Delta t \tag{3.26}$$

Therefore the objective function of the above simplified equations can be expressed as

$$F = \Delta t [zeros(1,N), zeros(1,N), a * ones(1,N), e(1,N), zeros(1,N), zeros(1,N), e(1,N), c * ones(1,N)] \tag{3.27}$$

### 3.3.2. *Constraints definition in linear programming*

#### 3.3.2.1. Power balance

The linear equality constraints of the power supplied by the different sources can be expressed as shown in Eq. 3.3. These constraints can be divided into two *j* sampling intervals e.g.

$$N = 1 \rightarrow X_1 + X_3 + X_5 + X_7 = P_{L1} \tag{3.28}$$

$$N = 2 \rightarrow X_2 + X_4 + X_6 + X_8 = P_{L2} \tag{3.29}$$

The system constraints can also be written in a form of matrix:

$$\begin{pmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{16} \end{bmatrix} = \begin{pmatrix} P_{L1} \\ P_{L2} \end{pmatrix} \tag{3.30}$$

Finally, the canonical form of the power balance is expressed as shown in Eq. 3.31 and 3.32 below.

$$Aeq = [eye,(N,N), eye(N,N), eye(N,N), eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), zeros(N,N)] \quad (3.31)$$

$$beq = P_L(1:N) \quad (3.32)$$

3.3.2.2. Variable limits

- Lower bounds

The lower bounds are the minimum values of power source produced in different time intervals and that will be zero. Hence, the system lower bounds changes can be expressed in vector form and will be expressed as follows:

$$Lb_1 = P_1^{\min} * ones\ (N:1) \quad (3.33)$$

$$Lb_2 = P_2^{\min} * ones\ (N:1) \quad (3.34)$$

$$Lb_3 = P_3^{\min} * ones\ (N:1) \quad (3.35)$$

$$Lb_4 = P^{\min} * ones\ (N:1) \quad (3.36)$$

$$Lb_5 = p_5^{\min} * ones\ (N:1) \quad (3.37)$$

$$Lb_6 = P_6^{\min} * ones\ (N:1) \tag{3.38}$$

$$Lb_7 = P_8^{\min} * ones\ (N:1) \tag{3.39}$$

$$Lb_8 = P_8^{\min} * ones\ (N:1) \tag{3.40}$$

Then the lower bounds of all the power sources will finally be expressed as:

$$Lb = [Lb_1, Lb_2, Lb_3, ..., Lb_8] \tag{3.41}$$

- Upper bounds

The upper bounds sets are the maximum allowable installed capacity of each renewable energy source. Hence, the system upper bounds changes can be expressed in vector form and will be expressed as follows:

$$Ub_1 = P_1^{\max}(1:N) \tag{3.42}$$

$$Ub_2 = P_2^{\max}(1:N) \tag{3.43}$$

$$Ub_3 = P_3^{\max} * ones\ (N:1) \tag{3.44}$$

$$Ub_4 = P_4^{\max} * ones(1:N) \tag{3.45}$$

$$Ub_5 = P_5^{\max}(1:N) \tag{3.46}$$

$$Ub_6 = P_6^{\max}(1:N) \tag{3.47}$$

$$Ub_7 = P_7^{\max} * ones(1:N) \tag{3.48}$$

$$Ub_8 = P_8^{\max} * ones(1:N) \tag{3.49}$$

$$Ub = [Ub_1, Ub_2, Ub_2 ..., Ub_8] \tag{3.50}$$

3.3.2.3. Battery variables

As described before, in one of the developments the battery bank is installed as storage system. In my research, the mathematical model of batteries is going to be taken into consideration.

Constraint of SOC boundary: The SOC of the battery must be not as much of as the battery's capacity $SOC^{max}$ and also be greater than the minimal acceptable value $SOC^{min}$ such as:

$$SOC^{\min} \le SOC_j \le SOC^{\max} \tag{3.51}$$

$$SOC^{\min} \le SOC(0) + \sum_{j=1}^{N} [P_{5j} + P_{6j} + P_{7j}] \frac{\Delta t.\eta_C}{E_{ne}} - \sum_{j=1}^{N} \left(P_{3j} + P_{8j}\right) \frac{\Delta t}{E_{nom}.\eta_D} \le SOC^{\max} \tag{3.52}$$

For $SOC^{max}$ is an important parameter as well as being a measure of the amount of available power and this must be kept within certain limits, for instance nominal when $j=1$:

$$SOC_{(0)} + [x_9 + x_{11} + x_{13})d - e[x_5 + x_{15}] \leq SOC^{\max} \tag{3.53}$$

And also when *j=2*, therefore:

$$SOC_{(0)} + d(x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14}) - e(x_5 + x_6 + x_{15} + x_{16}) \leq SOC^{\max} \tag{3.54}$$

For $SOC^{min}$ is for during the discharging of the battery and the constrains will be like this;

When *j=1*:

$$SOC^{\min} \leq SOC_{(0)} + d(x_9 + x_{11} + x_{13}) - e(x_5 + x_{15}) \tag{3.55}$$

$$-ex_5 + dx_9 + dx_{11} + dx_{13} - ex_{15} \geq SOC^{\min} - SOC_{(0)} \tag{3.56}$$

Eq. (3.56) can be multiply by negative in order to make $ex_5$ term to be positive.

$$ex_5 - dx_9 - dx_{11} - dx_{13} + ex_{15} \leq SOC_{(0)} - SOC^{\min} \tag{3.57}$$

When *j=2*

$$ex_5 + ex_6 - dx_9 - dx_{10} - dx_{11} - dx_{12} - dx_{13} - dx_{14} + ex_{15} + ex_{16} \leq SOC_{(0)} - SOC^{\min} \tag{3.58}$$

This also can be rewritten as matrix form:

$$\left\{\begin{matrix} 0 & 0 & 0 & 0 & -e & 0 & 0 & 0 & d & 0 & d & 0 & d & 0 & -e & 0 \\ 0 & 0 & 0 & 0 & -e & -e & 0 & 0 & d & d & d & d & d & d & -e & -e \\ 0 & 0 & 0 & 0 & e & 0 & 0 & 0 & -d & 0 & -d & 0 & -d & 0 & e & 0 \\ 0 & 0 & 0 & 0 & e & e & 0 & 0 & -d & -d & -d & -d & -d & -d & e & e \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{matrix}\right\} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \\ x_{15} \\ x_{16} \end{bmatrix} x \le b \tag{3.59}$$

The battery linear inequality constrains in linear programming will be used and be expressed by using a canonical formulation as follows:

$$\begin{aligned} A_1 = [&zeros(N,N), zeros(N,N) - e * tril(onesN,N), zeros(N,N), d * tril(onesN,N), \\ &d * tril(onesN,N), d * tril(onesN,N) - e * tril(N,N)] \end{aligned} \tag{3.60}$$

$$A_2 = -A_1 \tag{3.61}$$

$$\begin{aligned} A_3 = [&eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N), \\ &zeros(N,N), zeros(N,N)] \end{aligned} \tag{3.62}$$

$$\begin{aligned} A_4 = [&zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N), \\ &zeros(N,N), zeros(N,N)] \end{aligned} \tag{3.63}$$

$$A = [A_1 ; A_2 ; A_3 ; A] \tag{3.64}$$

$$b_1 = \begin{Bmatrix} soc^{\max} - soc_{(0)} \\ soc^{\max} - soc_{(0)} \end{Bmatrix} \tag{3.65}$$

$$b_2 = \begin{Bmatrix} soc_{(0)} - soc^{\min} \\ soc_{(0)} - soc^{\min} \end{Bmatrix} \tag{3.66}$$

$$b_3 = \begin{Bmatrix} Ppv^{\max} \\ Ppv^{\max} \end{Bmatrix} \tag{3.67}$$

$$b_4 = \begin{Bmatrix} Pw^{\max} \\ Pw^{\max} \end{Bmatrix} \tag{3.68}$$

$$b_1 = \left(soc^{\max} - soc_{(0)}\right) * ones(N:1) \tag{3.69}$$

$$b_2 = \left(soc_{(0)} - soc^{\min}\right) * ones(N:1) \tag{3.70}$$

$$b_3 = Ppv^{\max}(1:N) \tag{3.71}$$

$$b_4 = Pw^{\max}(1:N) \tag{3.72}$$

$$b = [b_1 , b_2 , b_3 , b_4] \tag{3.73}$$

## 3.4. Conclusion

This chapter was about developing the mathematical modelling of the hybrid system consisting of the PV system, wind system and the battery bank. The objective function as well as constraints are expressed and discretized using the linear programing syntax.

# CHAPTER 4: SIMULATION RESULTS AND DISCUSSIONS

## 4.1. Introduction

This chapter discussed the simulations results based on the optimization model explained in chapter 4. The aim of the model is to reduce the cost of electricity and maximize the power sold to the grid using TOU tariff scheme as explained in the previous chapters. The simulations are implemented using the linear programming as to be applied in MATLAB software. The results are analysed and discussed in this chapter.

## 4.2. Case studies presentation

The simulation results will be discussed and categorized according to the behaviour of the proposed grid-connected PV-WT-battery based hybrid system. Different settings such as control system parameters, tariff prices, and load demands used during the simulations are explained in Table 4.1.

### *4.2.1 The control system settings*

Different control settings for the power supply components (Battery, PV system, Wind system) as well as the sampling time during simulation are shown in Table 4.1 below.

Table 4.1: Control settings for the power supply components

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

The sizing of PV, WT and battery bank is based on a sizing model done by Kusakana et al. [50]. The parameters of this hybrid system are available in ref [51].

### *4.2.2 TOU tariff price settings*

The utility based TOU tariff prices for different period (peak, standard and off-peak periods) as well as the contracted ratio used during simulations has been shown in Eq. (3.1) and (3.2) available from Chapter 3, section 2.

### *4.2.3 Different load settings*

As mentioned earlier, this study is conducted with the intention of using grid-connected PV-WT-battery based hybrid system to meet the demand of residential, commercial and industrial loads, respectively. The different load profiles reveal different patterns due to daily activities of the user and this can change depending on different times of the day or seasons of the year. For better comparison purpose, each load type has been standardised to have the same daily energy demand of 75kWh/day with different power on peak demand due to different load profile shapes. The load profile for each demand sector is shown. For the Fig. 4.1, 4.2, 4.3 the model can be used to study the influence of each load profile on the proposed hybrid system operation.

Based on the behaviour of each load profile, the industrial load has a peak power demand of 9 kW at about 10h00. At around 12h00 the demanded power drops at a high rate when compared to other daily working hours and then increases after 13h00. Because many factories usually allow workers to simultaneously take a lunch break whereas the commercial businesses agree on different lunch break shifts.

Based on the selected residential and commercial load profiles, it can be seen that the residential load demands the peak power of 6.6kW between 20h00 and 21h00 whereas the commercial load demands a peak power of 6.4kW between 15h00 and 17h00. Therefore, the optimal energy control model must be designed to allow the proposed hybrid system to adequately respond to each load demand, respectively.

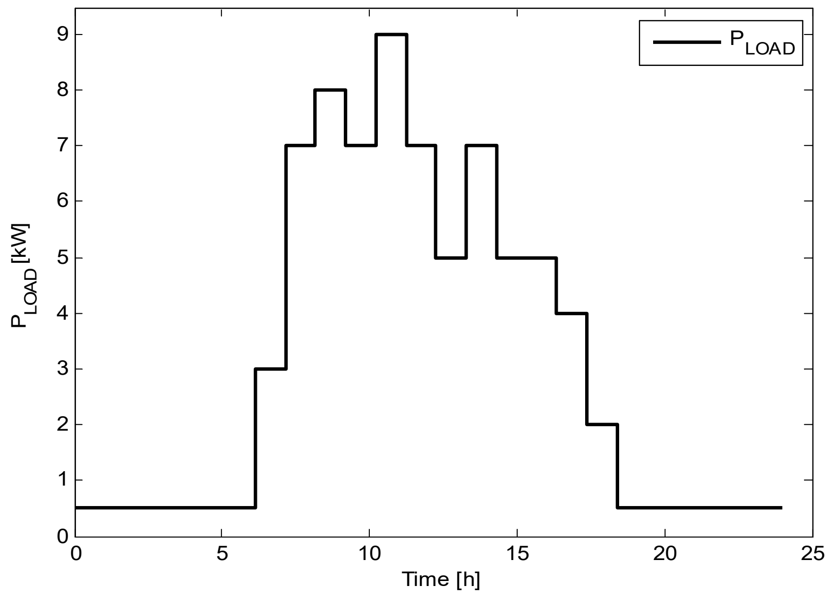


Figure 4.1: Industrial daily load profile

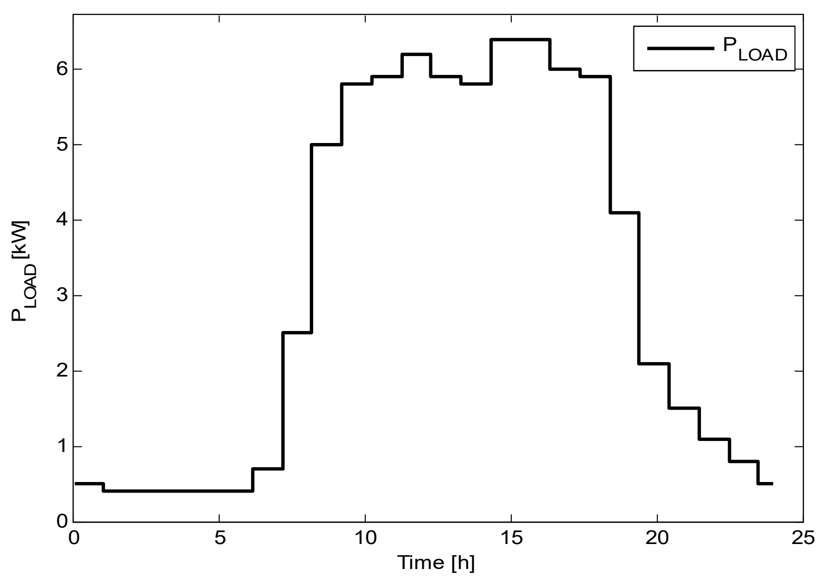


Figure 4.2: Commercial daily load profile

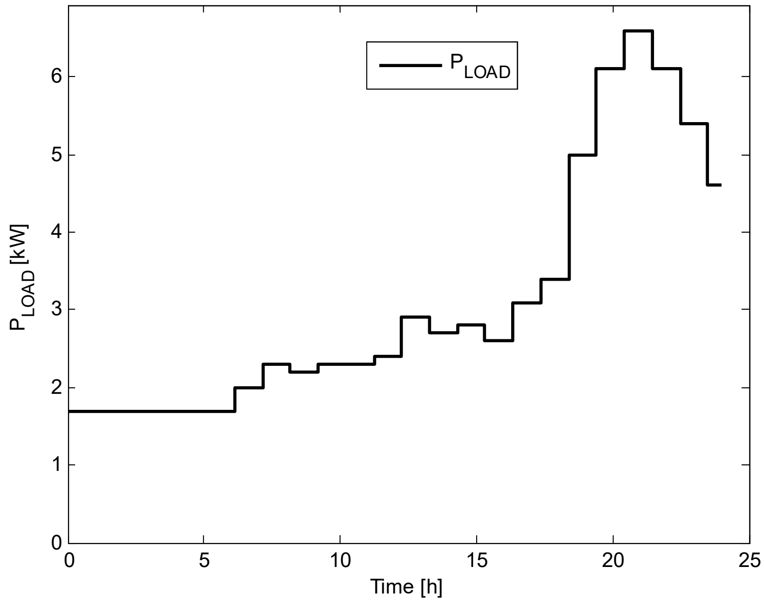


Figure 4.3: Residential daily load profile

### *4.2.4 Renewable energy sources settings*

The renewable energy resources have been used as input to assess the performance of the system submitted to the developed optimal energy management system. The wind and solar resource hourly data are presented in Table 4.2 below:

Table 4.2 Hourly Data

| Time (h) | Global Solar (kW/m$^2$) | Wind speed (m/s) |
|---|---|---|
| 00:00 | 0.000 | 0.821 |
| 01:00 | 0.000 | 1.665 |
| 02:00 | 0.000 | 0.998 |
| 03:00 | 0.000 | 0.956 |
| 04:00 | 0.000 | 2.549 |

| | | |
|---|---|---|
| 05:00 | 0.000 | 2.558 |
| 06:00 | 0.000 | 2.775 |
| 07:00 | 0.002 | 3.754 |
| 08:00 | 0.141 | 2.948 |
| 09:00 | 0.417 | 2.828 |
| 10:00 | 0.687 | 2.870 |
| 11:00 | 0.940 | 2.522 |
| 12:00 | 1.062 | 1.766 |
| 13:00 | 1.061 | 2.576 |
| 14:00 | 0.978 | 2.017 |
| 15:00 | 0.846 | 2.282 |
| 16:00 | 0.679 | 3.116 |
| 17:00 | 0.464 | 2.626 |
| 18:00 | 0.208 | 3.427 |
| 19:00 | 0.043 | 2.972 |
| 20:00 | 0.000 | 2.543 |
| 21:00 | 0.000 | 2.336 |
| 22:00 | 0.000 | 1.863 |
| 23:00 | 0.000 | 1.231 |

## 4.3. Industrial load simulation results

The PV system and the wind can both supply the load and charge the battery due to its availability as we know that renewable resources depend on weather. Fig. 4.4 and 4.5 below show the power flow from the PV and wind systems to the load. It can be seen that from twelve noon to five o'clock, there is no power supplied to the load until six when we have excess of solar energy. Similarly, when there is availability of the wind, the wind turbine system supply electricity to the load. This normally occurs early in the morning e.g. from six o'clock to ten o'clock and also in the afternoon between 6 o'clock and 8 o'clock late. This also shows that the power generated by the renewable resources is used to satisfy the load demand during the peak load period.

### *4.3.1 Power flow under off-peak periods*

#### 4.3.1.1 Off-peak time period [0, 6]

The power delivered to the load from different sources is shown in Figure 4.4, 4.5, 4.6 and 4.7. The battery system will provide the power to the load as demonstrated in Figure 4.6 and its equivalent state of charge decreases as presented in Figure 4.11 below. As for conclusion, the PV, WT and the grid does not supply the load during the period of [0, 6] as shown in the Figure 4.4, 4.5 and 4.7. There will be sufficient power coming from the battery to supply the load and to be retailed to the grid to produce profits. No matter how low the price will be during this period, the excess power that was not used to supply the load will be sold to the grid as shown in Fig. 4.12 below.

#### 4.3.1.2 Off-peak time period [10:00, 18:00]

During this off-peak load period, both the load demand and the price of electricity are low. For that reason, the power from the grid will primarily be used to supply the load and recharge the battery at the same time. This can be seen when looking at Fig. 4.7 and Fig.4.10 respectively. Fig. 4.5 and Fig. 4.6 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. 4.11.

4.3.1.3 Off-peak time period [22:00, 24:00]

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. 4.7, Fig. 4.11 and Fig. 4.12.

### *4.3.2 Power flow under standard time periods*

4.3.2.1 Standard time period [6, 7]

During this standard price period, even though the battery system can completely satisfy the load demand, the power from the grid has been used as a main supply that is to the load as well as to recharge the battery. These can be seen from Fig.4.7 and Fig.4.10 respectively. There is a very small output power from the PV and WT and these are used to recharge the battery as shown in Fig. 4.8 and Fig 4.9.

4.3.2.2 Standard time period [20:00, 22:00]

During this second standard price period, the power from the grid is used as main supply to the load as well as to recharge the battery. These can be seen from Fig.4.7 and Fig. 4.10 respectively. There is no output from the PV and WT.

### *4.3.3 Power flow under peak periods*

4.3.3.1 Peak time period [7, 10]

For the duration of the peak load period, the load is essentially 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 (Figures. 4.4, 4.5, 4.6). In Fig. 4.11 it shows how the state of charge decreases when the battery is giving power to the load. If the PV, WT and battery cannot sufficiently respond to the demand, the grid can be used as a back-up to balance the power needed to satisfy the load demand as shown in Fig. 4.7. 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.4.12 that the power sold the grid at the end of this period is minimum.

4.3.3.2 Peak time period [18:00, 20:00]

In this second peak load period, the load demand is low and there will be a very small amount of power generated by the PV. Maximum of the power consumed by the load is coming from the WT, the battery and the grid as shown in Fig. 4.5, Fig 4.6 and Fig.4.7. Maximum of the power sold to the grid in this high demand pricing period come from the battery as illustrated from Fig.4.11.

### *4.3.4 Daily generated income and cost*

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. Meaning the customer can get the discount to \$12.09 from what is bought from the grid and what is sold to the grid. This income will depend of the size of the hybrid system's components, the battery initial state of charge as well as on the load profile.

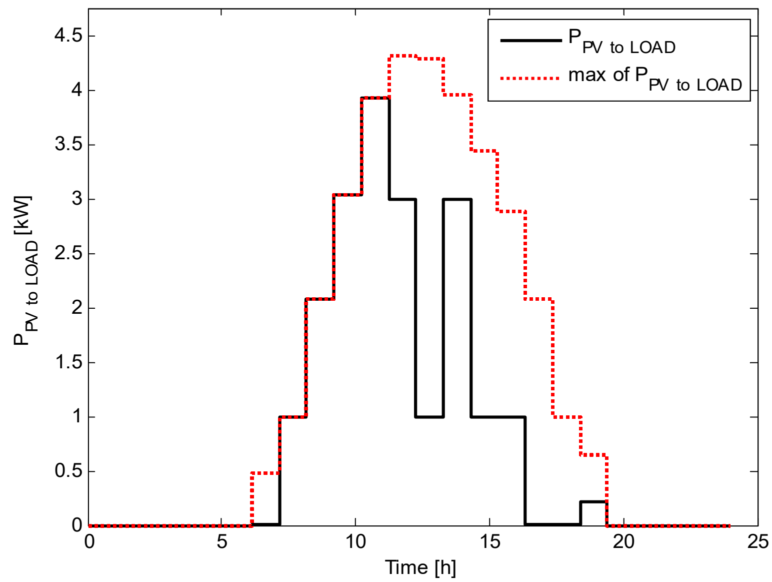


Figure 4.4: PV output power to the load

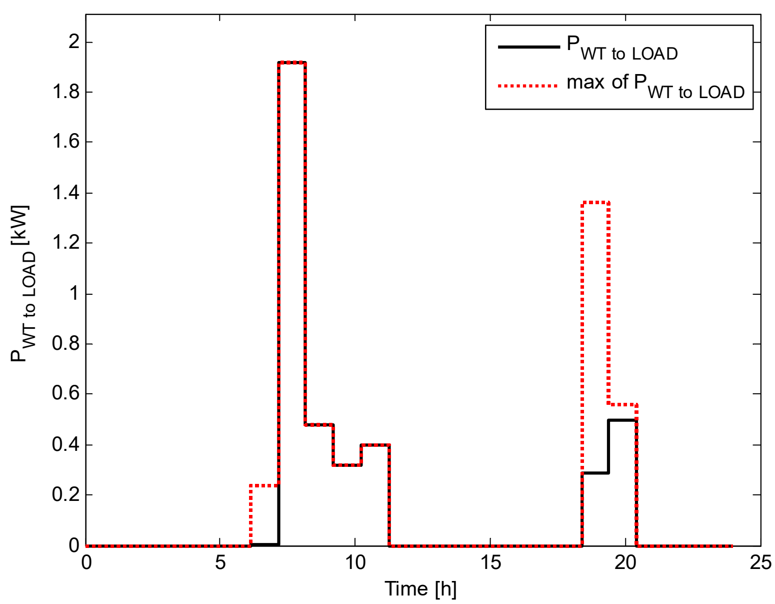


Figure 4.5: WT output power to the load

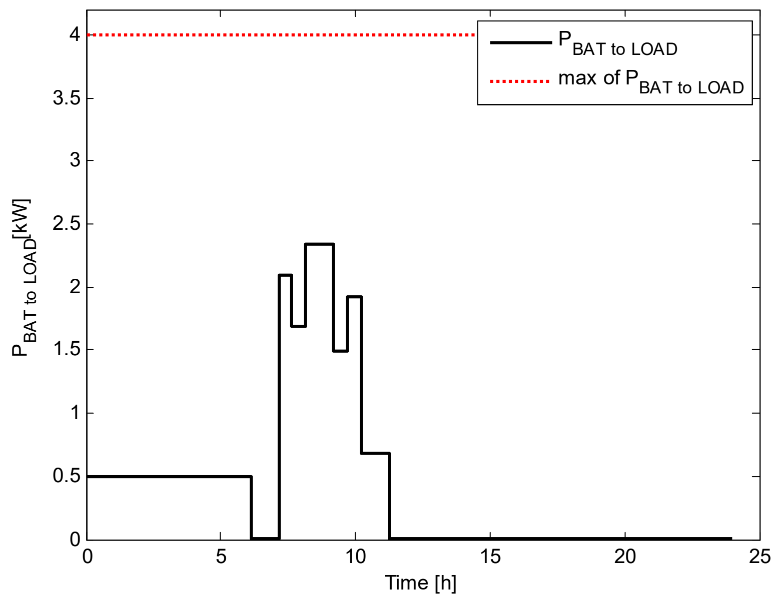


Figure 4.6: Battery output power to the load.

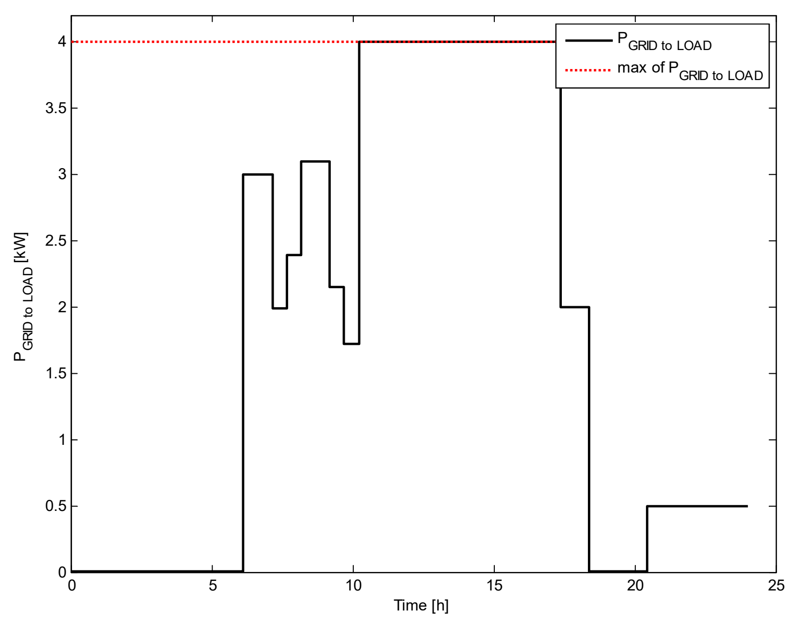


Figure 4.7: Grid power to the load

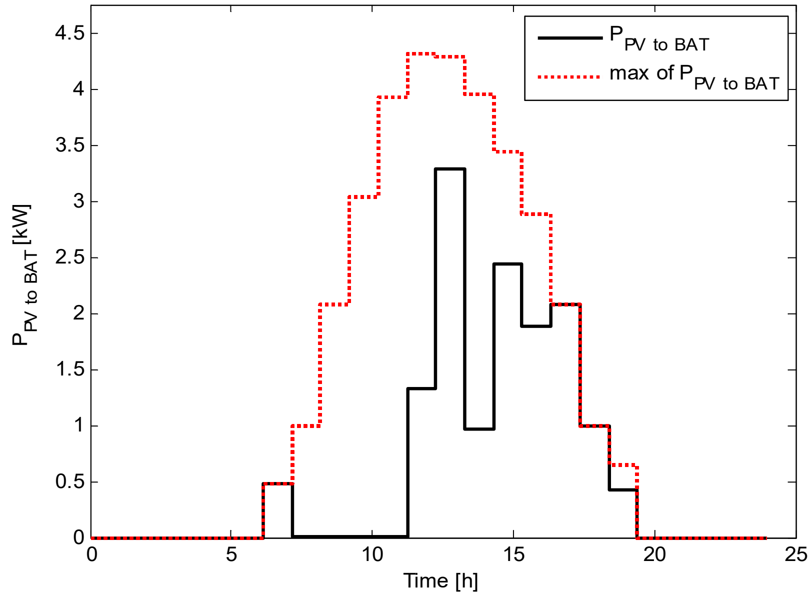


Figure 4.8: PV output power to the battery

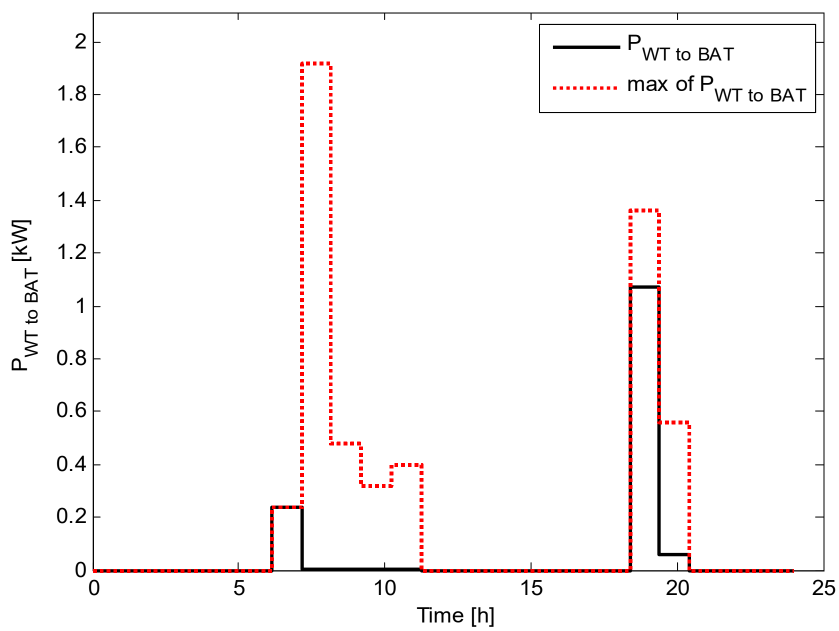


Figure 4.9: Power from the wind to the battery

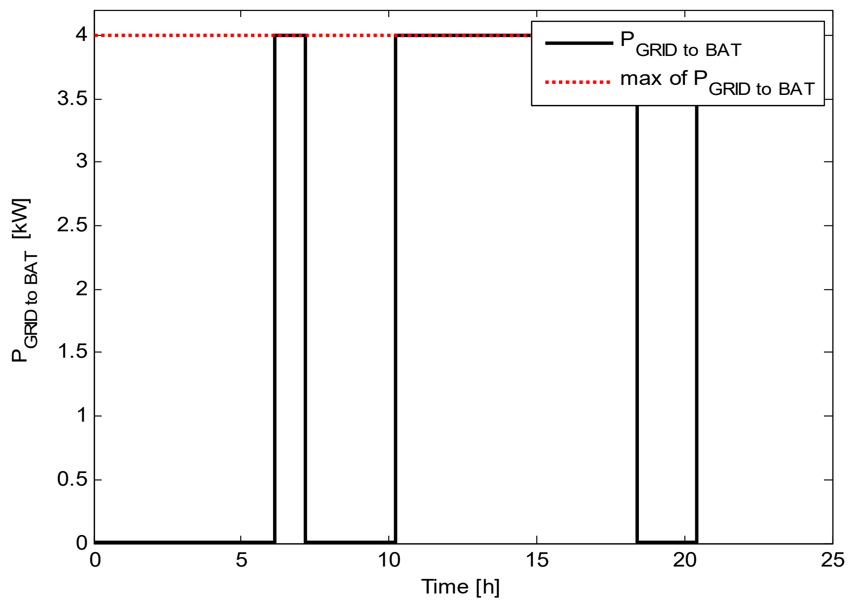


Figure 4.10: Power from the grid to the battery

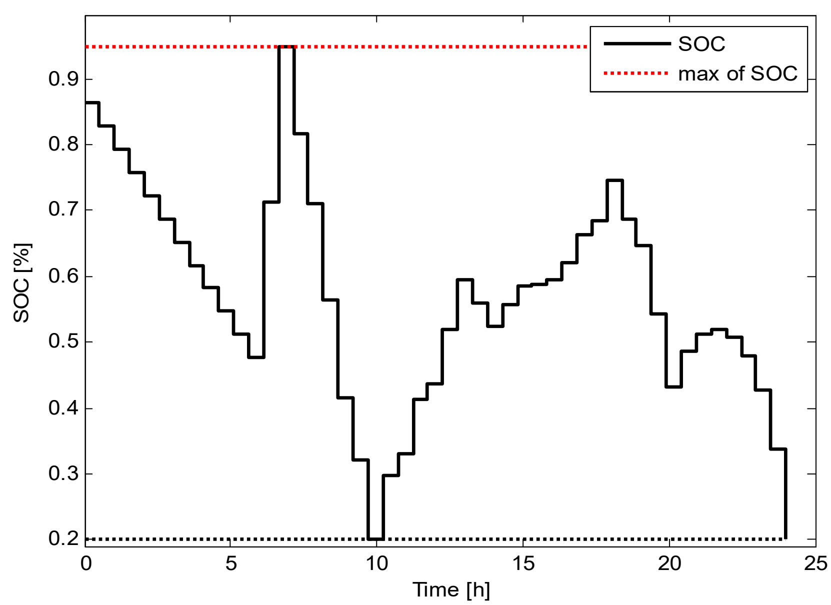


Figure 4.11: Battery state of charge

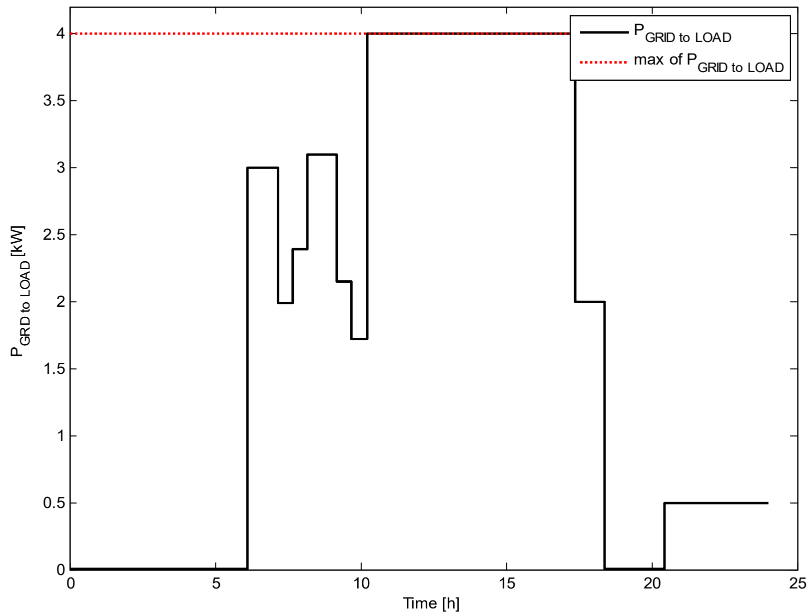


Figure 4.12: Power sold to the grid

## 4.4. Commercial and residential load simulation results

The previous section discussed the industrial load profile results only. In this section, the impact of both the commercial and residential load profiles on energy management of the proposed hybrid system using the developed energy management model is discussed. The overall results for both the commercial and residential load profiles are found in Appendix A and B respectively. Similarly, to the industrial load profile, the commercial and residential daily load profiles have also been supplied using the proposed hybrid system, respectively.

Table 4.3 below shows that the monetary value of the power sold to the grid when the hybrid system supplied different load profiles respectively. Considering the three different load demand profiles, the commercial load resulted into the highest energy sales revenue ($55.41) as compared to both residential and industrial loads as shown in Table 4.3 below:

Table 4.3: Power sold on different loads

| *Load profile types* | *Monetary value of the power sold (US$)* |
|---|---|
| Industrial | $12.0856 |
| Commercial | $55.4099 |
| Residential | $18.9375 |

## 4.5. Conclusion

TOU tariff pricing scheme have been used for the power selling to the grid and buying from the grid also. The simulation results are based on industrial, residential and commercial daily load profiles using the developed optimal operation and control model for the proposed hybrid system resulting into the maximal use of energy from the PV, WT and battery storage system. The developed model has proved to be a powerful control method for power flow management of the grid-connected PV-WT-battery based hybrid system.

The simulation results showed the importance of a battery when used to store energy from the utility grid during off-peak periods and supply the stored energy to the load during peak periods. Therefore, by optimally operating the hybrid system, the load consumes minimal amount of power from the utility grid and this results into energy cost savings and income revenue generation for the consumers.

It has been noted that both the industrial and commercial loads demand more energy during the day as compared to the residential load. However, the commercial load type proved to yield the highest energy sale revenue to the grid as compared to both industrial and residential load types. Hence for the same energy demand, the revenue generated by a grid connected hybrid system operating under time of use is mainly dependent on the load profile.

# CHAPTER 5: CONCLUSION AND FUTURE STUDIES

## 5.1. Conclusion

The research was about the development of models on the control of the operation of PV-WT-battery power system in two different matters, on which the first objective was to minimize the system operation cost that is saving the use of electricity and by using the renewable energy resources such as wind and solar energy. The second objective was about maximizing the selling of energy being stored in the battery bank generated by the resources to the grid applying the TOU tariffs scheme.

In this dissertation chapter 2 discussed the review of literatures done by other researchers based on renewable energy resource optimization control studies, battery bank technologies as well as on grid connected systems and TOU tariff schemes.

Chapter 3 discussed different system components of the proposed PV-WT-Battery hybrid system as well the development of the proposed optimal energy management model for controlling the operation of the proposed grid-connected hybrid system as applied in MATLAB software.

Chapter 4 presented the simulation results of the developed optimal energy management model in order to show the technical advantage/benefit of the proposed model using TOU tariff scheme. The results have shown that the inclusion of a storage device (battery) play an important role when used to store power from the utility grid during off-peak period and to supply the load during peak periods under TOU tariff scheme.

The optimal energy management was tested using different load profiles (demanding the same daily energy) for comparison and supplementary purpose. The results have shown that the commercial load customers can sell more power to the grid as compared to the residential and industrial load customers when consuming the same daily energy.

## 5.2. Suggestions for further studies

Based on the study, the following research gaps have been identified for future studies:

- Model predictive control will be developed to handle the control when the hybrid system experiences some disturbances in PV and wind output and load demand.
- Other different renewable energy sources can be considered and studied.
- Practical implementation of such control system needs to be tested since the study concentrated mainly on developing the energy management model as applied in MATLAB simulation tool.

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# APPENDICES

## Appendix A: Simulation results

*Appendix A1: Commercial load*

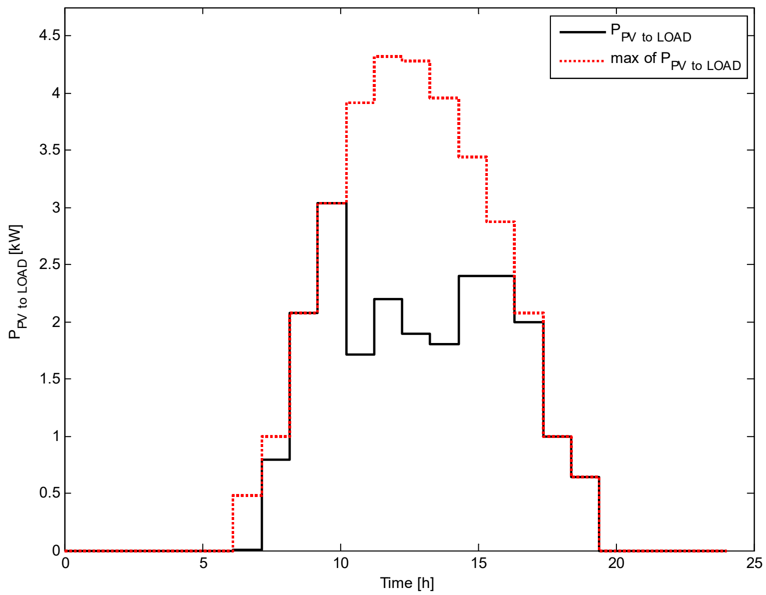


Figure A1.1: PV output power to the load

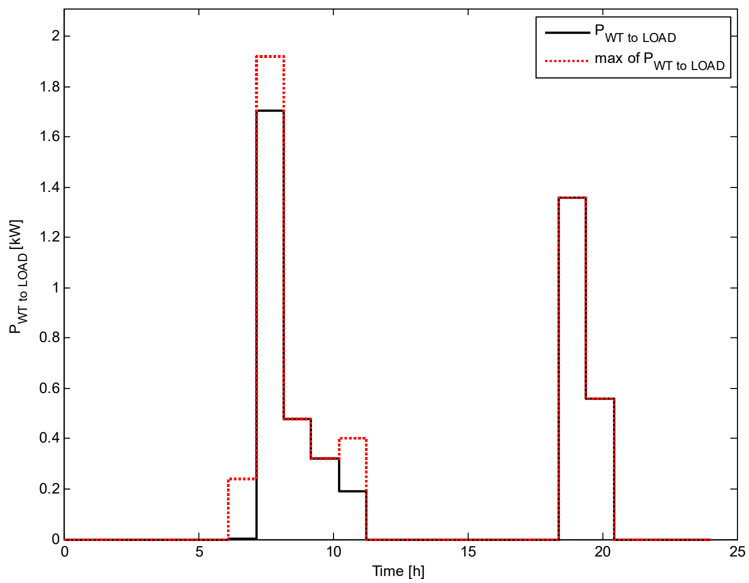


Figure A1.2: WT output power to the load

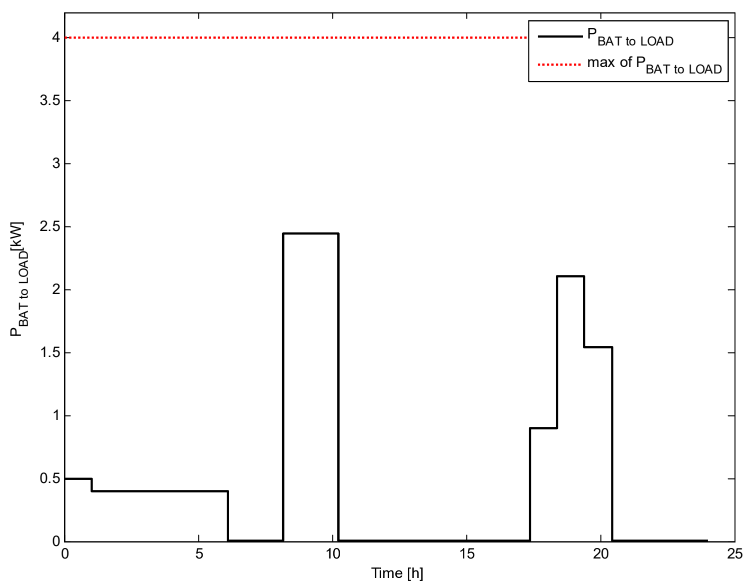


Figure A1.3: Battery output power to the load

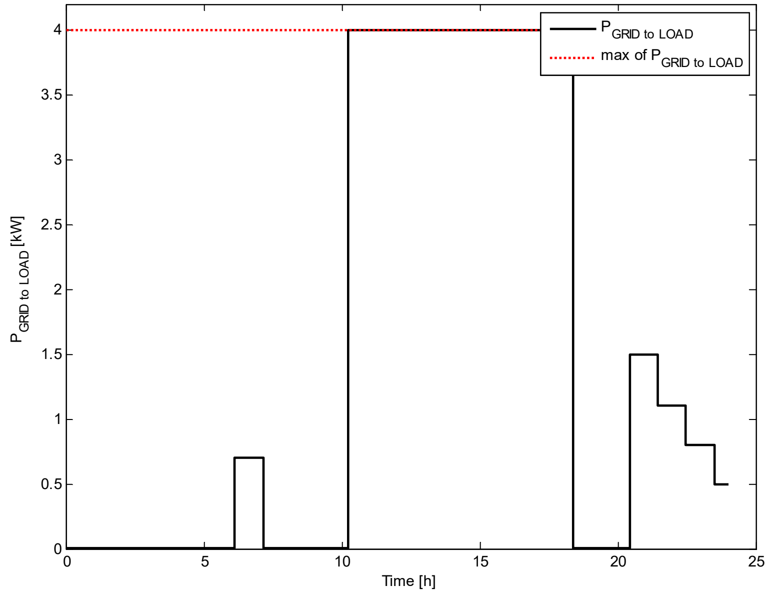


Figure A1.4: Grid power to the load

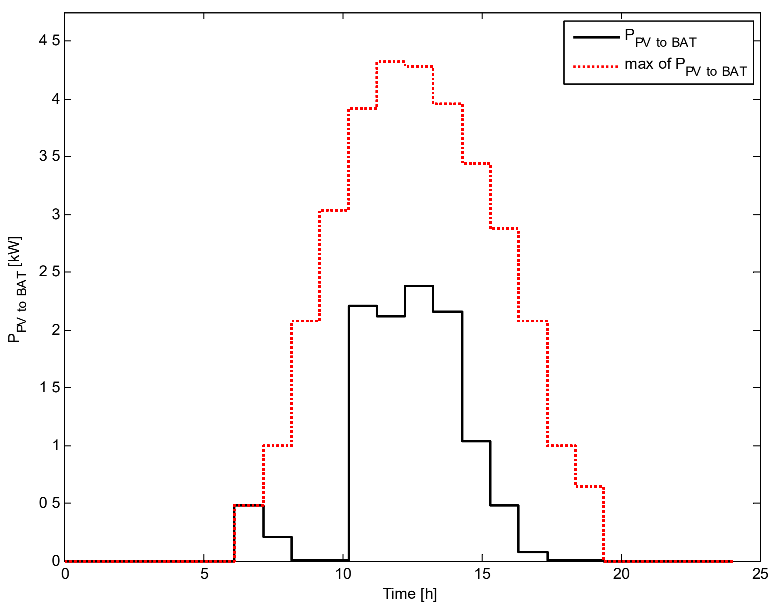


Figure A1.5: PV output power to the battery

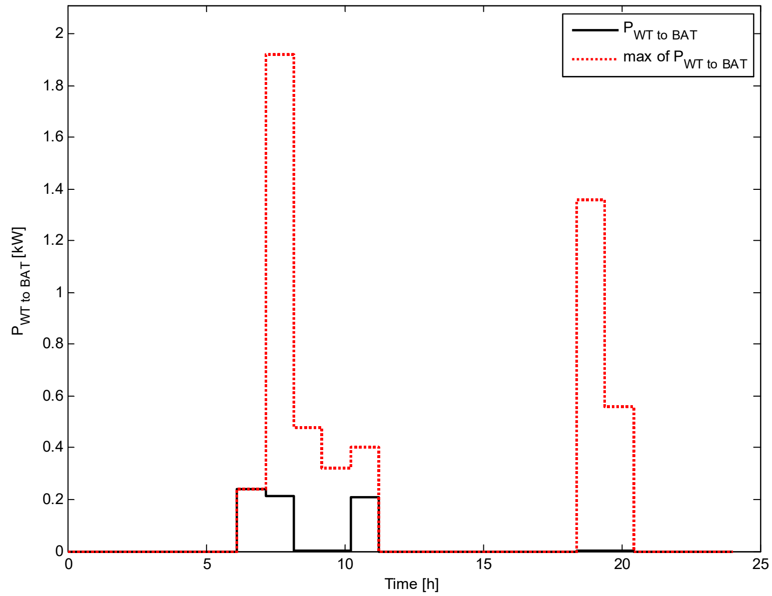


Figure A1.6: WT output power to the battery

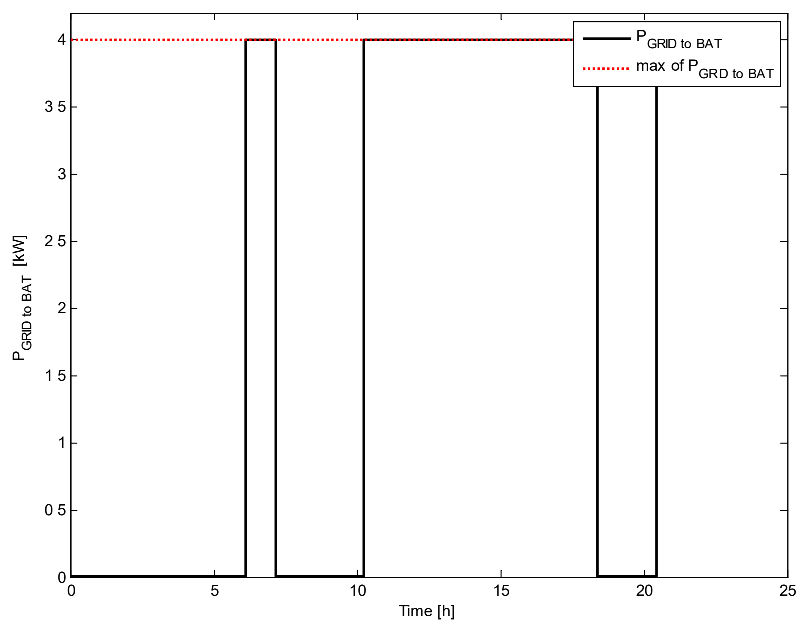


Figure A1.7: Grid power to the battery

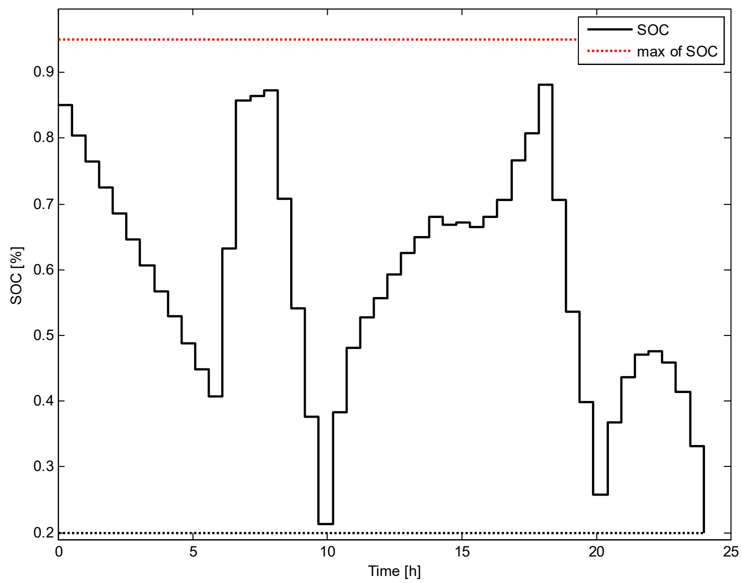


Figure A1.8: Battery SOC dynamics

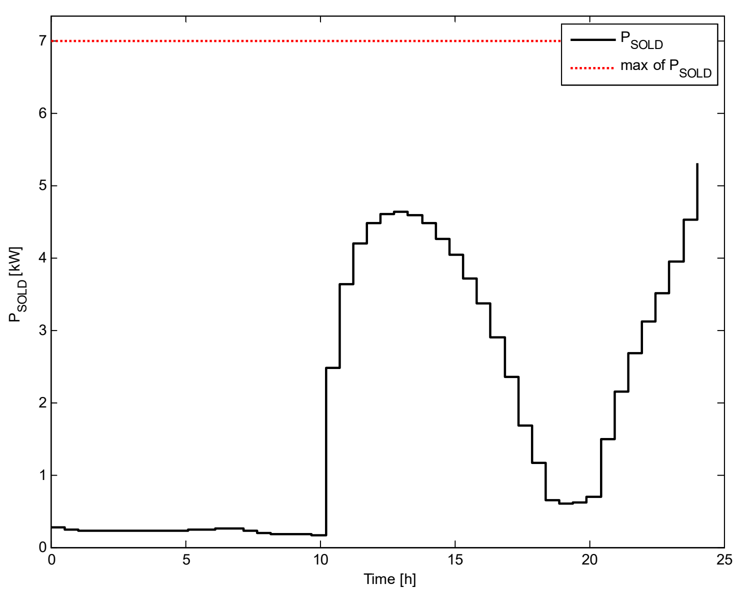


Figure A1.9: Profile of power sold to the grid

*Appendix A2: Residential load*

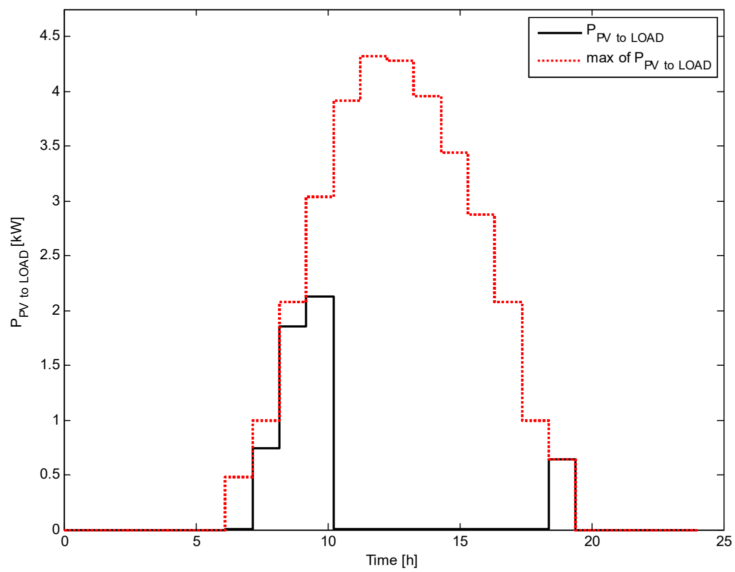


Figure A2.1: PV output power to the load

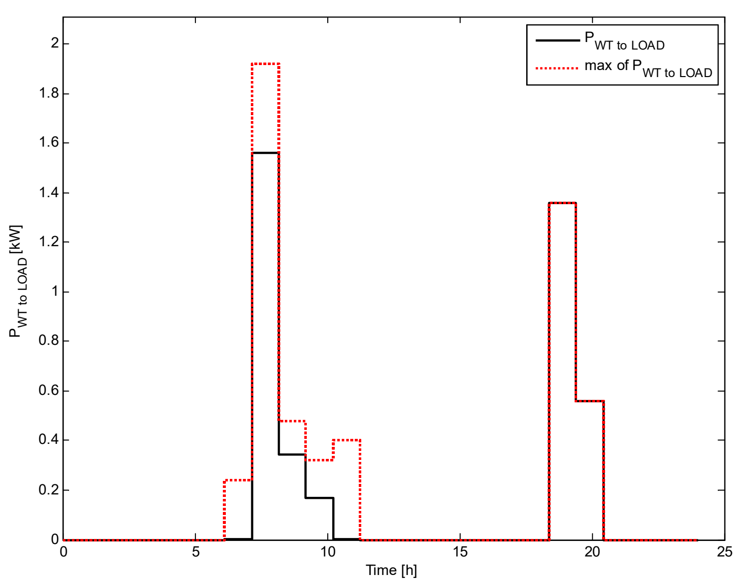


Figure A2.2: WT output power to the load

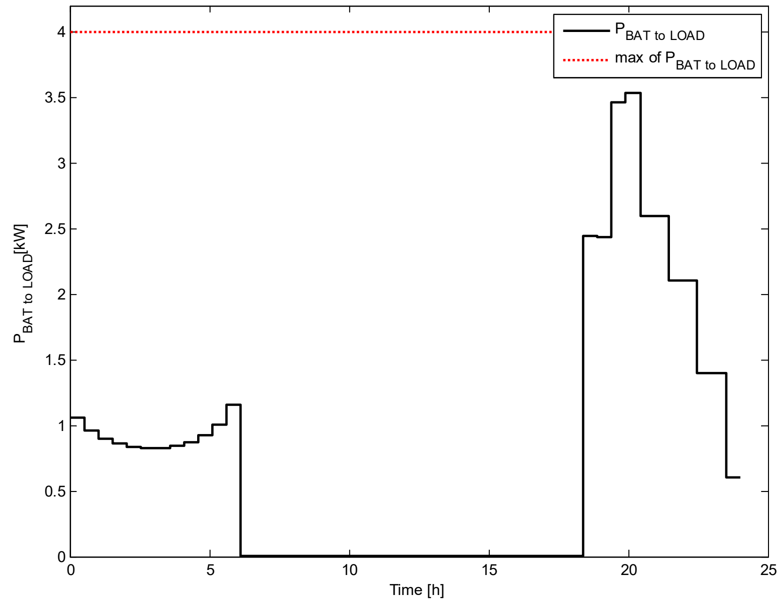


Figure A2.3: Battery output power to the load

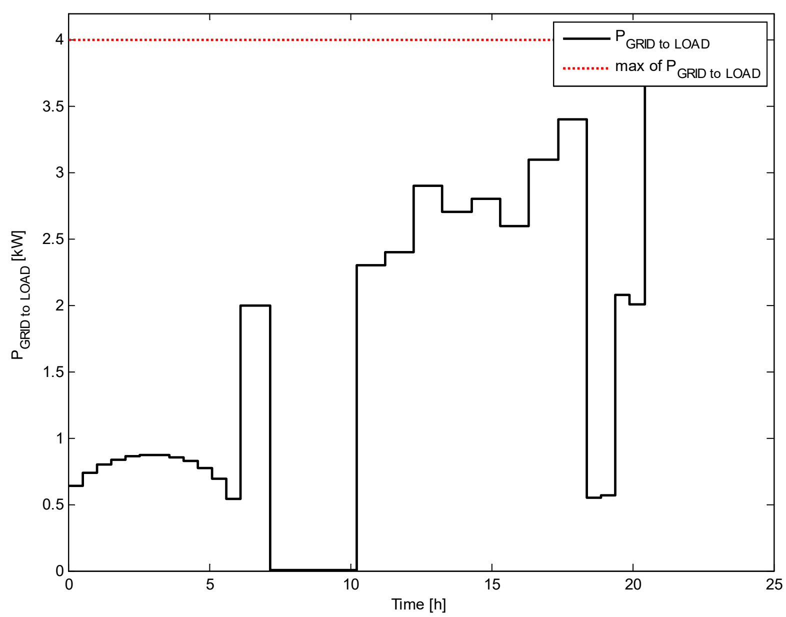


Figure A2.4: Grid power to the load

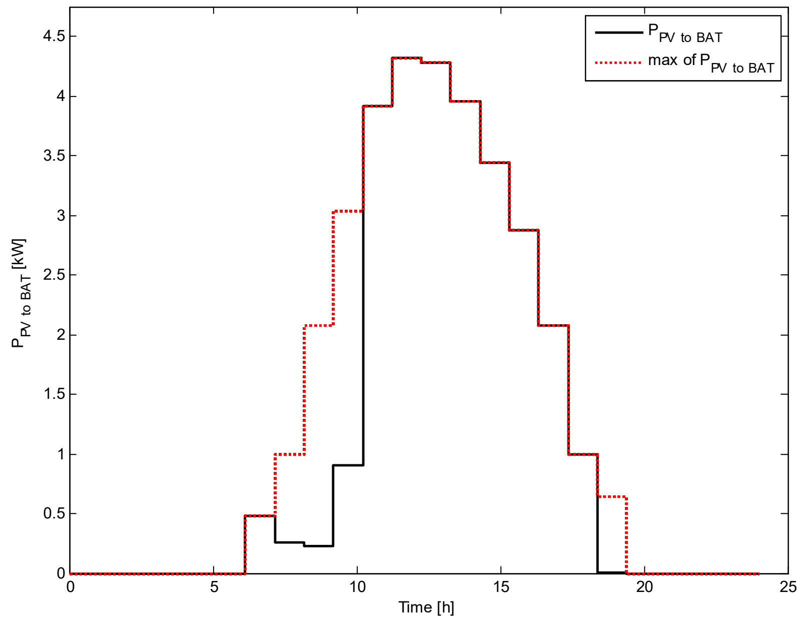


Figure A2.5: PV output power to the battery

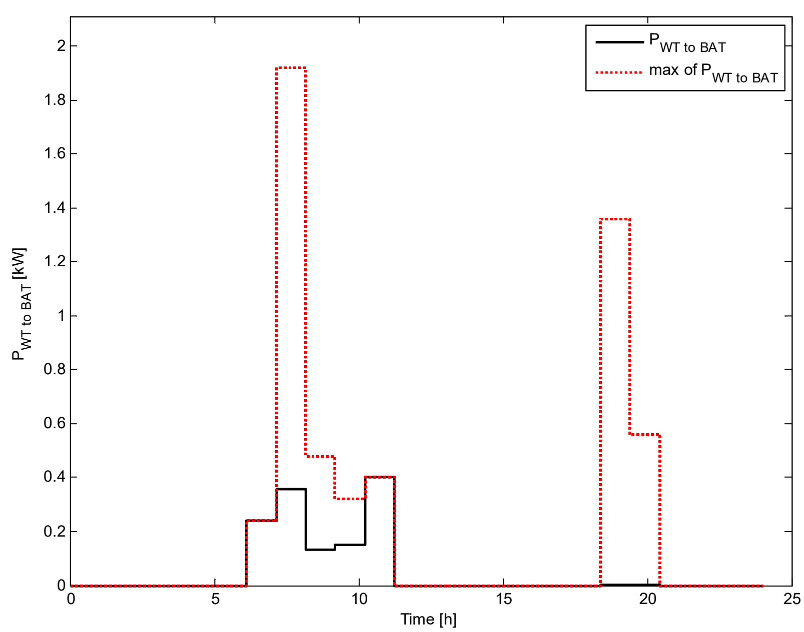


Figure A2.6: WT output power to the battery

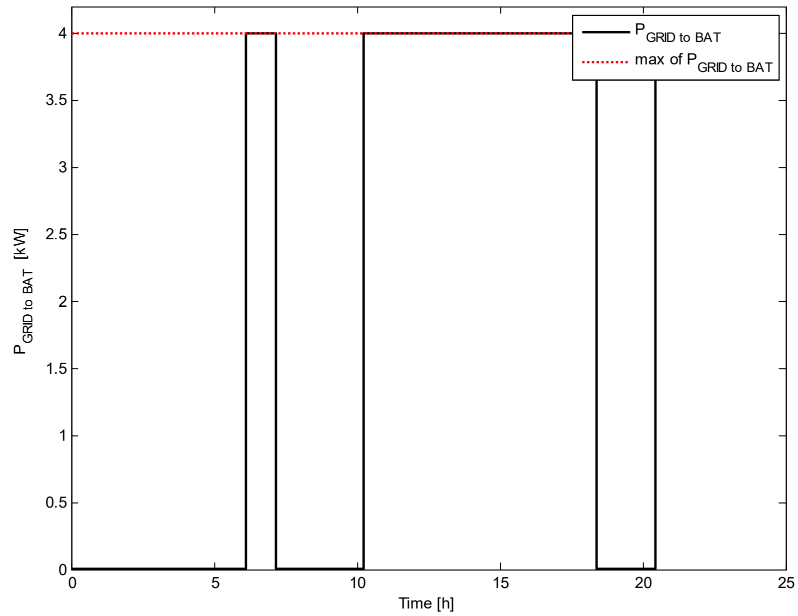


Figure A2.7: Grid power to the battery

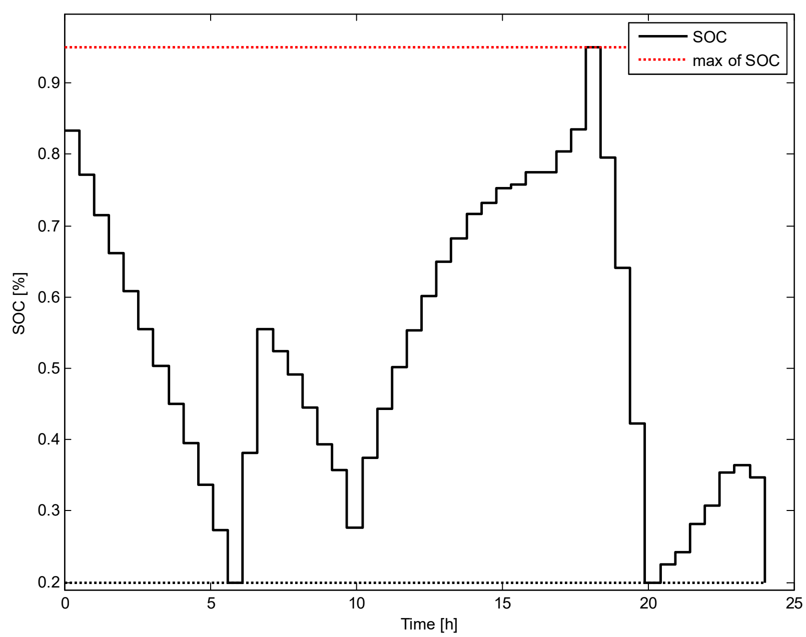


Figure A2.8: Battery SOC dynamics

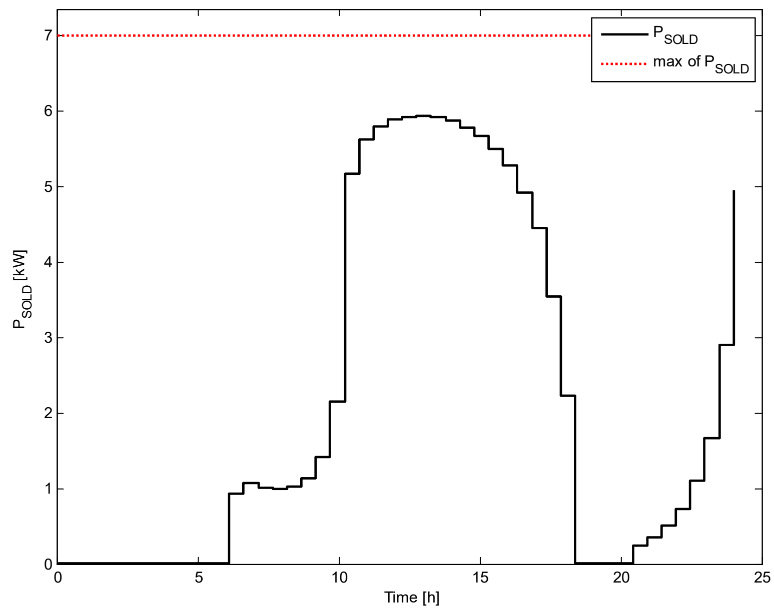


Figure A2.9: Profile of power sold to the grid

# Appendix B: Sample of Matlab code (Industrial demand)

```
deltaT=30;
hours=24;
N=hours*60/deltaT;
soc_max=0.95;
Soc_min=0.20;
soc0=0.9;
Eff_c=0.85;
Eff_d=0.95;
En=500;
d=(deltaT*Eff_c)/En;
e=deltaT/(En*Eff_d);
rho1=0.20538;
r=0.65;
a=0.001;
c=a-r*rho1;
PPV_max=[0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),
0*ones(1,N/24),0.48*ones(1,N/24),1*ones(1,N/24),2.08*ones(1,N/24),3.04*ones(1,N/24),3.9
2*ones(1,N/24),4.32*ones(1,N/24),4.28*ones(1,N/24),3.96*ones(1,N/24),3.44*ones(1,N/24),
2.88*ones(1,N/24),2.08*ones(1,N/24),1*ones(1,N/24),0.64*ones(1,N/24),0*ones(1,N/24),0*
ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24)]';
PWT_max=8*[0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0.03*ones(1,N/24), 0.24*ones(1,N/24), 0.06*ones(1,N/24),
0.04*ones(1,N/24), 0.05*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
```

```
0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.17*ones(1,N/24),
0.07*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24)]';
P1_min=0; P2_min=0; P3_min=0; P4_min=0;P5_min=0;P6_min=0;P7_min=0;P8_min=0;
P1_max=[0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0
*ones(1,N/24),0.48*ones(1,N/24),1*ones(1,N/24),2.08*ones(1,N/24),3.04*ones(1,N/24),3.92
*ones(1,N/24),4.32*ones(1,N/24),4.28*ones(1,N/24),3.96*ones(1,N/24),3.44*ones(1,N/24),2
.88*ones(1,N/24),2.08*ones(1,N/24),1*ones(1,N/24),0.64*ones(1,N/24),0*ones(1,N/24),0*o
nes(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24)]';
P2_max=8*[0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0.03*ones(1,N/24), 0.24*ones(1,N/24), 0.06*ones(1,N/24),
0.04*ones(1,N/24), 0.05*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.17*ones(1,N/24),
0.07*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24)]';
P3_max=4; P4_max=4;
P5_max=[0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0
*ones(1,N/24),0.48*ones(1,N/24),1*ones(1,N/24),2.08*ones(1,N/24),3.04*ones(1,N/24),3.92
*ones(1,N/24),4.32*ones(1,N/24),4.28*ones(1,N/24),3.96*ones(1,N/24),3.44*ones(1,N/24),2
.88*ones(1,N/24),2.08*ones(1,N/24),1*ones(1,N/24),0.64*ones(1,N/24),0*ones(1,N/24),0*o
nes(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24)]';
P6_max=8*[0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0.03*ones(1,N/24), 0.24*ones(1,N/24), 0.06*ones(1,N/24),
0.04*ones(1,N/24), 0.05*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.17*ones(1,N/24),
0.07*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24)]';
P7_max=4;
```

```
P8_max=7;
PL=[0.5*ones(1,N/24), 0.5*ones(1,N/24), 0.5*ones(1,N/24), 0.5*ones(1,N/24),
0.5*ones(1,N/24), 0.5*ones(1,N/24), 3*ones(1,N/24), 7*ones(1,N/24), 8*ones(1,N/24),
7*ones(1,N/24), 9*ones(1,N/24), 7*ones(1,N/24), 5*ones(1,N/24), 7*ones(1,N/24),
5*ones(1,N/24), 5*ones(1,N/24), 4*ones(1,N/24), 2*ones(1,N/24), 0.5*ones(1,N/24),
0.5*ones(1,N/24), 0.5*ones(1,N/24), 0.5*ones(1,N/24), 0.5*ones(1,N/24), 0.5
*ones(1,N/24)];
rho=[0.3558*ones(1,N/24),0.3558*ones(1,N/24),0.3558*ones(1,N/24),0.3558*ones(1,N/24),
0.3558*ones(1,N/24),0.3558*ones(1,N/24),0.05948*ones(1,N/24),0.20538*ones(1,N/24),0.2
0538*ones(1,N/24),0.20538*ones(1,N/24),0.05948*ones(1,N/24),0.05948*ones(1,N/24),0.05
948*ones(1,N/24),0.05948*ones(1,N/24),0.05948*ones(1,N/24),0.05948*ones(1,N/24),0.059
48*ones(1,N/24),0.05948*ones(1,N/24),0.20538*ones(1,N/24),0.20538*ones(1,N/24),0.0594
8*ones(1,N/24),0.05948*ones(1,N/24),0.03558*ones(1,N/24),0.03558*ones(1,N/24)];
A1=[zeros(N,N),zeros(N,N),-
e*tril(ones(N,N)),zeros(N,N),d*tril(ones(N,N)),d*tril(ones(N,N)),d*tril(ones(N,N)),-
e*tril(ones(N,N))];
A2=-A1;
A3=
[eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N),eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N)];
A4=
[zeros(N,N),eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N),eye(N,N),zeros(N,N),zeros(N,N)];
A=[A1;A2;A3;A4];
b=[(soc_max-soc0)*ones(N,1);(soc0-Soc_min)*ones(N,1);PPV_max(1:N);PWT_max(1:N)];
Aeq
=[eye(N,N),eye(N,N),eye(N,N),eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N),zeros(N,N)];
```

```
beq=PL(1:N);
lb=[P1_min*ones(N,1);P2_min*ones(N,1);P3_min*ones(N,1);P4_min*ones(N,1);P5_min*o
nes(N,1);P6_min*ones(N,1);P7_min*ones(N,1);P8_min*ones(N,1)];
ub=[P1_max(1:N);P2_max(1:N);P3_max*ones(N,1);P4_max*ones(N,1);P5_max(1:N);P6_m
ax(1:N);P7_max*ones(N,1);P8_max*ones(N,1)];
x0=ub;
options=optimset('Algorithm','interior-point');
 optnew=optimset(options,'MaxFunEvals',90000,'Tolx',1e-8);
f=deltaT*[zeros(1,N),zeros(1,N),a*ones(1,N),rho(1:N),zeros(1,N),zeros(1,N),rho(1:N),c*one
s(1,N)]';
[x,sold]=linprog(f,A,b,Aeq,beq,lb,ub,[],optnew);

P_1=x(1:N);
P_2=x(N+1:2*N);
P_3=x(2*N+1:3*N);
P_4=x(3*N+1:4*N);
P_5=x(4*N+1:5*N);
P_6=x(5*N+1:6*N);
P_7=x(6*N+1:7*N);
P_8=x(7*N+1:8*N);

for i=1:N
 soc(i)=soc0+d*(P_5(i)+P_6(i)+P_7(i))-e*(P_3(i)+P_8(i));
 soc0=soc(i);
end
```

```
soc1=soc(1:N);



figure (1)
stairs(linspace(0,hours,N),PL(1:N),'k','linewidth',1.5)
ylabel('P_L_O_A_D [kW]')
axis([0 hours+1 0 1.05*max(PL)]);
xlabel('Time [h]')
legend('P_L_O_A_D')

figure (2)
stairs(linspace(0,hours,N),P_1(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),PPV_max*ones(1,N),':r','linewidth',1.5)
ylabel('P_P_V _t_o _L_O_A_D [kW]')
xlabel('Time [h]')
legend('P_P_V _t_o _L_O_A_D','max of P_P_V _t_o _L_O_A_D')
axis([0 hours+1 0 1.1*max(P1_max)]);

figure (3)
stairs(linspace(0,hours,N),P_2(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),PWT_max*ones(1,N),':r','linewidth',1.5)
ylabel('P_W_T _t_o _L_O_A_D [kW]')
xlabel('Time [h]')
```

```
legend('P_W_T _t_o _L_O_A_D','max of P_W_T _t_o _L_O_A_D')

axis([0 hours+1 0 1.1*max(P2_max)]);


figure (4)

stairs(linspace(0,hours,N),P_3(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),P3_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_B_A_T _t_o _L_O_A_D[kW]')

xlabel('Time [h]')

legend('P_B_A_T _t_o _L_O_A_D','max of P_B_A_T _t_o _L_O_A_D')

axis([0 hours+1 0 1.05*max(P3_max)]);


figure (5)

stairs(linspace(0,hours,N),P_4(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),P4_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_G_R_I_D _t_o _L_O_A_D [kW]')

xlabel('Time [h]')

legend('P_G_R_I_D _t_o _L_O_A_D','max of P_G_R_I_D _t_o _L_O_A_D')

axis([0 hours+1 0 1.05*max(P4_max)]);



figure (6)

stairs(linspace(0,hours,N),P_5(1:N),'k','linewidth',1.5)

hold on
```

```
stairs(linspace(0,hours,N),PPV_max*ones(1,N),':r','linewidth',1.5)
ylabel('P_P_V _t_o _B_A_T [kW]')
xlabel('Time [h]')
legend('P_P_V _t_o _B_A_T','max of P_P_V _t_o _B_A_T')
axis([0 hours+1 0 1.1*max(P5_max)]);

figure (7)
stairs(linspace(0,hours,N),P_6(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),PWT_max*ones(1,N),':r','linewidth',1.5)
ylabel('P_W_T _t_o _B_A_T [kW]')
xlabel('Time [h]')
legend('P_W_T _t_o _B_A_T','max of P_W_T _t_o _B_A_T')
axis([0 hours+1 0 1.1*max(P6_max)]);


figure (8)
stairs(linspace(0,hours,N),P_7(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),P7_max*ones(1,N),':r','linewidth',1.5)
ylabel('P_G_R_I_D _t_o _B_A_T  [kW]')
xlabel('Time [h]')
legend('P_G_R_I_D _t_o _B_A_T','max of P_G_R_I_D _t_o _B_A_T')
axis([0 hours+1 0 1.05*max(P7_max)]);
```

```
figure (9)

stairs(linspace(0,hours,N),soc1(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),soc_max*ones(1,N),':r','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),Soc_min*ones(1,N),':k','linewidth',1.5)

ylabel('SOC [%]')

axis([0 hours+1 0.19 1.05*max(soc_max)]);

xlabel(' Time [h]')

legend('SOC','max of SOC')



figure (10)

stairs(linspace(0,hours,N),P_8(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),P8_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_S_O_L_D [kW]')

xlabel('  Time [h]')

legend('P_S_O_L_D','max of P_S_O_L_D')

axis([0 hours+1 0 1.05*max(P8_max)]);
```