OPERATION OF BATTERY EXCHANGE STATIONS FOR ELECTRIC VEHICLES

by

Ghady Khalil Zaher

A thesis presented to the Faculty of the
American University of Sharjah
College of Engineering
In Partial Fulfillment
of the Requirements
for the Degree of

Master of Science in
Electrical Engineering

Sharjah, United Arab Emirates

May 2019

Approval Signatures

We, the undersigned, approve the Master's Thesis of Ghady Khalil Zaher.

Thesis Title: Operation of Battery Exchange Station for Electric Vehicles.

Signature	**Date of Signature** (dd/mm/yyyy)
_______________________ Dr. Mostafa Shaaban Assistant Professor, Department of Electrical Engineering Thesis Advisor	_____________
_______________________ Dr. Shayok Mukhopadhyay Assistant Professor, Department of Electrical Engineering Thesis Committee Member	_____________
_______________________ Dr. Di Zhang Assistant Professor, Department of Sustainable and Renewable Energy Engineering University of Sharjah Thesis Committee Member	_____________
_______________________ Dr. Nasser Qaddoumi Head, Department of Electrical Engineering	_____________
_______________________ Dr. Lotfi Romdhane Associate Dean for Graduate Affairs and Research College of Engineering	_____________
_______________________ Dr. Naif Darwish Acting Dean, College of Engineering	_____________
_______________________ Dr. Mohamed El-Tarhuni Vice Provost for Graduate Studies	_____________

Acknowledgement

I would like to thank my advisor Dr. Mostafa Shaaban for providing knowledge, guidance, support, and motivation throughout my research stages. I’m deeply beholden for his great assistance, worthy discussion and suggestions.

I would like to thank the American University of Sharjah for offering me graduate teaching assistant scholarship for two years and the professors of the Electrical Engineering department who taught me the master level courses with mighty teaching methods and skills. I am really appreciating their dignified advices and motivation.

The success and outcome of this thesis required a lot of guidance and assistance from my family and friends and I am extremely privileged to have got this all along the completion of my thesis. All that I have done is only due to such supervision and assistance and I would not forget to thank them.

Dedication

To my family…

Abstract

Due to environmental and energy security concerns, low emission vehicles present a vital necessity for clean transportation. In particular, Electric Vehicles (EV) are the most promising solution due to the fact that the electrical power system is the most ready infrastructure to supply their requirement. Two possible energy delivery solutions to the EVs, namely the charging stations and the Battery Exchange Stations (BES), are taking the interest of the research nowadays. In this research, a new operation approach is proposed for the BESs. The proposed approach models and optimizes the performance of the charging, discharging and the replacement of the batteries throughout the day taking into consideration the customers arrivals to the BES. The main targets of this approach are to satisfy the EV owners charging requests and to minimize the operating costs. In addition, the batteries in possession of the BES are used to secure more profit to the investor by performing energy arbitrage and supplying ancillary services to the grid. This thesis is targeting the EV manufacturers and EV charging service providers who are directly affecting the development of the EV market. The BES operation optimization problem is formulated as mixed-integer nonlinear programming and is solved as a day-ahead operational problem. The behaviour of charging/discharging power, the state of charge and the stored and replaced energy for all batteries in the station is observed for different case studies. The effect of different aspects such as the grid power limitation, solar photovoltaic system addition and battery self-degradation on the operation of the BES is designed and discussed. Also, a comparison between the charging station operation and the BES is conducted and the results show the benefits of implementing the concept of BES on the EV market. The results prove the effectiveness of the proposed approach in satisfying the EV owners and maximizing the BES investor profit.

Keywords - Battery Exchange Stations, Charging Stations, Electric Vehicles, Optimization, Smart Grid.

Table of Contents

Abstract… ……………………………………………………………………………6

List of Figures 9

List of Tables 11

List of Abbreviations 12

Nomenclature 13

Chapter 1. Introduction 15

1.1 Overview 15

1.2 Thesis Objectives 16

1.3 Research Contribution 16

1.4 Thesis Organization 16

Chapter 2. Background and Literature Review 18

2.1 Background to Electric Vehicles and Stations 18

2.1.1 Electric vehicles stations………………………………..………….........19

2.1.2 Charging stations and BES comparison………………………….........19

2.2 Related Work 20

Chapter 3. Proposed Work 23

3.1 BES System Structure 23

3.2 Proposed Smart BES Operation Approach 24

Chapter 4. Proposed Operation Approach Description and Formulation 26

4.1 Proposed Approach Description 26

4.2 Problem Formulation 27

4.2.1 Objective function……………………………………………………. 27

4.2.2 Battery charging/discharging……………………………………….........27

4.2.3 Energy replacement……………………………………………….. 28

4.2.4 Grid power limitation………………………………..………. 29

4.2.5 Solar PV system generation… ……………………………………… 29

4.2.6 Battery self-degradation effect……………………………………. 30

4.3 Charging Station Formulation 31

4.4 Optimization Unit 31

Chapter 5. Results and Analysis 33

5.1 Results Summary 33

5.1.1 Proposed operation approach development…………………….. 33

5.1.2 Proposed operation approach testing……………………………….........33
5.2 Developed Versions of the Approach 35
5.2.1 V0.0 – Charging/discharging cycles……………………………….........35
5.2.2 V0.1 – Battery parameters variation with time for three stations……........36
5.2.3 V0.2 – Batteries selection for each customer (24 segments)……… 37
5.2.4 V0.2’ – Batteries selection for each customer (288 segments)……….......40
5.3 Case Studies 42
5.3.1 Case 1: base case……………………………………………….............42
5.3.2 Case 2: grid power limitation effect……………………………….........46
5.3.3 Case 3: solar PV system addition……………………………….........47
5.3.4 Case 4: comparison between BES and charging stations………….........48
Chapter 6. Conclusion and Future Work 50
References ………………………………………………………………………...51
Appendix A...55
Appendix B...68
Vita……………...72

List of Figures

Figure 1: Global EV sales, 2010-2017[5]. 19
Figure 2: Tesla charging stations in Europe and Middle East [7] 19
Figure 3: Battery exchange stations robots [12]. 20
Figure 4: BES schematic diagram 23
Figure 5: BES structure. 24
Figure 6: Proposed BES operation approach flow inputs and outputs. 25
Figure 7: Proposed operation approach flowchart. 26
Figure 8: The rooftop solar PV system. 29
Figure 9: The change in SOC caused by degradation with the number of charging/discharging cycles [30]. 30
Figure 10: The charging/discharging cycles with grid price variation for V0.0. 35
Figure 11: State of charge with time for V0.0. 35
Figure 12: Charging power variation with the time for the three stations in V0.1. 36
Figure 13: Discharging power to grid variation with the time for the three stations in V0.1 36
Figure 14: State of charge variation with the time for the three stations in V0.1. 37
Figure 15: Replacement energy for the three stations in V0.1. 37
Figure 16: Charging power variation with the time for the three stations in V0.2. 38
Figure 17: Discharging power to grid variation with the time for the three stations in V0.2 38
Figure 18: State of charge variation with the time for the three stations in V0.2. 39
Figure 19: Energy delivered to customers by battery exchange in V0.2. 39
Figure 20: Charging power variation with the time for the three stations in V0.2’ 40
Figure 21: Discharging power variation with time for the three stations in V0.2’. 40
Figure 22: State of charge variation with the time for the three batteries in V0.2’. 41
Figure 23: Energy delivered to customers by battery exchange in V0.2’. 41
Figure 24: Charging cycles vs. time segments for the four stations. 42
Figure 25: Discharging cycles vs. time segments for the four stations. 42
Figure 26: State of charge variation vs. time segments for the four stations. 43
Figure 27: Batteries/Customers selection. 43
Figure 28: Charging cycles vs. time segments for the 13 stations. 44

Figure 29: Discharging cycles vs. time segments for the 13 stations. 44
Figure 30: State of charge variation vs. time segments for the 13 stations. 45
Figure 31: Batteries/Customers selection. 45
Figure 32: Charging cycles vs. time with and without the grid power limitation. 46
Figure 33: Batteries/Customers selection with grid power limitation. 46
Figure 34: The grid charging power vs. time segments with and without solar energy. 47
Figure 35: The solar and the total charging power vs. time segments. 48
Figure 36: Charging power variation vs. time for the BES and the charging stations. 48
Figure 37: The side and top view of the rooftop solar system. 68

List of Tables

Table 1: Monthly charges for Industrial Customers. 34
Table 2: Technical battery parameters. 34
Table 3: Grid price per hour for one day [23]. 34
Table 4: Monthly charges for Industrial Customers. 34

List of Abbreviations

BARON	The Branch-And-Reduce Optimization Navigator
BES	Battery Exchange Stations
BEV	Battery Electric Vehicles
EV	Electric vehicles
GAMS	General Algebraic Modelling System
GHG	Green-House Gases
HEV	Hybrid Electric Vehicles
IESO	Independent Electricity System Operator
MINLP	Mixed-Integer Nonlinear Programs
NLP	Nonlinear Programs
PCC	Point of the Common Coupling
PHEV	Plug in Hybrid Electric Vehicles
PV	Photovoltaic
SOC	State of Charge

Nomenclature

Sets:

$\mathbb{B}$	Set of Batteries
$\mathbb{C}$	Set of Customers
$\mathbb{T}$	Set of Time Segments

Indices:

b	Index of Batteries
c	Index of Customers
t	Index of Time Segments

Parameters:

$ar_{(t,c)}$	Customer Arrivals to The Station (0/1)
$Cyc_{(c)}$	Number of Charging/Discharging Cycles (#)
Δt	Time Step (Minutes)
E^{max}	Maximum Battery Energy (kWh)
$E^{stored-int}$	Initial Stored Energy in The Battery (kWh)
$MDOD$	Maximum Depth of Discharge (%)
η	Charging Efficiency (%)
N_t	Number of Time Segments (#)
$P_{Historical}^{MAX}$	Historical Maximum Power Extracted from Grid (kW)
P^{max}	Maximum Chargers' Power (kW)
$P^{grid-max}$	Maximum Grid Power Limits (kW)
$p^{grid-Rep}$	Replacement Energy Price (\$/kWh)
$p^{grid-kW}$	Demand Power from Grid Price (\$/kW)
$p_{(t)}^{grid-kWh}$	Energy Price from Grid (\$/kWh)

$p_{(c)}^{deg}$	Degradation Effect Price (\$/%)
SOC_o	Initial State of Charge (%)
γ	Customer Satisfaction Factor

Variables:

C^{kW}	Cost of Demand Charges (\$)
C^{kWh}	Cost of Charging/Discharging Battery Cycles (\$)
$C^{charging}$	The Charging Station Cost (\$)
C^{DEG}	The Self-Degradation Effect Cost (\$)
$E_{(t,b,c)}^{rep}$	Replacement Energy (kWh)
$E_{(t,b)}^{stored}$	Stored Energy in The Battery (kWh)
P^{ExMax}	Maximum Exchanged Power from Grid (kW)
$P_{(t,b)}^{Charging}$	Charging Power from Grid (kW)
$P_{(t,b)}^{Discharging}$	Discharging Power to Grid (kW)
$P_{(t)}^{limit}$	Maximum Exchanged Power Under Grid Limitation (kW)
$P_{(t,b)}^{PV}$	Solar PV Power (kW)
R	Revenue of Sold Energy by Battery Replacement (\$)
$SOC_{(t,b)}$	State of Charge (%)
$\Delta SOC_{(c)}^{deg}$	Change in SOC by Degradation
$x_{(b,c)}$	Binary Variable for Serving the Customers
z	Total Revenue (\$)

Chapter 1. Introduction

In this chapter, we provide a short introduction about the necessity of clean transportation and Electric Vehicles (EVs). Then, we present the research contribution and the thesis objectives. Finally, the general organization of the thesis is presented.

1.1 Overview

Global warming due to Green-House-Gas (GHG) emissions raised critical environmental concerns in the last few decades. In addition, several concerns regarding the security of energy resources are raised due to the dependency of some essential sectors (e.g. transportation) on a single source of energy (e.g. fossil fuel). To lower the GHG emissions and to increase energy security by diversifying the energy sources, EVs represent the most promising solution. This is due to the availability of electric power systems' infrastructure almost everywhere and the electricity generation sector has well established and economically feasible low-emission energy resources such as solar panels and wind turbines.

There are numerous challenges facing the integration of EVs on roads. Among these challenges, the charging time and the impacts on the electrical grid are most salient. However, the charging time may take hours and the grid was not originally designed to accommodate such extra load.

In addition, several problems may appear for an EV user that limit the range of EVs noticed in the road. The first inconvenience problem is the fear of the driver that the battery will be depleted before reaching the destination. This is possible since most of EV's battery ranges are limited for short distances while there are not enough stations available on the road. Solving this issue needs bigger batteries capacities, larger space and more expensive EV. In addition, the charging stations should be reachable and located based on the EV ranges, which makes the users more comfortable. Nonetheless, today the range of EVs exceeds 500 km thanks to advanced battery technologies. The other inconvenience problem is the long time needed for an EV to charge compared to refilling a fuel tank in gasoline vehicles. Nowadays, with the availability of the DC fast chargers, the best time recorded is about 20 minutes. Nevertheless, installing those chargers requires big investment and has negative impacts on the power grid caused by their high switching magnitudes. Thus, using ordinary charging stations introduces a tradeoff between battery sizes, chargers' capacities and charging time. For example, longer battery range requires bigger capacity, which needs bigger chargers and more charging time. To reduce the user waiting time, battery-swapping may be a solution. By this, a fully charged battery will be ready to be replaced by the empty battery once the user arrives at the station. Then, the empty battery will be charged during the low energy prices and ready to be swapped once another vehicle arrives at the station in the high demand. This concept can help in improving performance as it provides some form of demand buffering and shifting.

After reviewing the state-of-the-art work in the field of EV charging and Battery Exchange Stations (BESs), it is obvious that this area is still in primitive stages and proper models and management strategies are required.

Accordingly, this research proposes to develop different methodologies to facilitate accommodating high penetration of EVs through the operation approach.

1.2 Thesis Objectives

The main target of this work is to develop a new approach for operating BESs for EVs. All possible technical and economic aspects for the BESs, EVs, and the electrical grid are considered. The main objective of this thesis is developing an operation approach for BESs in a day-ahead scheme. The proposed approach takes into consideration:

- Satisfying the EV owners and grid technical requirements.
- Minimizing the operating costs.
- Securing more profit to the investor by performing energy arbitrage and supplying ancillary services to the grid.

1.3 Research Contribution

The contributions of this research work can be summarized as follows:

- Propose an operation approach for the BES to satisfy customers’ requirements and minimize the operation costs.
- Provide detailed analysis for the simulation results on a typical charging station under different case studies.

1.4 Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 provides a brief background about EVs technology and a comparison between the charging station types. Moreover, related works to this research are discussed. The system structure and design and the smart BES operation and planning approaches are discussed in Chapter 3. Chapter 4 presents the proposed model description along with the problem formulation. The simulated results and analysis for different case studies are discussed in Chapter 5. Finally, Chapter 6 concludes the thesis and outlines the future work.

Chapter 2. Background and Literature Review

In this chapter, the basics of EVs technologies and a comparison between the charging stations and the battery exchange stations are discussed. In addition, the previously related work is studied, and the proposed objectives of this work will be explained.

2.1 Background to Electric Vehicles and Stations

An EV is any vehicle with an electric motor as a source of propulsion. There are three main types of EVs classed by the degree that electricity is used as their energy source, the Hybrid Electric Vehicles (HEV), the Plug-in Hybrid Electric Vehicles (PHEV) and the Battery Electric Vehicles (BEV) [1]. HEVs are powered by both petrol and electricity. The electric energy is generated by the car's own braking system to recharge the battery [2]. An example of this type is the Honda Civic Hybrid and Toyota Camry Hybrid. The PHEV, which is also known as extended range EVs, is powered by both petrol and electricity. However, it can recharge the battery through both regenerative braking and plugging-in to an external electrical charging outlet. Toyota Prius and Chevrolet Volt are models for PHEV. On the other hand, BEVs are fully EVs, meaning they are only powered by electricity and do not have a petrol engine, fuel tank or exhaust pipes such as BMW I3, Chevrolet Bolt, and Nissan Leaf [3].

Figure 1 shows the global EV sales from 2010 to 2017. EVs are moving forward in the market and people are using these cars more and more. However, the percentage on roads are almost negligible and most people are still not comfortable with this technology [4]. This is due to many factors that make EVs users have a different life pattern compared to the normal fuel cars we use nowadays. Some of these factors that limit the widespread of EVs are the time required to charge the EVs' battery and the limitation of the available charging stations. In addition, the energy consumed by the high penetration of EV may cause severe consequences on the electrical grid, such as thermal overloading, under-voltage, and fuse failure. Therefore, the study on the charging technology and the charging stations should be managed carefully to decrease the negative impacts on the grid side, increase the users' satisfaction, the charging stations' owners' profit, and service quality.

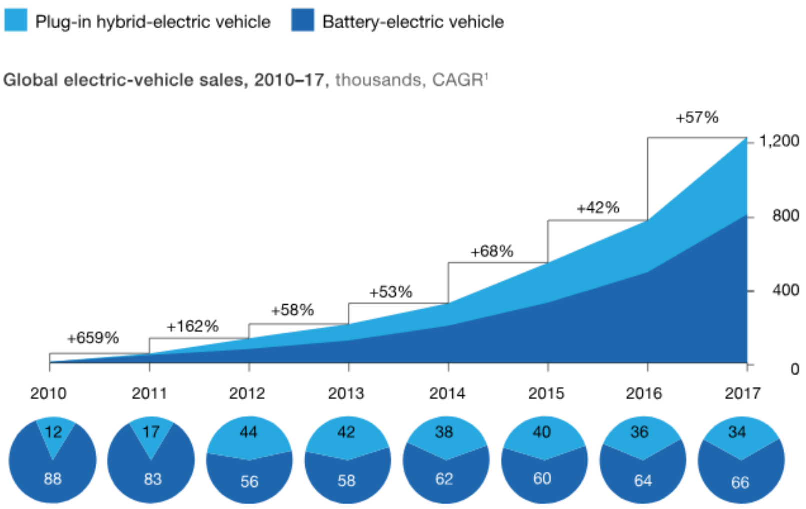


Figure 1: Global EV sales, 2010-2017[5].

2.1.1 Electric vehicles stations. EV stations can be categorized into two types: charging stations and BES. The best EV conventional charging stations have fast chargers, which can charge the battery fully in as low as half an hour. Tesla charging stations are developing very fast in the world reaching around 1,327 stations [6]. Figure 2 shows the available charging stations in Europe and the Middle East. Battery exchange stations work in a different way where the service needs only five minutes by exchanging the battery with a previously charged one. However, BES is still under research in its primitive stages and further intensive research is required to be practically feasible.

Figure 2: Tesla charging stations in Europe and Middle East [7].

2.1.2 Charging stations and BES comparison. Each type of EV stations has its own benefits and drawbacks. The capital construction investment of BESs is two to three times the conventional charging stations. BESs have chargers just like the charging stations to prepare the batteries for swapping [8]. In addition, very complicated and expensive robots are needed to do the exchanging process as shown in Figure 3. As a result, the initial cost of BES is much higher. Furthermore, BES needs a full check system on the batteries of the customers and the station [9]. Before swapping, the measurement of the charging curve and charging capacity is required which will increase the cost further. On the other hand, the operation cost of the BES is lower since high current and high voltage are always being used in the charging stations which may affect the electric power system quality [10]. Finally, the main difference is that BES service is very fast like the fuel stations that everyone is used to. People will not care about when and how much time do they need to charge their cars. So, BES can help in accelerating the widespread of EVs [11], which coincide with the UAE future plans. The UAE Presidents office has recently launched the ‘EV Accelerator Initiative’ to promote and facilitate the use of EVs on UAE roads.

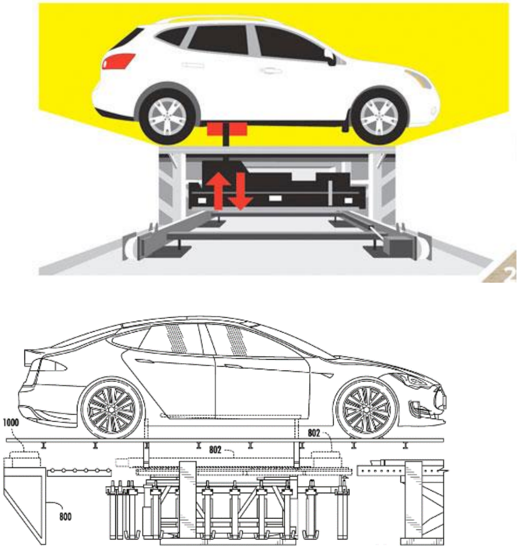


Figure 3: Battery exchange stations robots [12].

2.2 Related Work

In [13], the authors used the driving patterns for EVs and the time variations in electricity prices to minimize EV owner charging costs and maintain acceptable distribution system voltages. In [14], new logistical issues related to the limited driving range of each EV’s set of charged batteries is discussed. They addressed the locations of BESs and the sizing of each facility. In [15], the authors proposed an ant colony optimization to study the EVs charging coordination at the standalone grid in order to overcome the bad effects of decentralized control method. In addition, a capacity optimization method of the PV-based BESs is proposed in [16]. The calculation model was done using Monte Carlo simulation method which includes the capacity degradation and the statistical model of EV daily driving distance. In [17], a novel centralized charging station strategy considering urban power network structure strength is proposed. In [18], the trends of EV in China and abroad are revised. The authors studied the development trend of battery electric vehicles and its energy supply in China. The difference between the charging station and BES in terms of the cost and technical factors has been investigated in [19]. In addition, the load scheduling schemes for hybrid electric vehicle BESs in smart grid has been studied in [20]. In [21], a business case for battery swapping stations is optimized including the customers benefiting and the effect of BES on the power system. In [22], the authors built a model that estimates the energy consumption of an EV based on the driving style of the user. Also, many other papers considered using a renewable source of energy with BESs. In [23] and [24], the authors focused on building a model to provide the foundation for the planning and design of Photovoltaic (PV) system as a source of energy in the BES by modeling an optimization tool for finding the annual profit and the power generated by PV system. Furthermore, an optimization model for minimizing the cost of an off-grid connected wind power system along with the BES has been discussed in [25]. With a different approach, the authors in [26] analyzed the historical sensing data of taxi routes and evaluated the battery swapping demand profile and the power consumption of individual taxis to propose a method to calculate an optimized battery swapping station scheme. The authors also describe a real-time algorithm to schedule a subset of the unoccupied electric taxicabs to swap batteries early by giving them allowances to avoid congestion. Also, in [27], the aim was to minimize the total cost considering three factors: the number of batteries taken from the stock to serve all the swapping orders from incoming EVs, potential charging damage with the use of high-rate chargers and electricity cost for different time periods of the day. In [28], the authors considered predicting the power loads due to fast charging stations for plug-in EV. The authors in [29] concentrated on combining the operation optimization and the optimal investment strategies for BES considering multi-scenarios solar power generation and swapping demands.

All the previous work didn’t consider the operation design of BES in terms of building the system of batteries and considering serving the customers in a short period of time. Based on the previous discussion and the limited work in this area, it is obvious that the research in the field of BES is still in its early stages.

Accordingly, this research proposes to model the building blocks of the BES and to use this model to develop an operational approach for smart BES. The proposed models and approaches will include consideration of the charging and discharging cycles of the battery pack, and the operation of multiple batteries while being exchanged in BES, the arrivals of different customers over the day, and the grid technical constraints.

Chapter 3. Proposed Work

In this chapter, the structure of the BES and the proposed operation and planning approaches are described. All possible technical and economic aspects are discussed along with the proposed approaches.

3.1 BES System Structure

The design of the BES is similar in some aspects to the available gas stations. For example, a typical BES may have 3-6 exchanging units so that a maximum of six cars can exchange their batteries at the same time and the rest will be waiting in the queue as shown in Figure 4.

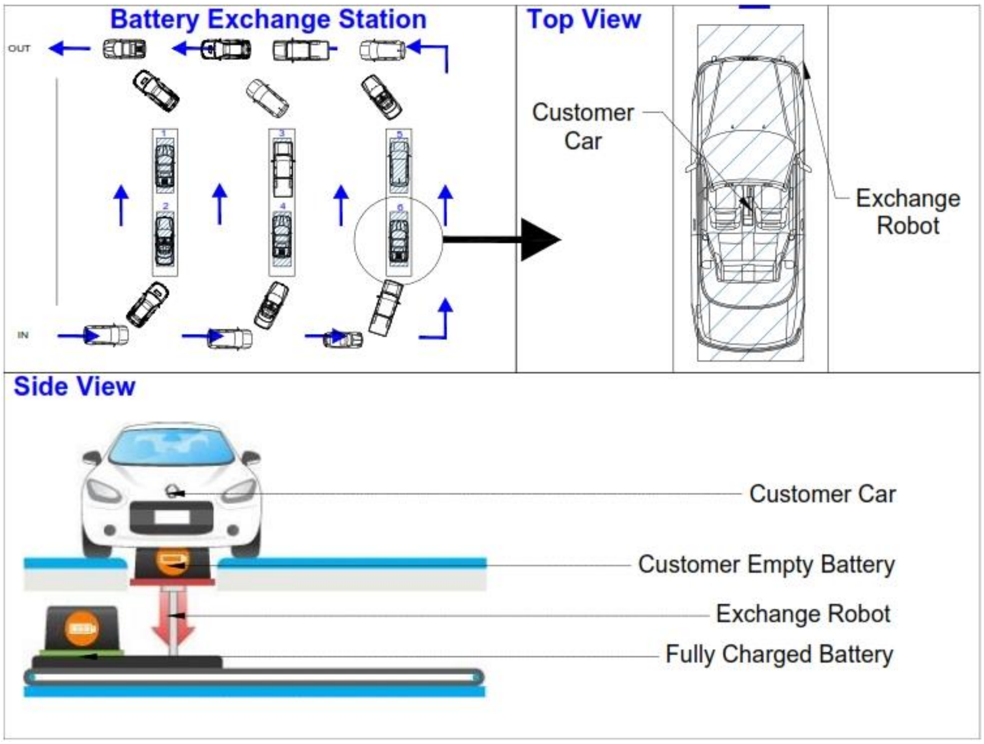


Figure 4: BES schematic diagram.

The system structure shown in Figure 5 consists of five main parts: the grid-side unit, the battery-side unit, the EVs/customers, the optimization unit, and the control unit. The grid-side unit is a bidirectional AC/DC converter to be used to maintain a fixed DC link voltage and desired power factor at the point of the common coupling (PCC). The battery-side unit is a DC/DC converter that follows the battery characteristics and reference signals for charging/discharging. The reference signals from the control unit define the charging mode or discharging mode for each battery.

The charging and discharging decisions are dependent on the limitation of the power system, grid price, and the customers' arrivals.

The third unit receives the coming EVs to exchange the EV battery with the assigned battery to meet the station requirements. The assigned battery has to be disconnected from the battery-side unit before being exchanged with the depleted battery in the EV. The optimization unit is responsible for developing the optimal decisions based on the inputs assigned from the control unit. Finally, the control unit gets the data from the other three units and take decisions about the charging, discharging and exchanging cycles [22].

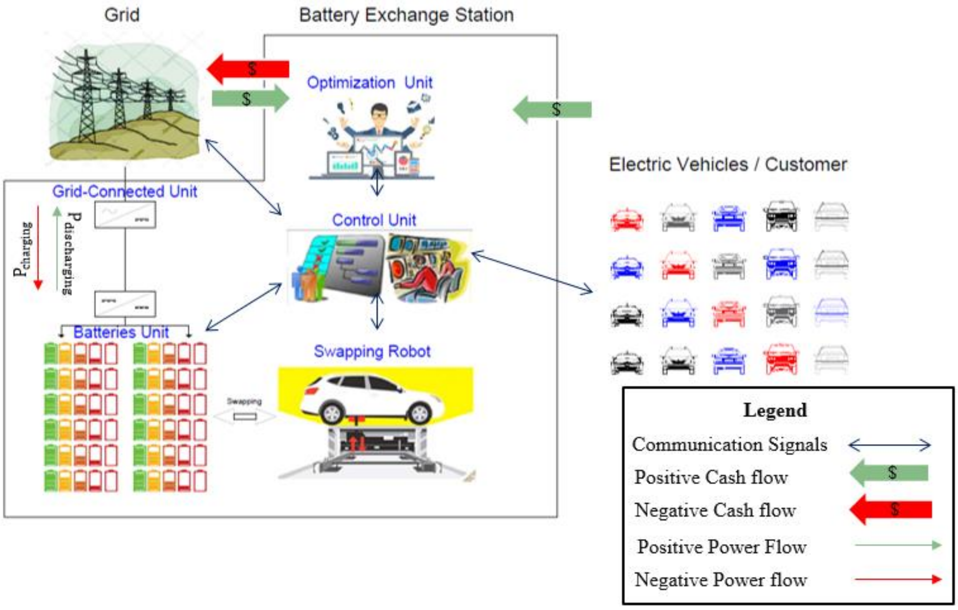


Figure 5: BES structure.

3.2 Proposed Smart BES Operation Approach

The inputs to the operation approach include economic aspects such as:

- The day-ahead electricity prices
- The cost of battery exchange service.

Also, the inputs include technical aspects such as:

- The battery exchange requests from EV drivers.
- Batteries status in the stock.
- Grid technical limitations.

All the inputs and outputs of the proposed smart operation approach are shown in Figure 6. Also, the EV arrivals schedule and their required energy should be known day-ahead. Furthermore, the status of the batteries that are being charged and replaced in the station should be tracked to serve the customers accordingly. For example, consider a battery with 35 % State of Charge (SOC) is being replaced with a fully charged one. If the battery needs an hour to be fully charged again, then this battery should be eliminated from the active service during that hour. However, the system will include this battery in the service for the customers coming in the next few hours. Therefore, the state of each battery entering and exiting the station should be known and noted. At the end of the day, the outputs of the proposed smart operation approach will include the total cost of charging the batteries using the grid and the revenue of replacing and selling the energy to the customers. In addition, a full analysis of the customers that have been served with the corresponding battery that was used will be reached to help in the future analysis and design. For instance, if the customer/battery selection during this day reached to a conclusion that one customer cannot be served for different reasons, such as the customers queue was long, or the batteries were not available when the customer arrived, a study will be conducted on it to prevent this problem in the next day analysis. In this case, different solutions may appear. For example, the batteries/customers selection may be done differently to optimize the outputs or the number of batteries in the station may be increased to serve more customers.

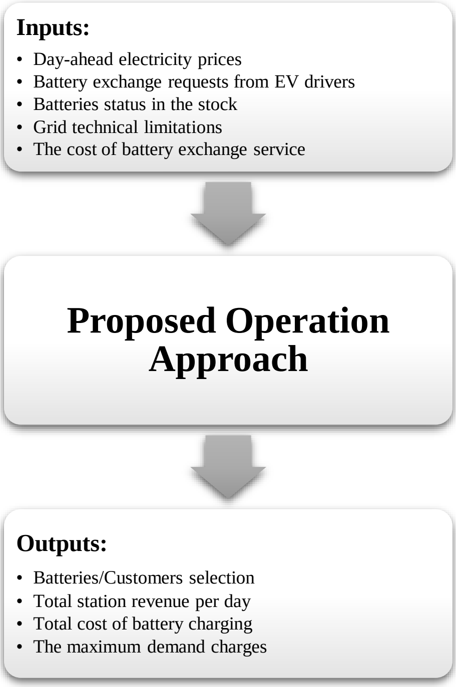


Figure 6: Proposed BES operation approach flow inputs and outputs.

Chapter 4. Proposed Operation Approach Description and Formulation

In this chapter, the proposed smart BES operation approach is explained in detail with the problem formulation. The approach is used to optimize the charging, discharging, state of charge and the energy replacement for each battery in the station depending on a specific customers' arrival and the grid price. In addition, the sensitivity analysis for different factors such as: grid power limitation, battery self-degradation and solar PV system addition is discussed. Moreover, the charging station formulation is explained to be compared with the BES.

4.1 Proposed Approach Description

The inputs to the proposed smart operation approach are the technical and economical parameters mentioned before. The decisions that need to be taken are charging, discharging or replacing the battery. When a customer arrives, the third decision, which is exchanging a battery, will be valid. But, the decision of serving that customer or not depends on the availability of the required charged battery. By this, the approach should assign the batteries to the customers depending on their known daily arrivals in order to maximize the number of customers being served during the day as well as the operational profit. The scheduling period is 288 hourly time segments, i.e. $t \in \mathbb{T} = \{1,2,\dots,N_t\}$, where t and $\mathbb{T}$ are the index and the set of time segments respectively. N_t is the number of time segments in the period under study. Furthermore, the customer can be served a battery with SOC in the range of 90 % to 100 % depending on the availability.

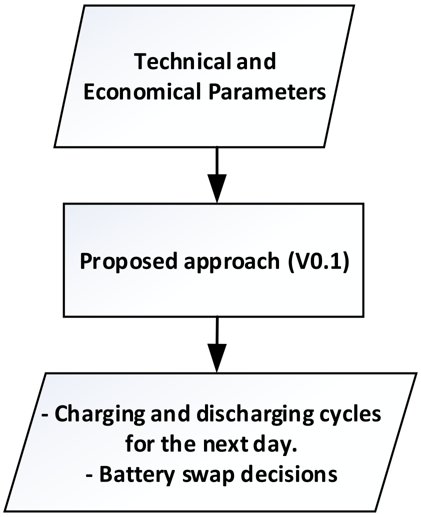


Figure 7: Proposed operation approach flowchart.

In addition, the demand charges are added to the approach, as described in Table 3 and Table 4, where the maximum energy extracted from the grid is controlled in order not to exceed a specific limit. This limit is known from historical data for the station. The index and the set of the batteries in the station are b and $\mathbb{B}$ respectively. Finally, the index and the set of the customers coming to the station are c and $\mathbb{C}$ respectively. Figure 7 shows the flowchart of the proposed operation approach.

4.2 Problem Formulation

4.2.1 Objective function. The objective of the proposed operation approach is maximizing the revenue of the BES. It's formulated as shown in (1) - (4). The revenue (R) is for the sold energy by battery replacement. The included costs in the BES are the demand charges (C^{kW}) and the charging/discharging costs (C^{kWh}).

$$Max\ (z) = R - (C^{kW} + C^{kWh}) \tag{1}$$

$$R = \sum_{t\in\mathbb{T}} \sum_{b\in\mathbb{B}} \sum_{c\in\mathbb{C}} E_{(t,b,c)}^{rep} \times p^{grid-Rep} \tag{2}$$

$$C^{kW} = p^{grid-kW} \times max\left(0, \left(\max_t \left(\sum_{b\in\mathbb{B}} \frac{P_{(t,b)}^{Charging}}{\eta}\right) - P_{Historical}^{MAX}\right)\right) \tag{3}$$

$$C^{kWh} = \sum_{t\in\mathbb{T}} \sum_{b\in\mathbb{B}} p_{(t)}^{grid-kWh}\ (\Delta t) \left(\frac{P_{(t,b)}^{Charging}}{\eta} - P_{(t,b)}^{Discharging} \times \eta\right) \tag{4}$$

4.2.2 Battery charging/discharging. In the BES, three main decisions can be taken which are the charging power ($P_{(t,b)}^{Charging}$), discharging power ($P_{(t,b)}^{Discharging}$) and the replacement energy ($E_{(t,b,c)}^{rep}$). In (5), the stored energy in the batteries inside the station ($E_{(t,b)}^{stored}$) is calculated and (6) is used to find the initial stored energy for each battery reaching the station ($E_{(t=1,b)}^{stored}$). The stored energy and the maximum battery capacity (E^{max}) are used to find the state of charge ($SOC_{(t,b)}$) for each battery as in (7). The charging and discharging powers are limited by the maximum chargers power (P^{max}) formulated in (8) - (9). Also, the state of charge is limited by the maximum depth of discharge ($MDOD$) for each battery as shown in (10).

$$E_{(t,b)}^{stored} = E_{(t-1,b)}^{stored} + (\Delta t)\left(P_{(t,b)}^{Charging} - P_{(t,b)}^{Discharging}\right) - \sum_{c\in\mathbb{C}} E_{(t,b,c)}^{rep} \quad \forall t \in \{2,3,\dots,N_t\} \,\&\, b \in \mathbb{B} \,\&\, c \in \mathbb{C} \tag{5}$$

$$E_{(t=1,b)}^{stored} = E^{stored-int} + (\Delta t)(P_{(t=1,b)}^{Charging} - P_{(t=1,b)}^{Discharging}) \ \forall\, b \in \mathbb{B} \tag{6}$$

$$SOC_{(t,b)} = E_{(t,b)}^{stored} \times \frac{100\ \%}{E^{max}} \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \tag{7}$$

$$P_{(t,b)}^{Charging} \le P^{max} \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \tag{8}$$

$$P_{(t,b)}^{Discharging} \le P^{max} \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \tag{9}$$

$$100\ \% - MDOD \le SOC_{(t,b)} \le 100\ \% \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \tag{10}$$

4.2.3 Energy replacement. The replaced energy is limited by the maximum energy capacity of the battery as mentioned in (11). The decision of serving the customer or not depends on the customers arrival pattern ($ar_{(t,c)}$) and the availability of the batteries which is controlled by the binary variable ($x_{(b,c)}$). This is formulated in (12) - (14). As in (15) - (16) the charging and discharging cycles cannot happen at the same time with the replacement. Also, the customer satisfaction factor (γ) which includes a range of SOC for the desired service by each customer is included in (17). Furthermore, the maximum demand power (P^{ExMax}) control compared to a historical maximum power consumption by the station ($P_{Historical}^{MAX}$) is formulated in (18).

$$E_{(t,b,c)}^{rep} \le E^{max} \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \,\&\, c \in \mathbb{C} \tag{11}$$

$$E_{(t,b,c)}^{rep} = 0 \ \therefore \ ar_{(t,c)} = 0 \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \,\&\, c \in \mathbb{C} \tag{12}$$

$$E_{(t,b,c)}^{rep} \times x_{(b,c)} = E_{(t,b)}^{stored} \ \therefore \ ar_{(t,c)} = 1 \ \forall t \in \mathbb{T} \,\&\, b \in \mathbb{B} \,\&\, c \in \mathbb{C} \tag{13}$$

$$\sum_{b\in\mathbb{B}} x_{(b,c)} \le 1 \tag{14}$$

$$P^{Charging}_{(t,b)} \;\&\; P^{Discharging}_{(t,b)} = 0 \;\therefore\; E^{rep}_{(t,b,c)} \neq 0 \;\forall t \in \mathbb{T} \;\&\; b \in \mathbb{B} \;\&\; c \in \mathbb{C} \tag{15}$$

$$P^{Charging}_{(t,b)} \;\&\; P^{Discharging}_{(t,b)} \neq 0 \;\therefore\; E^{rep}_{(t,b,c)} = 0 \;\forall t \in \mathbb{T} \;\&\; b \in \mathbb{B} \;\&\; c \in \mathbb{C} \tag{16}$$

$$E^{stored}_{(t,b)} \geq \gamma \times E^{max} \;\therefore\; ar_{(t+1,c)} = 1 \;\forall t \in \mathbb{T} \;\&\; b \in \mathbb{B} \;\&\; c \in \mathbb{C} \tag{17}$$

$$P^{ExMax} \geq P^{MAX}_{Historical} \;\&\; P^{ExMax} \geq \sum\nolimits_{b \in \mathbb{B}} \frac{P^{Charging}_{(t,b)}}{\eta} \;\forall t \in \mathbb{T} \;\&\; b \in \mathbb{B} \tag{18}$$

4.2.4 Grid power limitation. The charging power supplied from the grid at the same time segment is limited by (19) - (20):

$$P^{limit}_{(t)} = \sum\nolimits_{b \in \mathbb{B}} P^{Charging}_{(t,b)} \;\forall t \in \mathbb{T} \;\&\; b \in \mathbb{B} \tag{19}$$

$$P^{limit}_{(t)} \leq P^{grid-max} \;\forall t \in \mathbb{T} \tag{20}$$

4.2.5 Solar PV system generation. In this analysis, a rooftop solar PV system is designed and simulated using PVsyst. PVsyst is a software used for the analysis of solar production throughout the year for a specific solar system. The simulation includes the system design, detailed losses and shading analysis for the roof of the BES.

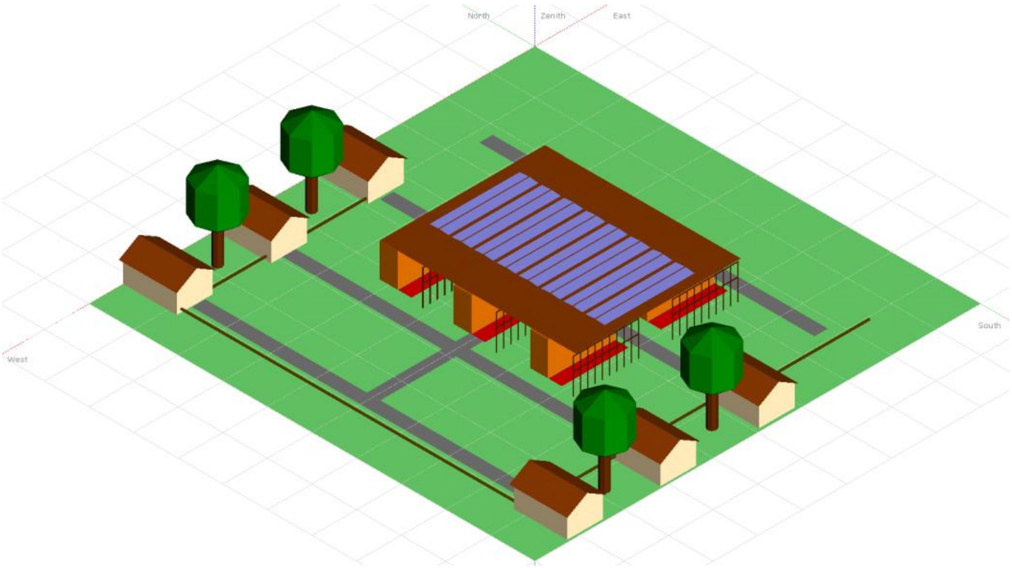


Figure 8: The rooftop solar PV system.

The system has East-West structures for a total of 120 solar panels and one inverter. The solar panels used are Canadian Solar 365W and the inverter used is

Sungrow 36kW. The maximum solar power that can be extracted from this system is 43.8 kW. The detailed report is added in Appendix B. Figure 8 shows the rooftop solar PV system. The size of the roof is assumed to be similar to the roof of a conventional fuel station. For this analysis, (4) will be written as follows in (21):

$$C^{kWh} = \sum_{t\in\mathbb{T}}\sum_{b\in\mathbb{B}} p_{(t)}^{grid-kWh}\,(\Delta t)\left(-P_{(t,b)}^{PV} + \frac{P_{(t,b)}^{Charging}}{\eta} - P_{(t,b)}^{Discharging} \times \eta\right) \qquad (21)$$

4.2.6 Battery self-degradation effect. The batteries in the BES undergo many charging/discharging cycles which reduce the ability for the battery to store energy inside it causing an effect on the maximum capacity of the battery. This is called the battery degradation. As a result, the battery self-discharge rate and the internal resistance increase which cause the battery to heat up due to power loss and lowers the output voltage. The degradation effect is added to the formulation by replacing (1) with (22). The battery lifetime is assumed by the number of charging/discharging cycles. So, the number of cycles for each battery $(Cyc_{(c)})$ is measured to find out the loss in SOC caused by degradation using (23). which is fitted from previous data in [30] as shown in Figure 9. This is updated every time the battery is charged to keep track of the health of the battery which is required for proper replacement. Then, the change in the price of the battery due to degradation can be defined as C^{DEG} as in (24).

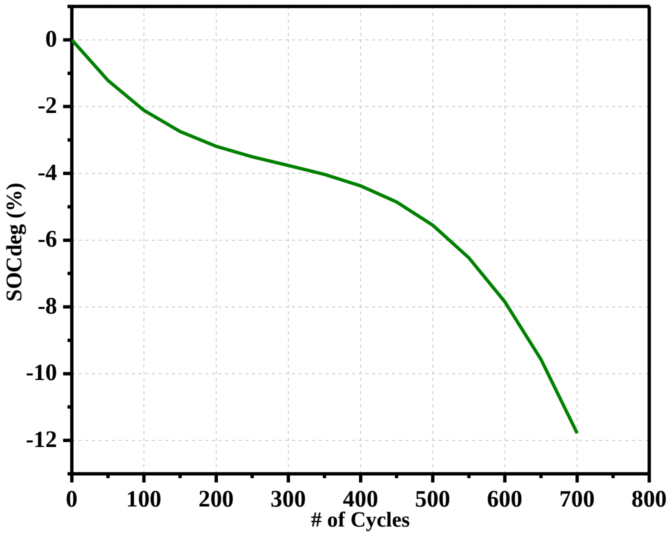


Figure 9: The change in SOC caused by degradation with the number of charging/discharging cycles [30].

$$Max\ (z) = R - (C^{kW} + C^{kWh} + C^{DEG}) \tag{22}$$

$$\Delta SOC_{(c)}^{deg} = -8.954 \times 10^{-10} \times Cyc_{(c)}^{3} + 7.883 \times 10^{-7} \times Cyc_{(c)}^{2} - 2.814 \times 10^{-4} \times Cyc_{(c)} \tag{23}$$

$$C^{DEG} = \sum_{c \in \mathbb{C}} 100\ \% \times \Delta SOC_{(c)}^{deg} \times p_{(c)}^{deg} \tag{24}$$

Finally, the BES optimal operational problem can be defined as follows:

$$\left.\begin{array}{c} Obj.Fun.in\ (22) \\ Defined\ in\ ((2)-(4),(24)) \\ S.T.((5)-(21),(23)) \end{array}\right\} \tag{25}$$

4.3 Charging Station Formulation

In the charging station, the only decision that can be taken is charging the batteries from grid once the customer plug in his EV. The objective function, described in (26), is to minimize the cost of charging while serving all the customers through the day. The constraints for the charging station operation are discussed in (27) - (29).

$$Min\ (C^{charging}) = \sum_{t \in \mathbb{T}} \sum_{b \in \mathbb{B}} p_{(t)}^{grid-kWh}\ (\Delta t) \left(\frac{P_{(t,b)}^{Charging}}{\eta} \right) \tag{26}$$

$$E_{(t,b)}^{stored} = E_{(t-1,b)}^{stored} + (\Delta t)(P_{(t,b)}^{Charging}) \quad \forall t \in \{2,3,\ldots,N_t\}\ \&\ b \in \mathbb{B} \tag{27}$$

$$E_{(t=1,b)}^{stored} = E^{stored-int} + (\Delta t)(P_{(t=1,b)}^{Charging})\ \forall\ b \in \mathbb{B} \tag{28}$$

$$P_{(t,b)}^{Charging} \leq P^{max}\ \forall t \in \mathbb{T}\ \&\ b \in \mathbb{B} \tag{29}$$

4.4 Optimization Unit

The proposed operation approach was discussed in detail with the problem formulation in the previous sections of Chapter 4. The approach utilizes the General Algebraic Modeling System (GAMS) [22], which is a mathematical tool specialized in solving large scale optimization problems, as the optimization unit in Figure 5. The inputs and outputs to and from GAMS are controlled by MATLAB, which emulates the control unit. GAMS have different types of solvers. The Branch-And-Reduce

Optimization Navigator (BARON) is the solver used for this optimization unit. BARON is used for the global solution of nonlinear (NLP) and mixed-integer nonlinear programs (MINLP) [32]. It implements deterministic global optimization algorithms of the branch-and-bound type that are guaranteed to provide global optima under general assumptions. These include the existence of finite lower and upper bounds on nonlinear expressions in the NLP or MINLP to be solved. Since the problem needs about two hours to be solved using the electrical engineering server at the American University of Sharjah, it is done on a day ahead scheme for the next 24 hours of operation. The server is used to make the simulation faster and more reasonable for a daily basis operation.

Chapter 5. Results and Analysis

In this chapter, the results of the analysis of the BES under different situations will be discussed. The assumptions made for all the case studies are listed below:

- All batteries are assumed to be the same shape and size.
- Price of replacement is fixed throughout the day.
- The customers' arrivals are all known one day before.
- No walk-in customers are served.
- The service takes 5 minutes to be done for all customers.
- All customers need to be served directly after reaching to the station.
- The analysis is for one day of operation in the BES.

5.1 Results Summary

5.1.1 Proposed operation approach development. In this section, the development of the proposed BES operation approach is explained in details. This is done in step by step analysis starting with a simple approach to study the operation pattern of a single battery depending on the grid price variation in hourly basis during a day which is named as V0.0. Then, the approach is modified to include the replacement energy from the battery swapping concept. It studies the customer service under the assumption that there is an available fully charged battery in the station whenever a customer arrives. This version is denoted by V0.1. Finally, the approach is improved by eliminating the previously stated assumption and including the station demand charges as well as the customer satisfaction index. This version of the approach is named as V0.2.

5.1.2 Proposed operation approach testing. In this section, different cases will be studied, summarized in Table 1, to investigate the effect of several aspects on the technical and economical features of the station. The first case study will be conducted on two different scenarios, 10 and 20 customers, which are considered as the base case and will be used for the comparison with the following cases. The second case study will focus on the effect of the grid power limitation on the charging power and the revenue of the station. Furthermore, the third case study will have a rooftop solar PV system as a source of energy for the BES. The last case is a comparison between the conventional charging station and the BES in terms of the total power consumed and the charging cost. All cases include the battery self-degradation factor and study its negative effect on the state of charge of the battery and the maximum capacity. Finally, a summary of the different case studies and their results will be discussed. For all cases, the time segment is adjusted to 5 minutes, which means that the total number of time segments in the day would be 288, i.e. $N_t = 288$. The replacement for each customer is done within one-time segment. The battery parameters used are shown in Table 2, which corresponds to the Nissan leaf EV battery specifications.

Table 1: Monthly charges for Industrial Customers.

Case Study #	Description
Case Study #1	Base Case
Case Study #2	Grid Power Limitation Effect
Case Study #3	Solar PV System Addition
Case Study #4	Comparison between Charging station and BES

Table 2: Technical battery parameters.

Type: lithium-ion battery

Parameter	Symbol	Value	Unit
Maximum Depth of Discharge	MDOD	80	%
Maximum Power	Pmax	10	kW
Maximum Energy	Emax	50	kWh
Charging Efficiency	η	80	%
Initial State of Charge	SOC_o	Varies	%

One of the input parameters to the proposed approach is the grid energy price. The battery exchange station is considered as an industrial customer to the grid. Thus, the industrial tariff should be adopted as an input to the smart operation. As an example, an industrial customer in Ontario, Canada, would pay the real-time energy price in Table 3, in addition to, the charges shown in Table 4.

Table 3: Grid price per hour for one day [23].

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12
Price (¢/kWh)	2.444	2.095	2.502	2.506	2.141	1.74	1.908	3.239	3.302	3.302	3.657	4.225
Time (h)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Price (¢/kWh)	4.188	3.732	3.957	4.056	4.066	3.956	6.895	4.241	3.663	3.77	3.637	3.633

Table 4: Monthly charges for Industrial Customers.

Description	Amount
Hourly market price	Varies hourly as given in Table 3
Global adjustment (¢/kWh)	3
Wholesale market service (¢/kWh)	0.05
Transmission charges ($/kW)	5.1
Distribution charges ($/kW)	4.00

5.2 Developed Versions of the Approach

5.2.1 V0.0 – Charging/discharging cycles. As mentioned before, V0.0 is studying the performance of a single battery throughout the day. In this version, the main objective is to study the charging and discharging cycles of a single battery. The behavior of the battery will follow the change in grid price throughout the day. The results from this version show that the battery has been charged in the periods where the grid price is the lowest and discharged in the peak hours where the grid price is high. Figure 10 shows the charging and discharging cycles along with the grid price. The state of charge has been set to be 35 % at the beginning of the day and it is reaching the minimum value which is 20 % at the end of the day as shown in Figure 11. The total profit from this approach is \$0.646. In this case, the period under study is one day and the time segment is adjusted to one hour, i.e. $N_t = 24$.

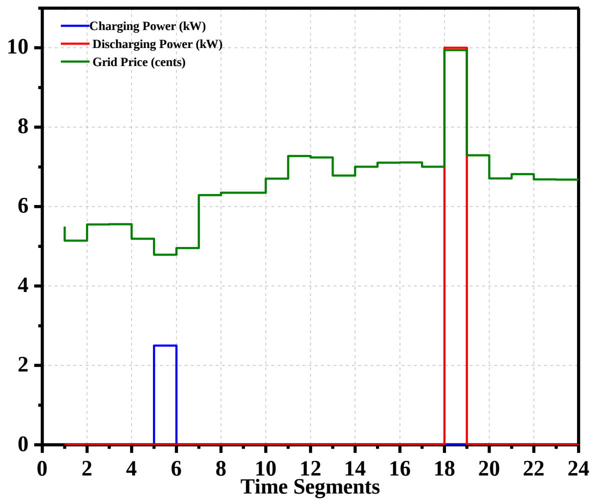


Figure 10: The charging/discharging cycles with grid price variation for V0.0.

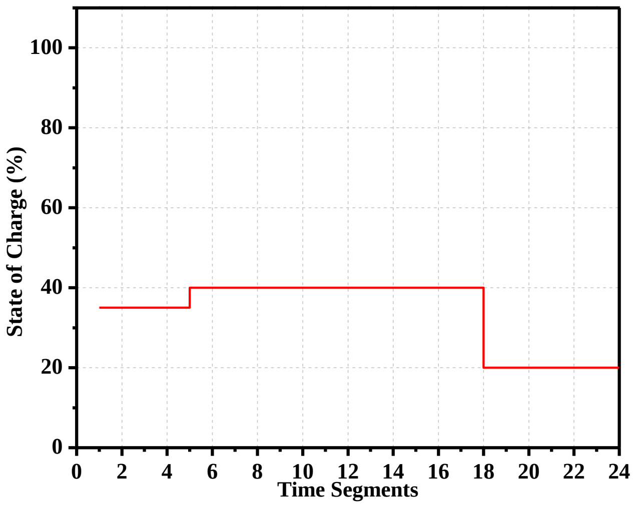


Figure 11: State of charge with time for V0.0.

5.2.2 V0.1 – Battery parameters variation with time for three stations.

Version 0.1 is considered as the simple building block for the operation approach of BESs. In this version, the number of batteries and customers are equal. There are three customers that need to be served, i.e. $b \in \mathbb{B} = \{1,2,3\}$. As shown in Figure 12, the three batteries are being charged at the same time segments which are controlled by the grid price. In addition, Figure 13 shows that the discharging cycles to grid happen at the end of the day when all the customers have been served. Similar to the first version, the time segment is set to one hour, i.e. $N_t = 24$.

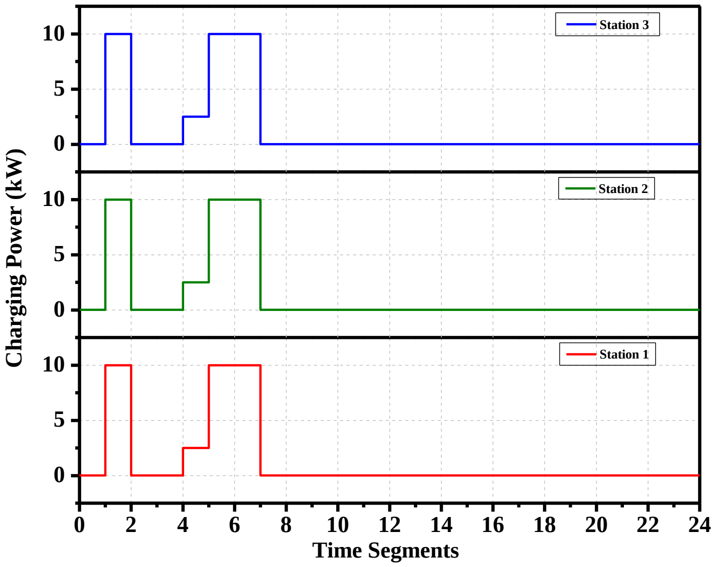


Figure 12: Charging power variation with the time for the three stations in V0.1.

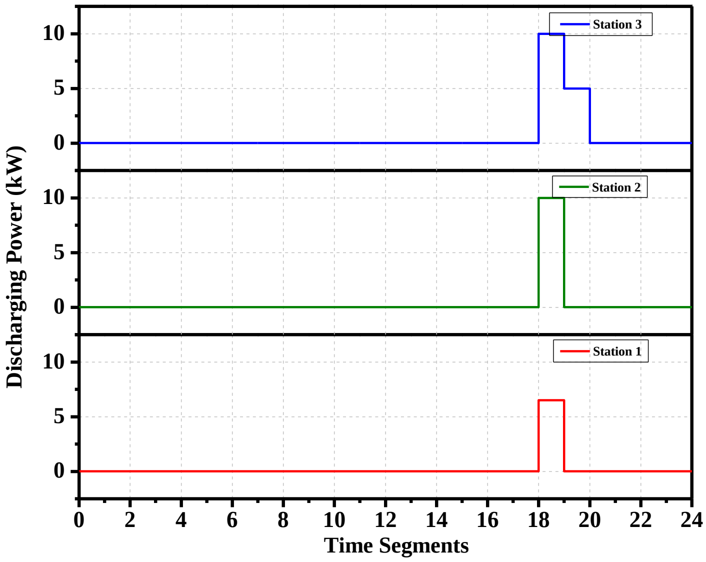


Figure 13: Discharging power to grid variation with the time for the three stations in V0.1.

Figure 14 shows the state of charge variation for the three batteries in the station. The three batteries start the day with 35 % SOC and end it fully discharged at 20 % SOC. The direct drop in the SOC indicates a battery replacement. The replacement happens at time segments 8, 12 and 16 (7:00, 11:00 and 15:00) as shown in Figure 15. The optimal solution found in this case is $19.

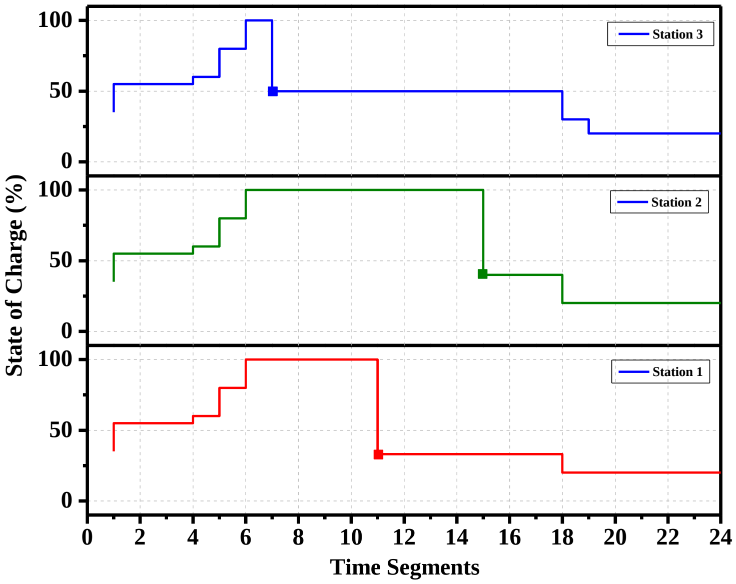


Figure 14: State of charge variation with the time for the three stations in V0.1.

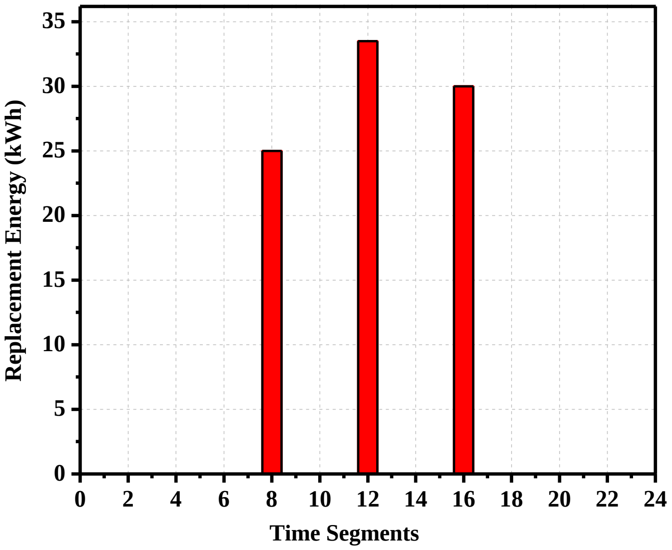


Figure 15: Replacement energy for the three stations in V0.1.

5.2.3 V0.2 – Batteries selection for each customer (24 segments). The difference in this version is that the number of customers is greater than the number of batteries. Therefore, some batteries will need to serve more than one customer on the same day. In this version, the time segment is adjusted to one hour, i.e. $N_t = 24$. The station has three batteries, i.e. $b \in \mathbb{B} = \{1,2,3\}$, with 35 % SOC at the beginning of the day and needs to serve seven customers, i.e. $c \in \mathbb{C} = \{1,2,\dots,7\}$, throughout the day. Figure 16 shows the charging cycles for the three batteries during the day. For example, battery 1 is being charged at the beginning of the day to serve a customer coming at 8:00 and then recharged after the replacement to serve another customer at 15:00. As shown in the previous version, the discharging cycles happen at the end of the day after serving all the customers. In station 2, a replacement happened at the end of the day which results in no discharging to the grid at all. Figure 17 shows the discharging power to grid variation with time. The change in state of charge shown in Figure 18 has seven direct drops at each replacement for the seven customers shown as dots.

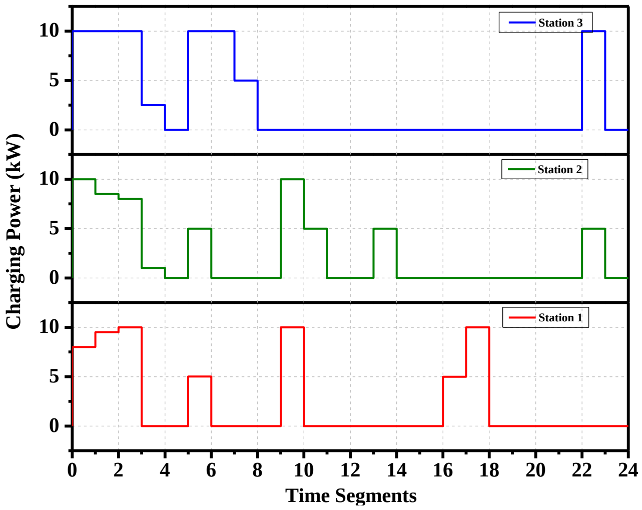


Figure 16: Charging power variation with the time for the three stations in V0.2.

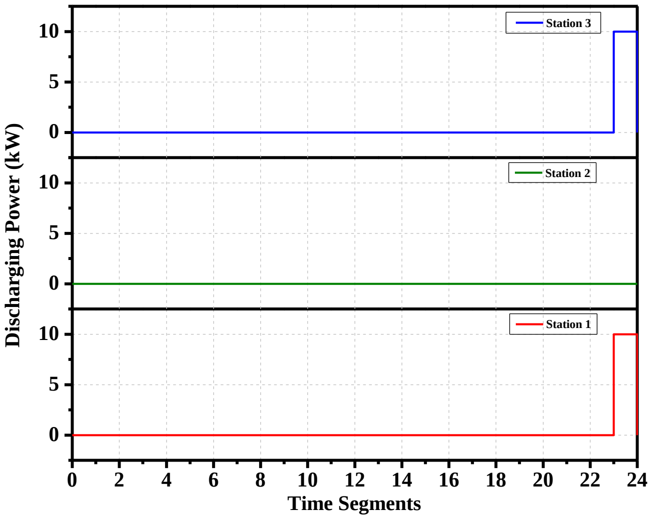


Figure 17: Discharging power to grid variation with the time for the three stations in V0.2.

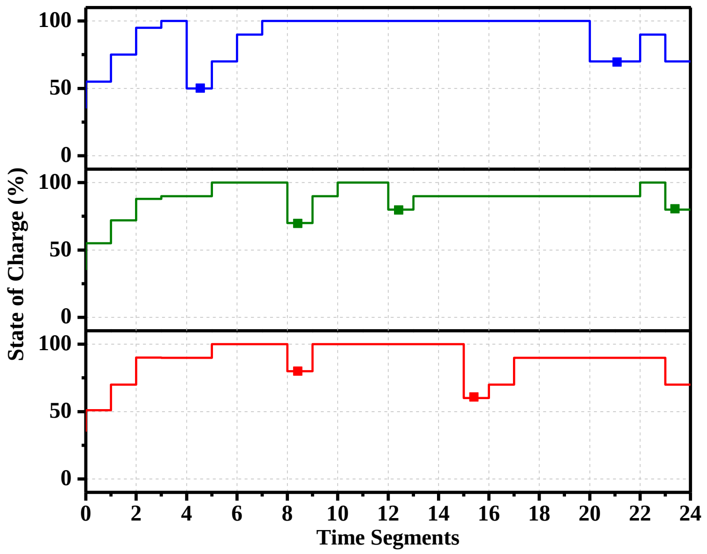


Figure 18: State of charge variation with the time for the three stations in V0.2.

Batteries selection depends on the amount of energy needed by each customer and the time segment of the customers' arrivals. As shown in Figure 19, battery 1 is chosen to serve two customers who need 20 and 10 kWh respectively. In addition, customers 2 and 3 came at the same time segment which makes serving them needs two available charged batteries. The highest energy is needed by customer 1 who is served using the third battery station. Since there are almost 16 hours between customers 6 and 1, the battery can be recharged and used to serve the other one. In this case study, all the customers are being served with fully charged batteries. The optimal solution with the lowest price is around $14. Having more customers ends up in less time to charge the batteries which made the profit lower.

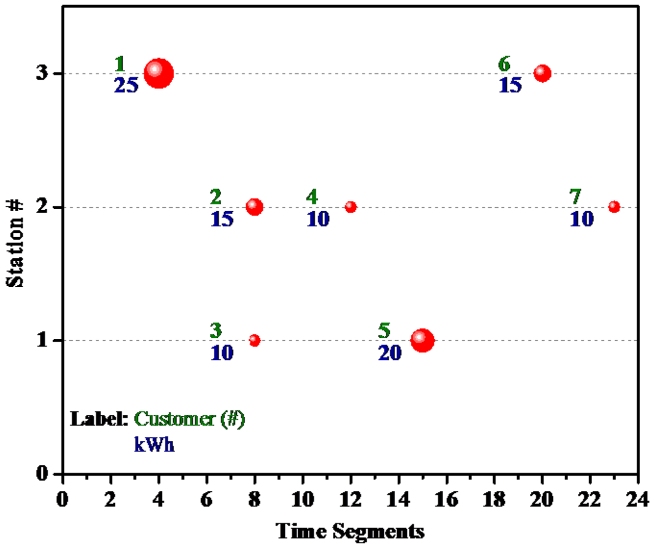


Figure 19: Energy delivered to customers by battery exchange in V0.2.

5.2.4 V0.2’ – Batteries selection for each customer (288 segments). In this case, the same approach is applied with small modifications. Since the service is done in five minutes, the time segments are divided into 288 segments per day, i.e. $N_t = 288$. However, the same number of batteries and customers in previous case are used. The charging and discharging cycles are shown in Figure 20 and Figure 21 respectively. The behaviour of the batteries is almost the same as the previous case. However, the number of charging and discharging cycles are much more. The state of charge has almost the same pattern since the customers are assumed to come at the same time segment with respect to the five minutes division.

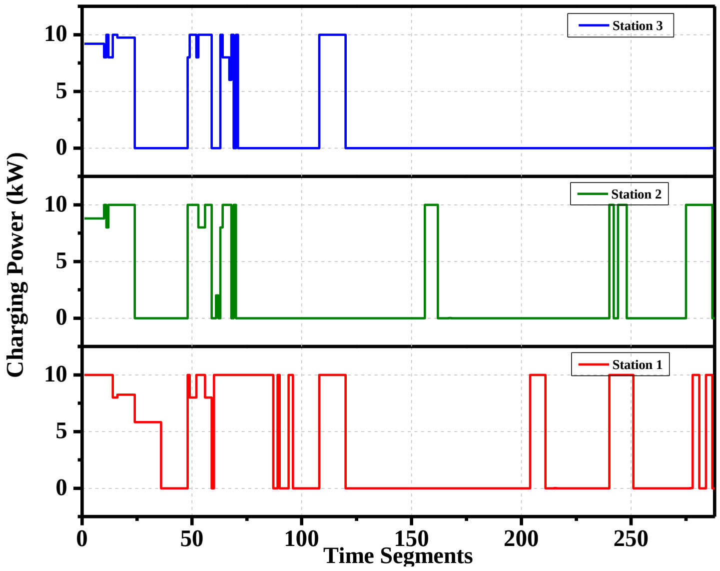


Figure 20: Charging power variation with the time for the three stations in V0.2’.

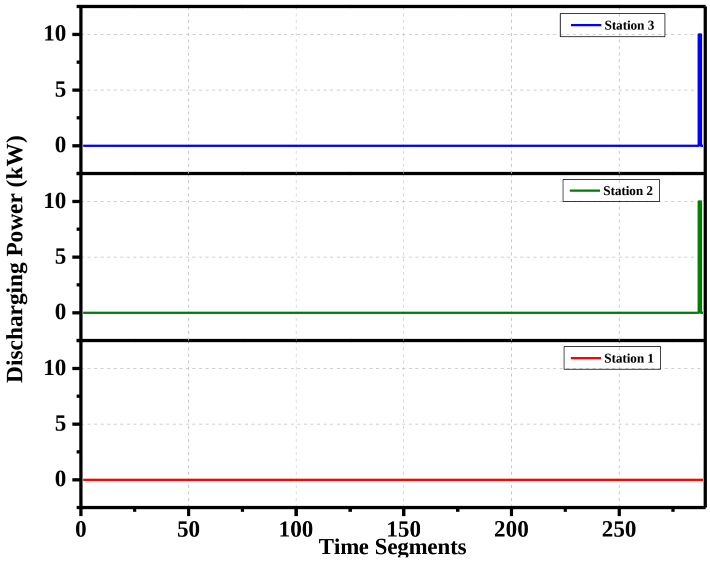


Figure 21: Discharging power variation with time for the three stations in V0.2’.

Figure 22 shows the state of charge variation in 288 time-segments approach. The seven direct changes, that are noted as dots in the graph, indicates the seven customers that are being served.

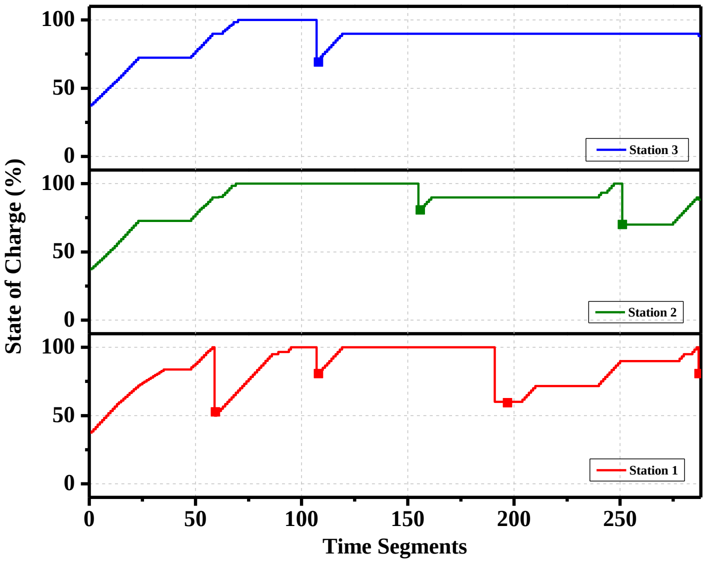


Figure 22: State of charge variation with the time for the three batteries in V0.2'.

Since the batteries behaviour is slightly different than V0.2 results, the batteries assigned to serve the customers are a bit different. As shown in Figure 23, customers 7 and 1 are now being served by station 1 instead of stations 2 and 3. In addition, customers 2 and 6 are swapped while customers 3, 4 and 5 are being served by the same batteries. The profit, in this case, is very close to the previous one which is $13. Changing the time segment into 288 made the problem more accurate and realistic.

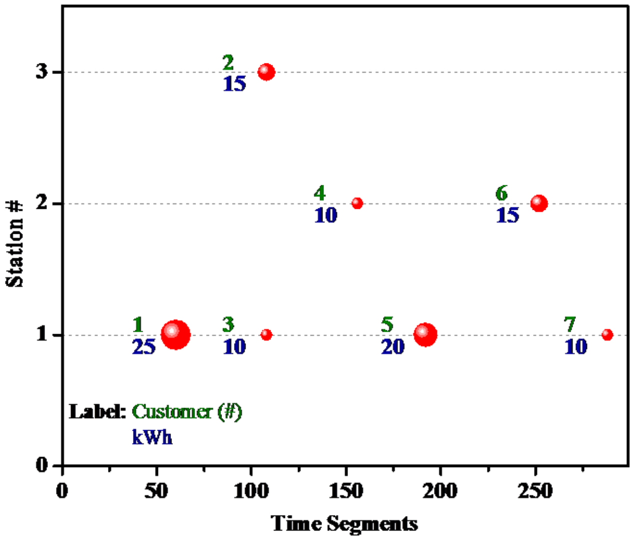


Figure 23: Energy delivered to customers by battery exchange in V0.2'.

5.3 Case Studies

5.3.1 Case 1: base case. This case study represents the base case where two different scenarios will be studied to be used for the sensitivity analysis. The first one will have four batteries, i.e. $b \in \mathbb{B} = \{1,2,3,4\}$, with 100 % SOC at the beginning of the day and needs to serve ten customers, i.e. $c \in \mathbb{C} = \{1,2,\dots,10\}$, throughout the day. Figure 24 and Figure 25 show the charging and discharging power for the four stations. The charging is happening at different rate and different time depending on the grid price and the customers assigned for each station. The discharging is happening at the end of the day where all the customers have been served and all the batteries are free to be fully discharged to the grid.

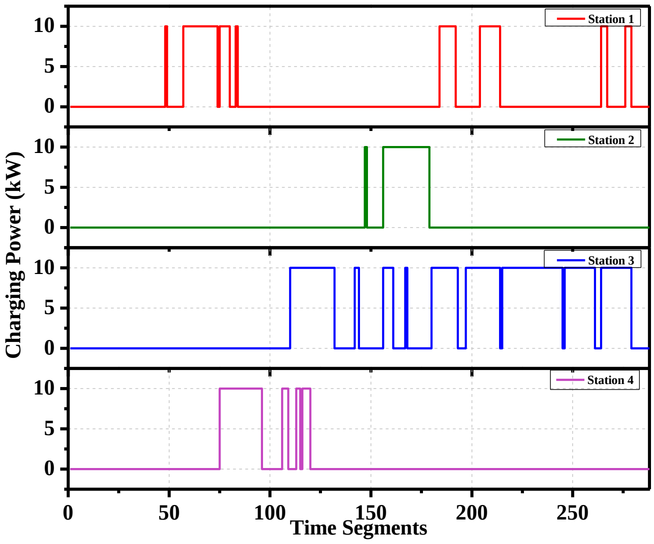


Figure 24: Charging cycles vs. time segments for the four stations.

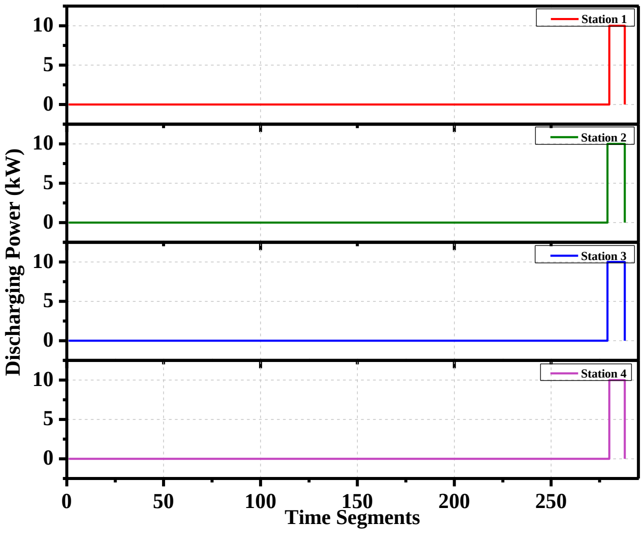


Figure 25: Discharging cycles vs. time segments for the four stations.

Figure 26 shows the SOC variation with time for the four stations. The SOC changes rapidly when the batteries are being replaced as shown in times segment #150 for station #2. The ten direct drops in the SOC in Figure 26 represent the ten customers. Figure 27 shows the customers numbers and their required energy for each station. For example, station 3 is going to serve four customers namely 3,6,7 and 8. Customers 9 and 10 are coming at the same time segment so they will be served by two different stations 1 and 4. The maximum revenue from this case is about $43.00.

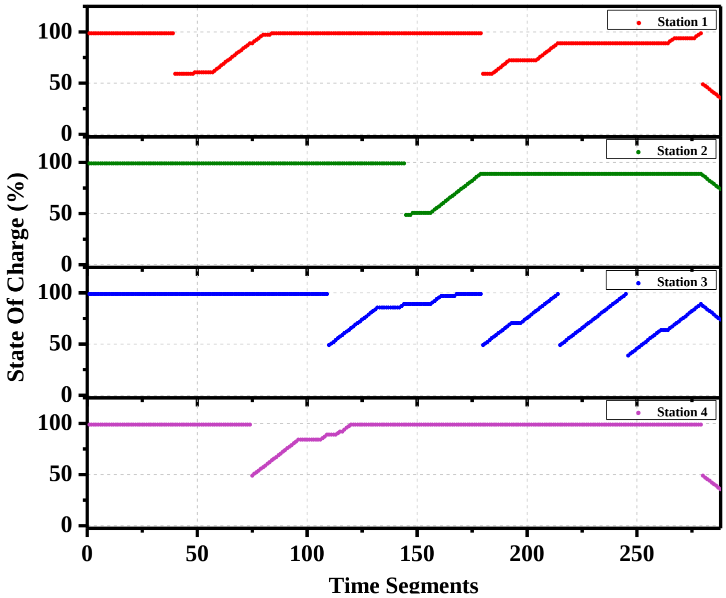


Figure 26: State of charge variation vs. time segments for the four stations.

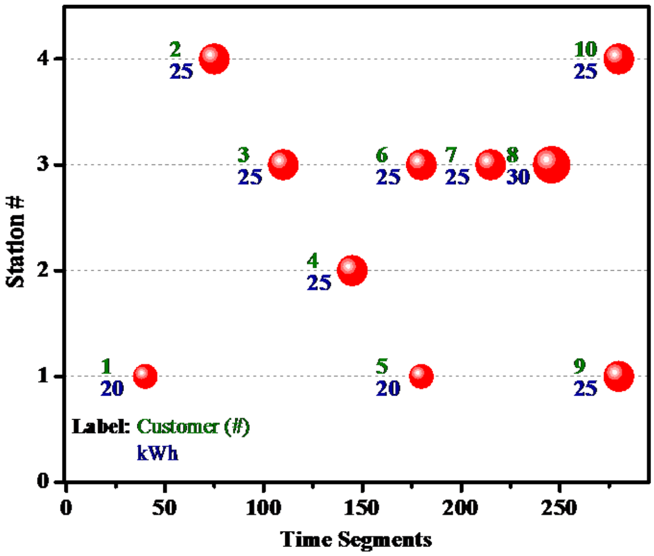


Figure 27: Batteries/Customers selection.

The second scenario is done on a more realistic numbers, which are 13 batteries, i.e. $b \in \mathbb{B} = \{1,2,\ldots,13\}$ and 30 customers, i.e. $c \in \mathbb{C} = \{1,2,\ldots,30\}$. Figure 28 and Figure 29 show the charging and discharging cycles for the 13 stations. It's similar to previous base case however the number of charging cycles for each station is lower than before. The discharging is almost negligible during the day in most of the stations. However, all stations have the discharging happening at the end of the day when all customers have been served as shown in Figure 29.

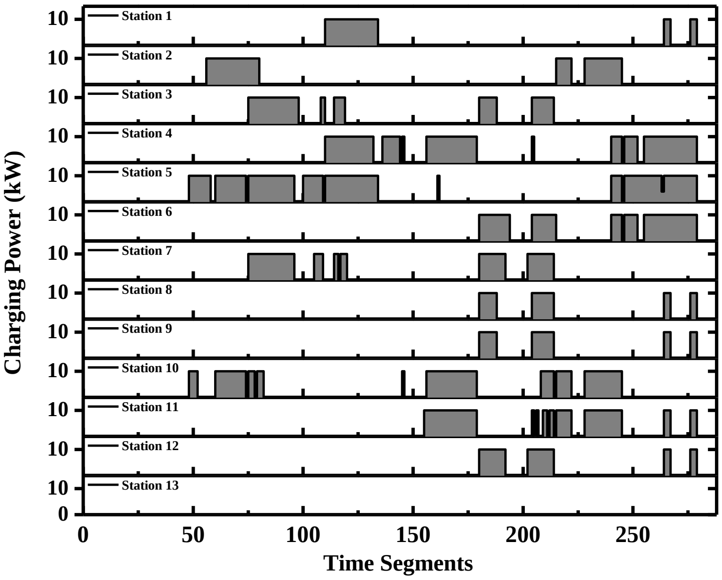


Figure 28: Charging cycles vs. time segments for the 13 stations.

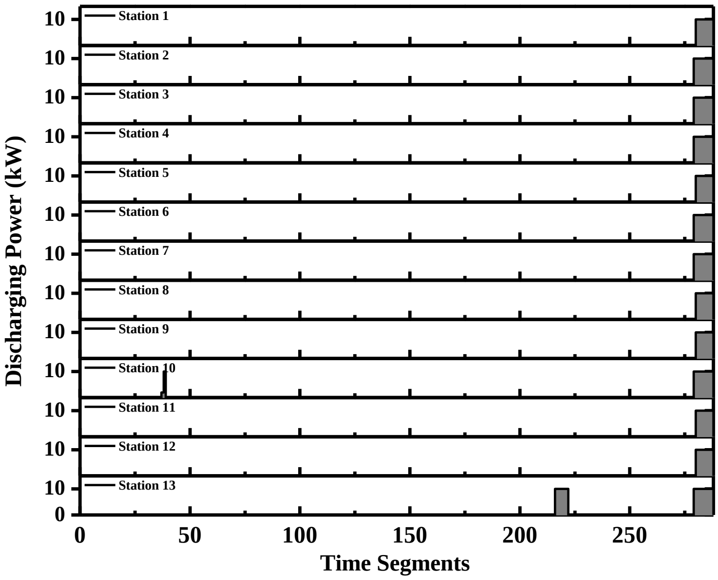


Figure 29: Discharging cycles vs. time segments for the 13 stations.

The SOC variation with time is shown in Figure 30. The small direct drops indicate the replacements as mentioned before. Figure 31 shows the batteries/customers selection. Some batteries are chosen to serve two customers like station 1 but others are serving 5 customers like station 5. This depends on the battery availability in each station, the required energy by each customer and the time segment when the customer will reach to the station. Customers 14, 15, 16 and 17 are being served by four different stations since they are reaching the station at the same time. All the 30 customers are being served without using all the 13 batteries. The maximum revenue from this case is about $143.00.

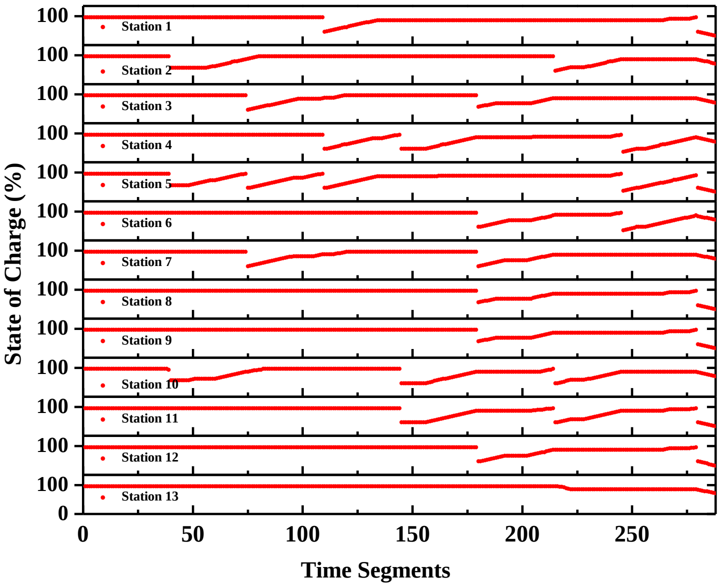


Figure 30: State of charge variation vs. time segments for the 13 stations.

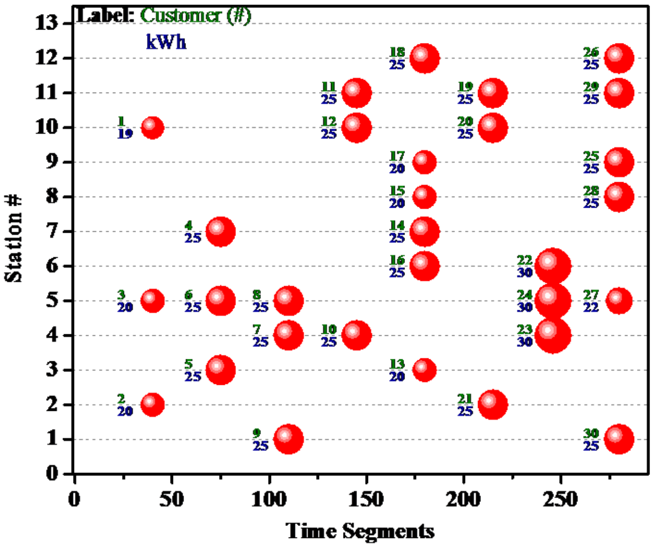


Figure 31: Batteries/Customers selection.

5.3.2 Case 2: grid power limitation effect.

Since the charging power in the BES is coming from the grid, this power is limited, and the station has a specific maximum load. In this case, the maximum power that can be taken from the grid at the same time is 50 kW, i.e. $P^{grid-max} = 50$ kW. Consequently, only five batteries can be charged from the grid simultaneously. Figure 32 shows the charging power variation with time with and without the grid power limitation. The charging periods has been changed slightly. With the grid power limitation, the width of the charging cycles is bigger to overcome the periods where the power was greater than 50 kW. As a result, the batteries/customers selection has been changed as shown in Figure 33. With the grid power limitation, the station needs 13 batteries to serve the same customers.

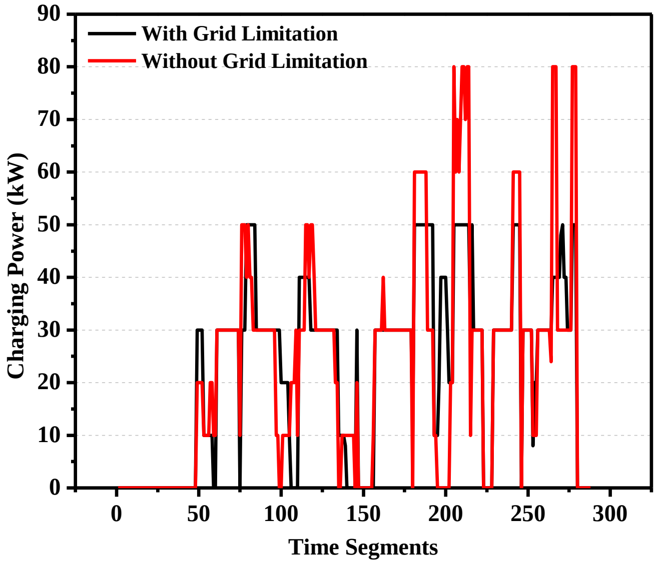


Figure 32: Charging cycles vs. time with and without the grid power limitation.

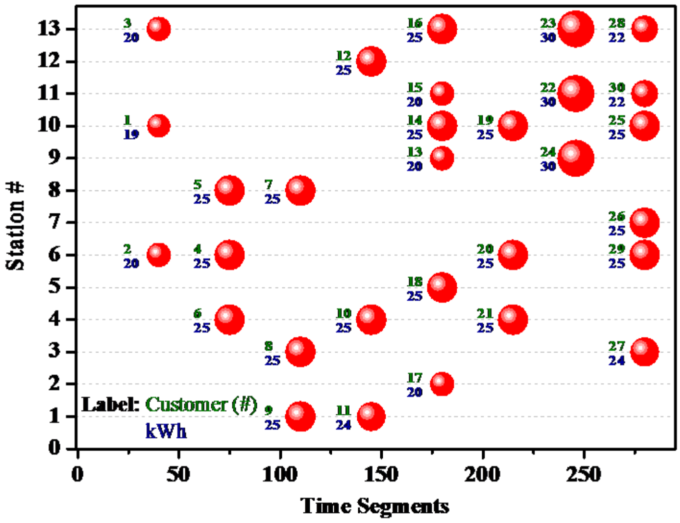


Figure 33: Batteries/Customers selection with grid power limitation.

So, battery 13 is now serving customers 3, 16, 23 and 28. Adding the grid power limitation in this case study did not affect the revenue of the station. However, it changed the decisions of the control unit.

5.3.3 Case 3: solar PV system addition.

Most of the operational cost in the BES is coming from charging the batteries from the grid. This is because the chargers are almost always occupied to serve the coming customers. So, adding a renewable source of energy would help in reducing the cost of charging and reduce the load in the grid side unit. In this case study, a small ground mount solar PV system is added to the station as a source of energy. The solar energy is assumed to be available between 10:00 AM and 3:00 PM. Figure 34 shows the power consumed from the grid with and without PV system.

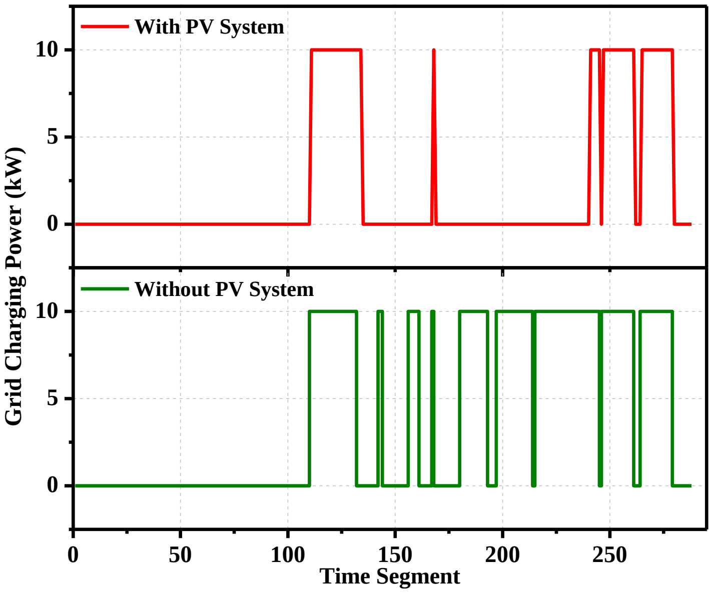


Figure 34: The grid charging power vs. time segments with and without solar energy.

The total power consumed by the grid is reduced by 50 % after adding the solar. Figure 35 shows the solar power and the total charging power (grid and solar) variation with time. The solar power appears in the middle of the day between time segments 50 and 100. As shown in the bottom graph, when the solar is available, it is covering all the charging power needed. The rest of the day is covered by the grid power. The solar power is 64 % of the total power needed during the day for charging.

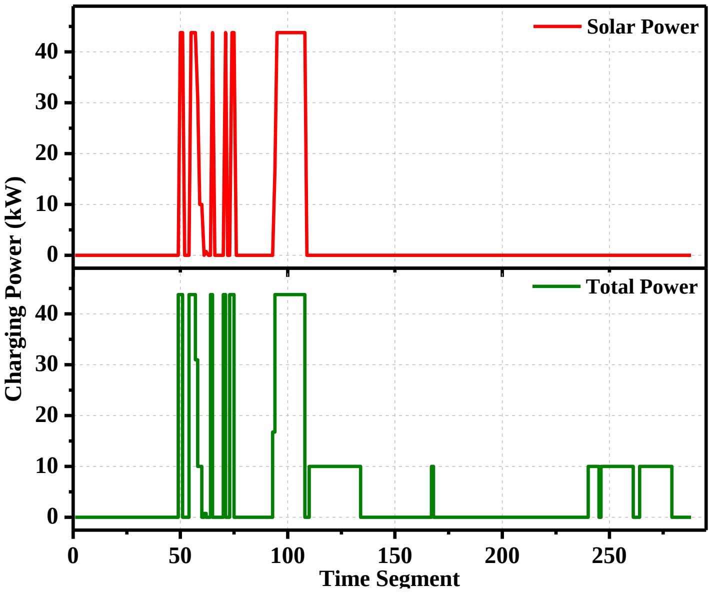


Figure 35: The solar and the total charging power vs. time segments.

5.3.4 Case 4: comparison between BES and charging stations. In this case study, a comparison between the charging and the BESs is conducted. The base case of serving 10 customers with four batteries is used for this comparison.

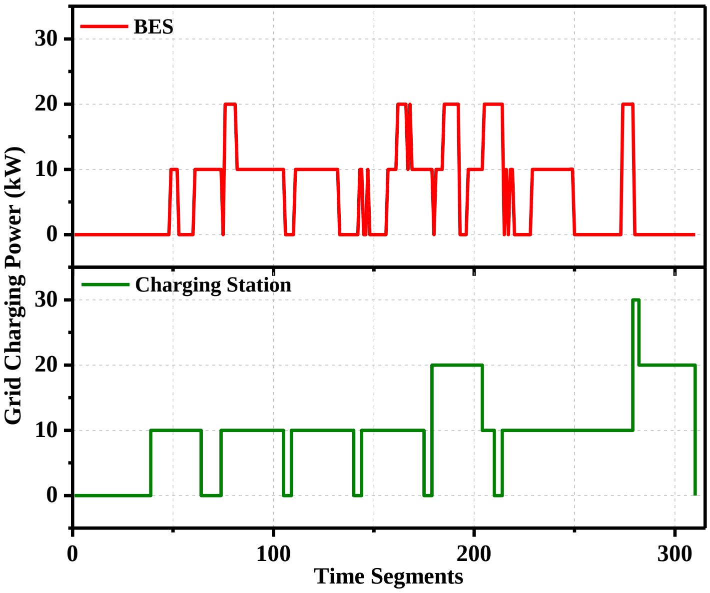


Figure 36: Charging power variation vs. time for the BES and the charging stations.

Figure 36 shows the charging curve for the BES and the charging station. The total power consumed by the BES and the charging station is 1,920 kW and 3,040 kW respectively. This is because the chargers in the charging stations are almost always occupied and providing maximum power. The width of the charging cycles in the charging stations are much bigger than the BES. In addition, serving the same number of customers required more time in the charging station.

Chapter 6. Conclusion and Future Work

To sum up, this work proposes a new approach for operating battery exchange station (BES). The proposed operation approach is used for optimizing the charging, discharging and the replacement decisions to maximize the profit based on the grid price and the customers’ requests. The optimization problem is formulated as MINLP with the objective of maximizing the BES investor profit while satisfying the EV owners’ requests. The approach is formulated and solved in the General Algebraic Modeling System (GAMS) using the Branch-And-Reduce Optimization Navigator (BARON) solver. The approach is developed in step by step analysis and different versions of it were discussed to formulate the final detailed proposed operation approach for BES.

The variation of charging/discharging power, the state of charge and the stored and replaced energy for all batteries in the station with time is observed for different case studies. The results from the case studies on a typical BES demonstrate the effectiveness of the proposed approach while considering practical grid tariff for industrial customer representing the BES owner. Moreover, the work provided a comparison between conventional charging stations and BES, which outperform the conventional charging stations in terms of the service time, number of served customers, and the operational cost. In addition, the grid power limitation, battery self-degradation and solar PV generation are all considered to represent a practical BES structure. This work proves the effectiveness of the proposed approach in satisfying the EV owners and maximizing the BES investor profit. It shows that the concept of BES will help in moving the EV technology forward in the market and reduces the users’ responsibility and fear of charging their EV batteries.

For the future work, a planning approach for the BES and conventional charging stations will be developed to determine the investment decisions for installing these kinds of stations. The outcome of the planning approach will include the location of the stations, their type, the optimal sizes and number of swapping or charging units in the selected BES or charging stations. This work will provide better insight on the economic feasibility for BES versus the conventional charging stations as it will include the capital costs in addition to the operational costs.

References

[1] A. Nagarajan and W. Shireen, “Grid connected residential photovoltaic energy systems with Plug-In Hybrid electric Vehicles (PHEV) as energy storage,” in *IEEE PES General Meeting*, 2010, pp. 1–5.

[2] S. W. Hadley, “Evaluating the impact of Plug-in Hybrid Electric Vehicles on regional electricity supplies,” in *2007 iREP Symposium - Bulk Power System Dynamics and Control - VII. Revitalizing Operational Reliability*, 2007, pp. 1–12.

[3] S. Shao, M. Pipattanasomporn, and S. Rahman, “Grid Integration of Electric Vehicles and Demand Response With Customer Choice,” *IEEE Trans. Smart Grid,* vol. 3, no. 1, pp. 543–550, Mar. 2012.

[4] L. Jian, H. Xue, G. Xu, X. Zhu, D. Zhao, and Z. Y. Shao, “Regulated Charging of Plug-in Hybrid Electric Vehicles for Minimizing Load Variance in Household Smart Microgrid,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 8, pp. 3218–3226, 2013.

[5] “EV-Volumes - The Electric Vehicle World Sales Database.” Internet. [Online]. Available: http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/. [Accessed: November 2, 2018].

[6] Z. M. Fadlullah, D. M. Quan, N. Kato, and I. Stojmenovic, “GTES: An Optimized Game-Theoretic Demand-Side Management Scheme for Smart Grid,” *IEEE Syst. J.*, vol. 8, no. 2, pp. 588–597, 2014.

[7] “Supercharger|Tesla.” Internet. [Online]. Available: https://www.tesla.com/en_AE/supercharger. [Accessed: April 27, 2019].

[8] E. Sortomme, M. M. Hindi, S. D. J. MacPherson, and S. S. Venkata, “Coordinated Charging of Plug-In Hybrid Electric Vehicles to Minimize Distribution System Losses,” *IEEE Trans. Smart Grid*, vol. 2, no. 1, pp. 198–205, 2011.

[9] C. Liu et al., “A new DC micro-grid system using renewable energy and electric vehicles for smart energy delivery,” in *2010 IEEE Vehicle Power and Propulsion Conference*, 2010, pp. 1–6.

[10] H. Li, X. Bai, and W. Tan, “Impacts of plug-in hybrid electric vehicles charging on distribution grid and smart charging,” in *2012 IEEE International Conference on Power System Technology (POWERCON)*, 2012, pp. 1–5.

[11] S. Bahrami and M. Parniani, “Game Theoretic Based Charging Strategy for Plug-in Hybrid Electric Vehicles,” *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2368–2375, 2014.

[12] “Inside EVs | Electric Vehicle News, Reviews, and Reports.” [Online]. Available: https://insideevs.com/. [Accessed: November 17, 2018].

[13] Y. Wang, D. Infield, and S. Gill, “Smart charging for electric vehicles to minimize charging cost,” in *Proc. Int. of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 2017, 526–534.

[14] P. Mirchandani, J. Adler, and O. B. G. Madsen, “New Logistical Issues in Using Electric Vehicle Fleets with Battery Exchange Infrastructure,” in *Proc. - Social and Behavioral Sciences*, 2014, pp. 3–14.

[15] M. Shindhuja, S. M. J. Mary, D. K. Punitha, and P. Scholar, “Ant Colony Optimization of Charging Coordination of Electric Vehicles Considering Vehicle-to-Grid (V2G) Technology in Multi- Micro Grid Power System,” *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 6, no. 1, p. 38–46, 2017.

[16] “Capacity Optimization Method for PV-based Battery Swapping Stations Considering Second-use of Electric Vehicle Batteries – Proc. of the CSEE - 2013-04.” Internet. [Online]. Available: http://en.cnki.com.cn/Article_en/CJFDTOTAL-ZGDC201304007.htm. [Accessed: April 13, 2019].

[17] Z. Pan and Y. Zhang, “A novel centralized charging station planning strategy considering urban power network structure strength,” *Electric Power Systems Research*, vol. 136, pp. 100–109, 2016.

[18] “Discussion on Development Trend of Battery Electric Vehicles in China and Its Energy Supply Mode - Power System Technology - 2009-04.” Internet. [Online]. Available: http://en.cnki.com.cn/Article_en/CJFDTOTAL-DWJS200904003.htm. [Accessed: April 13, 2019].

[19] Y. Liu, F. Hui, R. Xu, T. Chen, X. Xu, and J. Li, “Investigation on the Construction Mode of the Charging Station and Battery-Exchange Station,” in *Proc. of the 2011 Asia-Pacific Power and Energy Engineering Conference*, Washington, DC, USA, 2011, pp. 1–2.

[20] F. Ye, Y. Qian, and R. Q. Hu, “Incentive Load Scheduling Schemes for PHEV Battery Exchange Stations in Smart Grid,” *IEEE Syst. J.*, vol. 11, no. 2, pp. 922–930, 2017.

[21] M. R. Sarker, H. Pandžić, and M. A. Ortega-Vazquez, “Electric vehicle battery swapping station: Business case and optimization model,” in *2013 International Conference on Connected Vehicles and Expo (ICCVE),* 2013, pp. 289–294.

[22] J. Felipe, J. C. Amarillo, J. E. Naranjo, F. Serradilla, and A. Díaz, “Energy Consumption Estimation in Electric Vehicles Considering Driving Style,” in *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, 2015, pp. 101–106.

[23] Z. Chen, N. Liu, and X. Xiao, “Energy Exchange Model of PV-based Battery Switch Stations Based on Battery Swap Service and Power Distribution,” in *2013 IEEE Vehicle Power and Propulsion Conference (VPPC),* Beijing, 2013, pp. 1-6. [24] X. Tang, N. Liu, J. Zhang, and S. Deng, “Capacity optimization configuration of electric vehicle battery exchange stations containing photovoltaic power generation,” in *Proc. of The 7th International Power Electronics and Motion Control Conference,* Harbin, 2012, pp. 2061-2065.

[25] Y. Zhang, N. Liu, and J. Zhang, “Optimum sizing of non-grid-connected wind power system incorporating battery-exchange stations,” in *7th International Power Electronics and Motion Control Conference,* 2012, pp. 2123–2128.

[26] Y. Wang, W. Ding, L. Huang, Z. Wei, H. Liu, and J. A. Stankovic, “Toward Urban Electric Taxi Systems in Smart Cities: The Battery Swapping Challenge,” *IEEE Trans. Veh. Technol.*, vol. 67, no. 3, pp. 1946–1960, 2018.

[27] H. Wu, G. K. H. Pang, K. L. Choy, and H. Y. Lam, “An Optimization Model for Electric Vehicle Battery Charging at a Battery Swapping Station,” *IEEE Trans. Vehicle Technology*, vol. 67, no. 2, pp. 881–895, 2018.

[28] N. Korolko and Z. Sahinoglu, “Modeling and Forecasting of Self-Similar Power Load Due to EV Fast Chargers,” *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1620-1629, 2016.

[29] Y. Cheng and C. Zhang, “Configuration and operation combined optimization for EV battery swapping station considering PV consumption bundling,” *Protection and Control of Modern Power Systems*, vol. 2, no. 26, pp. 1–18, 2017.

[30] A. A. Hussein, “Capacity fade estimation in electric vehicles Li-ion batteries using artificial neural networks,” in *2013 IEEE Energy Conversion Congress and Exposition*, 2013, pp. 677–681.

[31] “User’s Guide.” Internet. [Online]. Available: https://www.gams.com/latest/docs/UG_MAIN.html. [Accessed: November 17, 2018].

[32] M. R. Sarker, H. Pandžić, and M. A. Ortega-Vazquez, “Optimal Operation and Services Scheduling for an Electric Vehicle Battery Swapping Station,” *IEEE Trans. Power Systems*, vol. 30, no. 2, pp. 901–910, 2015.

Appendix A

In this appendix, the MATLAB/GAMS code is included. The MATLAB code shows how the inputs are sent to GAMS and how the outputs are extracted and sent back to MATLAB. The GAMS code shows the formulation of the problem by defining the sets, parameters, variables and equations.

MATLAB Code: Battery Exchange Station

```
%Identifying the sets
nt=288; % # of time slots
time=[1:nt]';
nc=30; % # of customers
nb=13; % # of batteries
Customer=[1:nc]';
Battery=[1:nb]';

load('D:\Final-Results\Case4\grid_price.mat'); % CGrid(1x288)

%#####################################################################

req1=[
1   40  30
2   40  30
3   40  30
4   75  25
5   75  25
6   75  25
7   110 25
8   110 25
9   110 25
10  145 25
11  145 25
12  145 25
13  180 30
14  180 25
15  180 30
16  180 25
17  180 30
18  180 25
```

```
19   215 25
20   215 25
21   215 25
22   246 20
23   246 20
24   246 20
25   280 25
26   280 25
27   280 25
28   280 25
29   280 25
30   280 25
];

Ereq=zeros(nt,nc);
ar=zeros(nt,nc);
cycle=zeros(nt,nc);
SOCdeg=zeros(nt,nc);
for i=1:nc
    Ereq(req1(i,2),i)=req1(i,3);
    ar(req1(i,2),i)=1;
    cycle(req1(i,2),i)=req1(i,4);
    SOCdeg(req1(i,2),i)=100-((-0.0000000008954*
(cycle(req1(i,2),i))^3) + (0.0000007883*(cycle(req1(i,2),i))^2) -
(0.0002814*cycle(req1(i,2),i)) + 0.9984)*100;
end

%Loading the sets to GAMS

% Time -------------------------
A0.name='t';
A0.type='set';
A0.val=time;

% Customers --------------------
A1.name='c';
A1.type='set';
A1.val=Customer;
```

```
% Batteries ---------------------
A2.name='b';
A2.type='set';
A2.val=Battery;

%Loading Parameters to GAMS

% Grid Price ------------------
A3.name='Cgrid';
A3.type='parameter';
A3.val=[time CGrid];

% Maximum Energy --------------
A4.name='Emax';
A4.type='parameter';
A4.val= 50;

% Min. State of Charge --------
A5.name='SOCmin';
A5.type='parameter';
A5.val= 20;

% Efficiency ------------------
A6.name='Eff';
A6.type='parameter';
A6.val= 0.8;

% Ini. State of Charge --------
A7.name='SOC0';
A7.type='parameter';
A7.val= 100;

% Required Energy -------------
A8.name='Ereq';
A8.type='parameter';
A8.val= Ereq;
A8.form='full';
A8.dim= 2; %t and c
```

```
% Arrivals --------------------
A9.name='ar';
A9.type='parameter';
A9.val= ar;
A9.form='full';
A9.dim= 2; %t and c

% Cycles --------------------
A10.name='cycle';
A10.type='parameter';
A10.val= cycle;
A10.form='full';
A10.dim= 2; %t and c

% SOCdeg --------------------
A11.name='SOCdeg';
A11.type='parameter';
A11.val= SOCdeg;
A11.form='full';
A11.dim= 2; %t and c

%Write the sets and parameters in a gdx file to GAMS
wgdx('D:\Final-
Results\Case6\to_GAMS.gdx',A0,A1,A2,A3,A4,A5,A6,A7,A8,A9,A10,A11);
%Open the GAMS file
system ('D:\Final-Results\Case4\case4.gms lo=3 ');

%Load the results from GAMS

% Total Cost ------------------
x.name='z1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
TotalCost=x.val-10;
x=[];

% Charging Power --------------
```

```
x.name='Pch1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
Pcharging=x.val-10;
x=[];

% Discharging Power -----------
x.name='Pdch1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
Pdischarging=x.val-10;
x=[];



% Stored Energy ---------------
x.name='Est1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
Estored=x.val;
x=[];

% State of Charge -------------
x.name='SOC1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
SOC=x.val-10;
x=[];

% power limitation -------------
x.name='Plimit1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
Plimit=x.val-10;
x=[];
```

```
% Replaced Energy -------------
x.name='Erep1';
x.form='full';
x.compress=true;
x=rgdx('D:\Final-Results\Case4\to_MAT.gdx',x);
Ereplacement=x.val-10;
x=[];

[row,col,v] = find(Ereplacement);
Rep=[row,col,v];

for i=1:nc
while Rep(i,2)>288
      Rep(i,2) = Rep(i,2)-288;
end
end
```

MATLAB Code: Charging Station

```
%Identifying the sets
nt=288; % # of time slots
time=[1:nt]';
nc=10; % # of customers
Customer=[1:nc]';

load('D:\Final-Results\Case7\grid_price.mat');  % CGrid(1x288)
%
######################################################################
#
req1=[
1   40  30
2   75  25
3   110 25
4   145 25
5   180 30
6   180 25
7   215 25
8   246 20
9   280 25
10  280 25
```

```
];

Ereq=zeros(nt,nc);
ar=zeros(nt,nc);
for i=1:nc
    Ereq(req1(i,2),i)=req1(i,3);
    ar(req1(i,2),i)=1;
end

Pch=zeros(nc,nt);
chcost=zeros(nc,nt);

for i=1:nc
    for j=1:nt
        if j==req1(i,2)
            chtime(i)=((50-req1(i,3))/10)*12;
            range(i)=req1(i,2)+chtime(i);
            for z=req1(i,2):range(i)
            Pch(i,z)=10;
            Cost(i,z)=((CGrid(z)+0.0305)*Pch(i,z)*(1/12))/0.8;
            end
        end
    end
end

Ptotal=sum(Pch(:));
Total_Cost=sum(Cost(:));
```

GAMS Code: Battery Exchange Station

```
option decimals = 5;
$eolcom II
IInow we can use II as a comment symbol
IIoption iterlim=999999999; II avoid limit on it
option reslim=100000000; II timelimit for sol
$Ontext
ELE Thesis - Fall 2018 - Ghady Zaher - 74552
$Offtext

IIOpen the matlalsb file and specify the setsIparameters that needs to be upload»
```

```
   ed to GAMS
$set matout "'D:\Final-Results\Case4\to_MAT.gdx',
   z1,Pch1,Pdch1,SOC1,Erep1,Est1,» Plimit1";

sets
t          Time Segments
c          Customers
b          Batteries
;

parameters
Cgrid(t)        Grid Price in $
Emax            Maximum Energy(kWh)
SOCmin          MIn SOC (%)
Eff             Efficiency
SOC0            intitial SOC (%)
Est0            initial stored Energy in kWh
Ereq(t,c)       Required Energy by customers
ar(t,c)         Customers arrivals
;

IIopen the gdx file generated by MATLAB and load the
parameters from it
$gdxin D:\Final-Results\Case4\to_GAMS.gdx
$load t
$load c
$load b
$load Cgrid
$load Emax
$load SOCmin
$load Eff
$load SOC0
$load Ereq
$load ar
*end of loading sets and parameters

Variables
z                 Objective function variable $
Pch(b,t)          Charging Power   kW
```

```
Pdch(b,t)         Discharging Power  kW
Est(b,t)          Stored energy in kWh at end of time slot t
SOC(b,t)          State Of Charge at end of time t
M(b,t)            free negative varaiable
M1(b,t)           free variable
M2(b,t)           free variable
M3(b,t,c)         free variable
Cpeak             peak demand charges
Cch               charging cost from grid
Cdch              discharging revenue from grid
Crep              replacement revenue
;

positive variable Pmax_ex, Plimit(t);

integer variable
Erep(b,t,c)       Replacement energy in kWh
;

binary variable x(b,c) binary variable for serving the customers;

Pch.lo(b,t)=0;
Pch.up(b,t)=10;

Pdch.lo(b,t)=0;
Pdch.up(b,t)=10;

SOC.lo(b,t)=20;
SOC.up(b,t)=100;

Est0=SOC0*Emax/100;

Est.lo(b,t)=SOCmin*Emax/100;
Est.up(b,t)=Emax;

Erep.up(b,t,c)=0.8*Emax;
Erep.lo(b,t,c)=0;
```

```

M.up(b,t)=0;
M.lo(b,t)=-50;

M1.up(b,t)=1000;
M1.lo(b,t)=-1000;

M2.up(b,t)=1000;
M2.lo(b,t)=-1000;

M3.up(b,t,c)=0;
M3.lo(b,t,c)=-50;

EQUATIONS
OBJ         Objective function
Cost1
Cost2
Cost3
Cost4
Cons1       Constraints 1 - Stored energy at each time
Cons2       Constraints 2 - Stored energy of the first-time
segment
SOC_1       State of Charge of the first-time segment
Cons3       Constraints 3 -
Cons4       Constraints 4 - The charging power is zero when
the battery is being replaced
Cons5       Constraints 5 - The discharging power is zero when
the battery is being replaced
Cons6       Constraints 6 - The replacement energy is zero
when no customer arrivals
Cons7       Constraints 7 - The replacement energy is
available when a customer arrives
Cons8       Constraints 8 - One customer is served per time
segment
cons9       Constraints 9 - Energy sold to the customers is
90-100% of Emax
cons10
cons11
cons12
```

```
cons13
;

//Profit Equation
OBJ..      z =e= Cpeak+Cch+Cdch+Crep;
Cost1..    Cpeak =e= -9.1*(Pmax_ex-315);
Cost2..    Cch=e=sum(b,sum(t,(-(Cgrid(t)+0.0305)*Pch(b,t)*(1/12))/Eff)) ;
Cost3..    Cdch=e=sum(b,sum(t,(Cgrid(t)+0.0305)*Pdch(b,t)*(1/12)*Eff));
Cost4..    Crep=e=sum(b,sum((t,c),0.25*Erep(b,t,c)));

//Battery Equations
Cons1(b,t)$(ord(t) ge 2)..Est(b,t) =e= Est(b,t-1) + (Pch(b,t)*(1/12)) - (Pdch(b,t)*(1/12))-sum(c,Erep(b,t,c));
Cons2(b)..                      Est(b,'1') =e=  Est0 + (Pch(b,'1')*(1/12))- (Pdch(b,'1')*(1/12));
SOC_1(b,t)..                    SOC(b,t) =e=  100* Est(b,t)/Emax;

//Replacement Equations
Cons3(b,t,c)$(Ereq(t,c) ne 0)..  Est(b,t)$(Ereq(t,c) ne 0) +(1-x(b,c))*M(b,t) =e= x(b,c)*Ereq(t,c);
Cons4(b,t,c)$(ar(t,c)=1)..       Pch(b,t)$(ar(t,c)=1)+(1-x(b,c))*M1(b,t)      =e=  (1-x(b,c));
Cons5(b,t,c)$(ar(t,c)=1)..       Pdch(b,t)$(ar(t,c)=1)+(1-x(b,c))*M2(b,t)     =e=  (1-x(b,c));
Cons6(b,t,c)$(ar(t,c)=0)..       Erep(b,t,c)$(ar(t,c)=0) =e=  0;
Cons7(b,t,c)$(ar(t,c)=1)..       Erep(b,t,c)$(ar(t,c)=1)+x(b,c)*M3(b,t,c)     =e=  x(b,c);
Cons8(c)..                       sum(b,x(b,c)) =l=  1;
Cons9(b,t,c)$(ar(t+1,c)=1)..     Est(b,t)$(ar(t+1,c)=1) =g=  0.9*Emax;
Cons10(t)..                      Pmax_ex =g=  sum(b,Pch(b,t))/Eff;
```

```
Cons11..                          Pmax_ex
=g=  315;
cons12(t)..                       Plimit(t)
=e=  sum(b,Pch(b,t));
cons13(t)..                       Plimit(t)
=l=  50;

option minlp=BARON;
MODEL SingleBattery /ALL/;
SOLVE SingleBattery USING minlp MAXIMIZING z;

parameter Pall(t);
Pall(t)=   sum(b,Pch.l(b,t))/Eff;

Display z.l,Pdch.l, Est.l, SOC.l,Erep.l,M.l,M1.l,M2.l, Ereq,
ar,Pch.l,Pall, Plimit.l
Cch.l
Cdch.l
Crep.l
;


parameters
z1                Objective function variable $
Pch1(b,t)         Charging Power   kW
Pdch1(b,t)        Discharging Power  kW
SOC1(b,t)         SOC at end of time t
Erep1(b,t,c)      Replacement energy in kWh
Est1(b,t)         Stored energy in kWh at end of time slot t
Plimit1(t)
z1=              z.l+10;
Pch1(b,t)=       Pch.l(b,t)+10;
Pdch1(b,t)=      Pdch.l(b,t)+10;
SOC1(b,t)=       SOC.l(b,t)+10;
Erep1(b,t,c)=    Erep.l(b,t,c)+10;
Est1(b,t)=       Est.l(b,t)+10;
Plimit1(t)=      Plimit.l(t)+10;
//Infeasibility Test between GAMS and MATLAB
//set stat /modelstat,solvestat/;
```

```
//parameter returnStat(stat);
//returnStat('modelstat') = Problem.modelstat;
//returnStat('solvestat') = Problem.solvestat;
execute_unload %matout%;
```

Appendix B

This appendix includes the PVsyst report for the solar energy production simulation. The first page shows the system design in terms of type and quantity for each component such as the solar modules and the inverter. It shows the total peak solar power and the total AC power of the system. The second page shows the production ratio, the yield and the production in MWh for each month of the year. The third page shows the losses caused by the shading, system unavailability, inverter loss during operation, etc. Figure 37 shows the solar system as modelled in PVsyst.

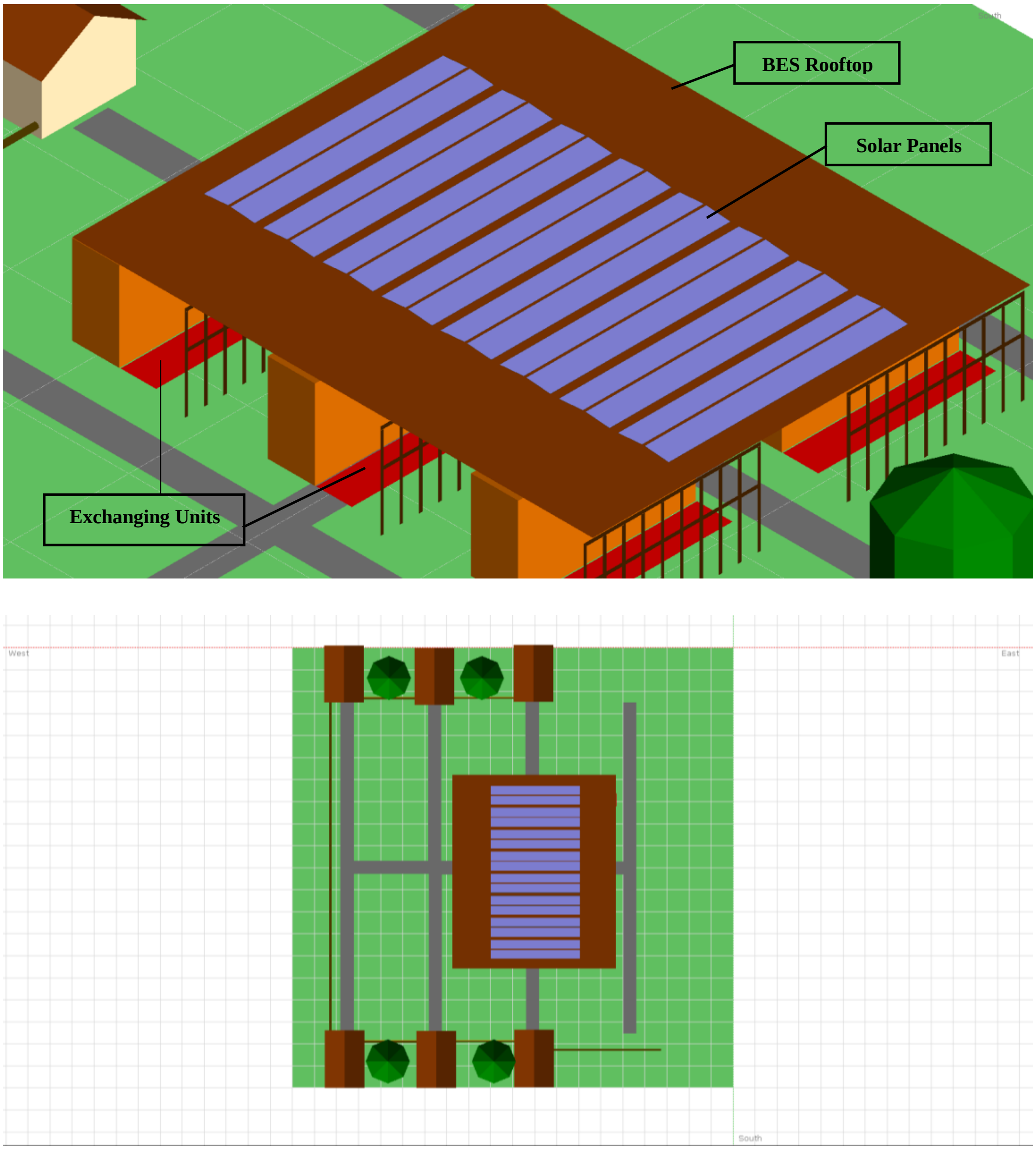
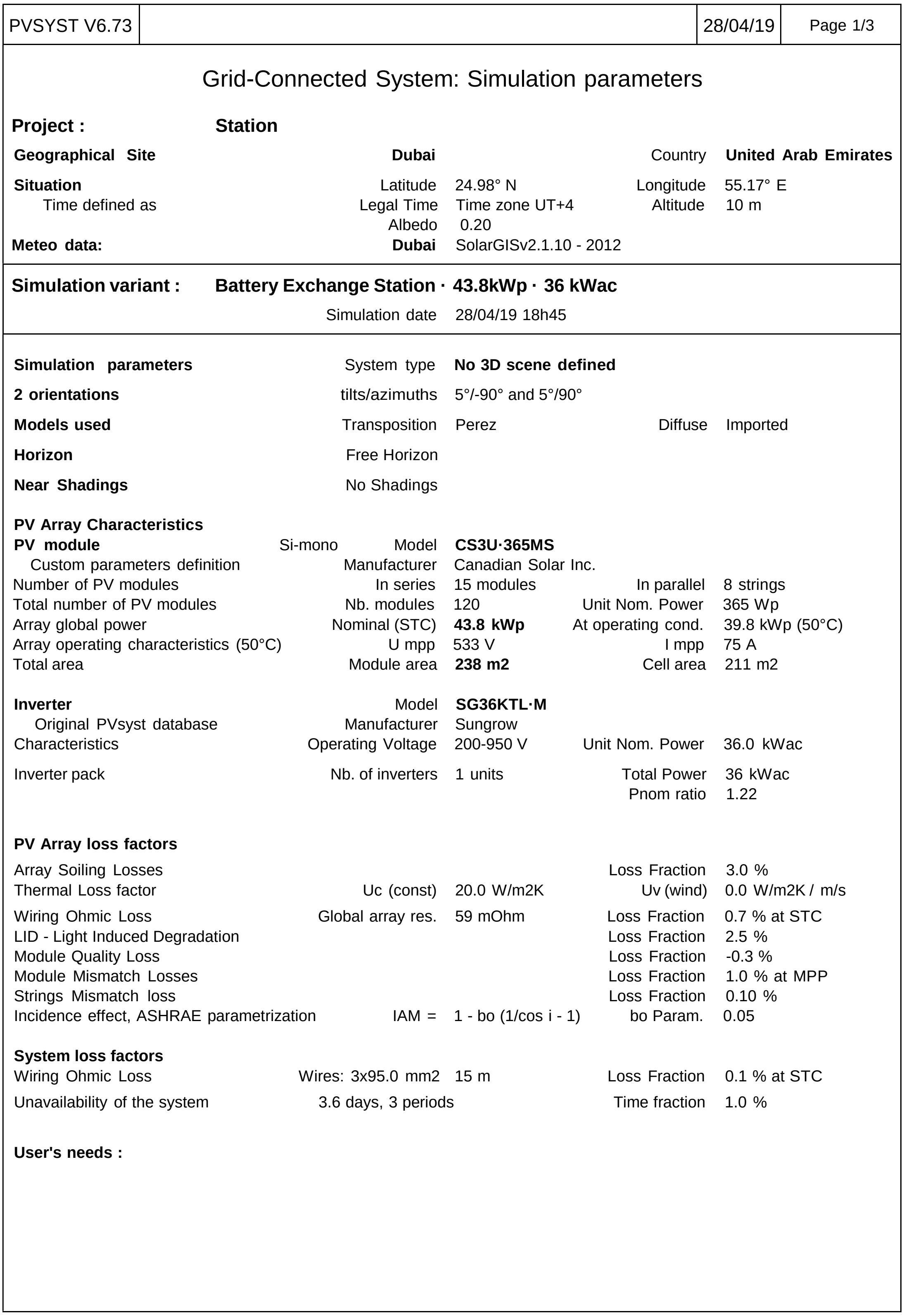


Figure 37: The side and top view of the rooftop solar system.



PVSYST V6.73		28/04/19	Page 1/3

Grid-Connected System: Simulation parameters

Project :	**Station**			
Geographical Site	**Dubai**		Country	**United Arab Emirates**
Situation	Latitude	24.98° N	Longitude	55.17° E
Time defined as	Legal Time	Time zone UT+4	Altitude	10 m
	Albedo	0.20		
Meteo data:	**Dubai**	SolarGISv2.1.10 - 2012		

Simulation variant :	**Battery Exchange Station · 43.8kWp · 36 kWac**			
	Simulation date	28/04/19 18h45		

Simulation parameters	System type	**No 3D scene defined**		
2 orientations	tilts/azimuths	5°/-90° and 5°/90°		
Models used	Transposition	Perez	Diffuse	Imported
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module	Si-mono	Model	**CS3U·365MS**		
Custom parameters definition		Manufacturer	Canadian Solar Inc.		
Number of PV modules		In series	15 modules	In parallel	8 strings
Total number of PV modules		Nb. modules	120	Unit Nom. Power	365 Wp
Array global power		Nominal (STC)	**43.8 kWp**	At operating cond.	39.8 kWp (50°C)
Array operating characteristics (50°C)		U mpp	533 V	I mpp	75 A
Total area		Module area	**238 m2**	Cell area	211 m2

Inverter	Model	**SG36KTL·M**		
Original PVsyst database	Manufacturer	Sungrow		
Characteristics	Operating Voltage	200-950 V	Unit Nom. Power	36.0 kWac
Inverter pack	Nb. of inverters	1 units	Total Power	36 kWac
			Pnom ratio	1.22

PV Array loss factors

Array Soiling Losses			Loss Fraction	3.0 %
Thermal Loss factor	Uc (const)	20.0 W/m2K	Uv (wind)	0.0 W/m2K / m/s
Wiring Ohmic Loss	Global array res.	59 mOhm	Loss Fraction	0.7 % at STC
LID - Light Induced Degradation			Loss Fraction	2.5 %
Module Quality Loss			Loss Fraction	-0.3 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

System loss factors

Wiring Ohmic Loss	Wires: 3x95.0 mm2	15 m	Loss Fraction	0.1 % at STC
Unavailability of the system	3.6 days, 3 periods		Time fraction	1.0 %

User's needs :

Grid-Connected System: Main results

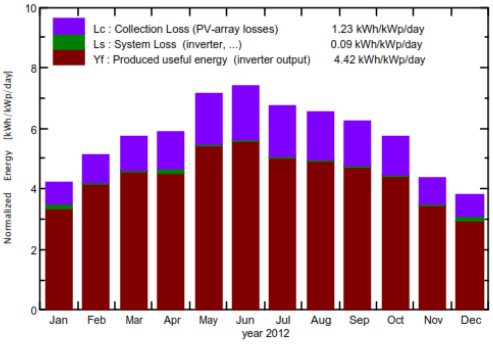
Project : **Station**

Simulation variant : **Battery Exchange Station ' 43.8kWp ' 36 kWac**

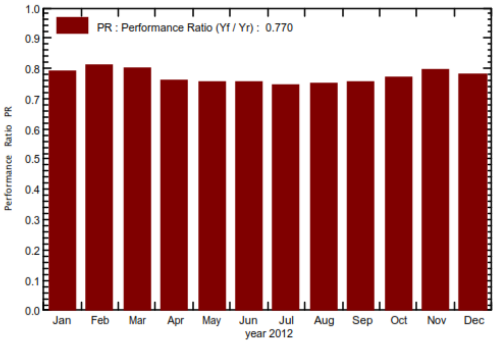
Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	2 orientations	Tilt/Azimuth = 5°/-90° and 5°/90°		
PV modules	Model	CS3U-365MS	Pnom	365 Wp PV
Array	Nb. of modules	120	Pnom total	**43.8 kWp**
Inverter	Model	SG36KTL-M	Pnom	36.0 kW ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**70.92 MWh/year**	Specific prod.	1619 kWh/kWp/year
	Performance Ratio PR	76.98 %		

Normalized productions (per installed kWp): Nominal power 43.8 kWp



Performance Ratio PR



Battery Exchange Station ' 43.8kWp ' 36 kWac

Balances and main results

	GlobHor kWh/m²	**DiffHor** kWh/m²	**T Amb** °C	**GlobInc** kWh/m²	**GlobEff** kWh/m²	**EArray** MWh	**E_Grid** MWh	**PR**
Jan. 12	131.3	52.3	19.80	131.3	121.5	4.763	4.544	0.790
Feb. 12	148.3	64.4	20.37	148.3	138.1	5.354	5.283	0.813
Mar. 12	177.4	80.3	22.83	177.4	166.2	6.293	6.202	0.798
Apr. 12	177.0	94.8	26.47	176.9	166.0	6.171	5.911	0.763
May 12	222.0	106.6	32.45	221.9	208.7	7.465	7.361	0.757
June 12	221.6	101.6	32.79	221.5	208.4	7.414	7.311	0.753
July 12	208.8	108.7	35.77	208.8	196.2	6.922	6.827	0.747
Aug. 12	203.4	101.3	35.31	203.3	191.1	6.772	6.679	0.750
Sep. 12	186.7	84.9	33.16	186.7	175.1	6.272	6.186	0.757
Oct. 12	177.7	61.1	29.54	177.9	166.4	6.102	6.019	0.772
Nov. 12	131.5	55.0	26.02	131.6	121.9	4.635	4.570	0.793
Dec. 12	117.7	51.4	22.87	117.8	108.7	4.239	4.029	0.781
Year	2103.3	962.3	28.14	2103.5	1968.4	72.403	70.922	0.770

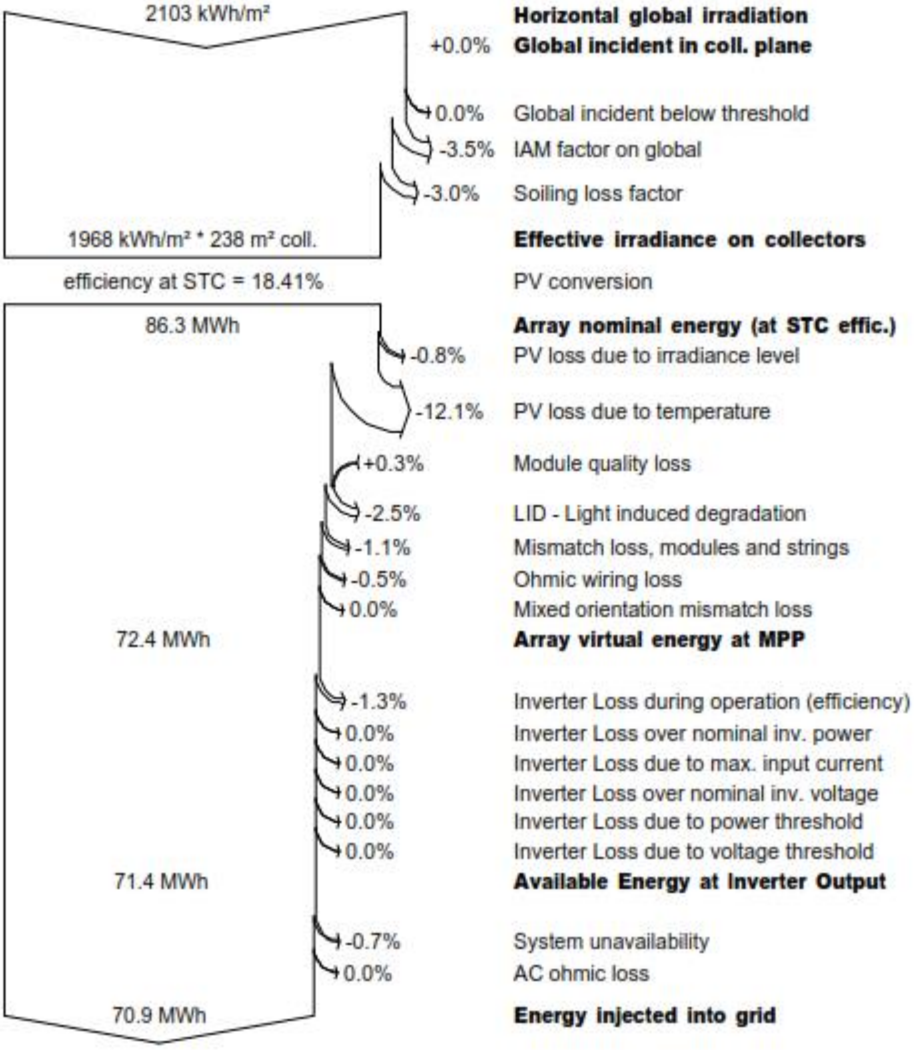
Legends:				
	GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
	DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	PR	Performance Ratio

Grid-Connected System: Loss diagram

Project : **Station**

Simulation variant : **Battery Exchange Station I 43.8kWp I 36 kWac**

Main system parameters	System type	**No 3D scene defined**		
PV Field Orientation	2 orientations	Tilt/Azimuth = 5°/-90° and 5°/90°		
PV modules	Model	CS3U-365MS	Pnom	365 Wp PV
Array	Nb. of modules	120	Pnom total	**43.8 kWp**
Inverter	Model	SG36KTL-M	Pnom	36.0 kW ac
User's needs	Unlimited load (grid)			



Vita

Ghady Khalil Zaher was born in 1996, in Tripoli, Libya. She received her primary and secondary education in Sharjah, UAE. She received her B.Sc. degree in Sustainable and Renewable Energy Engineering from University of Sharjah in 2017.

In September 2017, she joined the Electrical Engineering master's program in the American University of Sharjah as a graduate teaching assistant. During her master's study, she authored one paper which were presented in the IEEE Grand International Exposition and Conference Asia 2019, Bangkok, Thailand. Her research interests are in renewable energy technologies, smart grid and optimization.