Department of Mechanical and Aerospace Engineering

Techno-economic study of a photovoltaic electric vehicle charging station with battery swapping for supplying electricity to electric buses operating between La Granja de San Ildefonso and Segovia, Spain.

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Signed: Fernando Agudín Muñoz Date: 23/08/2019

Abstract

This thesis presents a feasibility analysis on photovoltaic (PV)-powered electric buses by considering the existence of a 28.8 kW photovoltaic electric vehicle charging station (ECVS) in the Spanish village of La Granja de San Ildefonso.

The analysis of this service is based on the fact that electric buses can provide energy storage capacity to use efficiently the intermittent PV power, hence reducing GHG emissions. The conceived buses must complete a weekday scheduled service between the mentioned location and the nearby town of Segovia. Electricity required to complete this service is calculated using a Chinese electric bus model. Value of the demand is 585.6 kWh/day.

Three models of power supply are assessed based on net present cost, cost of energy, and carbon emission intensity. HOMER software is used to implement these models and optimize the size of the current ECVS, creating five different scenarios. These scenarios are the following: 1a, which constitutes the current state of the ECVS (Grid-Current PV installed- Electric bus), 1b (Grid-Optimal PV- Electric bus), 2a (Grid-Current PV installed- Battery- Electric bus), 2b (Grid- Optimal PV- Battery- Electric bus), and 3 (Optimal PV- Wind turbine- Battery- Electric bus).

Technical results show that about 174 kW of PV panels optimize those systems where the grid is considered, while in the isolated full renewable system 344 kW of PV panels and a 9 kW wind turbine are optimal to satisfy the predefined demand. Values of Cost of Energy are 0.1534 (1a), 0.04928 (1b), 0.1901 (2a), 0.08241 (2b), and 0.1529 (3). System 3 costs of energy are lower than System 1 ones. However, as System 1a is already built, it is calculated that about 12 years would be enough to recover the investment of retrofitting the ECVS from System 1 to System 3. With the current PV capacity, 45.000 kg CO2/kWh are generated while System 3 emits none.

Apart from that, the feasibility of electric buses to cover the scheduled trips between the two locations for every single system is proven by swapping batteries strategy.

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List of Abbreviations

EV	Electric vehicle
PHEV	Plug-in electric vehicle
GHG	Greenhouse gas
PV	Photovoltaic
MPPT	Maximum power point tracker
HOMER	Hybrid optimization model for electric renewable
NPC	Net present cost
TAC	Total annualized cost
COE	Cost of energy
CEI	Carbon emission intensity
BEV	Bus electric vehicle
ECVS	Electric vehicle charging station
RF	Renewable fraction
B1	Electric bus number 1
B2	Electric bus number 2
bI	Electric battery number 1
bII	Electric battery number 2
bIII	Electric battery number 3
bIV	Electric battery number 4
AC	Alternating current
DC	Direct current

1. Introduction

1.1 Background

A new era of transport is about to start. Electrification of most of our traditional modes of transport is beginning. Electric vehicles are initially conceived as carbon-free vehicles. However, as these vehicles must be charged using the grid, the electricity that they receive could proceed from contaminant sources of supply. This depends on the grid supply mix of each country and would suppose contamination to move from cities to the location of contaminant power plants. (Kliesch and Langer, 2006) the study carried out for the American Council for an Energy Efficient Economy points out that, based on the distribution mix for America, an electric vehicle would only emit 15% less carbon dioxide than a conventional vehicle based on internal combustion engines. This study also states that greenhouse gases (GHG) emitted by electric vehicles are higher than the ones emitted by conventional petrol cars in those zones where coal-fired stations provide more than 80% of the total supply. Moreover (Meisterling and Samaras, 2008) compared the emission between plug-in hybrid electric vehicles (PHEVs) and conventional vehicles. They found that, in the state of Pennsylvania, PHEVs emissions are 32% lower than the conventional vehicle ones. Furthermore, (Electric Power Research Institute (EPRI), 2007) findings showed that, depending of the level of EV penetration in the U.S, GHG emissions could be reduced by 3.4-10.4 billion metric tons Based on all these studies, it can be inferred that the reduction of GHG provided using EVs depends ultimately on the power supply used. These power supplies must be low-carbon or, preferably, renewable.

Apart from that, it is necessary to mention the impact made to the grid and distribution systems due to an increasing EV demand. If the size of the local substations is not enough, they could not respond properly to a large number of electric vehicles connected to a power grid. Overload of lines and substations could constitute then a problem. For instance, (Hadley, 2006) findings show that residential circuits are not correctly prepared to accommodate new loads ranging from 1.4-6 kW during 2-6 hours. The problem gets worse by the fact of uncertainty on charging times. Overload of the lines is increased by the inclusion of "fast-charging modes" that are able to charge a single EV by feeding it with 50 kW. Moreover, research carried out by (TENG Le-tian,HE Wei-guo,DU Cheng-gang, 2010) concluded that 3rd and 5th harmonics are produced within the grid by charging numerous electric vehicles. The reason behind this is because of the phenomena of rectifying AC signals to DC on a large scale. Harmonic distortion could ultimately mean adding costs to the electricity grid as the increased temperatures caused to the transformers and other grid components reduce their lifespan. These findings are supported by the study of (TENG Le-tian,HE Wei-guo,DU Cheng-gang, 2010), which determines that, because of the uncertainty of charging times of EVs and the high power charging rate, frequency of the grid could fluctuate and consequently the stability of the grid could be challenged.

Additionally, charging time of an electric vehicle is much longer than the process of gasoline refueling within a conventional vehicle. This constitutes another challenge for the electrification of transport. As it is mentioned above, “fast-charging mode” could ease partially this task. However, best EV batteries, which range is 480 km, still takes 1 to 2.5 hours to get charged with a power input of 60-150 kW (Thomas, 2009).

At present, solar PVs are increasing rapidly all over the world. However, the intermittency of the resource makes charging electric vehicles difficult as the batteries of these require to be charged randomly throughout the day. One possible solution is to use electric vehicles as a storage battery for being used when the solar irradiance is at its lowest. The current thesis aims to propose a solution related to this issue by introducing PV electricity to power electric buses in a small Spanish village, consequently reducing overall GHG emissions from energy consumption of the electric buses.

1.2 Problem statement

This project focuses on proposing a sustainable application, as it is the inclusion of an electric bus service, to an existing charging facility equipped with PVs. In order to do so, the author aim is to model several configurations of micropower systems using determined software. All these micropower systems have two elements in common: a PV plant charging station and its electric load representing the demand of an electric bus. The overall objective of the project consists of providing a sustainable service to a renewable charging facility that is currently misused due to the low level of penetration of EVs.

1.3 Overall aims

The overall aim of the thesis is to study the feasibility of powering electric buses by using a photovoltaic based electric vehicle charging station (ECVS).

The main objectives are:

- Review the state of the art for electric transport: current models of charging stations powered by renewables, regulation of self-consumption and battery swap stations for electric vehicles.
- Identify and apply a technique for modeling the trips done by electric buses between two locations.
- Model several micropower system solutions representing the ECVS equipped with PVs and other supply sources in La Granja de San Ildefonso (Spain) along with the load represented by an electric bus.
- Check the feasibility of ensuring a scheduled electric bus service powered by renewable sources between the two locations.
- Evaluate the models proposed according to the parameters calculated: Net present cost, cost of energy and carbon emissions intensity.

1.4 Methodology overview

The methodology adopted in this thesis is the creation, simulation, and analysis of different scenarios.

First, an existing ECVS and its parameters are searched. Second, a calculation about the energy required to make the electrification of the route between the location of the ECVS and a nearby city is done. Then, different microsystem approaches comprising the ECVS and the demand of the electric buses are created. After that, these models are implemented in HOMER software. To do this, an extensive search of parameters of the different components as well as some assumptions need to be made. Then, the analysis stage begins. The different techno-economic parameters provided by HOMER are analysed. Finally, a method is developed to check the feasibility of matching the supply with the electric bus requirements in order to complete the scheduled trips.

1.5 Thesis outline

This thesis includes eight chapters and the order given below.

Chapter 1 – Introduction

This chapter includes the background of the thesis as well as the statement of the problem intended to be investigated. The main aims of the thesis are explained, an overview of the methodology carried out and a summary of the contents of the thesis are provided.

Chapter 2 – Literature Review

This chapter gives a detailed description of the self-consumption Spanish regulation and provides a summary of several pieces of research done about designing electric vehicle charging stations and battery swap stations.

Chapter 3 – Location and features of the Electric Vehicles Charging Station (ECVS)

This chapter provides a detailed explanation of the technical specifications of the ECVS subject of study and the location where it is installed.

Chapter 4 – Electrification of transport between La Granja de San Ildefonso and Segovia

This chapter presents the bus schedule between the two locations proposed. It also provides a calculation of how much electricity would be required to electrify the route of public bus service and the model approaches to do it based on the ECVS production.

Chapter 5 – Homer implementation and simulations performed

This chapter introduces the software chosen and the reason of such an election as well as the parameters required to simulate each one of the models. An overview of the results that are going to be analyzed is also presented.

Chapter 6 – Results and discussion

This chapter presents the results obtained from the simulations carried out. It also reflects the discussion adjoined to it about the parameters previously defined. Feasibility of achieving the main aim of the thesis is also discussed.

Chapter 7 – Conclusions

The final chapter presents a summary of the thesis outcome.

Chapter 8 – Future work

The final chapter provides recommendations about how to expand and improve the work carried out throughout the thesis.

2. Literature review

2.1 Review on Design of electric vehicles charging stations

(Domínguez-Navarro *et al.*, 2019) uses a generic algorithm based on economic and technical features for designing EV fast-charging stations. The authors determine the probabilistic model allows to achieve more accurate results of demand and renewable energy supply. Inclusion of key parameters of EV such as battery capacity, state of charge and driving patterns promote better results. All simulations run show EV charging stations as a profitable investment even though the expensiveness of current technology, being the cases with embedded renewables and storage the ones that reduce most the impact on the grid.

Research conducted by (Tang *et al.*, 2014) proposes four different models for PV powered electric vehicles for the Chinese city of Shenzhen: Grid-EV, Grid-PV-EV, PV-Battery-EV, and Grid-PV-Battery-EV. Simulations are developed using HOMER software and analyzed according to the parameters this software is able to calculate: net present cost (NPC), and cost of energy (COE). Moreover, carbon emissions intensity (CEI) is calculated. Results show that the difference COE between the Grid-PV-EV and Grid-PV-Battery-EV combinations is low. When reviewing CEI results, those combinations considering the grid within its model show increased values because of the high carbon dependency that Chinese grid has. Authors highlight that PV powered EV systems are able to have a key role in the near future due to four aspects: carbon emission costs, increased electricity supply costs and decreasing prices of PV components, and batteries.

(Vermaak and Kusakana, 2014) created a HOMER model for integrating Tuk-tuk vehicles within the operation of a photovoltaic-wind charging station. Renewable energy sources rated power, component cost and technical specifications constitute the input data that HOMER requires. The authors simulated two different strategies on operating the micropower system: firstly, charging a SINGLE Tuk-tuk per day, in other words, charging it throughout a twenty-four hours period, and second, charging Tuk-tuk consecutively one after another. The analysis of both dispatch strategies was done according to the parameters HOMER is able to simulate net present cost, cost of energy, capacity shortage and security of supply. The research concluded that the best strategy, according to the parameters describe above, for operating an existing plant in a remote area of Democratic Republic of Congo of 7.2 kW wind turbine, 1 kW PV array and 5 strings of 12 V, 120 Ah batteries was to charge one Tuk-tuk after another spending twenty-four consecutive hours.

In the overview research carried out by (Bhatti *et al.*, 2016), two types of patterns about electric vehicles powered by photovoltaics were identified: models considering the gird when feeding electric vehicles with PVs and stand-alone PV models. Authors point out that DC-DC converter with MPPT, bidirectional converter and inverter are mandatory elements when having the propose of integrating electric vehicles with photovoltaics. The research concludes that the trend in energy management techniques developed in recent years is based on optimization algorithms and soft computing.

(Zhang *et al.*, 2019) research places its study on analyzing the effects of fast charging on the distribution network. Major problems produced to the grid by this process are power fluctuation rapidly, and peak-valley loads alternating frequently. Analysis are performed after putting up together three major elements: queuing model for electric vehicles charging combined with a stochastic model for charging station supply and an algorithm incorporating two-time dimensions for storage. Results show that more EVs can be charged to greater energy storage capacities under the low rates of electric vehicle arrival. In contrast, under high rates of electric vehicle arrival, energy storages supply more energy than the grid, causing losses percentage not to be reduced.

The study of (Fathabadi, 2017) consisted of designing and constructing a wind-powered electric vehicle charging station with vehicle to grid storage capability. Authors considered the following hardware for designing the charging station: a wind energy conversion system, a unidirectional DC/DC, a maximum power point tracking controller (MMPT), bidirectional converters connected to each charging point and an inverter DC/AC for connecting the renewable source to the grid. Authors developed an innovative technique for operating the MMPT that, as the results confirm, maximized the conversion of wind energy into electricity. Moreover, the design proposed not only covered the EV demand modeled but also was able to contribute to bulk electricity to the grid at peak demand times.

When studying the interaction between electric vehicles and the grid, one of the key aspects to be treated is the harmonics produced on the grid due to the fast charging process. (Khan, Ahmad and Alam, 2019) focus their research on power transmission quality and load management techniques. Authors model separates the individual vehicle charging from the transmission of AC from the grid to the DC bus through the converter. Their investigation analyses the effect of adding a PV system to the grid-EV system for minimizing dynamic impacts and optimizing profits. Results show that the converter presents a good performance with a variable load. PV addition makes the whole system more profitable and reduces the harmonics on the grid by reducing the net energy drawn from the grid to the electric vehicle. Finally, the authors highlight the importance of strengthening the framework of the energy management system of electric vehicles. Market models should include new services such as load shifting, peak shaving, and voltage regulation.

Research conducted by (Alsharif, 2017) is focused on the capability of solar-powered base stations to power mobile communications. The authors analyze architecture, energy production, optimal system cost, and economic feasibility of solar stations in comparison to other conventional sources. Simulations carried out using HOMER software show that PV facilities modeled are able to cover load demand without any losses. The one-hour time step used by HOMER for simulating solar radiation resource is enough accurate to model PV arrays. Results also confirm that battery bank can supply the electricity required by the load in case of a PV operation and maintenance stop of 2 days. The authors demonstrated that up to 66% savings in operational expenses can be achieved through PV arrays in comparison to other conventional sources.

2.1 Review on Battery Swapping Electric vehicle station

Research conducted by (Dai *et al.*, 2014) consists of analyzing the role of battery-swap stations (BSSs) in order to make EV driving range longer. Authors point out that randomness of charging patterns and battery swapping make the demand for the BSS to be stochastic. Researches develop a Monte Carlo simulation in order to minimize the impact produced by uncoordinated charging behaviors on the distribution network This model presents four variables: number of EVs for battery swapping, charging start time, charging duration and travel distance. Results show an accurate prediction of load demand they deal effectively with the uncertainty of the variables. Moreover, this research allows further users to calculate the impact of the BSS on the grid, the coordination of the strategy of charging and the economics of this strategy.

When studying the impact of the BSS in the distribution systems, (Zheng *et al.*, 2014) investigates it through the life cycle cost of BSS. Researchers highlight the importance of the location and scalability of the BSS in order to reduce the impact during periods of increased power in the grid, which their protections must be reinforced. A Monte Carlo algorithm is used to solve the problem and optimize life cycle cost and safe operation. This algorithm is applied to two case studies: the IEEE 15 and 43 bus. Results show that the optimization of charging and discharging can be advantageous in order to balance the grid. Moreover, the operator is able to generate profits through optimization of planning. Trends show that the deployment of BSS will be expedited as the cost of batteries is decreasing.

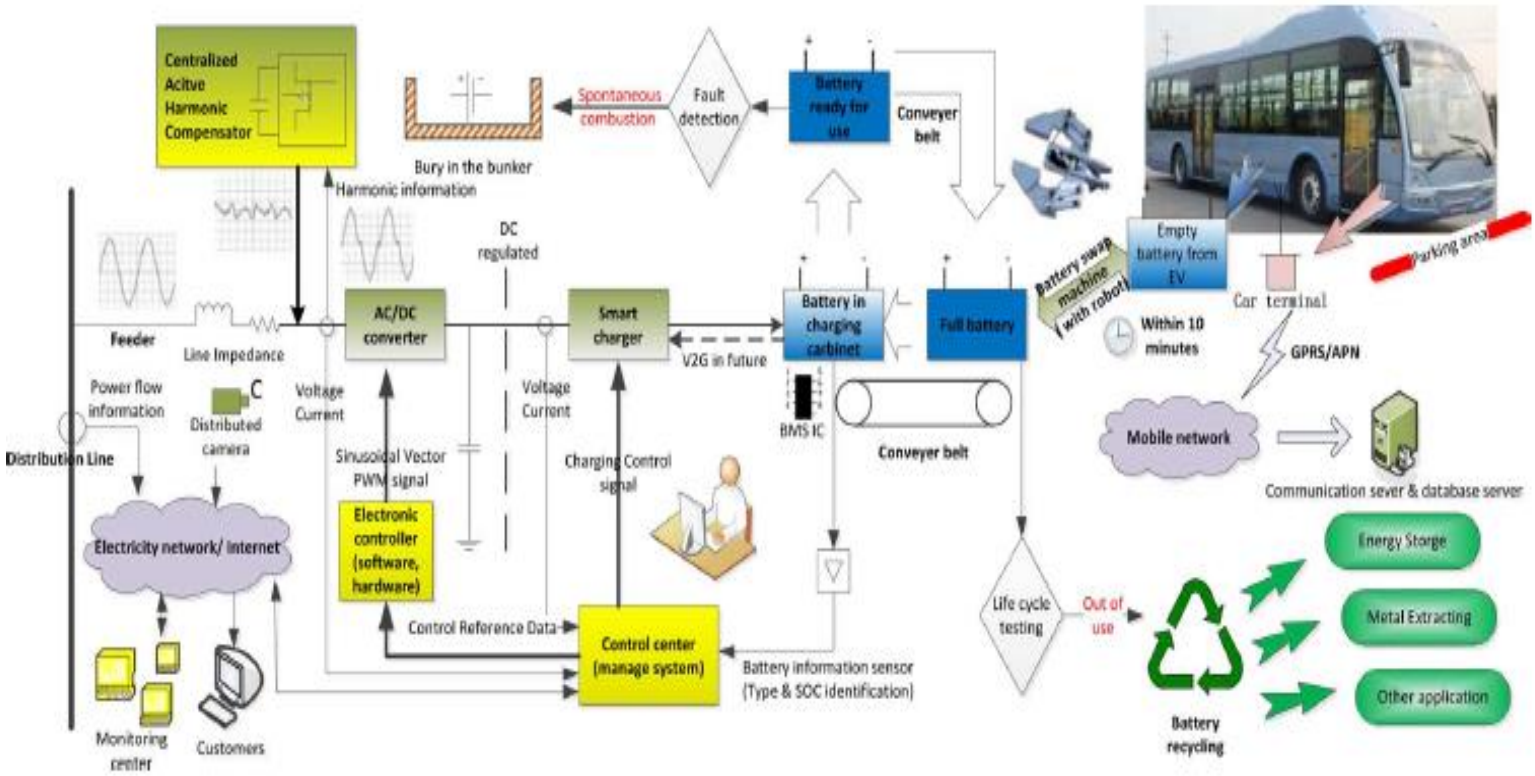

Figure 1: Topology of a battery-swap station. Source (Zheng et al, 2014)

The study conducted by (Sarker, Pandžić and Ortega-Vazquez, 2015) establishes a model whose main foundation is the day-ahead scheduling process in order to optimize the economics and operation of BSS. As it is reflected in prior papers mentioned, uncertainty about the state of charge of the battery is the major issue to deal with, as well as changing on electricity price throughout the day. Authors also take into account battery degradation and its economic devaluation within the model. Three ways of operation are considered when modeling the BSS: grid to battery, battery to grid and battery to battery. Results show that uncertainty coming from demand, electricity price and degradation reduce the profitability of battery to grid and battery to battery services. Between the variables, electricity price needs to be managed properly in order to avoid economic losses. Moreover, and as it is mentioned in prior studies investigated, cost of batteries and degradation cost make this type of BSS difficult to exploit at the moment, expecting this trend to change in the near future when the technology will achieve a more mature state. The research concludes that the mode in which BSS operates depends on the surplus of energy combined with battery swapping needs.

The research conducted by (Mak, Rong and Shen, 2013) centers their investigation on the infrastructure planning to make possible battery swapping in electric vehicles. By using optimization models, authors investigate the role of battery size standardization and technology improvements to optimize the strategy for infrastructure deployment in order to allow drivers of EVs to have a similar driving range as the one provided by internal combustion engines. Authors define two models of optimization that considers the uncertainty of demand and battery inventory: one that minimizes costs regarding the worst case of expected location and inventory costs, and another goal-driven one that maximizes the profits. By applying these non-linear models to a highway located in San Francisco, results of both models converge in terms of improving profits of the service provider.

2.2 Framework of self-consumption in Spain

Due to the political instability during the recent years, regulation about self-consumption through renewables has constituted a problem to be done.

Finally, Royal Decree of 5th of April to regulate administrative, technical and economic conditions of the self-consumption of electrical energy by the Spanish Government (BOE, 2019) states the main points about self-consumption, including remuneration about the surplus generated by self-consumption and sold to the grid, and the contribution of the self-consumer to the costs of the system.

According to this Decree, several types of self-consumption are defined:

- Self-consumption without surplus: this type refers to those facilities that cannot sell energy surplus to the grid. There only exists the Consumer Subject, who is also the cardholder of the generation facility.
- Self-consumption with surplus transferred to the grid: in this case, there exists a Consumer Subject and a Producer Subject. Depending on the surplus generated, this one is divided into different categories:

1. Self-consumer with surplus attached to monetary compensation: this option is only valid if the following conditions occur:
    - Rated power is less than 100 kW.
    - The consumer must agree on a contract with the marketer for the auxiliary services of production.
    - The consumer signs the contract of self-consumption attached to monetary compensation.
    - There is not any additional remuneration system.
2. Self-consumer with a surplus not attached to monetary compensation: this option takes place when the consumer does not want to get attached to monetary compensation or the consumer does not fulfill the conditions mentioned above. In this case, a consumer would receive compensation for the surplus energy bulked to the grid.

Moreover, self-consumption facilities can be divided into the other two categories:

- Individual self-consumer: a single consumer joined to one production facility.
- Collective self-consumer: several consumers joined to one or various production facilities. In this case, every single consumer that participates of this collective must belong to the same modality of self-consumption, and they must communicate individually an agreement to the distribution company or through the marketer one signed by every participant.

Another criterion for categorizing the self-consumption facilities is to separate them between "fencing facilities through the grid" and "fencing inner grid facilities". Within these categories, the following consumers can be found:

- Consumers allocated in the same cadastral reference according to their first fourteen digits.
- Consumers connected to the low-tension gird and within a distance minor than 500m to the measuring equipment.
- Consumers connected to the low-tension grid derived from the same transformer.
- Consumers connected to the inner grids or through direct lines.

If the facility is a fencing inner grid and collective, it would be allowed to have or not surplus.

If the facility is a fencing facility through the grid, collective self-consumption could only be the one with a surplus.

Moving to the auxiliary services of production, there is no need to make an agreement for them when the following conditions are met:

- The facility is categorized as “fencing inner grid facilities”.
- The installed capacity is minor than 100 kW.
- The energy consumed by those auxiliary services of production is less than 1% of the net energy generated by the facility.

When the auxiliary services of production are not negligible, a contract comprising supply and access to the associated consumer when the following conditions are met:

- Production facilities are connected to the inner grid of the consumer.
- The consumer and the holders of the production facility are the same legal or physical person.

The procedure of connection and access to the grid by the self-consumption facilities is divided as follows:

- Self-consumption facilities without surplus: this type of facilities only needs access and connection permission.
- Self-consumption facilities with a surplus, which power is minor than 15 kW and they are located within urbanized ground: his type of facilities only needs access and connection permission.
- Self-consumption facilities that do not meet the prior condition: they must have access and connection permission for their consume facilities and for each of their production facilities fencing and associated with the consuming ones.
- For the case of self-consumption collective facilities, the holders must attach an access and connection application when the surplus would be greater than 15 kW within non urbanized ground.

Consumers must communicate directly to the distribution company or by the intermediary of the marketing company the type of self-consumption to which they would be attached to make the distribution company change their contract.

On the one hand, in the case of self-consumption facilities of low tension and the ones with a rated power minor than 100 kW, this change on the contract is made by the distribution company, with the bureaucracy indicated by each Autonomous Community. On the other hand, in the case of self-consumption facilities with a surplus not attached to monetary compensation and whose auxiliary services of production are not negligible, the holder of each production facility must make an access contract or modify the existing one for the auxiliary services of production. The holders would do it directly with the distribution company or through the marketer one.

Regarding the supply contracts that consumers have with the marketer company, they must reflect the type of self-consumption to which they are attached to. Thus, the distribution company must communicate the date when the new contract of self-consumption of the consumer takes effect to the marketer one within 5 days. Moreover, storage is allowed in all self-consumption facilities. Storage must be installed in a way that the electronic counter can register the net generation.

Apart from that, with regards to the self-consumption record, it must be telematic, declarative, public, and free access. The self-consumption record presents two sections: self-consumption with and without surplus.

3. Location and features of the Electric Vehicles Charging Station (ECVS)

3.1 Location of the ECVS

The Spanish village of La Granja de San Ildefonso installed one of the first ECVS fed by PV panels in the whole country. La Granja de San Ildefonso is located embedded in the National Park of "Sierra de Guadarrama" that separates the Spanish provinces of Segovia and Madrid. Also, this village has been awarded as Biosphere Reserve by UNESCO in 2013. These entitlements show that the location constitutes a rich natural environment where all forms of life and nature must be preserved.

Nowadays there is not any consistent use of it because of the low level of penetration electric vehicles have on the zone. Moreover, mechanical adjustments must be carried out in order to fulfill the aims of the project, meaning equipping the ECVS with the devices needed to swap bus batteries.

Figure 2:Photovoltaic Electric Vehicle Charging Station.

3.2 Technical specifications of the ECVS

The installation was set on April 2017. The investment was fully carried out by the company "Electrolineras Sostenibles SL". It is made of ninety 320 Wp (28.8 kW rated capacity) photovoltaic (PV) panels, from "ATERSA" group. This PV array, along with the two ultra-rapid charging points (50 kW) from "EFACEC at 50 kW either by the current provided from the solar production during daytime or the one provided directly from the grid connection.

Figure 3: Technical Specifications of the EFACEC fast charger.

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Figure 4: EFACEC fast charger of the ECVS

4. Electrification of public transport between La Granja de San Ildefonso and Segovia

4.1 Trips route and schedule

In the village, there exist a considerable amount of people that work and study in the nearby city of Segovia, located eleven kilometers far from the village. In order to get to their jobs, commuters use the public bus service daily. All public transport is currently fully powered by fossil fuels.

The following tables illustrate the scheduled trips done during weekdays by the current fleet of combustion buses from location A (La Granja de San Ildefonso) to location B (Segovia) (Freno and Freno, 2019), and the distances and duration of the trips (Table 1 and Table 2 respectively).

Table 1: Weekdays scheduled bus trips between La Granja de San Ildefonso and Segovia

Departure Location A	7:30	8:15	9:00	9:45	10:30	11:15	12:00	12:45	13:30	14:15
	15:00	15:45	16:30	17:15	18:00	18:45	19:30	20:15	21:00	21:45
Arrival Location B	7:55	8:40	9:25	10:10	10:55	11:40	12:25	13:10	13:55	14:40
	15:25	16:10	16:55	17:40	18:25	19:10	19:55	20:40	21:25	22:10

Table 2: Parameters of the trip covered by the public bus service

Distance A-B	12 km
Distance A-B-A	24 km
Duration of route A-B	25 min
Duration of route A-B-A	50 min

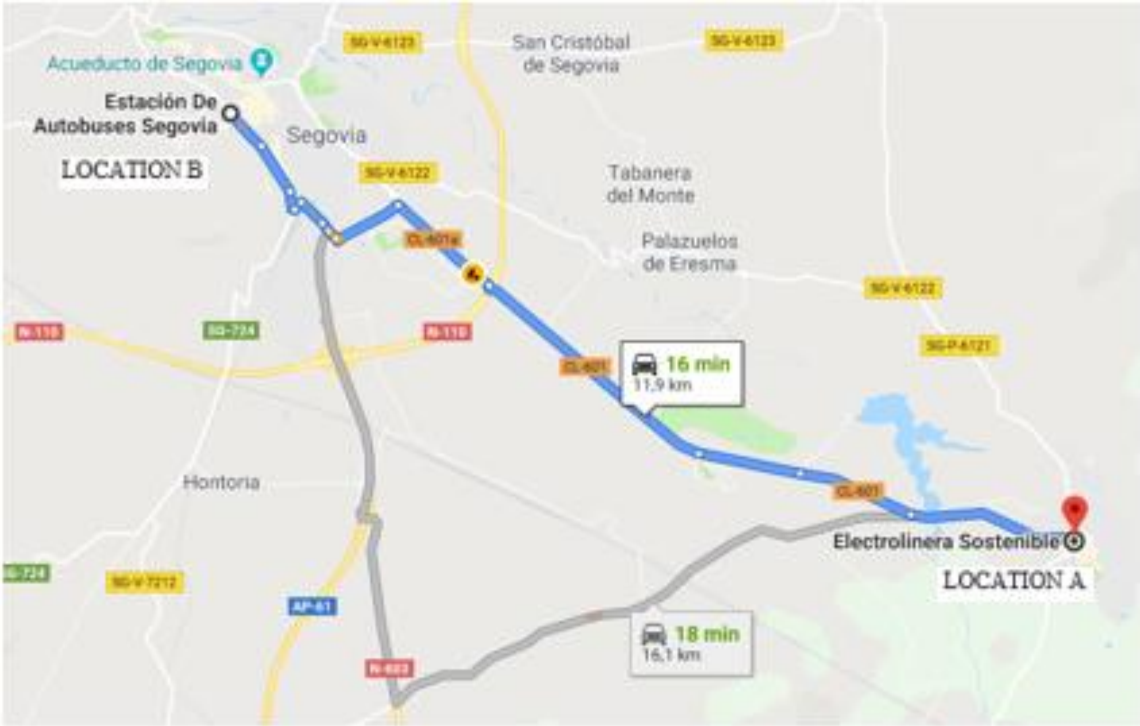

Figure 5: Overview of the route covered by the public bus service. Source: Google Maps

4.2 Electric bus model approaches

In order to try to reduce the CO2 emissions, the possibility of substituting the combustion buses by electric ones, powered by the ECVS shown in the previous chapter, to cover the trips scheduled along this route is analysed.

Different models of electric buses have been analysed to be chosen as the one to carry out this investigation, both from Europe (ZeEUS, 2016) and the rest of the world. The Chinese K9 BYD electric bus model was chosen as it is one of the most widespread models around the world. The electric consumption of this bus is 1.22 kWh/km and its battery capacity is 500 kWh (BYD, no date).

As it can be appreciated in Table 1, there are twenty services of 24 km (including the return trip) between La Granja de San Ildefonso (location A) and Segovia (location B), which supposes a total of 480 km covered per day. Then, the daily consumption for this service is equal to the product of the electric consumption per kilometer and the total distance in km covered per day. The result is a daily demand of 585.6 kWh/day.

In order to create a plan for addressing the bus services scheduled during weekdays between the two locations by electric buses fed by ECVS, three different approaches have been proposed by the author. All these approaches have three elements in common:

1. A photovoltaic supply with two charging points.
2. Two electric buses (B1 and B2) covering the route along the day.
3. Four bus batteries (bI, bII, bIII, and bIV respectively), which can be swapped between the buses depending upon the state of charge (Sarker, Pandžić and Ortega-Vazquez, 2015). In order to swap batteries, the current scheme of the ECVS should be modified with mechanical adjustments, allowing buses for both charging or substituting the battery implemented on them

Particularly, the first model represents the ECVS as its current state (Figure 6), where the grid is present; the second one investigates the role of battery storage on supplying energy to the bus batteries (Figure 7) while the third one seeks to prove the feasibility of supplying the required electricity only by renewable sources and storage (Figure 8).

To provide an overall picture of the functionality of the application proposed, the first electric bus (B1) would start the first trip at 7:30 and the second one (B2) would do it at 8:30. Each of the electric buses B1 and B2 would alternate the trips scheduled. When the initially mounted batteries, bI, and bII, would be depleted, electric buses would substitute them by bIII and bIV. This cycle would be repeated until cover the last trip scheduled over the week.

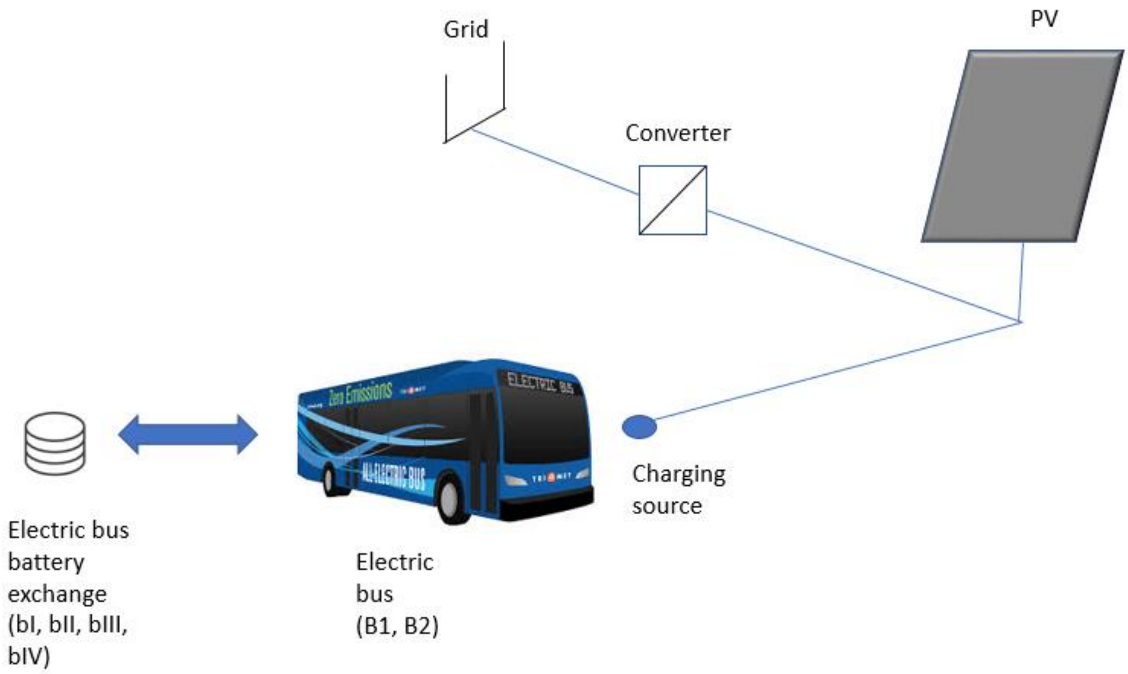

Figure 6: First model approach of the ECVS and the electric buses

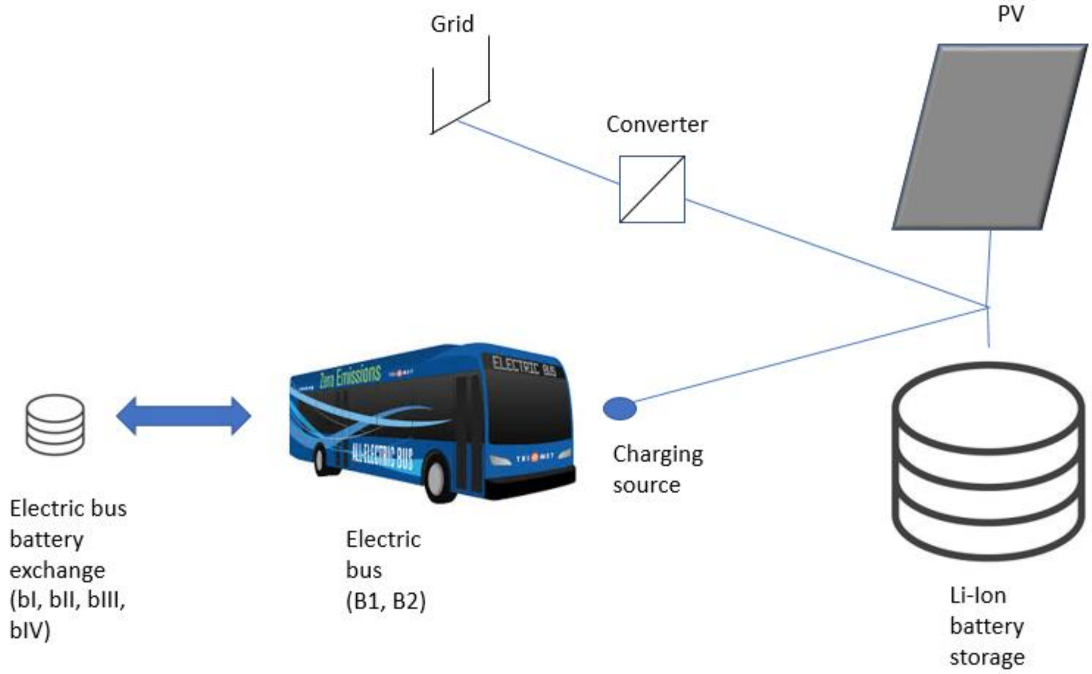

Figure 7: Second model approach of the ECVS and the electric buses

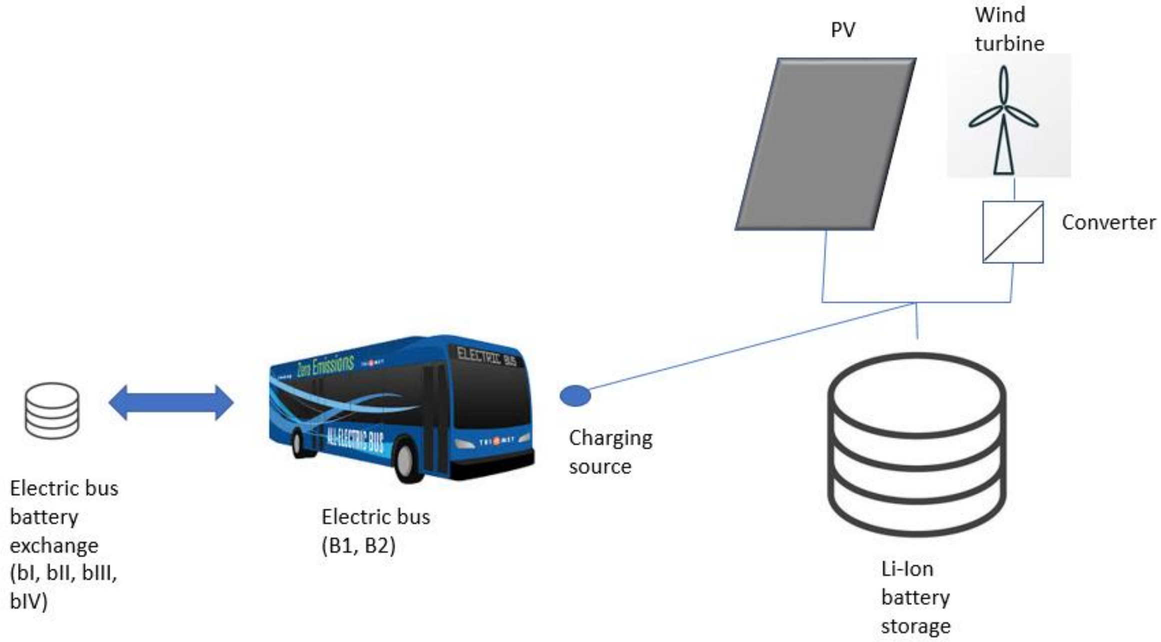

Figure 8: Third model approach of the ECVS and the electric buses

5. HOMER implementation and simulations performed

5.1 Introduction

This chapter presents the method which has been used to model the performance of the electric charging vehicle station (ECVS) and its electric buses.

HOMER has been selected as the software to implement the models explained in the prior chapter. The main reason why this software has been chosen is that this tool permits the user to create a wide range of power systems, using a huge variety of supply sources and different types of loads (Gilman and Lilienthal, 2006). Between the loads that the system is able to model, the presence of a particular variable load has been crucial in the election made by the author. HOMER optimizes the costs and components used in the application modeled so the user can compare easily several combinations of different supply technologies to build up the most cost-effective solution for the problem defined.

As (Lyden, Pepper and Tuohy, 2018) states, within a world where most community services are going to be renewable-based, software modeling becomes crucial to study the potential of different applications. In this case, HOMER is used to model the behavior of an existing facility and the potential improvements that could be added. Simulations about the models devised explained in the prior chapter, showing the current size of the ECVS and the optimal size of it in order to feed the load represented by the electric bus demand. are then performed, providing both technical and economic parameters of the systems designed.

5.2 Simulations performed

In order to implement the models described in the prior chapter in HOMER, several parameters must be introduced within the software interface for modeling each component of each system. General project parameters must also be set in order to run the simulations.

5.2.1 General project parameters of the simulations

- Location: the location of the project has been set where the current ECVS is placed that is La Granja de San Ildefonso, Spain. The cartesian coordinates are 40º 54.1’ N and 4º 0.5’W.

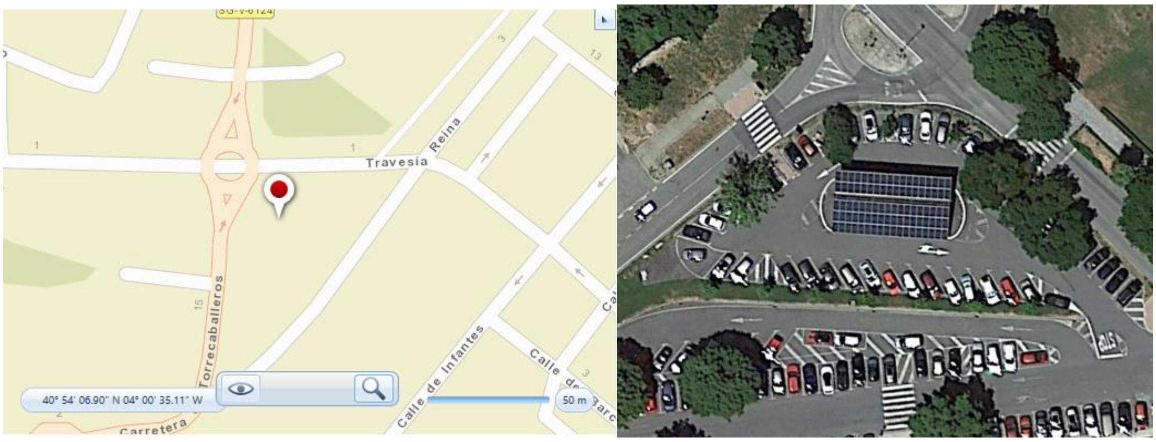

Figure 9: HOMER's project location

- Capacity shortage: 0%. There is no capacity shortage considered as the power installed must ensure the load-serving at the worst situation and at any given moment.
- Annual Interest Rate: 3% (Banco de España, 2019).
- Discount Rate: it is assumed as 8% for this type of renewable investments.
- Project lifetime: 25 years. The project lifetime has been set equal to the lifespan of the PV panels. (Dalton, Lockington and Baldock, 2009).
- Solar global horizontal irradiance: it has been calculated using the NASA database incorporated in HOMER. The scaled annual average for global horizontal irradiance is 4.39 kWh/m^2/day.

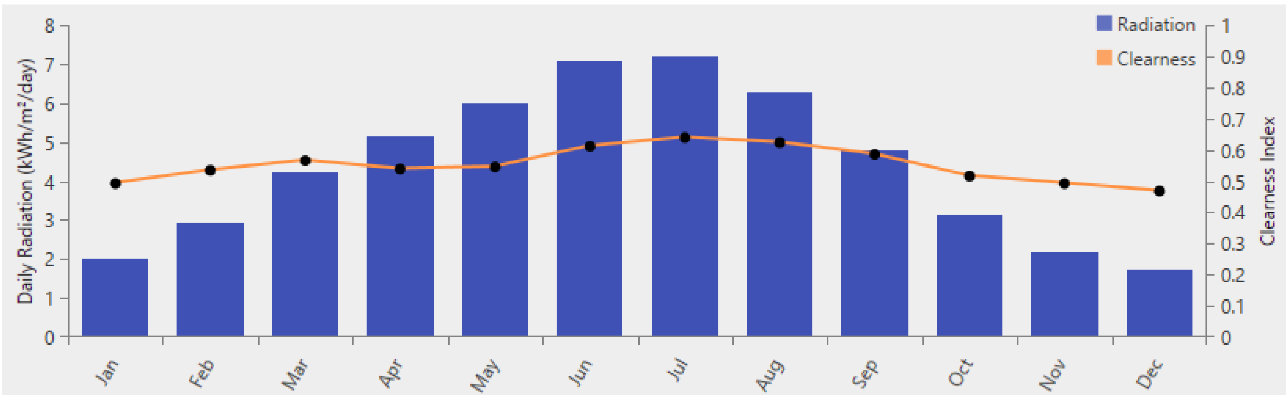

Figure 10: Solar global horizontal irradiance of the project location

- Electric bus demand: the electricity required by the fleet of electric buses has been modeled as a **deferrable load** (Tang *et al.*, 2014) as the storage inherent to the batteries of the electric buses makes the system more flexible in order to supply them.

The main parameters to model a deferrable load in HOMER are the following ones:

-Scaled annual average demand: 585.6 kWh/day. The obtention of this figure has been explained in section 4.2. It is constant throughout the year as it is the number of bus services during weekdays.

-Storage capacity: 2000 kWh. As all the model approaches made by the author have four batteries of the electric bus K9 BYD, and the capacity of one battery is 500 kWh, the total storage to represent four of them is 2000 kWh.

-Peak load: 100 kW. Peak load represents the maximum power that can be supplied to the load at any given time. The ECVS has two fast chargers from EFACEC group. The maximum power that "QC45" EFACEC charger can be provided in DC is 50 kW. As the facility has two of these fast chargers, the peak load is 100 kW (Efacec, 2017).

-Minimum load ratio: 0%. It represents the minimum power that can serve the deferrable load. Author assumption is to consider it as 0% as the four batteries of the electric buses that represent the load, could be empty at some point and not work.

5.2.2 System 1a simulation parameters

System 1a represents the ECVS at its current situation. PV power and inverter capacity as set as constant in order to represent it. The following parameters are required to model the situation described:

- PV specifications:

-Rated power: 28.8 kW

-Price of panel per kW: $678.5 /kW (ELECNOR, 2017)

-Operational and maintenance cost of PV panels: $10/year/kW (Fthenakis, Mason and Zweibel, 2009)

- Lifetime of the panels: 25 years (Dalton, Lockington and Baldock, 2009)

-Derating factor: 80% (Marion *et al.*, 2005). It represents the effect of dust, wiring losses and other loses that can make the efficiency of the PV panel to decrease.

- Inverter specifications:

-Inverter capacity: 33 kW (33-45 kW Input DC, 33 kW Output DC) (Ingeteam Power Technology S.A, no date)

-Price of inverter: $500/kW (Fthenakis, Mason and Zweibel, 2009)

-Operational and maintenance cost of inverter: $5/kW (Demiroren and Yilmaz, 2010)

-Lifetime of the inverter: 15 years (Demiroren and Yilmaz, 2010)

-Inverter efficiency: 90% (Demiroren and Yilmaz, 2010)

- Grid:

-Electricity price for commercial use (Spanish annual average 2018): $0.163/kWh (REE, 2019)

-Price of excess electricity sold to the grid: $0.06 /kWh (REE, 2019)

-GHG emissions of the grid: 253g CO_2 e/kWh (*electricityMap | Emisiones de CO2 del consumo eléctrico en tiempo real*, 2019)

5.2.3 System 1b simulation parameters

System 1b seeks to get the optimized size of the PV plant for the current approach of the ECVS. In other words, this simulation looks for getting the maximum power output of photovoltaics without adding any new elements the ECVS. The following parameters are required to model the situation described:

- PV specifications:

-Rated power: HOMER Optimizer used to find the best size.

-Price of panel per kW: $678.5 /kW (ELECNOR, 2017)

-Operational and maintenance cost of PV panels: $10/year/kW (Fthenakis, Mason and Zweibel, 2009)

- Lifetime of the panels: 25 years (Dalton, Lockington and Baldock, 2009)

-Derating factor: 80% (Marion *et al.*, 2005).

- Inverter specifications:

-Inverter capacity: HOMER Optimizer used to find the best size.

-Price of inverter: $500/kW (Fthenakis, Mason and Zweibel, 2009)

-Operational and maintenance cost of inverter: $5/kW (Demiroren and Yilmaz, 2010)

-Lifetime of the inverter: 15 years (Demiroren and Yilmaz, 2010)

-Inverter efficiency: 90% (Demiroren and Yilmaz, 2010)

- Grid:

-Electricity price for commercial use (Spanish annual average 2018): $0.163/kWh (REE, 2019)

-Price of excess electricity sold to the grid: $0.06 /kWh (REE, 2019)

-GHG emissions of the grid: 253g CO_2 e/kWh (*electricityMap | Emisiones de CO2 del consumo eléctrico en tiempo real*, 2019)

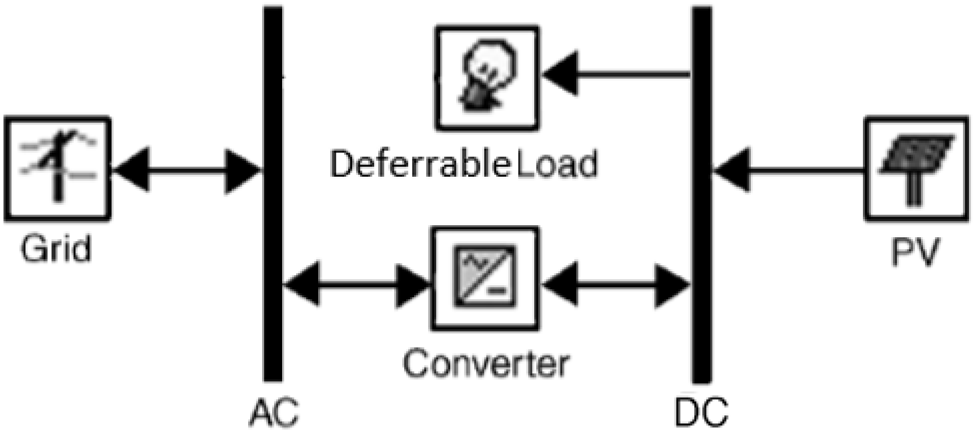

Figure 11: HOMER design of Systems 1a and 1b

5.2.4 System 2a simulation parameters

System 2a seeks to analyse the role of adding an optimized Li-Ion battery to the current ECVS. PV power and inverter capacity as set as constant in order to represent it. The following parameters are required to model the situation described:

- PV specifications:

-Rated power: 28.8 kW

-Price of panel per kW: $678.5 /kW (ELECNOR, 2017)

-Operational and maintenance cost of PV panels: $10/year/kW (Fthenakis, Mason and Zweibel, 2009)

- Lifetime of the panels: 25 years (Dalton, Lockington and Baldock, 2009)

-Derating factor: 80% (Marion *et al.*, 2005).

- Inverter specifications:

-Inverter capacity: 33 kW (33-45 kW Input DC, 33 kW Output DC) (Ingeteam Power Technology S.A, no date)

-Price of inverter: $500/kW (Fthenakis, Mason and Zweibel, 2009)

-Operational and maintenance cost of inverter: $5/kW (Demiroren and Yilmaz, 2010)

-Lifetime of the inverter: 15 years (Demiroren and Yilmaz, 2010)

-Inverter efficiency: 90% (Demiroren and Yilmaz, 2010)

- Storage specifications: a generic 100 kWh Li-Ion battery included in HOMER's library has been used for the academic purpose of this research. This type of batteries e is one of the most widely used around the world.

-Nominal capacity: HOMER Optimizer used to find the best string of batteries.

-Nominal voltage: 600 V

-Lifetime: 25 years

-Capital: $70,000

-Replacement: $70,000

-Operational and maintenance cost Li-Ion battery: $1000/year

- Grid:

-Electricity price for commercial use (Spanish annual average 2018): $0.163/kWh (REE, 2019)

-Price of excess electricity sold to the grid: $0.06 /kWh (REE, 2019)

-GHG emissions of the grid: 253g CO_2 e/kWh (*electricityMap | Emisiones de CO2 del consumo eléctrico en tiempo real*, 2019)

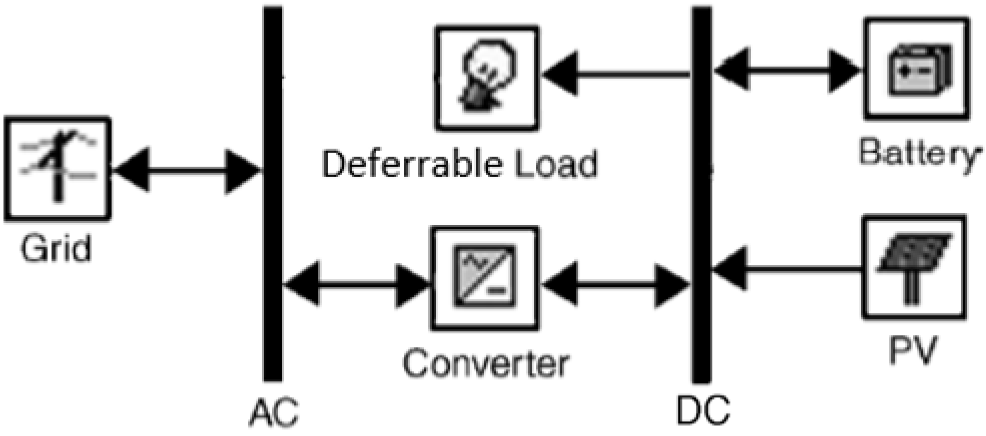

Figure 12: HOMER design of Systems 2a and 2b

5.2.5 System 2b simulation parameters

System 2b seeks to get the optimized size of the PV plant and inverter for the of the case in which the ECVS would have an Li-Ion storage, which size is optimized too, incorporated. The following parameters are required to model the situation described:

- PV specifications:

-Rated power: HOMER Optimizer used to find the best size.

-Price of panel per kW: $678.5 /kW (ELECNOR, 2017)

-Operational and maintenance cost of PV panels: $10/year/kW (Fthenakis, Mason and Zweibel, 2009)

- Lifetime of the panels: 25 years (Dalton, Lockington and Baldock, 2009)

-Derating factor: 80% (Marion *et al.*, 2005)

- Inverter specifications:

-Inverter capacity: HOMER Optimizer used to find the best size.

-Price of inverter: $500/kW (Fthenakis, Mason and Zweibel, 2009)

-Operational and maintenance cost of inverter: $5/kW (Demiroren and Yilmaz, 2010)

-Lifetime of the inverter: 15 years (Demiroren and Yilmaz, 2010)

-Inverter efficiency: 90% (Demiroren and Yilmaz, 2010)

- Storage specifications: a generic 100 kWh Li-Ion battery included in HOMER's library has been used for the academic purpose of this research. This type of batteries is one of the most widely used around the world.

-Nominal capacity: HOMER Optimizer used to find the best string of batteries.

-Nominal voltage: 600 V

-Lifetime: 25 years

-Capital: $70,000

-Replacement: $70,000

-Operational and maintenance cost Li-Ion battery: $1000/year

- Grid:

-Electricity price for commercial use (Spanish annual average 2018): $0.163/kWh (REE, 2019)

-Price of excess electricity sold to the grid: $0.06 /kWh (REE, 2019)

-GHG emissions of the grid: 253g CO_2 e/kWh (*electricityMap | Emisiones de CO2 del consumo eléctrico en tiempo real*, 2019)

5.2.6 System 3 simulation parameters

The last system devised, System 3, seeks to illustrate the capability of powering the whole fleet of electric buses by renewables. A wind turbine has been added to generate electricity in those moments where there exists a lack of sun. HOMER optimizer has been used to calculate the size of the required PV plant, inverter, Li-Ion battery storage and wind turbine. The following parameters are required to model the situation described:

- PV specifications:

-Rated power: HOMER Optimizer used to find the best size.

-Price of panel per kW: $678.5 /kW (ELECNOR, 2017)

-Operational and maintenance cost of PV panels: $10/year/kW (Fthenakis, Mason and Zweibel, 2009)

- Lifetime of the panels: 25 years (Dalton, Lockington and Baldock, 2009)

-Derating factor: 80% (Marion *et al.*, 2005)

- Inverter specifications:

-Inverter capacity: HOMER Optimizer used to find the best size.

-Price of inverter: $500/kW (Fthenakis, Mason and Zweibel, 2009)

-Operational and maintenance cost of inverter: $5/kW (Demiroren and Yilmaz, 2010)

-Lifetime of the inverter: 15 years (Demiroren and Yilmaz, 2010)

-Inverter efficiency: 90% (Demiroren and Yilmaz, 2010)

- Wind turbine specifications: a generic wind turbine included in HOMER's library has been used for the academic purpose of this research.

-Rated power: HOMER Optimizer used to find the best size.

-Hub height: 17 m

-Lifetime: 25 years

-Capital: $18,000

-Replacement: $18,000

-Operational and maintenance cost of the wind turbine: $180/year

- Storage specifications: a generic Li-Ion battery included in HOMER's library has been used for the academic purpose of this research. This type of batteries is one of the most widely used around the world.

-Nominal capacity: HOMER Optimizer used to find the best string of batteries.

-Nominal voltage: 600 V

-Lifetime: 25 years

-Capital: $70,000

-Replacement: $70,000

-Operational and maintenance cost Li-Ion battery: $1000/year

- Grid:

-Electricity price for commercial use (Spanish annual average 2018): $0.163/kWh (REE, 2019)

-Price of excess electricity sold to the grid: $0.06 /kWh (REE, 2019)

-GHG emissions of the grid: 253g CO_2 e/kWh (*electricityMap | Emisiones de CO2 del consumo eléctrico en tiempo real*, 2019)

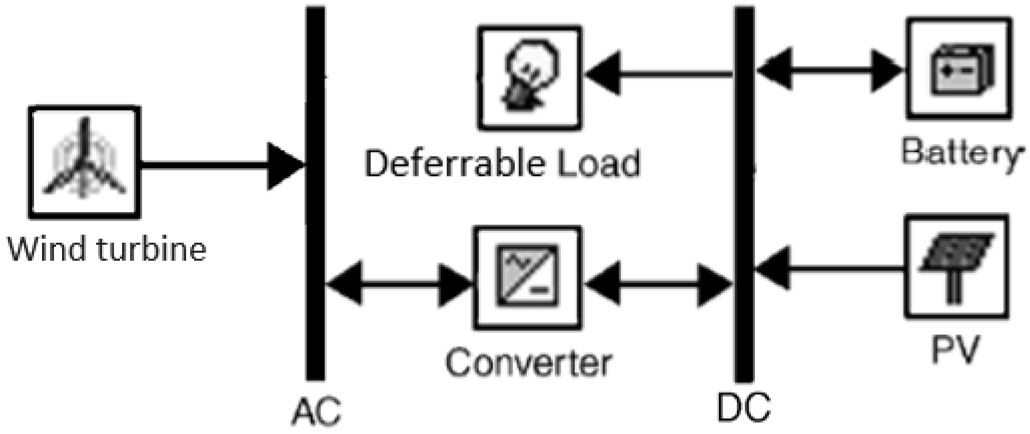

Figure 13: HOMER design of System 3

5.3 Main output results

This section introduces the theory about the parameters analysed in the following chapter.

5.3.1 Techno-economic parameters

On the one hand, the main technical parameters analyzed depend on the system considered:

- For the system 1a, total energy purchased from the grid and PV power produced to feed the load are studied.
- For the system 1b, the rated power of the optimized PV plant and its production, as well as total energy purchased from and sold to the grid are studied.
- For the system 2a, total energy purchased from the grid and PV power produced to feed the load are studied as well as the size of the storage and the state of charge of it.
- For the system 2b, the rated power of the optimized PV plant, the total energy purchased from and sold to the grid, and PV power produced to feed the load are studied, as well as the size of the storage and the state of charge of it.
- For the system 3, the rated power of the optimized PV plant and wind turbine, the PV and wind power produced to feed the load are studied, as well as the size of the storage and the state of charge of it.

On the other hand, the following economic parameters provided by HOMER are analysed:

- Net Present Cost, NPC ($): From (Gilman and Lilienthal, 2006), "total NPC condenses all the costs and revenues that occur within the project lifetime into one lump sum in today's dollars, with future cash flows discounted back to the present using the discount rate. The modeler specifies the discount rate and project lifetime. The NPC includes the costs of initial construction, component replacements, maintenance, fuel, plus the cost of buying power from the grid and miscellaneous costs such as penalties resulting from pollutant emissions. Revenues include income from selling power to the grid, plus any salvage value that occurs at the end of the project lifetime. With the NPC, costs are positive and revenues are negative."
- Cost of energy, COE ($/kWh): HOMER divides all the expenses of the system by the energy generated for each system simulated.
- Initial investment and operating costs ($) of each system.
- Renewable Fraction, RF (%): it represents the portion of renewable energy that serves the load. It constitutes a confusing value as HOMER algorithm also considers the sales made from the renewable sources to the grid within this percentage.
- Carbon Emissions Intensity, CEI (kgCO2/kWh): HOMER calculates the total CO2 emissions per kWh of each system depending on the carbon intensity of the grid set as an input parameter.
- Total annualized cost, TAC ($): HOMER divides the total cost of each component, including maintenance, replacement, and other expenses along with their entire operation by the project lifetime.

5.3.2 Feasibility of electric buses for covering scheduled trips by swapping batteries strategy.

A qualitative strategy of dispatching considering the day-ahead strategy (Sarker, Pandžić and Ortega-Vazquez, 2015) has been devised in order to ensure that the electric buses complete their trip between locations A and B. Deferrable load served daily profile graphs, which are provided by HOMER, are read as the state of charge of the four electric batteries. To plan the trips done by the electric buses, a directly proportional relationship between the electric bus range and the battery level is considered. Considering the specifications for the electric bus proposed (BYD, no date), the relation is presented as follows:

$$y = 410 * x$$

Where:

y – range in km that the electric bus is able to cover.

x – the state of charge of the battery. Its values are comprised between 0 and 1. They can be read from the “deferrable daily profile served” graphs.

410 – it is the constant of proportionality between “y” and “x”. It represents the maximum range in km that an electric bus can cover, taking place when the battery of the bus is at its fully charged.

After getting “y” through the equation stated above, and using the distance of the route A-B-A, which is 22 km, the number of trips that an electric bus is able to complete is calculated:

$$n = y/24$$

Where:

n – number of trips that the bus can complete given a range depending upon the state of charge.

y – range in km that the electric bus is able to cover for a given state of charge of its battery.

1/22- it is the constant of proportionality between “n” and “y”. 22 km is the distance to complete an entire route between A and B.

Finally, the state of charge of the batteries after completing “n” trips is calculated:

$$s = \left(\frac{y - 24 * n}{410}\right) * 100$$

Where:

s– the percentage of battery after completing “n” trips.

y – range in km that the electric bus is able to cover for a given state of charge of its battery.

n – number of trips that the bus can complete given a range depending upon the state of charge.

6. Results and discussion

6.1 Introduction

This chapter shows the main outcomes found by carrying out the different simulations in HOMER. First, figures about the costs of each model along with carbon emissions are put in contrast. After that, the load results, representing the electricity demand of electric buses are presented and discussed according to a potential dispatch strategy.

6.2 Techno-economic results

6.2.1 System 1a, Grid-Current PV-BEV

This system represents the current situation of the ECVS. 28.8 kW of photovoltaics are installed along with the converter of 33 kW.

HOMER results show that the initial costs are practically split equally into the panels and the inverter. However, from the global analysis of the system, the greatest cost is the one that electricity bought from the grid represents. This accounts for $415,504, which supposes 89% of the total NPC. Serving the electricity required by the buses with a configuration like this would result in a massive payment to the Spanish National Grid.

Table 3: Techno-economic results of System 1a

Component	Capacity (kW)	Initial capital ($)	TAC ($)	Total NPC ($)
PV	28.8	19,540	1,654	23,659
Grid	250	0	29,052	415,504
Converter	33	16,500	1,767	25,282
System 1a	311.8	36,040	32,473	464,445

Figure 14 shows that apart from the time frame between 12:00 and 18:00, about 30 kW are purchased from the grid each hour of the year to satisfy the electric demand.

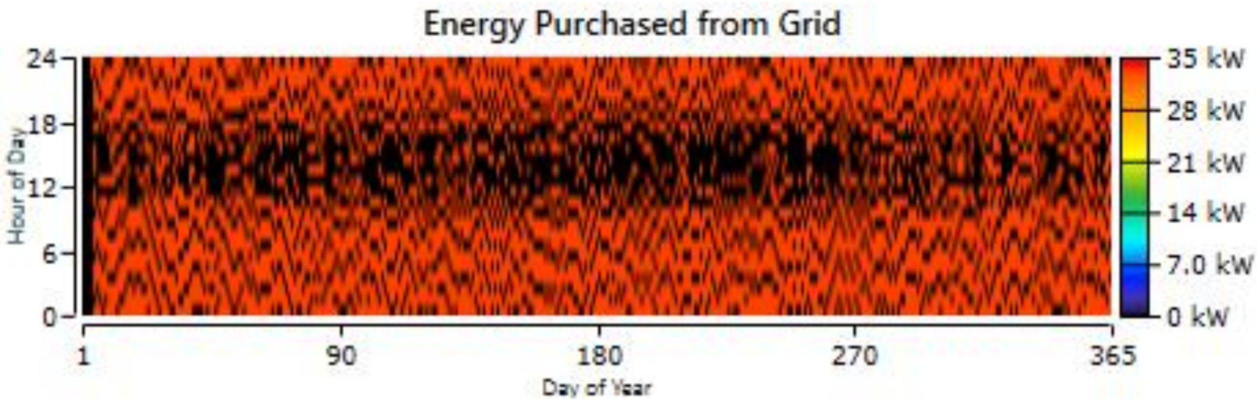

Figure 14: Energy Purchased from the grid of System 1a

Between 12:00 and 18:00, PV panels produce from 12 to 25 kW approximately every hour during the first nine months of the year.

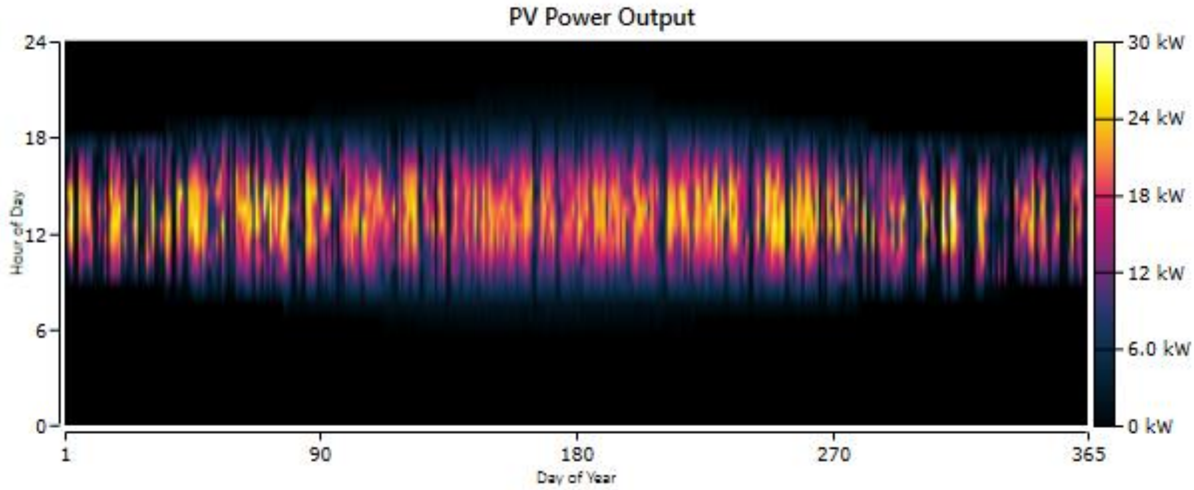

Figure 15: PV Power Output of System 1a

6.2.2 System 1b, Grid-Optimal PV-BEV

This result of applying the HOMER optimizer to the size of the PV plant and converter of the ECVS show that a total of 174 kW of PV and a 23.9 kW converter would optimize the costs of the plant. 174 kW of PV would suppose to multiply the size of the current PV plant about six times.

HOMER results show that although the initial investment of PV panels is elevated in comparison with the connection to the grid, that it is zero, there is not many more expenses during the operation of the system. Even though the total annualized cost, TAC of the grid is

$470,86, the total net present cost is much less due to the exports of electricity that the PV plant makes to the grid.

Table 4: Techno-economic results of System 1b

Component	Capacity (kW)	Initial capital ($)	TAC ($)	Total NPC ($)
PV	174	118,274	10,012	143,205
Grid	250	0	470,86	6,734
Converter	23.9	11,930	1,278	18,279
System 1b	447.9	130,204	11,290	168,218

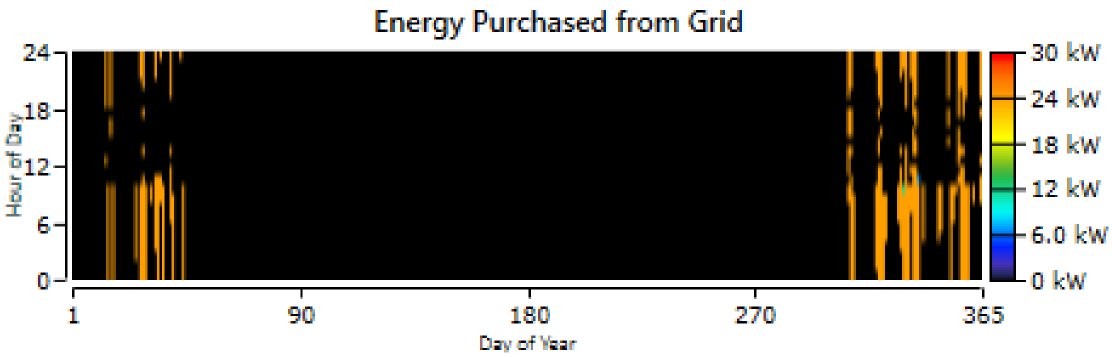

Figure 16: Energy Purchased from the grid of System 1b

In this case, about 25 kW are purchased from the grid during the hours with less sun irradiance in winter, while almost every single year, the PV plant exports electricity to the grid, achieving a constant sold rate of 22 kW during the sunny hours of the day at spring and summer.

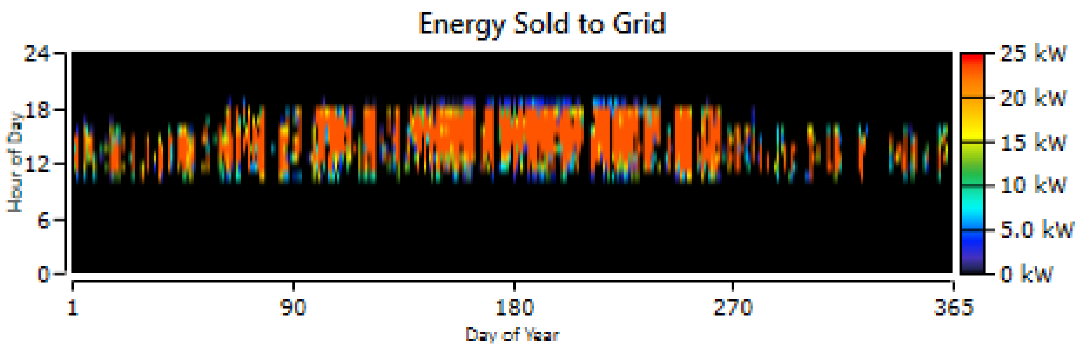

Figure 17: Energy Sold to the grid of System 1b

Between 12:00 and 18:00, PV panels produce from 80 to 170 kW approximately every hour of the year. PV production gets reduced during wintertime when sunny time is reduced.

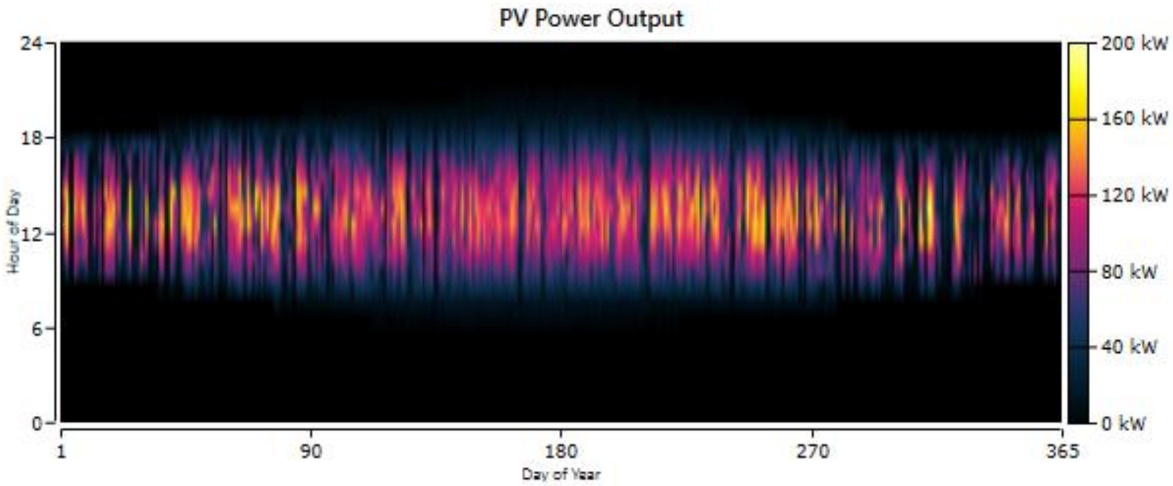

Figure 18: PV Power Output of System 1b

6.2.3 System 2a, Grid-Current PV-Battery-BEV

This result of applying the HOMER optimizer to the size of a Li-Ion battery for the current 28.8 kW photovoltaic ECVS are presented here.

The addition of a 100 kWh battery supposes an enormous cost to the system. Moreover, the expenses on purchasing electricity from the grid still continue being massive. This is because, even though the storage is added, the small size of the current PV plant makes impossible to have a surplus of photovoltaic energy to be stored.

Table 5: Techno-economic results of System 2a

Component	**Capacity**	**Initial capital ($)**	**TAC ($)**	**Total NPC ($)**
PV	28.8 kW	19,541	1,654	23,660
Grid	250 kW	0	29,210.80	415,343
Battery	100 kWh	70,000	7,799	111,548
Converter	33 kW	16,500	1,768	25,282
System 2a	-	106,041	40,432	575,833

As in the case of system 1a, Figure shows that apart from the time frame between 12:00 and 18:00, about 30 kW are purchased from the grid each hour of the year to satisfy the electric demand.

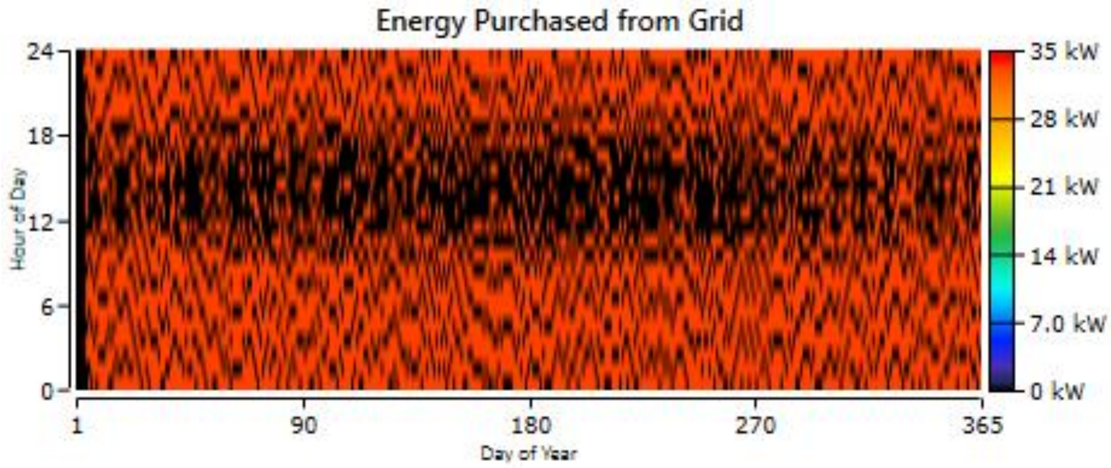

Figure 19: Energy Purchased from the grid of System 2a

As in the case of system 1a. between 12:00 and 18:00, PV panels produce from 12 to 25 kW approximately every hour during the first nine months of the year. During the last months of the year, a reduction in the PV can be appreciated.

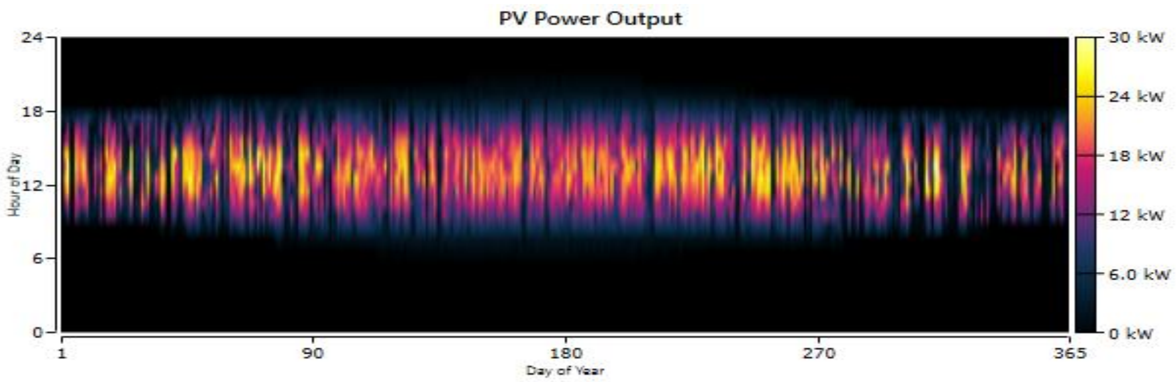

Figure 20: PV Power Output of System 2a

The storage level shows that the battery starts fully charged and, when the power is transmitted to the load on the first day, it never again gets charged. As it is mentioned above, the PV plant is so small that is not able to charge the storage. Moreover, an important amount of electricity must be purchased from the grid in order to supply the load. Therefore, the $111,548 spent on the 100 kWh Li-Ion battery constitutes a pointless investment for such a small PV plant. This system would never become reality.

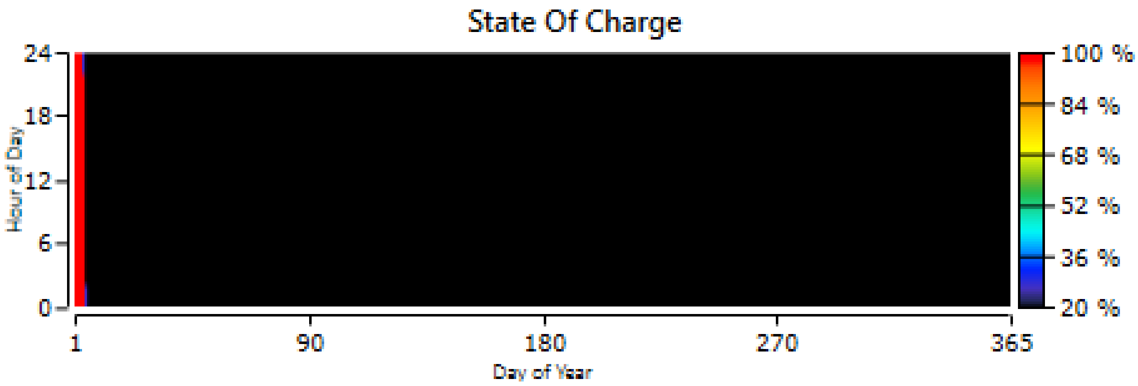

Figure 21: Li-Ion battery state of charge of system 2a

6.2.4 System 2b, Grid-Optimal PV-Battery-BEV

This result of applying the HOMER optimizer to the size of the PV plant, converter and a Li-Ion Battery of the ECVS show that a total of 172 kW of PV capacity, a 22.9 kW converter and a 100 kWh would put together the plant. 172 kW of PV would mean to multiply the size of the current PV plant about six times.

Both PV plant and Li-Ion battery constitute the major expenses of the system. PV and battery NPC accounts for 51% and 40% respectively of the total.

Table 6: Techno-economic results of System 2b

Component	**Capacity**	**Initial capital ($)**	**TAC ($)**	**Total NPC ($)**
PV	172 kW	116,418.35	9,855.84	140,957.97
Grid	250 kW	0	501.33	7,169.95
Battery	100 kWh	70,000	7,799.47	111,547.80
Converter	22.9 kW	11,435.25	1,225.12	17,521.63
System 2b	-	197,853.60	19,381.76	277,197.35

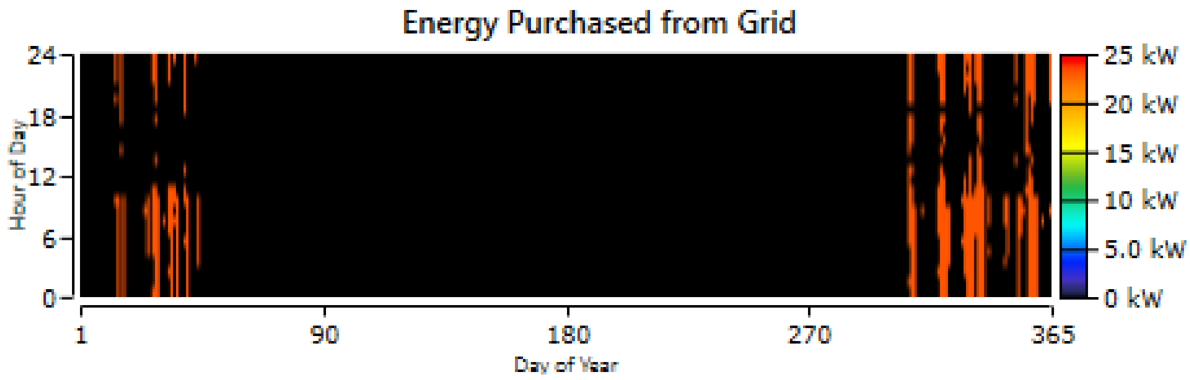

Figure 22: Energy Purchased from the grid of System 2b

In this case, as in system 1b , about 25 kW are purchased from the grid during the hours with less sun irradiance in winter, while almost every single year, the PV plant exports electricity to the grid, achieving a constant sold rate of 22 kW during the sunny hours of the day at spring and summer.

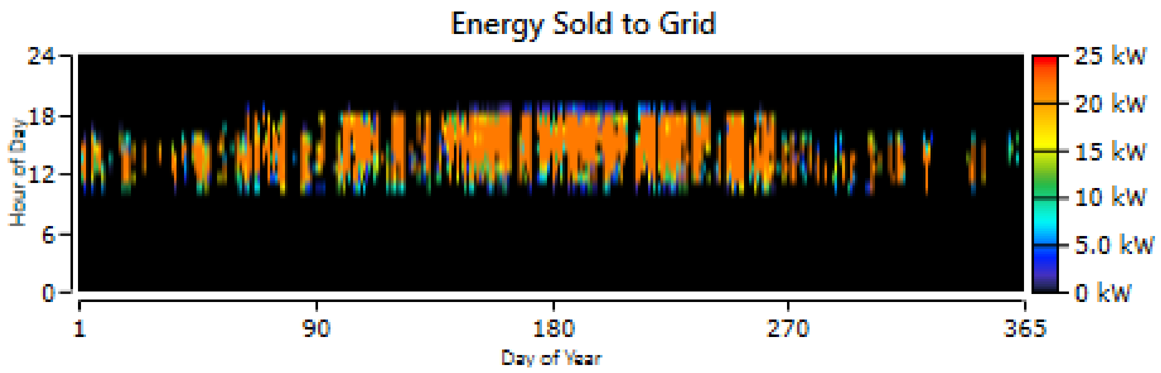

Figure 23: Energy Sold to the grid of System 2b

Again, PV panels produce between 120 and 170 kW during day time.

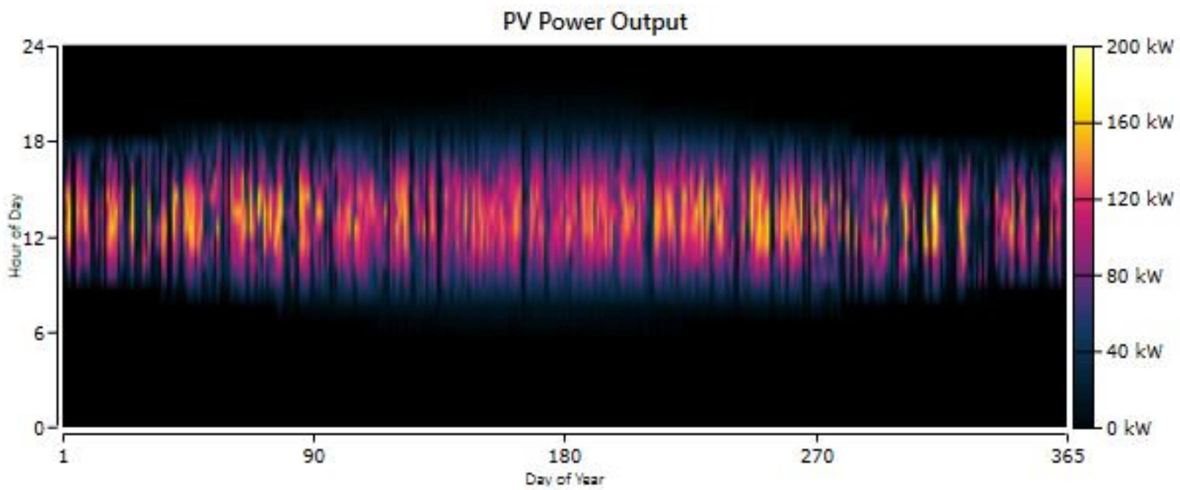

Figure 24: PV Power Output of System 2b

When it comes to analyzing the role of Li-Ion battery storage in this system, it can be appreciated from the figure that, it starts fully charged and its energy is used few days in January/February. Then the battery gets fully charged again until the end of the year when there are fewer hours of solar irradiance, and energy stored is used again. The main reason for the misuse of the storage during so many hours through the year is because, as the parameters have been set, HOMER optimizer makes the PV plant prioritize to bulk the majority of the electricity to the deferrable load, that can be charged at any time during the day, during times of maximum PV production.

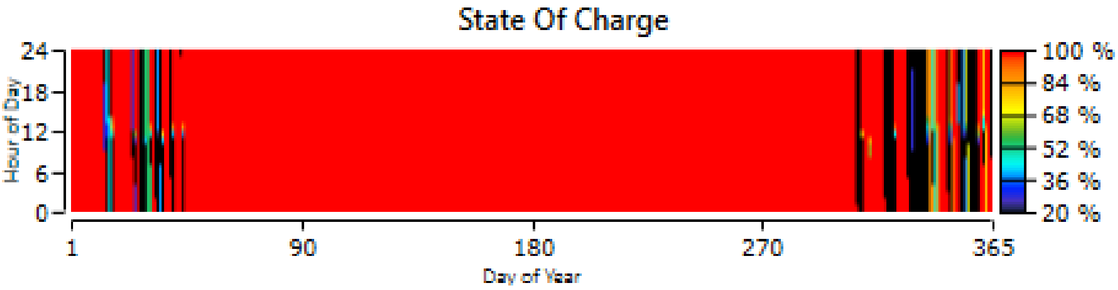

Figure 25: Li-Ion battery state of charge of system 2b

6.2.5 System 3, Optimal PV-Wind turbine-Battery-BEV

This system is the result of applying the HOMER optimizer to the size of the PV plant, converter, and a wind turbine. Results show that, in order to supply the defined demand only by renewable technologies, 344 kW of PV panels, a 9 kW wind turbine, a 100 kWh Li-Ion battery, and a converter of 1.35 kW would be the optimal solution. 344 kW of PV means to multiply the size of the current PV plant about twelve times. However, implementing this system results in acquiring a much smaller converter, so the expenses derived from this component are lower in comparison with the rest of the cases.

This size of PV plant would require an important initial investment of $233,066.15. Li-Ion battery and the wind turbine are considerable too.

Table 7: Techno-economic results of System 3

Component	Capacity	Initial Capital ($)	TAC ($)	Total NPC ($)
PV	344 kW	233,066.15	19,731.00	282,193.75

Wind Turbine	9 kW	54,000	4,913.00	70,265.93
Battery	100 kWh	70,000	7,799.47	111,547.80
Converter	1.35 kW	676	72.44	1,036.00
System 3	-	357,742.29	32,515.91	465,043.48

The PV power output of the plant fluctuates between 160 kW to 330 kW between 10:00 to 18:00. Again, a recess during wintertime can be appreciable.

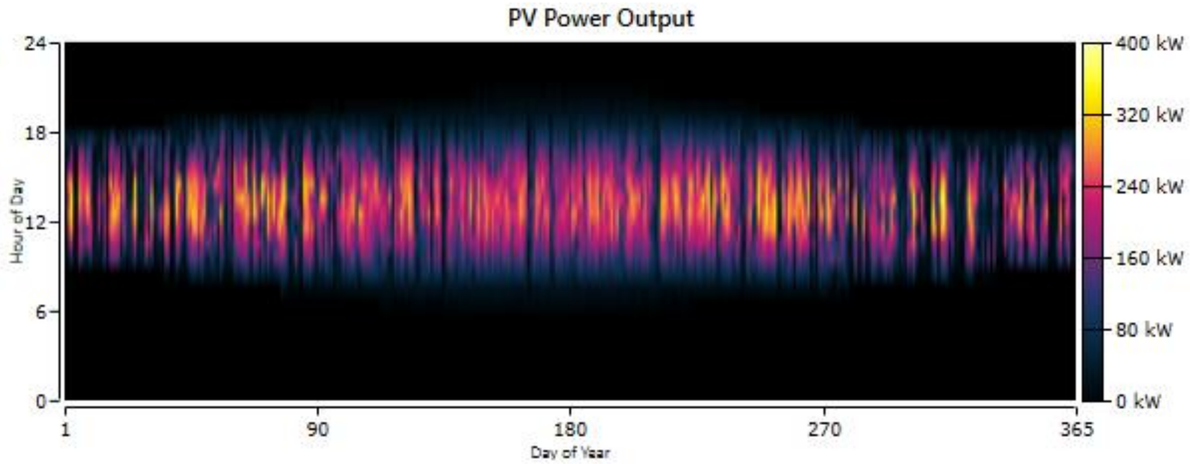

Figure 26: PV Power Output of System 3

Wind power output is very random and does not follow any pattern. Its main purpose is to act as a supplementary renewable source to the PV panels during the hours of less sun irradiance.

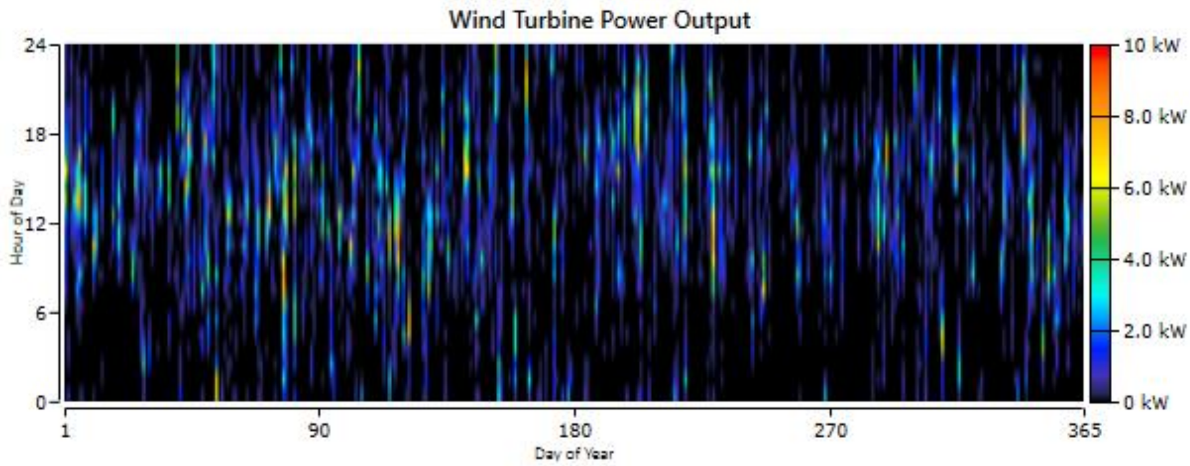

Figure 27: Wind Turbine Power Output of System 3

Again, the battery remains charged always, so its purpose is null. This occurs for the reason explained above: as the load is defined as deferrable, it has a storage capacity inherent to it, so the power is always transmitted to the load instead of the Li-Ion battery.

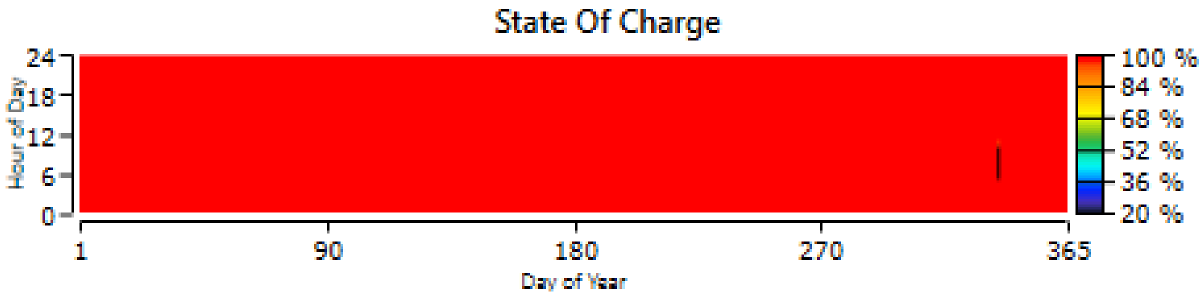

Figure 28: Li-Ion battery state of charge of system 3

6.2.6 Overall comparative of the systems

The first issue to be analyzed, due to the surprising character of the results, is the role of storage. Li-Ion battery increments the overall cost of all systems where it has been considered and have no action either in system 2a nor 3, while its contribution to 2b is minimum.

When referring to the NPC, the cheapest systems are 1b and 2b, the ones which size of PV power has been optimized with HOMER and are connected to the grid. Cost of energy (COE) and Operating cost values also match this pattern (Table 8).

Powering electric buses with a supply system as the one that ECVS has now (system 1a) means spending a massive amount of money, 415,000 $ through the lifetime of the project; while doing it with an optimized sized of the rated capacity of PV, 174 kW , supposes a NPC almost three times smaller than the one of the current system.

Apart from that, another comparison that is worth to be made is that, if the current situation of the ECVS, system 1a, was not built yet, the full renewable one would have an NPC $1423 cheaper.

Considering that the initial investment of system 1a is already done, and taking into account that it makes no sense to substitute the bigger inverter already installed in system 1a for the smaller proposed in system 3; the initial investment to bigger the plant to the one proposed in system 3 would be the subtraction of $357,742.29 (initial investment of system 3) and 19,540 (cost of the panels installed in system 1a), in other words, $338,202.29. Considering now the annual cost of electricity purchased from the grid in system 1a, $29,052, it would take 11.64 years to redeem the investment of evolving the system from 1a to 3. Keeping in mind that the first one emits 45,093 kg CO2/kWh and the renewable one emits 0 (excluding the emissions of manufacturing PV panels and wind turbine, only operation of the plant is considered), it would be sustainably and economically (life of the project is 25 years) worthy to move from the current state to the 100% renewable.

Another aspect to put attention into is the renewable fraction (RF). On the one hand, systems 1a and 2a, where the PV capacity is fixed as the current one, have a renewable fraction of 19.2%. So, powering the electric buses with this type of systems would produce 45,093 kg CO2/kWh. On the other hand, systems 1b and 2b, which PV capacity is much greater, have a renewable fraction of 95.3%. It must be pointed out that, this percentage includes the power that the PV panels of these systems sell to the grid, so the value of renewable fraction that is transmitted to the electric buses would be presumably a little bit smaller. At any case, powering the electric buses with this type of systems would emit 3,195 kg CO2/kWh approximately. Finally, the cleanest way to power the electric buses is system 3, which have a renewable fraction of 100 %, so the electric buses would operate without emitting any CO2 to the atmosphere (excluding the manufacturing process of the PVs, wind turbine and electric buses).

Table 8:Overall comparative between all the systems modeled

System	Total NPC ($)	COE ($/kWh)	Operating cost ($)	RF(%)	CEI (kgCO2/kWh)
1a, Grid-Current PV-BEV	466,466	0.1534	29,954.0	19.2	45,093.0
1b, Grid-Optimal PV-BEV	168,219	0.04928	2,658.0	95.3	3,195.0
2a, Grid-Current PV-Battery-BEV	575,833	0.1901	32,848.0	19.2	45,076.0
2b, Grid-Optimal PV-Battery-BEV	277,197	0.08241	5,547.8	95.5	2,978.0
3, Optimal PV-Wind turbine-Battery-BEV	465,043	0.1529	7,502.0	100.0	0.0

6.3 Feasibility of electric buses for covering scheduled trips by swapping batteries strategy.

It must be pointed out that the percentage shown on the daily profile graphs of deferrable load served represents the storage of the four electric bus batteries (bI,bII, bIII, bIV respectively) modeled as input previously. Then, the state of charge of the batteries would vary depending on the number of batteries connected at a certain time. In this case, as all the charging facilities have been modeled with two charging points, only two batteries could be charged at the same moment. To illustrate it, a 5% of deferrable served means that two batteries are charged to 10% as the graph shows the percentage for the whole set of four batteries but the physical constraint defined imposes that only two of them can be used to coordinate the strategy of dispatching. The last assumption by made the author, in order to ease the coordination of the bus services, is that the batteries are always swapped in couples, meaning that a single battery “bi” cannot be substituted unless another one “bii” is swapped too.

6.3.1 System 1a and System 2a

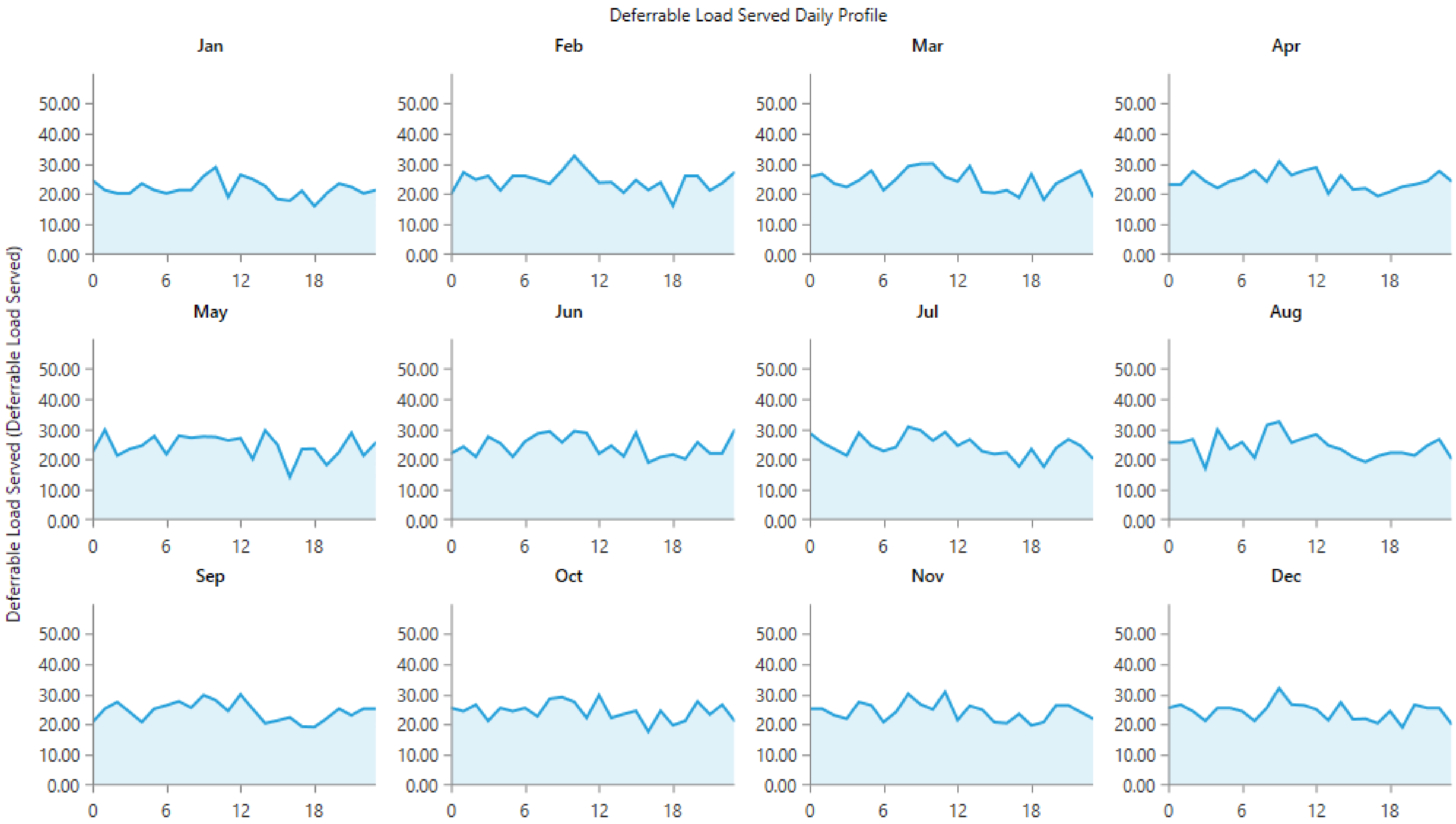

Figure 29: Battery Charging Load Served Daily Profile of System 1a

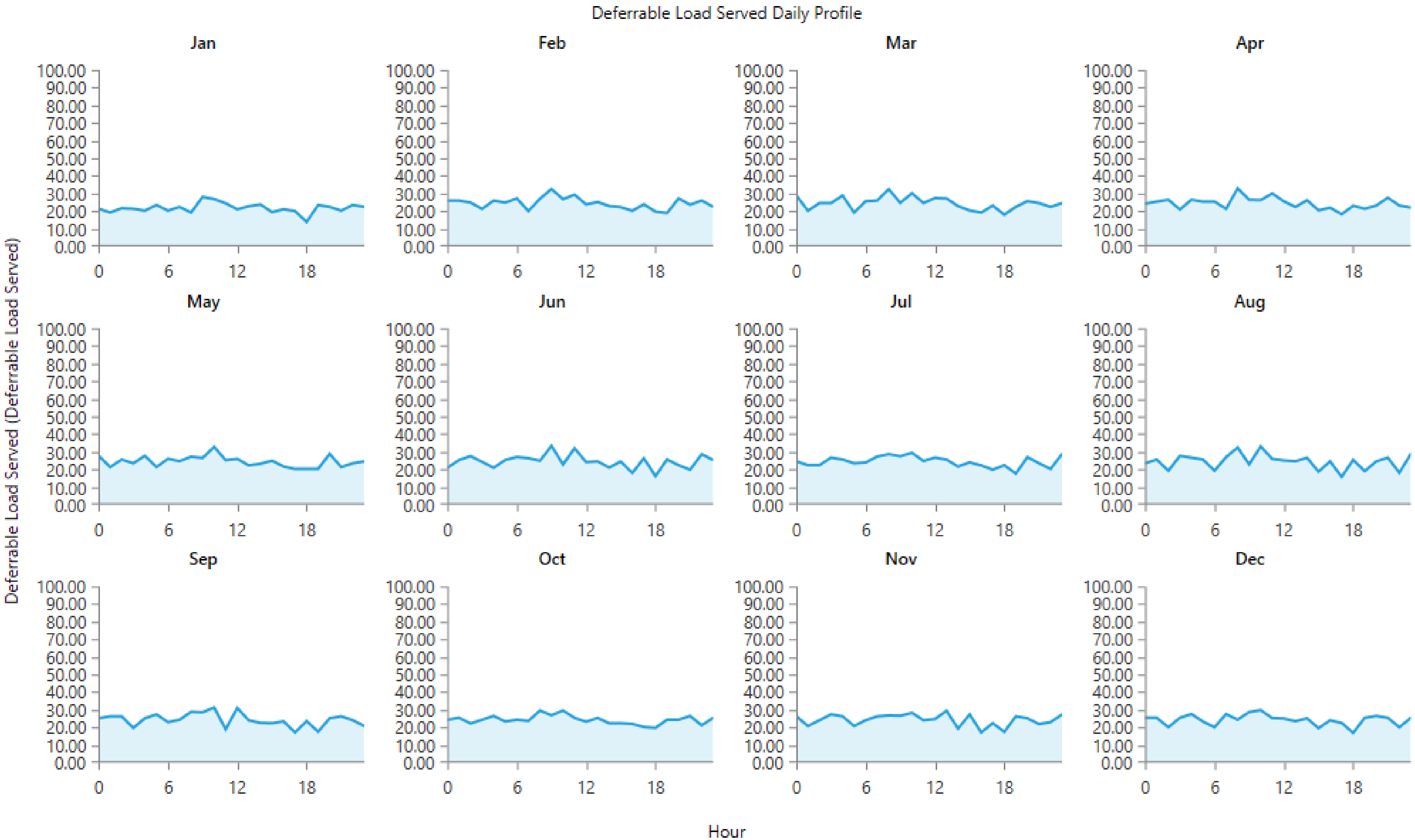

Figure 30: Battery Charging Load Served Daily Profile of System 1b

For this type of system, electric buses batteries, which represents the deferrable load served, shown in Figures 1a and 1b, can be charged homogenously. The yearly trend shows that a constant electric supply of 25% of the total battery capacity is served through the 24 hours of a day. In order to complete the scheduled trips during weekdays shown in Figure 1, the strategy of charging of the four batteries modeled could be divided as follows:

- Day 1, Monday

6:00 to 7:00: bI, mounted on the bus B1, and bII, mounted on the bus B2 are charged to 50%, enabling B1 and B2 to cover 205 km of trips each one.

205 km of range can cover 8.54 trips of 24 km (from location A to B and returning to A). Then, B1 would complete services scheduled at 7:30, 9:00, 10:30, 12:00, 13:30, 15:00, 16:30, and 18:00; while B2 would complete the ones scheduled at 8:15, 9:45, 11:15, 12:45, 14:15, 15:45, 17:15, and 18:45. After completing these trips bI and bII would be discharged to 7.7%

18:30 to 19:30: bIII and bIV, that are not initially mounted at any of the buses are charged to 50%.

Then, B1 and B2 would swap from bI and bII to bIII and bIV respectively, that have a range of 205 km. After this battery swapping process, B1 would complete the services scheduled at 19:30, and 21:00 while B2 would do the same with the one scheduled at 20:15 and 21:45. After completing these trips state of charge of bIII and bIV would be 39.3%, enabling them to start the trips of the following day, Tuesday.

- Day 2, Tuesday

Electric buses B1 and B2, with bIII and bIV implemented on them respectively, would have a range of 139.4 km. Therefore, 139.4 km allows each bus to complete 5.8 trips. Thus, B1 would complete services scheduled at 7:30, 9:00, 10:30, 12:00 and 13:30 while B2 would complete the ones scheduled at 8:15, 9:45, 11:15, 12:45 and 14:15. After completing these trips, the state of charge of bIII and bIV would be 4.73%.

13:15 to 14:15: bI and bII, that are not initially mounted at any of the buses are charged to 50% enabling them with 205 km of range or 8.54 trips each one.

Then, B1 and B2 would swap from bIII and bIV to bI and bII and would complete the 10 remainder trips scheduled for the day. State of charge of bI and bII would be 14,8%, enabling them to start the trips of the following day, Wednesday.

- Day 3, Wednesday

Electric buses B1 and B2, with bI and bII implemented on them respectively, would have a range of 60.7 km. Therefore, 60.7 km allows each bus to complete 2.5 trips. Thus, B1 would complete services scheduled at 7:30 and 9:00 while B2 would complete the ones scheduled at 8:15 and 9:45. After completing these trips, the state of charge of bI and bII would be 3.09%.

08:30 to 9:30: bIII and bIV, that are not initially mounted at any of the buses are charged to 50% enabling them with 205 km of range or 8.54 trips each one.

Then, B1 and B2 would swap from bI and bII to bIII and bIV and would complete the 16 remainder trips scheduled for the day. State of charge of bIII and bIV would be 3.17%. Therefore, as the state of charge of both batteries is very low to continue operating the following day, a new cycle of dispatching would start on the next day, Thursday; being this operated as the Monday was.

- Day 4, Thursday

Operation strategy is similar to the one devised above for Monday. State of charge of bIII and bIV would be 39.3% at the end of the day, enabling them to start the trips of the following day, Friday.

- Day 5, Friday

Operation strategy is similar to the one devised above for Tuesday. State of charge of bI and bII would be 14,8% at the end of the week, enabling them to start the trips of the following day, next Monday.

To summarize, systems 1a and 1b could be operated under a cycle of swapping batteries which is repeated through periods of 3 days.

6.3.2 System 1b and System 2b

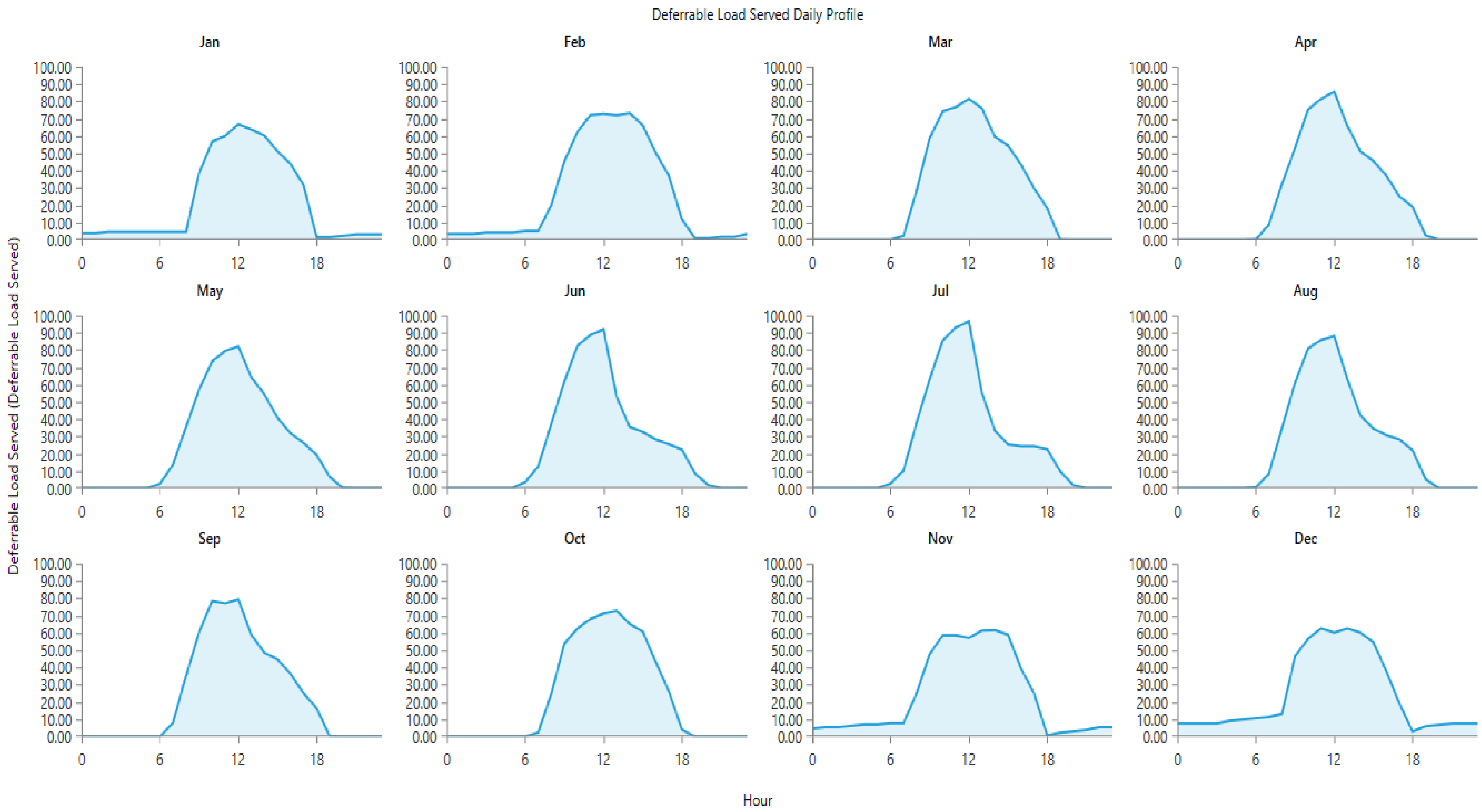

Figure 31: Battery Charging Load Served Daily Profile of System 2a

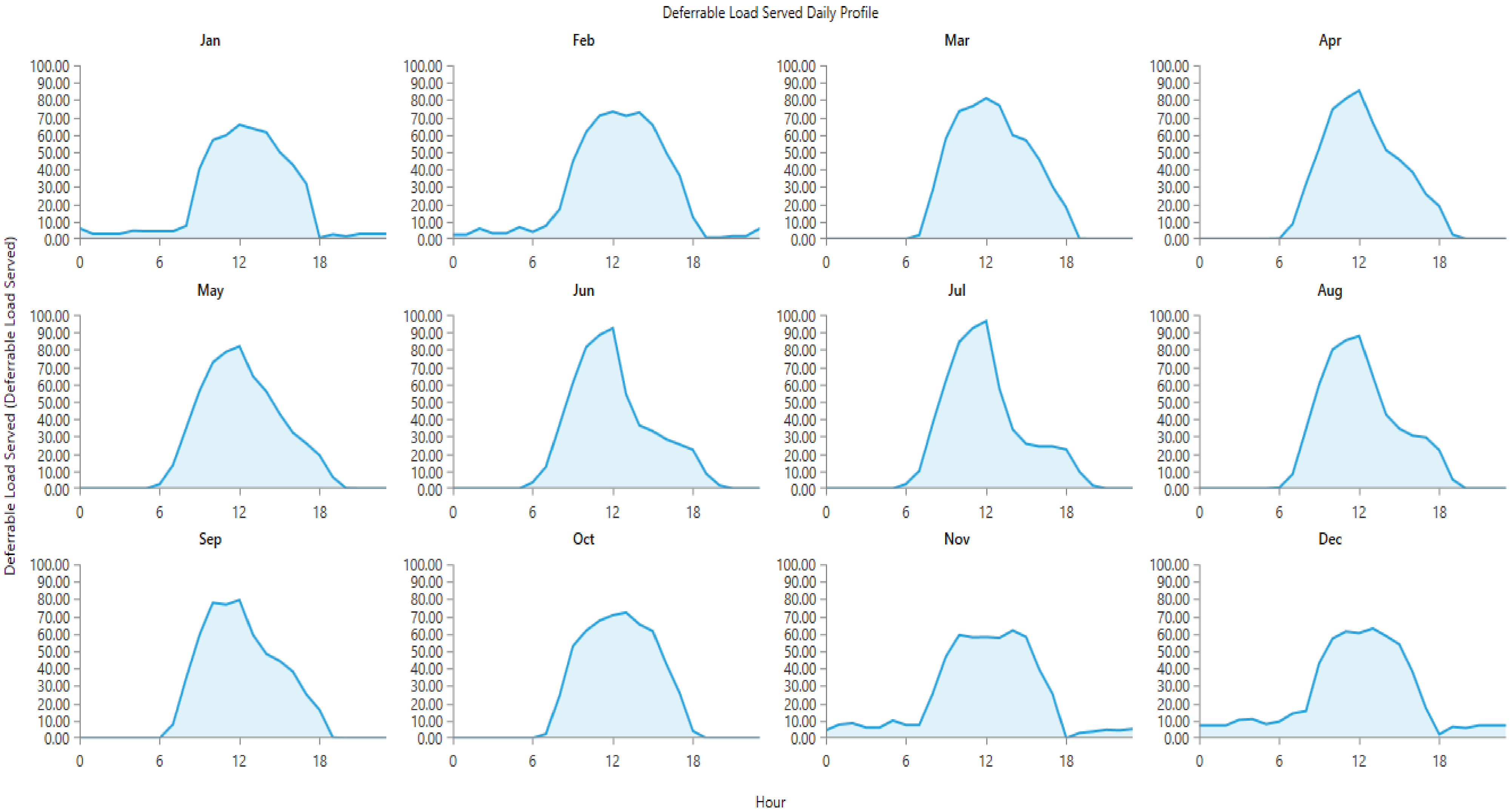

Figure 32: Battery Charging Load Served Daily Profile of System 2b

Devising a dispatch electric batteries strategy for this system results difficult as electric power transfer is mainly produced when the PV generation occurs. From the daily profiles for each month, the following trend can be extracted to create the dispatching strategy and completing the weekday trips:

- Day 1, Monday

6:00 to 7:00: bI, mounted on the bus B1, and bII, mounted on the bus B2 are charged to 10%, enabling B1 and B2 to cover 41 km of trips.

B1 would complete the trip scheduled at 7:30 while B2 would do the same with the one scheduled at 8:15. State of charge of bI and bII after these trips would be 4.14%

7:00 to 9:00: bIII and bIV are charged until 40%, allowing them to cover a range of 160 km.

bIII and bIV would substitute bI and bII after the first and second trip scheduled. Therefore, trips starting at 9:00 and 9:45 would be done by B1 and B2 after the battery replacement. These batteries would allow buses to complete 6.6 trips. Then B1 would complete services scheduled at 9:00, 10:30, 12:00, 13:30, 15:00, and 16:30; while B2 would to the same with the ones scheduled at 9:45, 11:15, 12:45, 14:15, 15:45, and 17:15 State of charge of bIII and bIV after completing these trips would be 3.9%.

9:00 to 12:00: bI and bII would be charged fully as the deferrable load served overcomes 50%. As it is mentioned at the beginning of the chapter, this figure represents the power hypothetically transmitted to the whole set of 4 batteries, 2 of them, which are the amount that the ECVS allows to connect, could absorb their total capacity.

Then, B1 and B2 would swap from bIII and bIV to bI and bII, with a range of 410 km. Thus, B1 and B2 could cover the remaining six trips scheduled for the day. State of charge of bI and bII after completing these trips would be 65%, enabling them to begin the services the following day, Tuesday.

- Day 2, Tuesday

Electric buses B1 and B2, with bI and bII implemented on them respectively, would have a range of 266.5 km. Therefore, 266.5 km allows each bus to complete 11.1 trips. Thus, B1 and

B2 would complete ten services each one to cover the whole twenty services scheduled for the day. After completing these trips, the state of charge of bI and bII would be 6.4%, enabling them to start the first two trips (7:30 and 8:15 respectively) of the following day, Wednesday.

- Day 3, Wednesday

Operation strategy is similar to the one devised above for Monday. State of charge of bI and bII after completing these trips would be 65%, enabling them to begin the services the following day, Thursday.

- Day 4, Thursday

Operation strategy is similar to the one devised above for Tuesday. State of charge of bI and bII would be 6.4% at the end of the day, enabling them to start the first two trips of the following day, Friday.

- Day 5, Friday

Operation strategy is similar to the one devised above for Monday. State of charge of bI and bII after completing these trips would be 65%, enabling them to begin the services the following Monday.

To summarize, systems 2a and 2b could be operated under a cycle of swapping batteries which is repeated through periods of 2 days.

6.3.3 System 3

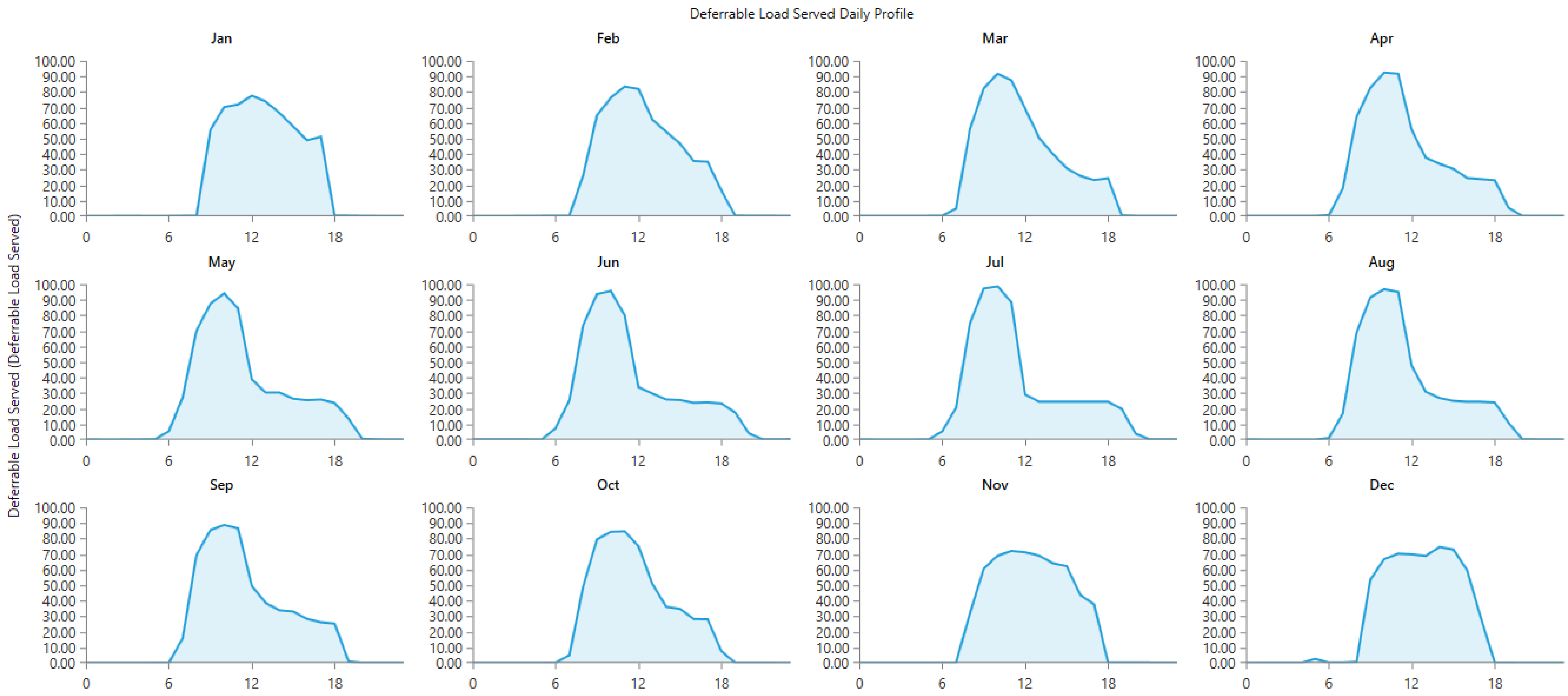

Figure 33: Battery Charging Load Served Daily Profile of System 3

In the case of the 100% renewable system feeding the electric batteries of the buses, the dispatch strategy is divided into two different categories because there exist three months, which are November, December, and January, where the batteries cannot be charged between 6:00 and 7:00.

1. Winter dispatch strategy

As it is mentioned above, this dispatch strategy covers the months from November to January, and it would be performed as follows. This case requires batteries to be charged during Sunday afternoon in order to complete the weekdays' scheduled trips.

- Day 1, Monday

17:00 (Sunday prior to Monday): bI and bII would be charged fully as the deferrable load served overcomes 50%. Therefore, the range of each of the batteries would be 410 km or 17.1 trips.

Then, B1 and B2 would integrate bI and bII at the beginning of the day, with a range of 410 km. Thus, B1 and B2 could complete the twenty trips scheduled for the day. State of charge of bI and bII would be 41.5%, enabling them to start the trips of the following day, Tuesday.

- Day 2, Tuesday

Electric buses B1 and B2, with bI and bII implemented on them respectively, would have a range of 170.15 km. Therefore, 170.15 km allows each bus to complete 7.1 trips. Thus, B1 would complete the services scheduled at 7:30, 9:00, 10:30, 12:00, 13:30, 15:00, and 16:30 while B2 would do the ones scheduled 8:15, 9:45, 11:15, 12:45, 14:15, 15:45, and 17:15. After completing these trips, the state of charge of bI and bII would be 0.52%,

12:00: bIII and bIV are charged fully, providing them with a range of 410 km

Then, B1 and B2 would swap from bI and bII to bIII and bIV, with a range of 410 km. Thus, B1 and B2 could cover the remaining six trips scheduled for the day. State of charge of bI and bII after completing these trips would be 65%, enabling them to begin the services the following day, Wednesday.

- Day 3, Wednesday

Electric buses B1 and B2, with bIII and bIV implemented on them respectively, would have a range of 266.5 km. Therefore, 266.5 km allows each bus to complete 11.1 trips. Thus, B1 and B2 would complete ten services for each one to cover the whole twenty services scheduled for the day. After completing these trips, the state of charge of bIII and bIV would be 6.4%, enabling them to start the first two trips (7:30 and 8:15 respectively) of the following day, Thursday.

- Day 4, Thursday

12:00 (Wednesday prior to Thursday): bI and bII are charged fully, providing them with a range of 410 km.

B1 would complete the trip scheduled at 7:30 while B2 would do the same with the one scheduled at 8:15. State of charge of bIII and bIV after these trips would be 0.54%.

After that, B1 and B2 would swap from bIII and bIV to bI and bII, that were charged totally the prior day; allowing them to have a range of 410 km or 17.1 trips each one. Thus, B1 and B2 would cover the remainder eighteen services scheduled for the day. After completing these trips, the state of charge of bI and bII would be 47.3%, enabling them to start the trips of the following day, Friday.

- Day 5, Friday

Electric buses B1 and B2, with bI and bII implemented on them respectively, would have a range of 193.93 km. Therefore, 193.3 km allows each bus to complete 8.1 trips. Thus, B1 would complete the trips scheduled at 7:30, 9:00, 10:30, 12:00, 13:30, 15:00, 16:30, and 18:00 while B2 would cover the ones scheduled at 8:15, 9:45, 11:15, 12:45, 14:15, 15:45, 17:15, and 18:45. State of charge of bI and bII after completing these trips would be 0.31%.

17:00: bIII and bIV would be charged fully as the deferrable load served overcomes 50%. Therefore, the range of each of the batteries would be 410 km or 17.1 trips.

Then, B1 and B2 would swap from bI and bII to bIII and bIV at the beginning of the day, with a range of 410 km. Thus, B1 and B2 could complete the remainder 4 trips scheduled for the day. State of charge of bI and bII after these trips would be 88.3%, enabling them to start the trips of the following Monday.

To summarize, system 3 is the one which operation does not match exactly with any type of cycle. Peaks of charging are concentrated between noon and 17:00, so the viability of completing the weekday's services bases its foundations on charging fully the batteries at these times to maximize the range of the two buses.

2. Rest of the year

During the remaining months, the viability of scheduled trips could follow the same strategy as to systems 1b and 2b.

7. Conclusions

This thesis has investigated the use of the grid and renewable energy supply, with special focus on photovoltaics, for the deployment of electric buses between the locations of La Granja de San Ildefonso and Segovia due to the existence of an already built and misused photovoltaic Electric Vehicle Charging Station (ECVS).

On the one hand, the demand side is constituted by electric buses, which must complete twenty trips of twenty-four kilometers each day of the week. As the number of trips that the buses must complete is constant throughout the year, so it is the electric demand required by them. Two electric buses equipped with their respective batteries and two spare batteries, that can be swapped when the equipped ones are depleted, comprise the electric demand required for the electrification of the route. It is proven through the literature review that the mechanism of swapping batteries in electric vehicle charging stations can be cost-effective.

On the other hand, and in order to optimize the best supply for the electric buses, different configurations of supply have been analyzed. Beginning from the current model of the ECVS, which comprises 28.8 kW of PVs and grid connection, different types of retrofit have been proposed. These retrofits comprise the addition of Li-Ion battery storage, the increasement of the photovoltaic capacity installed, and the addition of a wind turbine to model a full renewable supply system.

Then, HOMER software is used to implement both electric demand and the different combinations of supply modeled. Optimization of the size of the PV plant has been used for each of the retrofit models proposed. A sensitive analysis is performed according to NPC, COE, and CEI. Finally, using a rough method of proportional relationships between energy stored and an equivalent range of kilometers, a strategy of coordination for the buses is proposed in order to complete their scheduled weekdays' trips.

Based on the simulations and studies performed it can be concluded that:

- An Electric Vehicle Charging Station (ECVS) can be easily modeled using HOMER. The "Deferrable Load", included within the software, allows any user to set an electric load which has a daily demand, storage capacity, and a peak load consumption. Thus, this type of load can represent accurately the behavior of an electric vehicle through the demand and storage values and the power with what it is charged through the peak load value.

- The role of Li-Ion storage battery (system 2a 2b and 3) is basically null for each system modelled because most of the electricity generated by the different systems modeled is transferred to the batteries of the electric buses. Therefore, this retrofit proposal is bad and shouldn't be implemented in the real world. However, consider more exchangeable batteries for the buses could constitute a would way to store energy.
- Retrofitting the ECVS in a way to power the electric bus service only by renewables is possible. However, this would suppose a huge investment with a return period of almost 12 years.
- For every system modeled, the feasibility of completing the scheduled trips between the two locations is ensured. Intermittency of the renewable sources makes the coordination of the dispatch strategy more difficult for the full renewable supply system (System 3) though. However, the introduction of swapping batteries technology would ease this task at any of the cases, including System 3.

To sum up, every single aim has been successfully achieved: a literature review about the field of EVCS has been carried out, a strategy of electrification of public transport between the two locations has been proposed, the current ECVS is been modeled along with some potential retrofit improvements, and an evaluation of the costs of each model as well as a study of the feasibility to complete the trips in accordance with the different supply models have been done.

8. Limitations and future work

Although this thesis has managed to achieve the objectives initially purposed, there exist some limitations concerning the method applied. Those are the following ones:

- The foundations of the project encounter a major problem. Strategy for operating the bus service requires of swapping batteries between the ECVS and the bus. Current ECVS does not have all the mechanical equipment to make this process possible now. Then, an upgrade to the ECVS would be required before the solution proposed in this thesis could become real.
- The peak load defined as 100 kW within the parameters for the deferrable load means that only two electric batteries can be charged at the same time. The project has been defined to have only two charging sources. This constitutes a problem because there are some moments throughout the day when all the electricity generated cannot be bulked towards the four batteries that put together the whole storage of the buses. Consequently, a loss of half of the electricity is occurring when the "Battery Charging Load Served Daily Profile" value is 100%. 50% represents the moment where two batteries are fully charged. However, above these values, as there not exist more than two power plugs in sockets, the energy would be lost.

Based on these limitations found, there exist some issues that could make it greater and more valuable. Those are the following ones:

- A comparison between different types of electric buses done within the simulation stage would improve the range of election when potentially implementing public electric transport.
- Model hydrogen-fueled buses to compare with the electric ones.
- A similar study can be conducted between the location where the ECVS is installed and the capital, Madrid, which is 88 km to the South.
- Model the behavior of the MPPT more in detail.
- Model the deferrable load with a different value of peak load, meaning more charging points could provide power at the same time.
- The role of other types of renewable supply sources could be analyzed in order to continue seeking the best combination. Between these sources, hydrogen fuel cells appear to be promising on powering this type of loads.

Moreover, a further study could be the analysis of the harmonics produced in the grid when plugging the electric buses into the charging source and how to make them be relieved. This could be analyzed using other types of software such as Simulink.

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