FEDERAL UNIVERSITY OF JUIZ DE FORA

ENGINEERING DEPARTMENT

ELECTRICAL ENGINEERING GRADUATE PROGRAM

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Economic assessment of an electric vehicle parking lot equipped with photovoltaic generation, energy storage system and electric vehicle chargers

Juiz de Fora

2020

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Master's thesis presented to the Electrical Engineering Graduate Program at Federal University of Juiz de Fora, in the area of concentration in Electrical Energy Systems, as a partial requirement to obtain the title of Master in Electrical Engineering.

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Juiz de Fora

2020

Ficha catalográfica elaborada através do Modelo Latex do CDC da UFJF
com os dados fornecidos pelo(a) autor(a)

Xavier, Edgar Bellini.
Economic assessment of an electric vehicle parking lot equipped with photovoltaic generation, energy storage system and electric vehicle chargers / Edgar Bellini Xavier. – 2020.
86 f. : il.

Advisor: Dr. Bruno Henriques Dias
Co-Advisors: Dr. Bruno Soares Moreira Cesar Borba, PhD Jairo Quirós-Tortós
Master's Thesis – Federal University of Juiz de Fora, Engineering Department. Electrical Engineering Graduate Program, 2020.

1. Distribution Networks. 2. Economic Assessment. 3. Electric Vehicles. 4. Parking Lots. 5. Photovoltaic Generation. 6. Real Applications. 7. Storage Systems. I. Dias, Bruno Henriques, orient. II. Borba, Bruno Soares Moreira, coorient. III. Quirós-Tortós, Jairo, coorient. IV. Título.

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Economic Assessment of an Electric Vehicle Parking Lot Equipped with Photovoltaic Generation, Energy Storage System and Electric Vehicle Chargers

Dissertação apresentada ao Programa de Pós-Graduação em Engenharia Elétrica da Universidade Federal de Juiz de Fora, na área de concentração em Sistemas de Energia Elétrica, como requisito parcial para obtenção do título de Mestre em Engenharia Elétrica.

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This work is dedicated to all my family, particularly to my parents, José Eduardo and Maria das Graças, and my sisters Eduarda and Alice. It is also dedicated to my sweet love, Alyne Neves. Without your support, encouragement, and education, nothing would be possible.

Dedico este trabalho à toda minha família, em especial meus pais, José Eduardo e Maria das Graças, e minhas irmãs Eduarda e Alice. Este trabalho também é dedicado ao meu amor, Alyne Neves. Sem o suporte, incentivo e educação de vocês, nada teria sido possível.

ACKNOWLEDGEMENT

First, I must be thankful to God for giving me strength, wisdom and standing by my side in all moments, especially in the most difficult ones.

I would like to acknowledge my parents, José Eduardo and Maria das Graças. You have always helped me, taught me and support me whenever I needed.

I would also like to thank my love, Alyne Neves, who has always been by my side giving me a pep talk, love and handling my worst and doubtful moments.

To my advisors, Bruno Dias, Jairo Quirós and Bruno Borba, I'm very thankful for all the knowledge you have given me and for the patience you had. I would also like to thank professors Madson Cortes and Leonardo Willer for accepting to be part of the examination board of this thesis and for the contribution to this work.

A special thanks must be expressed to some friends: Daniel Lucena, João Ricardo Pereira, Jean-Philippe Bilger, Gustavo Reis and Lucas Deotti. Each one of you surely has helped me achieve the results in this thesis.

I'm also very thankful to my cousin Paula Bara for her affection, attention, and dedication to helping me edit and correct this thesis.

Finally, I would like to thank the National Council for Scientific and Technological Development (CNPq), the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), FAPEMIG and INERGE for their financial and/or technical support for the development of this thesis.

AGRADECIMENTOS

Primeiramente agradeço a Deus por ter me dado força, sabedoria e estado ao meu lado em todos os momentos, principalmente nos mais difíceis.

Também gostaria de agradecer aos meus pais, José Eduardo e Maria das Graças. Vocês sempre me ajudaram, ensinaram e me deram todo o suporte que precisei para chegar até aqui.

Agradeço também ao meu amor, Alyne Neves, por sempre ter estado ao meu lado com uma palavra de conforto, amor e me ajudando nos momentos mais difíceis.

Agradeço imensamente os meus orientadores, Bruno Dias, Jairo Quirós e Bruno Borba. Sou muito grato por todo conhecimento recebido e por toda paciência que tiveram. Agradeço também aos professores Madson Cortes e Leonardo Willer, por terem aceitado serem parte da banca examinadora desta dissertação e pelas contribuições dadas a este trabalho.

Um agradecimento especial deve ser feito para alguns grandes amigos: Daniel Lucena, João Ricardo Pereira, Jean-Philippe Bilger, Gustavo Reis e Lucas Deotti. Com certeza cada um de vocês contribuíram um pouco para os resultados desse trabalho.

Agradeço muito à minha prima Paula Bara pelo carinho, atenção e dedicação em me ajudar com a revisão e correção desta dissertação.

Finalmente, também agradeço ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), à Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), à Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) e ao Instituto de Estudos e Gestão Energética (INERGE) pelo suporte financeiro e/ou técnico para desenvolvimento deste trabalho.

“Many hypotheses proposed by scientists as well as by non-scientists turn out to be wrong. But science is a self-correcting enterprise. To be accepted, all new ideas must survive rigorous standards of evidence.” (Carl Sagan, 1980, p.91)

ABSTRACT

The electric vehicle (EV) fleet has been growing considerably in the last decades, bringing new challenges and opportunities for the electricity system, especially for the Distribution System Operators. In this regard, it is of the utmost importance that governments adopt policies to ensure a robust infrastructure to serve the electric vehicle owners in order not to discourage them from buying those vehicles. This is important since electric vehicles are an eco-friendly mobility fleet that can reduce fossil fuel dependency, noise pollution, help countries to reach the Paris Agreement's terms and bring some benefits to the electricity system. In this regard, electric vehicle parking lots (EVPL) can play an important role by providing charging stations to those vehicles. But it is very important that the EVPLs are well located and well sized in order to ensure that they can be profitable. This work presents a methodology to determine the optimal size of an EVPL that will not only charge EVs but also have an energy storage system (ESS) and photovoltaic generation (PV) services. The aim of this thesis is to evaluate the profitability of the EVPL operation for 20 years. The proposed methodology shows that a well-sited and well-sized EVPL can be profitable. Moreover, this thesis shows the importance of an energy storage system (ESS) to ensure the profitability of the EVPL and also the positive impact of the photovoltaic (PV) generation in the EVPL profit, when combined to the ESS.

Keywords: Electric Vehicles. Parking Lots. Photovoltaic Generation. Storage Systems. Economic Assessment. Distribution networks. Real Applications.

RESUMO

A frota de veículos elétricos cresceu consideravelmente nas últimas décadas, trazendo novos desafios e oportunidades para o sistema elétrico, especialmente para as empresas de distribuição de energia. Nesse sentido, é de extrema importância que os governos adotem políticas para garantir uma infraestrutura robusta a fim de atender os donos de veículos elétricos, não os desencorajando a comprar esses veículos. Isso é importante, pois os veículos elétricos são considerados uma frota de mobilidade ecológica que pode reduzir a dependência de combustíveis fósseis, a poluição sonora, ajudar os países a cumprir os termos do Acordo de Paris e trazer benefícios para o sistema elétrico. Nesse sentido, os estacionamentos para veículos elétricos podem desempenhar um papel importante, fornecendo estações de carregamento para esses veículos. Mas é muito importante que esses estacionamentos estejam bem localizados e dimensionados para garantir sua rentabilidade. Esta dissertação apresenta uma metodologia para determinar o tamanho ideal de um estacionamento para veículos elétricos que não apenas os recarregue, mas também seja dotado de um sistema de armazenamento de energia (ESS) e serviços de geração fotovoltaica (PV). O objetivo deste trabalho é avaliar a rentabilidade da operação do estacionamento para veículos elétricos em um horizonte de 20 anos. A metodologia proposta mostra que um estacionamento para veículos elétricos bem locali-zado e dimensionado pode ser rentável. Além disso, este trabalho mostra a importância de um sistema de armazenamento de energia para garantir a rentabilidade do estacionamento para veículos elétricos e também o impacto positivo da geração fotovoltaica no lucro deste estacionamento, quando combinado ao sistema de armazenamento de energia.

Palavras-chave: Veículos Elétricos. Estacionamento. Geração Fotovoltaica. Sistemas de Armazenamento. Avaliação Econômica. Redes de distribuição. Aplicações reais.

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ABNT	Associação Brasileira de Normas Técnicas
ABRASCE	Associação Brasileira de Shopping Centers
AC	Alternate Current
ANEEL	Agência Nacional de Energia Elétrica
ANFAVEA	Associação Nacional dos Fabricantes de Veículos Automotores
BEV	Battery Electric Vehicles
CAN	Controller Area Network
CCS	Combined Charging System
CEMIG	Companhia de Eletricidade de Minas Gerais
CO_2	Carbon Dioxide
CS	Charging Station
CSP	Concentrating Solar Power
DC	Direct Current
DG	Distribution Generation
DSO	Distribution System Operator
EMS	Energy Management Strategy
ESS	Energy Storage System
EV	Electric Vehicles
EVCIPA	Electric Vehicle Charging Infrastructure Promotion Agency
EVPL	Electric Vehicle Parking Lot
EVSE	Electric Vehicle Supply Equipment
FCLM	Flow-Capturing Location Model
FCS	Fast Charging Station
G2V	Grid-to-vehicle
ICE	Internal Combustion Engine

IEA	International Energy Agency
IEC	International Electrotechnical Commission
IRR	Internal Rate of Return
PbA	Lead-Acid
LDV	Light-duty Vehicles
Li-ion	Lithium-ion
MILP	Mixed Integer Linear Programming
MIP	Mixed Integer Programming
Na-S	Sodium-sulfur
Ni-Cd	Nickel–Cadmium
Ni-MH	Nickel–Metal Hydride
NPV	Net Present Value
O&M	Operation and Maintenance
PbA	Lead-Acid
PDF	Probability Density Function
PHEV	Plug-in Hybrid Electric Vehicles
PSO	Particle Swarm Optimization
PSB	Polysulfide-bromine
PV	Photovoltaic
REDOX	Reduction-oxidation
RER	Renewable Energy Resources
RFB	Redox Flow Batteries
ROI	Return of Investment
RTP	Real Time Pricing
SAE	Society of Automotive Engineers
SOC	State-of-Charge

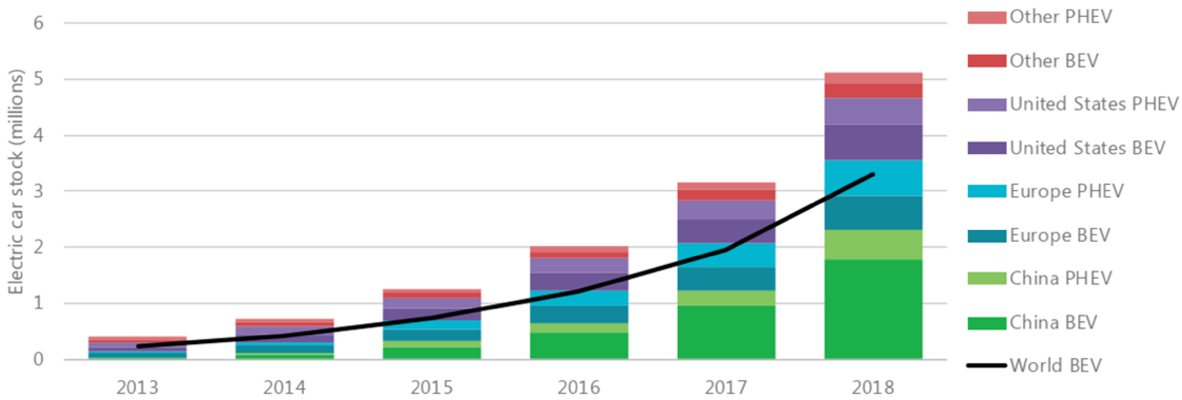
T&D	Transmission and Distribution
ToU	Time-of-Use
UK	United Kingdom
UPS	Uninterruptible Power Supply
V2G	Vehicle-to-grid
Zn-Br	Zinc-Bromine

SUMMARY

1 INTRODUCTION

The world has witnessed an expressive growth in the Electric Vehicle (EV) stocks, considering both Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV), as can be seen in Graph 1. In 2018, the EV fleet overcame the 5-million-unit barrier. It represents 63% increment from the previous year and was similar to the year-on-year growth in 2017, 57%, and 2016, 60%. It is also important to remark that in 2018 China had 45% (2.3 million) of the world's EV fleet, while Europe contributed to 24% (1.2 million) and the United States, 22% (1.1 million) (1). This shows that governments in those three regions are deploying policies that favor the EV fleet growth.

Graph 1 – Global EV stock 2013 to 2018



Source: 2019 Global EV Outlook (1).

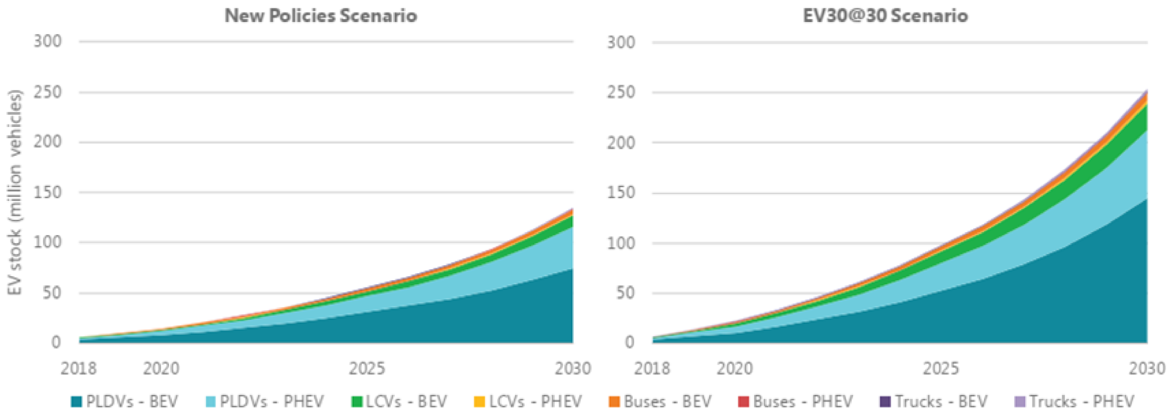
Going further, the 2019 Global EV Outlook defines 2 scenarios to analyze the deployment of EVs:

a) New Policies Scenario: Central scenario of the International Energy Agency (IEA) *World Energy Outlook*. This scenario considers the key policies adopted by governments around the world and the expected effects of announced policies expressed in official targets or plans;

b) 30@30 Scenario: This scenario considers that the 30% market share of EVs for Light-Duty Vehicles (LDVs), buses and trucks collectively is met at the global level. This will be achieved if it is followed by a reduction on the carbon intensity of power generation in more than 50% by 2030 (as proposed in the Paris Agreement), since the EV market share will continue to increase after 2030.

While the first scenario projects that the EV fleet will exceed 130 million units by 2030, the 30@30 scenario projects that in 2030 the world might reach more than 250 million EVs (excluding two and three-wheelers), as showed in Graph 2.

Graph 2 – Global EV (2018 to 2030) projected stocks



Source: 2019 Global EV Outlook (1).

Going further, the Paris Agreement defined several goals that will only be achieved if governments start to act towards a regulation that promotes the decarbonization, and the EVs can be a key tool that should be considered. So, in order to increase the EV penetration it is of utmost importance that governments define regulations to incentivize the acquisition of EVs and also the installation of charging stations, specially EVPLs. Today, only three Latin America countries (Costa Rica, Panama, Uruguay) have policies that make the acquisition of EVs to be cost-effective to their owners, compared with an internal combustion engine (ICE) vehicle, in less than 10 years (2).

Concerning the electricity generation and transportation, according to (3), the transport and energy generation sectors can be directly associated with key aspects that have been discussed this century: oil, climate changes, energy dependence. Furthermore, coal and oil are the main electricity generation and transportation sources, respectively (4). In this regard, new technologies (i.e.: EVs and renewable generation) must be considered as a key solution to reduce the world's dependence on these fossil energy sources as well other environmental benefits (e.g., reduce greenhouse gases emission and noise pollution), as presented in (5) and (6). The adoption of those new technologies will reduce greenhouse gas emissions; besides that, the combination of EVs and renewable energy might provide a significant reduction of the world's dependence on fossil fuels and the consequent emission of greenhouse gases (3). However, it is of the utmost importance to be prepared to well integrate all this fleet of EVs in order to achieve the previously mentioned benefits.

Related to the electricity system, especially the distribution system, the EVs can provide ancillary services (i.e.: peak shaving, spinning reserve, voltage and frequency regulations) (7). But all the mentioned benefits can only be obtained if there is a proper charging infrastructure (i.e.: Electric Vehicle Parking Lots (EVPLs) with adequate size and located in places that favor the EV users) (8).

Going further, the integration of the increasing fleet of electric vehicles requires attention to the EV charge and discharge operations, in special the uncoordinated charging and discharging (9) which can hamper the occurrence of the EV benefits.

In this regard, the EVPL might help to avoid the uncoordinated charge and discharge problem since the EVPL operator will be able to define the charge and discharge plans according to the EV fleet and electricity market aspects. However, it is important to bear in mind that the EVPL should not be randomly allocated. If that happens, the EVPL might be located in an inappropriate point of the grid causing problems (i.e.: voltage and frequency fluctuation, increase of peak demand).

To avoid a bad siting of the EVPL, it is of utmost importance that the Distribution System Operator (DSO) provides studies about the integration of this charging infrastructure in order to ensure that the place to install the PL and its size are well suited from the perspective of the EVPL operation and grid impacts.

1.1 AIMS AND OBJECTIVES

The growing deployment of EVs in the last decade shows how important it is for governments to be prepared to provide a robust charging infrastructure in order to increase the EV sales and achieve the benefits of this new transportation technology. In this regard, the Electric Vehicle Parking Lot (EVPL) is a useful resource, but it is important to perform previous studies in order to ensure the profitability and feasibility of the installation.

This thesis provides an economical evaluation of the installation and operation of an EVPL installed in a shopping center or another public strategic place, considering a long term (i.e.: 20 years) operation planning. The economic impact in the EVPL operation is also investigated considering different governments policies that reflect in the growth of the EV fleet. The EVPL may be equipped with an Energy Storage System (ESS) that can be used to store energy to be used to charge the EVs when the energy tariff is higher, Photovoltaic (PV) panels that generate energy to be injected into the grid and also to charge the EVs in the EVPL and/or the battery system and, of course, commercial EV chargers. The economic impact of the installation of an ESS and PV generation will also be investigated.

It is not the aim of this work:

a) To propose an Energy Management System (EMS);

b) To propose a charging schedule for EV;

c) To evaluate the impact of batteries on nature;

d) It was not taken into consideration the economic impact of the EVPL providing ancillary services;

e) The EVPL was not considered to be providing V2G service.

1.2 RELATED PUBLICATIONS

XAVIER, E. B.; DIAS, B. H.; BORBA, B. S. M. C.; QUIRÓS-TORTÓS, J. Sizing and Placing EV Parking Lots: Challenges Ahead in Real Applications. In: **IEEE PES INNOVATIVE SMART GRID TECHNOLOGIES LATIN AMERICA**, 2019, Gramado, Brazil. IEEE DOI: 10.1109/ISGT-LA.2019.8895420

XAVIER, E. B.; DIAS, B. H.; BORBA, B. S. M. C.; QUIRÓS-TORTÓS, J. Methodology to Economic Evaluation of an Electric Vehicle Parking Lot Equipped with PV and Storage. In: **IEEE PES TRANSMISSION AND DISTRIBUTION CONFERENCE AND EXPOSITION – LATIN AMERICA**, 2020, Montevideo, Uruguay.

1.3 STRUCTURE OF THE THESIS

This thesis is organized in six chapters: Chapter 2 presents a literature review about siting and sizing electric vehicle parking lots, and possible revenues that might increase the EVPL profitability, besides that, it also introduces the importance of considering the technical aspects; in Chapter 3, the proposed methodology is detailed; the numeric results to evaluate the proposed methodology is presented in Chapter 4; Chapter 5 presents the conclusion of this thesis and some proposed future works.

Three appendixes are presented to help better understand some concepts: Appendix A details the technical aspects about batteries and electric vehicle chargers; Appendix B summarizes the main tariff structures adopted in some countries; finally, Appendix C presents the Brazilian tariff system.

2 BRIEF LITERATURE REVIEW, POSSIBLE FUTURE REVENUES AND TECHNICAL ASPECTS

In order to properly define a location and the size of an EVPL, there are some key aspects that must be taken into account, as presented by (8). Sometimes not all of those aspects can be considered; the definition of which of them will be considered relies on the level of detail needed and the data availability:

a) Computational Effort: This aspect is related to the proposed method (especially the time needed to achieve the best solution) and the level of details of the model (i.e.: analysis of real data and network data). It is very important that the computational resources to be spent must be according to the objective of the problem. Concerning the modeling adopted, there are two main strategies:

   – minimization of costs: the goal is to reduce the global costs of installation and operation (i.e.: land acquisition, municipal fees, market energy costs, maintenance, batteries degradation and so on);

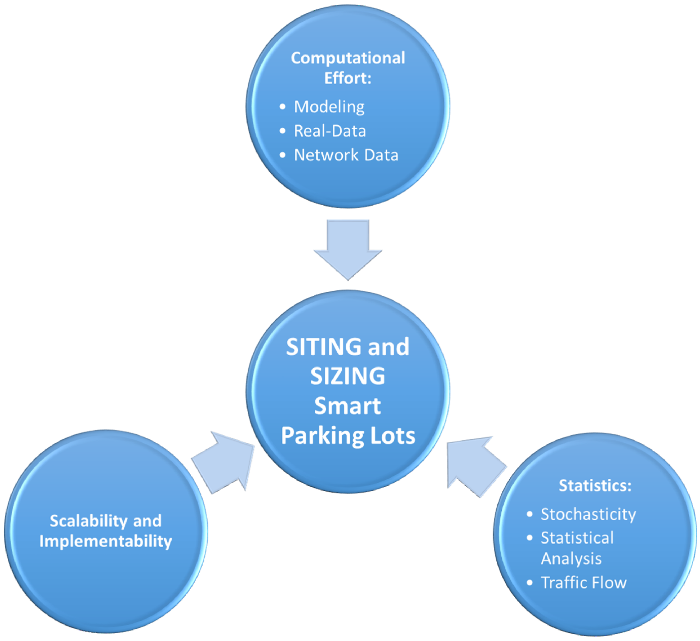
   – maximization of the total profit: in this strategy the goal is to maximize the difference between costs and revenues (i.e.: energy and reserve market, parking rates, market interaction with EV‘ owners and so on).

b) Statistics: When trying to define a proper location and size for an EVPL, we are handling with a large amount of stochastic and uncertain data (i.e.: State-of-Charge (SOC), number of EVs and traffic and charging behavior). This is the real nature of EVs and their owners' behavior. In order to consider those uncertainties, it is extremely important to use statistical methods to define scenarios that can be used in realistic, stochastic detailed studies related to EVPLs, in order to ensure the Return of Investment (ROI) and feasibility of the EVPLs allocation and size. It is very important to say that, when we neglect the stochasticity of the data, we are performing a simplification that does not match the real nature of the EV behavior and owners' habits;

c) Scalability and Implementability: In this aspect, it is important to consider how the proposed solution will perform in conditions similar to those found in real systems, as well as if the software used can be adopted by the EVPL's planner and if the solution is scalable. In this regard, it is extremely important to perform tests in conditions (i.e.: distribution systems and scenarios based in real EV observation) similar to those found in the real world.

This section presents previous works which give reasons and support the proposed research. It starts presenting the papers according to the key aspects defined by (8) (as explained above and showed in Chart 1) and then it moves to the operation of an EVPL equipped with renewable generation (i.e.: PV) and ESS (i.e.: battery), which is the focus of this thesis.

Chart 1 – Summary of the key aspects for sitting and sizing EVPL



Source: Prepared by the author (2020).

2.1 COMPUTATIONAL EFFORT

In what concerns the solution of the proposed method, some papers have presented a partial side approach to define the optimization function (not considering some aspects or points of view). An example of this can be seen in (10) according to which the authors have proposed an Energy Management Strategy (EMS) based only on the point of view of the EVPL operator, instead of considering the DSO point of view as well, and the EVPL was modeled in a Direct Current (DC) grid.

Other example of a partial side approach is to analyze the impact of an EVPL in a single building with solar-based distributed generation (DG) installed on the rooftop (11). In this paper, the authors have proposed a framework to integrate energy sources, energy storage and electric vehicles. The coordinated and uncoordinated charging schemes were compared, and the authors also considered the behavior of EV owners according to different charging prices through modeling the energy required by EVs as a function of the charging prices. The costs considered were the electricity purchase and fixed capital and maintenance costs, while the revenues considered were the electricity sold to charge EVs and the feed-in tariff resource of selling energy from solar-based DG units to the grid.

A third example of this approach is not to consider the installation and maintenance costs when analyzing the behavior of an EVPL considering the deployment of a vehicle-to-grid (V2G) mode as can be seen in (12). The aim of this work was to evaluate the impact of the traffic pattern of EVs on the EVPL energy market participation. This evaluation was performed by comparing two EVPL, one that provides only G2V service while the other can provide Grid-to-Vehicle (G2V) and V2G services.

Another strategy that affects the computational effort is to use metaheuristics to achieve a solution. It is important to bear in mind that the use of this optimization strategy is very sensible to the metaheuristic parameters. Therefore, it is extremely important to well define and select those parameters, as they can have significant effect on the model output.

One example of this strategy can be found in (13) in which the authors compare two metaheuristics, Artificial Bee Colony algorithm and the Firefly Optimization algorithm, in order to determine the optimal number of EVPLs that should be allocated in a distribution system. The goal of the objective function of this problem is to minimize costs (i.e.: energy loss of the network, energy imported from the main grid, energy supplied by the DGs of the network and energy supplied by the EVPL during battery discharge to support the network) and maximize the power supplied to the EVPL to charge the EV batteries.

The Genetic Algorithm is another metaheuristic that was considered in some papers, such as (14) and (15). The first proposed a methodology to optimally site and size an EVPL based on direct load control programs of demand response in order to enhance the reliability of the distribution network. The objective function proposed in (14) aims to minimize the investment, maintenance, reliability and energy purchasing costs. The second paper, (15), proposed a method to determine the number of EVPLs and also their capacity and location. The objective function goal is to maximize the profit of the DSO (owner of the EVPL in this case). The profit considered revenues from selling energy to customers and charging electric vehicles in the EVPLs, while the costs considered were the EV discharging costs, installation, and operation and maintenance (O&M).

The Simulated Annealing algorithm was used in (16) to proper locate EVPLs aiming to achieve the maximum profit over a defined planning period, considering the following costs investment for structuring the EVPL, maintenance, batteries aging costs due to V2G and G2V services, charging discount (in order to encourage the use of the EVPL by EV owners), while the incomes considered were from energy market participation and reliability improvement, partnering with the DSO.

A fourth example of metaheuristics that was considered is the Particle Swarm Optimization (PSO) algorithm. In (17) the authors proposed a planning framework to proper site and size different EV charging stations in urban areas from the perspective of a social planner. The PSO was used because the proposed methodology is a NP-hard problem.

Besides the use of metaheuristics, some papers also consider the classic optimization methods such as Mixed Integer Programming (MIP) or Mixed Integer Linear Programming (MILP). For example, in (18) the authors proposed a model for adequate location of charging stations based on two main travel behaviors: short and long distance. The goal of the objective function proposed is to maximize the coverage of all EV flows, defining the location of fast and slow chargers. To achieve the solution, the authors used branch-and-cut search to solve a proposed MIP model.

The MILP formulation was used in (19) and (20). In the first paper, the authors proposed a model of the EV power flow due to their traffic flow. Moreover, they analyzed the impact of the EV traffic flow in EVPL and charging station (CS) operation. The proposed objective function, in (19), aimed at maximizing the profit of the aggregator (system player responsible for managing all the EVPL and CS) through selling energy to EVs and market interactions.

The second paper, (20), proposed a two-stage optimization model in order to allocate EVPLs in distribution systems. In the first stage, the model aimed at determining the optimal behavior of the EVPL, considering the possibility of market interactions (G2V) by the EVPL owner. The goal of the second stage was to proper allocate the EVPL, considering the behavior determined in the first stage and network constraints.

Although the proposed model plays a major role in the computational effort needed to achieve the optimal solution of a model, it is important to have in mind that the use of real data also affects the time needed by the proposed model. Moreover, when a model considers real data, it aims at ensuring that the optimal size and place of the EVPLs is as close as possible to a real application solution (8). Board 1 summarizes some examples of papers that have considered some types of real data and what types these data are. It is important to say that some papers have not considered any real data at all, such as (12, 13, 14, 15). It is noteworthy that not considering real data is an accepted simplification that does not make the results wrong, but only not too close from a real application solution in what concerns the sizing and placing of Electric Vehicle Parking Lots.

Board 1 – Examples of use of Real-Data

Reference	Type of real-data
(10)	Electricity price, base load profile, grid generation and consume limitations.
(11)	Arrival rates and parking durations of conventional vehicles, batteries and solar-based DG unit.
(16)	Battery data (power and capacity)
(17)	Practical travel survey data to simulate EV behaviors.
(18)	Road infrastructure and administrative division of a city
(19)	Traffic behavior in each zone and distribution system characteristics
(20)	EV availability, batteries classes and day-ahead market prices.

Source: Prepared by the author (2020).

2.2 STATISTICS

When trying to determine a proper charging infrastructure which favors the growth of the EV fleet, it is important to have in mind that the data required to be analyzed is vastly uncertain and stochastic. Due to this nature of the EV fleet and owners' behaviors, it is required to perform statistical analysis in order to determine scenarios that can be used to evaluate the actions that can be performed in order to ensure the Return on Investment (ROI) and feasibility of the EVPLs.

In (15) the authors have considered different Probability Density Function (PDF) to model some of the parameters considered in the problem. A log-normal distribution was considered to define the distance covered by each EV, whereas the arrival time and departure time were modeled by a Gaussian distribution function. Finally, the initial State-of-charge (SOC) of each EV was modeled as a random variable under log-normal PDF.

Another example of statistical analysis found in the literature is what the author have performed in (10). They divided the Parking lot in two cases: the first was Residential Parking Lot (evening and night-time parking) while the second one was a Business Area Parking Lot (day-time parking). For both cases, the authors assumed that the arrival and departures times were normally distributed (the variance was always 1h, while the mean time was different in each case and if the vehicle was arriving or departing).

A lognormal distribution function was used to generate a sort of inputs (i.e.: EV daily traveled distance) for the first stage of the optimization problem proposed in (20). The same paper also considered the Weibull distributions to determine different probabilistic density functions of wind speed in order to define wind generation scenarios. Still in this paper, the authors have considered four energy and reserve prices scenarios, defined as the average price of 90 days for each season.

The Normal Distribution Function was used in (16) to determine the uncertainties considered in the proposed model: hourly number of newly connected/disconnected EVs and the SOC of EV batteries while connecting to EVPL. The authors defined five different scenarios with the probabilities μ-2σ, μ-σ, μ, μ+σ and μ+2σ.

More robust statistical methods were considered in (17) and (11). In the first paper, the authors used the Monte Carlo Simulation method to sample the EV parking, driving and charging behaviors, considering a 15-minute time interval on the simulation. The second paper, on the other hand, considered the Markov Chain Monte Carlo Simulation to create generalized models to EV arrivals and parking duration and also to determine artificial annual scenarios for the solar irradiance (used in the solar generation).

A final example of statistical analysis was found in (21) according to which the authors defined a series of probability density functions (PDFs) based on the charging behavior of 221 real residential EV owners monitored over a year, across the United Kingdom (UK). The PDFs created can be used in realistic, stochastic detailed studies related to EV in order to consider the impacts of the EV owner behavior (i.e.: number of connections per day, initial/final SOC, start charging time for both weekdays and weekends). The biggest advantage of the PDFs defined in this paper is the fact that they were based on observations of EVs instead of internal combustion engine vehicles, what makes the PDF closer to a real EV owners' behaviors.

When performing a study to proper site and size EVPL, the data that will be handled is in its majority stochastic. When this stochasticity is neglected, it simplifies the problem but does not match to the real nature of the EV characteristics and the owners' behaviors (9). Going further, remembering that most of the data is naturally stochastic (i.e.: load, EV demand and SOC) in (22) it was demonstrated that a deterministic approach cannot properly determine the frequency of technical problems and their consequences. Moreover, the stochastic approach can be adapted to special EV conditions such as locations and type of consumers. As can be seen in Board 2 the most common approach is the deterministic.

Board 2 – Stochastic and Deterministic Approaches

Reference	Approach
(11)	Stochastic approach: EV Demand considered stochastic. Considered a deterministic approach to solve the problem.
(16)	Hourly number of newly connected/disconnected EVs and SOC considered Stochastic. The planning period, inflation rate, size of EVPL, number of EVs considered Deterministic.
(15)	The input data of the model were considered stochastic (i.e.: distance that EV covers, arrival/departure time, SOC).
(17)	While the EV charging loads and the charging demands for the fast charging station (FCS) were modeled as stochastic data. On the other hand the travel speed, SOC, average day temperature and EV type were considered deterministic.
(20)	Fully stochastic approach.
(10), (13), (14), (12), (18), (19)	Deterministic.

Source: Prepared by the author(2020)

A very important stochastic data, when sizing and siting EVPLs, is the traffic flow and the EV owners' behavior (23). The main reason is that these data will define when and where the EV will be charging, how many EVs will be charging at the same time and how long it will last (24). Furthermore, these data will affect directly the profit of the EVPLs (8).

One of the first attempts to solve the location of charging points, considering the traffic flow, was formulated by (25). The authors proposed a formulation based on the flow-capturing location model (FCLM) and previously extended considering the flow-based and node-based demands. The disadvantage of the proposed method relies on the fact that it assumes that a facility located in a certain path will serve all passing vehicles, while it is known that EVs require multi-charging station system in order to accomplish long journeys (18).

In (26) the authors used transportation models to define a transportation network traffic flow, creating an unconstrained traffic assignment model transportation system behavior. The drawback of this model is that it is not based on real systems like the one proposed in (27), based in Western Denmark historic data from January 2006 to December 2007. Good models of EV behavior were found in (21) according to which the authors developed a series of PDFs to define charging behaviors of EV owners, based on the observation of more than 200 EVs for 2 years. As it can be seen in Board 3, the traffic flow is not taken into consideration in most of the studies.

Board 3 – Traffic-flow considerations in some papers

Reference	Traffic-Flow Considered
(10), (11), (13), (14), (17)	No traffic-flow considered.
(16)	EV traffic behavior based on (28).
(15)	Distance covered by each EV.
(20)	It was assumed that the EVs in a certain geographical area follows a certain behavior.
(12)	Arrival/departure patterns scenarios considered as the base for defining traffic-flow.
(18)	Authors considered that the EVs travel only through the shortest path.
(19)	Authors considered 2 main types of traffic patterns: Residential to Commercial area travel and Residential to Industrial area travel.

Source: Prepared by the author (2020).

It is important to remark that not considering the traffic flow does not invalidate the method, but it makes it only less close to a real application solution. Furthermore, adjusting the charging infrastructure closer to traffic patterns, gathered from the statistical analysis performed, is very important to encourage people to buy EVs. In other words, as showed in (29) it is important to consider the interaction between the transport system and the power system. Another example that reinforces this can be found in (30) that demonstrated the higher request for public charging infrastructure in long drives, while, for short drives EV owners usually charge the vehicles during the evening at home. Moreover, (31) highlights how psychological factors (i.e.: EV costs/benefits, social influence and consumer's range anxiety) have an enormous influence not only in the drivers' behaviors, but also the charging behaviors.

2.3 IMPLEMENTABILITY AND SCALABILITY

In what concerns the implementability and scalability of a solution to site and size EVPLs, it is important to answer some questions such as:

a) How will the model perform in conditions similar to those found in real systems?

b) About the software used, can it be adopted by the planner of EVPLs?

c) Is it possible to scale the proposed solution?

A simplified system must be used in preliminary studies, in order to easily analyze the performance of the method. But it is really important to test the proposed solution in more complex systems to properly evaluate its scalability. An interesting example of a simplified case study used in preliminary studies and then tested in a more complex system was found in (26). In this paper, the authors mixed two different networks, transportation network and distribution network, in order to define a planning strategy to place EV charging stations. Firstly, they evaluated the proposed method in a 12-node transportation network highway coupled with the 33-bus IEEE test system and, in a second step, they tested the method in the IEEE 123-bus test system coupled with 4 12-node transportation networks.

The IEEE test systems are a good starting point to evaluate the performance of the methods. Some examples of IEEE test systems found in the literature are the IEEE 13-bus radial distribution system used in (20) and the IEEE 37-bus radial distribution system considered in (19). Other works performed simulation in simplified generic systems, such as the 28-bus system used by (16), the 33-bus radial distribution systems considered in (13) and a modified version found in (14), the 69 node radial system used in (15).

The main drawback of the IEEE test systems is that they generally do not reflect all the challenges faced in real and large systems. In this way, it is important to test those methodologies in order to validate them to be used in more complex systems like the observed in the real world. An example of a real system used to test a methodology was found in (18). The authors considered that the government will deploy battery charging and recharging stations in order to stimulate the use of EVs in the Dalian District (China).

In (17), the authors considered the development planning map of the Longgang District in Shenzhen (China) in order to proper locate charging stations along the district. The area covers about $196km^2$ with a population of 740,000 inhabitants and an EV population of 16,000 predicted for 2020. The author also considered a dynamic equilibrium of the EVs coming into and out of the area under study, so the charging demands occur only in the district.

According to (32), the simulation environment must be prepared to exchange information to be used in specialized grid impact simulations and optimally evaluate the performance and economic benefits of EV insertion and the EVPLs. Moreover, it is important that the selected software should be able to handle stochastic data, as well as be widely adopted by EVPL planners.

elated to the simulation environment used in some studies, a few of them used the software Matlab®, which was used in (10) and (14). The last also used the Global Optimization Toolbox from Matlab® in order to use the Genetic Algorithm method to achieve an optimal solution for the proposed method.

Another software used was the high-level modeling system for mathematical optimization, called GAMS. It is designed for modeling and solving linear, nonlinear, and mixed-integer optimization problems. In (11) the authors used the BARON solver to validate the proposed model. The BARON solver can implement deterministic techniques relying in methods for global optimization (33). The CPLEX solver, designed to solve large, difficult problems quickly and with minimal user intervention, was used in (20) and (19). to solve the Mixed Integer Linear Programming (MILP) formulated in each paper.

2.4 VEHICLE-TO-GRID AND ANCILLARY SERVICES: POSSIBLE FUTURE REVENUES FOR EVPL

Although this work has not considered the EVPL to operate using the V2G protocol, this can be an interesting strategy in the near future in order to increase the revenue possibilities and then the profitability of the EVPL business.

V2G uses communication protocols to exchange messages between EVs and power grid in order to control and manage the EV loads (batteries) by the EVPL operator or the DSO. The V2G strategy can be classified in unidirectional or bidirectional V2G. In the first one, the communication occurs only to charge the EV batteries, while in the bidirectional V2G the batteries of EVs might be charged and/or discharged.

Both V2G categories might be useful to the system. Unidirectional V2G might help in grid overloading, system instability and voltage drop issues by providing active power supply (34, 35). Bidirectional V2G not only provides active power supply but also reactive power supply. In this way, bidirectional V2G would provide reactive power support, power factor regulation and support for the integration of renewable energy resources (RER) (36).

This strategy becomes stronger with the increase of RER and their intermittency due to the fact that EVs might act as a load (absorbing the excess of generation provided by RER) or a generator (delivering power to the grid when RER are in the low generation scenarios) (3). Other positive impact of the V2G strategy is the reduction of greenhouse gas emissions when this strategy is applied integrated to distributed RER (37).

Despite the benefits of the V2G strategy, the smart grid and V2G technologies are under development and the main challenges are: communication schemes, power interfaces, battery technology (38). Furthermore, other energy storage system schemes have been proved to be more efficient (pumped hydroelectric storage, fly wheel and concentrating solar power (CSP) are among the developed technologies used worldwide). For example, the CSP has 99% efficiency and can store energy further than EV batteries (39, 40).

Although the V2G strategy has a very positive future perspective, it has not matured yet; therefore, it requires more detailed studies relying, specially, on battery lifetime, communication schemes, weak grid dynamics, network protection and reliability, and so on (7). Other V2G challenges are investment costs, especially in hardware and software infrastructure (36), and the social barriers. This last challenge refers to the growth of EV fleet and the anxiety range of EV owners who tends to ensure a certain SOC in the EV batteries for unpredicted cases (28, 40).

Despite the-above mentioned benefits, the V2G bidirectional strategy causes battery degradation and must avoid social barriers. This social barriers come from the habit that EV owners tend to have of usually charging the battery with the highest SOC level as possible (36).

Furthermore, V2G and ancillary services are intimately connected since the first can be used to provide this type of service. If an EVPL has the capability to allow EVs to perform V2G process, it is possible to offer high market value services to the grid with minimum effect on the EV storage system, such as regulation, spinning reserve, peak power support, power quality (41)-(47). In Brazil the ANEEL's Regulation nº697/2015 defines the procedures and parameters to provide ancillary services.

Some papers have analyzed the feasibility of the electric vehicles contribution to the grid ancillary services. In (48) it was analyzed the feasibility of the V2G in acillary services considering the French electric vehicle market and the EV production from 2010 to 2013. The authors considered 8 EV scenarios and different commuting behaviors. The main restrictions to the availability of the V2G ancillary services, according to the author, are related to the need of performing depth cycles (around 80% of discharge), which may lead to a degradation of the EV batteries.

Another interesting approach considered a typical case in the Western Danish power system with large wind power production was found in (49). The authors performed simulations considering the use of an aggregated battery storage model in load frequency control in order to analyze the application of V2G systems to provide power regulation. A real application was found in (50), where the authors performed a practical demonstration of the V2G applied to provide real-time frequency regulation from EVs in the PJM power system.

In (51) the authors analyzed the impact of the journey patterns of EVs related to the capability to provide ancillary services. The study considered the traffic data of 349 electric vehicles from across the UK to explore journey patterns, focusing on duration and range. Based on this data the authors identify generic journey patterns for a range of commercial and domestic users. They identified that in the majority of the cases drivers required less than half of the battery capacity to the daily journey. The authors also demonstrated that the commercial and private fleets profiles can provide a limited peak shaving service. On the other hand, there are some opportunities for those vehicles not used primarily for commuting activities.

2.5 TECHNICAL ASPECTS

In order to achieve a technical and economical feasible EVPL infrastructure, it is crucially important to define which technologies will be used. For example, what battery technology will be used (e.g.: Lead-acid or Lithium-ion)? This is necessary to ensure that the EVPL will be profitable for owners and able to offer quality service to consumers. In this regard, the EVPL owner must be aware of the technological options available.

Concerning batteries, since they have experienced a significant evolution in the last years, there are great options depending on the objectives and the investment capacity. On the other hand, the charger market is quite new, compared to the batteries market; however, different available options can be found in charger technology.

In Appendix A there is a detailed discussion about the state of the art of batteries and EV chargers. Their characteristics, as well as their technological details, are presented.

2.6 SUMMARY OF THE CHAPTER

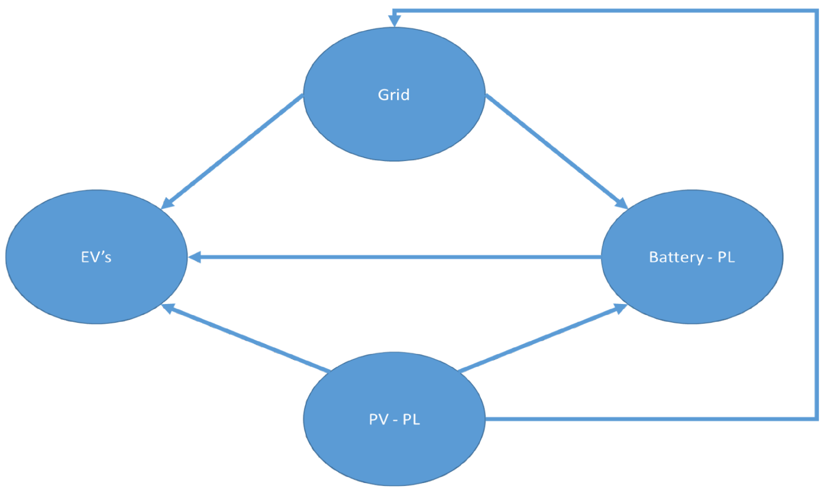
This chapter presented the key aspects to site and size EVPLs in real applications as well as its operation with renewable energy available to do so. The main topics approached were related to computational effort, statistics, scalability and implementability and its impact when determining a methodology to be adopted when planning the installation and operation of an EVPL. This chapter also approached the proposed strategies, available in literature, to operate an EVPL with renewable energy. It also deals with the importance of considering the technological aspects related to batteries and charges.

3 PROPOSED METHODOLOGY

As presented in Section 1.1 the main goal of this work is to propose a method to evaluate the installation of an Electric Vehicle Parking Lot (EVPL) in public and strategic places, such as a shopping center parking lot. The proposed strategy will define the best sizes of an Energy Storage System (ESS) considered as a battery, Photovoltaic (PV) panels and chargers to be used by the Electric Vehicles (EV) that would come, in order to ensure that the EVPL has the greatest profit during the considered planning period.

This is related not only to the EV load profile, but also to the cost of buying and the revenue of selling energy to charge EVs. Chart 2 show all the possible energy flows during the EVPL operation.

Chart 2 – Energy Flow



Source: Prepared by the author (2020).

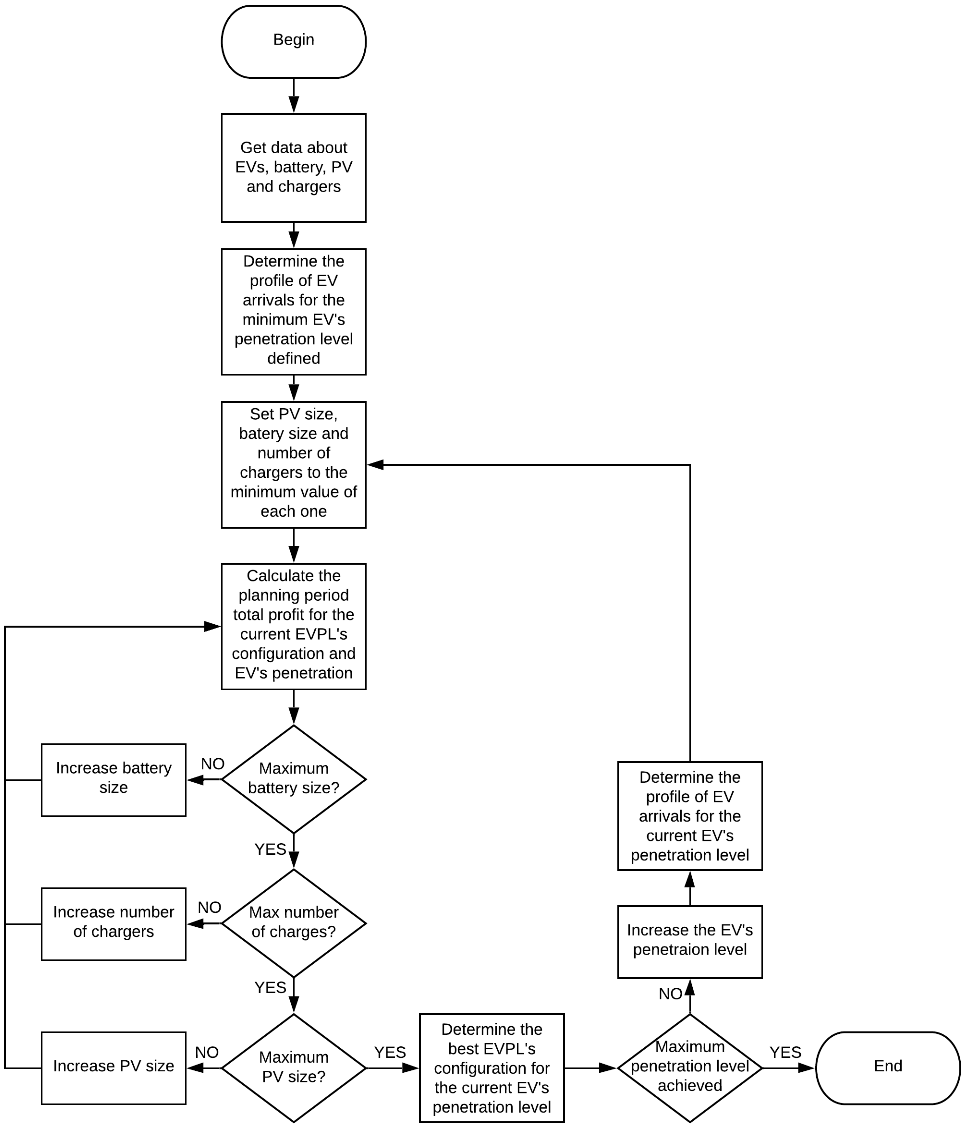
The EVPL will be have the option to inject the excess of solar energy generation. This work did not consider any possible renevenues from the injection of energy into the grid, such as feed-in tariff, metering system, free market operation and ancillary services. The EVPL can store energy (from PV panels or the grid) in the ESS batteries in order to use this energy to charge EVs when the energy tariff is higher. Finally, all EVs will be charged only by the EVPL's PV panels, ESS batteries and DSO grid, using one or more of them at the same time.

3.1 PROBLEM FORMULATION AND METHODOLOGY PROCEDURE

The goal of this problem is to minimize the overall costs related to the installation, operation and maintenance (O&M) of the EVPL. To do so, it is performed an approximation. This methodology first minimizes the operational costs of the EVPL for a typical week and determines the profit of this week. After this it is calculated the annual profit of the

EVPL multiplying the operational profit for the number of weeks in a year (52 weeks). During the first year of the planning period, the investment costs are discounted, as well as the energy demand costs. In the following years, the maintenance costs and the energy demand cost are to be discounted. If any equipment requires replacement due to the fact it has reached its lifespan, the replacement cost will be discounted as well at the respective year. Those costs will be discussed later on. Finally, the results of each year are aggregated in order to determine the planning period total profit. Flowchart 1 summarizes the process.

Flowchart 1 – Flow chart to determine the total profits for the considered planning period and each EV penetration level



Source: Prepared by the author (2020).

3.1.1 Objective Function

In order to minimize the operational costs, based on Figure 2 the objective function can be written as Equation 3.1:

$$\min \sum_{h=1}^{N} \left\{ \begin{array}{l} -C^h_{sell} \times E^h_{bat-EV} + C^h_{buy} \times E^h_{grid-bat} + C^h_{PV-bat} \times E^h_{PV-bat} + \\ +(C^h_{buy} - C^h_{sell}) \times E^h_{grid-EV} + C^h_{PV-grid} \times E^h_{PV-grid} + C^h_{surp} \times E^h_{surp} - \\ -C^h_{sell} \times E^h_{PV-EV} \end{array} \right\} \quad (3.1)$$

Where:

a) N: Number of discretion time intervals;

b) h: time interval;

c) C^h_{buy} and C^h_{sell}: to buy from the grid and sell to EVs, respectively;

d) C^h_{PV-bat} and $C^h_{PV-grid}$: Costs to send energy from the PV to charge the battery or feed the grid, respectively;

e) C^h_{surp}: Cost of wasted surplus PV generation;

f) E^h_{bat-EV}, $E^h_{grid-EV}$ and E^h_{PV-EV}: Energy used to charge the EVs from battery, grid and PV, respectively;

g) $E^h_{grid-bat}$ and E^h_{PV-bat}: Energy used to charge the battery from grid and PV, respectively;

h) $E^h_{PV-grid}$: Energy injected into the grid from the PV;

i) E^h_{surp}: Surplus PV energy generated.

3.1.2 Constraints

To ensure the feasibility of the solution it is necessary to consider the following constraints:

a) EV charge constraint (Equation 3.2): To ensure that all the energy needed to charge the EVs will be supplied, through the use of batteries, PV panels or the grid;

$$\sum_{h=1}^{N} \left\{ E^h_{bat-EV} + E^h_{PV-EV} + E^h_{grid-EV} \right\} = \sum_{h=1}^{N} E^h_{Charge_EV} \quad (3.2)$$

b) ESS battery charge/discharge constraint (Equation 3.3): This constraint represents the energy balance of the battery. Thus, this constraint relates the time interval $h-1$ with the current interval h. In this constraint L_{ChBat} and $L_{DischBat}$ represents the losses when charging and discharging the ESS battery, respectively. Also, the amount of energy stored in the ESS battery at the end of interval h and in the previous interval are E_{bat}^{h} and E_{bat}^{h-1}, respectively;

$$\sum_{h=1}^{N} \left\{ \begin{array}{l} E_{bat}^{h} + E_{bat}^{h-1} + (1 - L_{DischBat}) \times E_{bat-EV}^{h} - (1 - L_{ChBat}) \times E_{grid-bat}^{h} - \\ -(1 - L_{ChBat}) \times E_{PV-bat}^{h} \end{array} \right\} = 0 \tag{3.3}$$

c) PV panels constraint (Equation 3.4): To ensure that all the photovoltaic energy generation is used to charge the ESS battery, charge the EVs, injected to the grid or lost;

$$\sum_{h=1}^{N} \left\{ E_{PV-bat}^{h} + E_{PV-grid}^{h} + E_{PV-EV}^{h} + E_{surp}^{h} \right\} = \sum_{h=1}^{N} E_{PV}^{h} \tag{3.4}$$

d) ESS battery charge/discharge rate limits: Equation 3.5 shows the ESS battery charge rate limit, while 3.6 the discharge rate limit constraint. B_{size} is the size of the ESS battery, in kWh;

$$\sum_{h=1}^{N} \left\{ E_{grid-bat}^{h} + E_{PV-bat}^{h} \right\} \leq \Delta_{Charge} \times B_{size} \tag{3.5}$$

$$\sum_{h=1}^{N} E_{bat-EV}^{h} \leq \Delta_{Discharge} \times B_{size} \tag{3.6}$$

e) Bounds: No decision variable can have a value lower than 0 (zero). Related to the upper limit:

- ESS battery SOC limits: The SOC in each time interval must be equal or greater than 0 (zero) and and cannot be lower than SOC_{min} or bigger than SOC_{max}, which must be predefined and depends on the battery technology considered;
- PV generation energy flows: All the energy flows from the PV panels in a specific time interval must be equal or greater than 0 (zero) and cannot exceed the PV generation at that time interval;
- The energy from the grid has no limits.

3.1.3 Calculating the planning period profit

After determining the profit on the operation of the EVPL considering all of the N time intervals the Objective Function result will give the total profit of this operation. The next step is to calculate the total profit for the planning period. In order to do so, as presented in Section 3.1 the profit for each year must be calculated. Equations 3.7, 3.8 and 3.9 summarize this process. It is important to remark that the EVPL's operation profit was negative because it is minimizing the costs.

a) Profit of the first year of operation (P_Year in Equation 3.7):at this stage, it must be discounted from the operational profit ($Profit_{Oper}$) the energy demand cost defined as the product of the contracted energy demand (E_{Dem}) with the energy demand tariff ($C_{E_{Demand}}$) charged to the A4 consumers group. Moreover, the following equipment investments must be deducted from the operational profit:

   - Chargers (I_{chs}): the money invested to buy the EV chargers;
   - Battery (I_{bat}): the cost of the ESS battery based installed in the EVPL;
   - PV generation equipment (I_{PV}): This is related to the amount invested to buy and install the photovoltaic generation system.

$$P\_Year = -52 \times Profit_{Oper} - I_{chs} - I_{bat} - I_{PV} - E_{Dem} \times C_{E\_Demand} \times 12 \quad (3.7)$$

b) Profit of all year, excepting the first year and years during which it was required to replace any equipment (P_Year in Equation 3.8): This is done similarly to the profit of the first year. The difference is that at this point there is no deduction of the investment in equipment, but only the maintenance costs of them. The energy demand cost is also deducted the same way as in the first year;

   - Chargers (M_{chs}): EV chargers maintenance costs;
   - Battery (M_{bat}): ESS Battery maintenance costs;
   - PV generation equipment (M_{PV}): PV panels maintenance costs.

$$P\_Year = -52 \times Profit_{Oper} - M_{chs} - M_{bat} - M_{PV} - E_{Dem} \times C_{E_{Dem}} \times 12 \quad (3.8)$$

c) Profit of years in which any piece of equipment required replacement (P_Year in Equation 3.9: The only difference from the previous equations is that when any equipment reaches its lifespan and needs to be replaced by a new one, at this year the investment cost of all the replaced pieces of equipment is deducted instead of the maintenance costs of them. Equation 3.9 is an example of the photovoltaic generation inverters.

$$P\_Year = -52 \times Profit_{Oper} - M_{chs} - M_{bat} - M_{PV} - E_{Dem} \times C_{E_{Dem}} \times 12 - I_{Invts} \quad (3.9)$$

3.2 SUMMARY OF THE CHAPTER

This chapter presented the proposed methodology adopted in this work in order to evaluate the feasibility of the EVPL operation in a long-term planning period. The energy flow considred and the proposed problem were discussed. Furthermore, the objective function and the constraints were also presented and detailed in this chapter, also.

4 RESULTS

This work analyzed the feasibility of installing an EVPL in a shopping center. In order to do so, different EV penetration levels and configurations were simulated (with and without batteries and PV panels) and the following economic aspects were determined to the best configuration in each case:

a) Net Present value (NPV): this economic index represents the difference between the present value of cash inflows and the present value of cash outflows over a period of time;

b) Internal Rate of Return (IRR): it compares the initial investment and the future project expenses with the potential return of this project. The IRR is expressed as percentage and is based on the project's cash flow. To say if the project is valuable or not, the IRR must be compared with the investor's hurdle rate.

The option to consider these two aspects is related to the fact that not always a single economic aspect is enough to determine if investments in a specific project are valuable from the economic perspective. Sometimes, by analyzing only the NPV, for example, it is possible to find positive values, but the IRR is lower than the hurdle rate. In this case, it might lead to the conclusion that investments in such a project are not so attractive.

4.1 PARAMETERS OF THE ANALYSIS

To proper evaluate the proposed methodology, some parameters were assumed. The key parameters are related to the economic aspects (i.e.: dollar exchange rate, planning period, energy and demand tariffs), the EVs and charger characteristics, battery technology and the PV panels details. Although some of them have been cited before in this thesis, they will be summarized in this section.

4.1.1 **Economic Parameters**

Before the installation of any business, it is very important to perform an economic evaluation of it. This will help investors to have a clearer idea about the return they can achieve before investing their money on this business. In other words, the economic analysis will show the profitability of the investment.

Power system projects normally have a quite long lifespan (15 years or more). Also, the operational costs (i.e.: fuel) of those projects occur after they have been commissioned. So, this expenditure will happen throughout the project lifespan. Therefore, it is of the utmost importance to consider the value of money over time, considering an adequate discount rate (52).

In the present work, a set of real data has been considered to proper evaluate the methodology. The energy costs were obtained from tariffs of a DSO in the southeast of Brazil: Companhia de Eletricidade de Minas Gerais (CEMIG).

a) Planning period: 20 years;

b) Discount Rate: 10% yearly;

c) Hurdle Rate: 10% yearly;

d) Dollar exchange rate: 4.00 R$/US$ (53);

e) Contract Demand tariff: 13.95 R$/$kW$ (54). This cost was considered since the EVPL will be a consumer of the A4 group of CEMIG and the tariff considered in this study is the Green Tariff. More details can be found in Appendix C;

f) Tariff to sell energy to EVs: 0.62833 R$/$kWh$ (54);. In order to encourage EV owners to charge their vehicles in the EVPL, the tariff for them to charge their EVs was considered the same as the residential tariff for CEMIG's group B3 residential consumer.

In this study, the EVPL was considered a heavy load supplied above 2.3kV. In this regard it is necessary to consider that the EVPL will be under the time-of-use (ToU) tariff system. More details about this can be found in Appendix C. So much so, the considered costs from Equation 3.1, presented in Section 3.1.1, are:

a) C^h_{buy}: due to consumers' characteristics (i.e.: Shopping Center), in this work the cost to buy energy from the grid was considered the CEMIG's Green Tariff for consumers group A4 (2.3kV to 25kV voltage supply). Moreover, it was considered the green flag standard in this work. In this regard:

   – Peak tariff (5pm to 8pm): 1.59969 R$/kWh (CEMIG – Green Tariff for consumers of the A4 group) (54);

   – Off-peak tariff (0am to 17pm and 20pm to 24pm): 0.35666 R$/kWh (CEMIG – Green Tariff for consumers of the A4 group) (54).

b) C^h_{sell}: in this work it was considered the CEMIG residential green flag tariff (0.62833 R$/kWh) (54) as the price of selling energy to charge the EVs;

c) C^h_{PV-bat}: 0.0001 R$/kWh. To incentivize the use of PV generation to charge batteries, this cost was considerably lower than the others;

d) $C^h_{PV-grid}$: 0.0001 R$/kWh. In order to incentivize the injection of PV generation into the grid in order to reduce the monthly net energy consume, this cost was considerably lower than the others;

e) C^h_{surp}: 100 R$/kWh. in order to penalize the surplus of generation this value was considerably higher than the other costs.

It is important to highlight that the costs C^h_{PV-bat}, $C^h_{PV-grid}$ and C^h_{surp} were discounted when calculating the weekly profit of the EVPL, since those costs were adopted in order to penalize or encourage some energy flow.

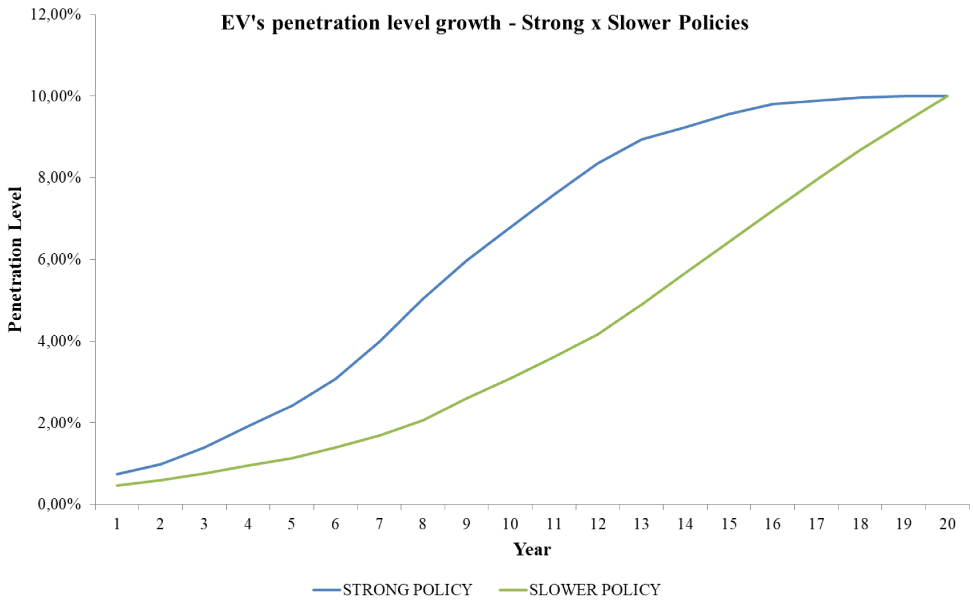
4.1.2 EV and Chargers Parameters

Since it is quite difficult to get data about EVs, specially owners' behavior, traffic flow was assumed to be the arriving vehicles in a shopping center parking lot during a typical week. The considered shopping center is also located in the southeast of Brazil, in a region with social-economic conditions similar to the region of the DSO. It is important to remark that detailed data about the shopping center parking lot (e.g.: number of vehicles and parking behavior of users) are quite difficult to collect because these are strategic information for this business.

In this regard, this work considered the total vehicles traffic flow presented in (55), that estimated the hourly flow of vehicles in a shopping center parking lot for one week. In (55) the authors collected data from a shopping center located in Rio de Janeiro among several months. The data were analyzed, and it was observed that the parking behavior varies in special days (e.g.: weekends and holidays). From this analysis, the authors defined a typical week in order to avoid outliers and future under/over analysis, and to have an adequate representation of the traffic profile of a generic shopping center parking lot. Based on this, this work considered the EV traffic flow based on the typical week proposed in (55) and the operational results for this typical week were exploited for the year.

In order to define the growth of the penetration level two curves were defined to also evaluate the impact of the EV penetration level growth. To do so, the Brazilian market growth of light vehicles was estimated considering the mean growth of licensed vehicles from 2000 up to 2019 (4% yearly), according to the Brazilian Automotive Industry Association (ANFAVEA) (56). Following, in order to estimate the EV market share growth, two policy-based curves were considered based on (57). The first curve considers a Strong Policy that incentivizes the insertion of EVs (e.g.: tax reduction, dedicated parking spaces) while the second considers a Slower Transition representing either a weaker policy or greater practical or economic obstacles. Graph 3 shows an example of these curves for the 10% penetration growth.

Graph 3 – EV growth - policies comparison for 10% penetration level

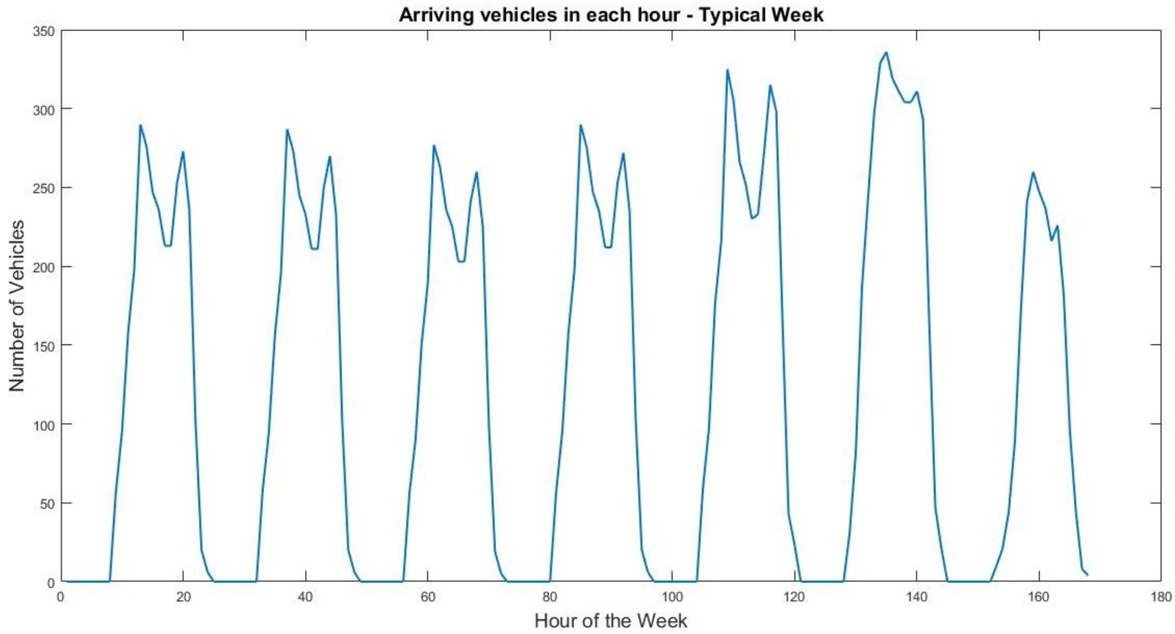


Source: Prepared by the author (2020).

From the perspective of the EV penetration growth, in (2) the authors presented some factors (e.g.: upfront costs, subsidized fossil fuels, lacking of charging infrastructure and high purchasing costs), which are impacting the progress of EVs in Latin America. Even though Latin America governments are deploying some incentives (financial or non-financial) to increase the feasibility of owning an EV, the number of EVs in Latin America is still lower than 10,000 units. This highlights that there is still more work to be done in the future to achieve a greater number of EVs in Latin America countries, and therefore reduce the greenhouse gas emissions.

In this work, the EV traffic flow was estimated considering different EV penetration levels, varying from 1% up to 10% of the total number of vehicles that enter the shopping center parking lot. And for each penetration level this methodology defined the best configuration (battery and PV generation sizes and number of chargers) of the Electric Vehicle Parking Lot (EVPL). Graph 4 is an example of the arriving EVs for 5% penetration.

Graph 4 – Example of EV traffic flow for 5% penetration level



Source: Prepared by the author (2020).

Concerning the EVs, since the Nissan Leaf has one the biggest market share worldwide, aspects of this vehicle were considered in this work. In addition, EV chargers will always be considered in the analyses since the main goal of the EVPL is to provide energy to charge EVs. In this regard, the parameters related to the EVs and chargers are summarized below:

a) EV battery size: 40 kWh. In this thesis, it was assumed that all EVs present a battery similar to the Nissan Leaf (58);

b) EV charging rate: 7.4kWh. All the chargers were assumed to be a "DARK Wallbox Tipo 2 32 Amperios – 230V – Manguera"from (59). The EV charging losses were considered in the EVPL batteries losses;

c) Chargers investment costs (I_{chs}): $US\$$ 860.00 per unit (59);

d) Chargers maintenance costs (M_{chs}): 2.7% of the investment cost (60);

e) Number of chargers: Varied accordingly to the penetration level;

f) Charger life cycle: 20 years.

Since no charging control scheme was considered until this part of the thesis, it was assumed that each EV will be charged for 1 hour and then it leaves the shopping center EVPL. This is in line with a market research made by the Brazilian Association of Shopping Centers (ABRASCE) in 2016 (61). This market research reached the conclusion that consumers stay in a shopping center for 76 minutes in average. Thus, considering 1 hour seems to be a reasonable choice.

4.1.3 Batteries Parameters

As presented in Chapter A there are several battery technologies that can be used as Energy Storage System (ESS) in an EVPL. In this work, the chosen technology was the Li-ion. And the parameters of batteries are as follows:

a) Minimum and Maximum State Of Charge (SOC_{min} and SOC_{max}): 25% and 90%, respectively (13). To avoid damaging the battery during charge and discharge, it is not recommended to charge the battery up to 100% and neither discharge it until 0% (the called deep cycle);

b) Initial State of Charge: 25%, the same as SOC_{min};

c) Discharge and Charge battery losses ($L_{DischBat}$ and L_{ChBat}): 10% (62);

d) Charge and Discharge rates (Δ_{Charge} and $\Delta_{Discharge}$): 100% each (62);

e) Battery investment costs (I_{bat}): 200.00 $US\$/kWh$ (63), considering the installation costs;

f) Battery maintenance costs (M_{bat}): 2.7% of the investment cost (60);

g) Battery maximum size: 1500 kWh;

h) Batteries life cycle: 20 years.

4.1.4 PV Parameters

The PV generation was installed in order to provide energy to charge EVs, charge the EVPL's battery or even inject energy into the grid. It is important to remark that in Brazil there is no feed-in tariff; the regulatory agency, Agência Nacional de Energia Elétrica (ANEEL), determined in Res.482/2012 (64) that the distribution generation is based on the net metering concept. Therefore, in the Brazilian energy system the energy generated by the PV panels can only be injected into the grid in order to reduce the energy consumption, and no money is payed to this energy. In this work, the net metering concept was not implemented. In this regard, PV panels are used just to reduce the energy required from the grid by charging EVs and batteries with the energy generated by the PV panels instead of the energy from the grid.

Since the PV generation system (PV panels, inverters, cables and so on) are quite expensive, but with a considerably long-life cycle, it is very likely that it must be well sized in order not to spend a lot of money in a system that will generate too much energy that it will be lost (neither injected or used in the EVPL) or even invest in a system that will not help to reduce the energy bill since the PV generation is undersized. Following are the parameters of the PV generation system adopted in this work:

a) PV Investment costs considering the inverters and the installation costs (I_{PV}): 1000.00 $US\$/kWp$ mean cost from the presented in (65);

b) Maintenance cost (M_{PV}): 1% of the investment cost (66);

c) PV generation losses: 0%;

d) PV panels life cycle: 20 years;

e) Inverters replacement cost (I_{Invts}): Table 1 summarizes the retail costs of each inverter module market available according to (67). To simplify the analysis, the installation or taxes costs were not considered. Furthermore, the replacement cost is calculated depending on the PV generation system size;

Table 1 – Inverter costs

kWp	**R$**
1	2,250.00
2	2,500.00
3	4,500.00
4	5,000.00
5	6,000.00
6	8,500.00
8	10,500.00
15	14,000.00
25	16,500.00
75	37,000.00

Source: (67).

f) Inverters life cycle: 12 years;

g) PV system maximum size: 1500 kWp.

4.2 RESULTS

To evaluate the economic impact of the PV and ESS battery system in the Electric Vehicle Parking Lot (EVPL) operation, 4 (four) scenarios were simulated. Since the considered EVPL aims at charging EVs, in all of the following scenarios the availability of EV chargers was considered:

a) Battery, PV and chargers available (Scenario 1);

b) Battery and chargers only (Scenario 2), no PV available;

c) PV and chargers only (Scenario 3), no battery available;

d) Chargers only (Scenario 4), no PV or battery available.

For Scenario 1, the results for the Strong Policy and Slower Transition scenarios related to the EV penetration level growth were compared in order to evaluate how it can impact the economic results and, therefore, have some influence in the investment decision of possible investors. For Scenarios 2, 3 and 4 it was considered only the "Strong Policy"curve.

4.2.1 Scenario 1 - Battery, PV and chargers available

In this scenario the EVPL operator can use all the equipment (Battery, chargers and PV generation). In this thesis, as presented in Subsection 4.1.2, the penetration level varied from 1% to 10% of the total number of vehicles, considering the Strong Policy and Slower Transition scenarios for EV penetration level growth. Tables 2 and 3 summarize the best configuration (number of chargers units, ESS battery size, PV generation system size) for each penetration level in each scenario of penetration level growth.

Table 2 – Scenario 1: best configuration for each EV penetration level and financial results - Strong Policy

EV Penetration	Chargers [units]	ESS size [kWh]	PV size [kWp]	Initial Investment [R$]
1%	1	30	10	67,440
2%	2	60	20	134,880
3%	2	60	20	134,880
4%	3	90	30	202,320
5%	3	90	30	202,320
6%	7	210	50	392,080
7%	7	210	50	392,080
8%	7	210	60	432,080
9%	7	210	70	472,080
10%	7	210	70	472,080

Source: Prepared by the author (2020).

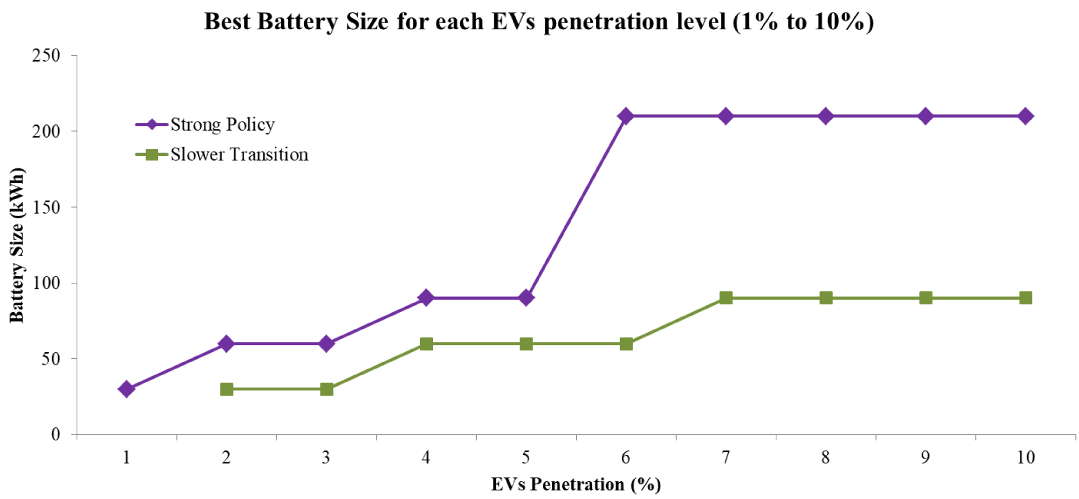
Table 3 – Scenario 1: best configuration for each EV penetration level and financial results - Slower Transition

EV Penetration	Chargers [units]	ESS size [kWh]	PV size [kWp]	Initial Investment [R$]
1%	-	-	-	-
2%	1	30	10	67,440
3%	1	30	10	67,440
4%	2	60	20	134,880
5%	2	60	20	134,880
6%	2	60	20	134,880
7%	3	90	30	202,320
8%	3	90	30	202,320
9%	3	90	30	202,320
10%	3	90	30	202,320

Source: Prepared by the author (2020).

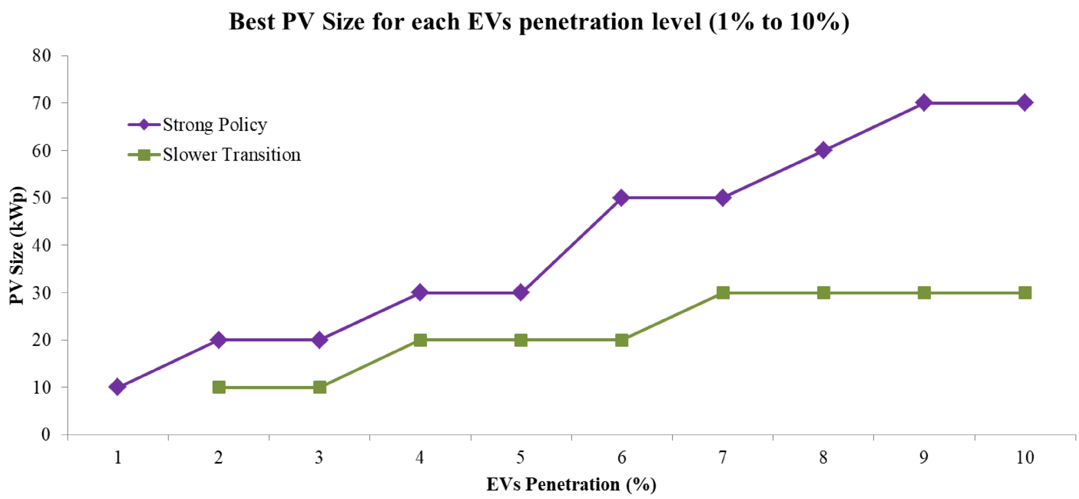
It is interesting to observe that even a linear growth of the EV penetration level does not cause a linear growth of the PV system or the ESS battery system sizes. This reinforces the importance to perform economic studies before installing an EVPL. Graphs 5 and 6 present the variation of the ESS battery and PV system sizes, respectively, for each penetration level analyzed.

Graph 5 – Best ESS battery sizes for each EV penetration level



Source: Prepared by the author (2020).

Graph 6 – Best PV system sizes for each EV penetration level

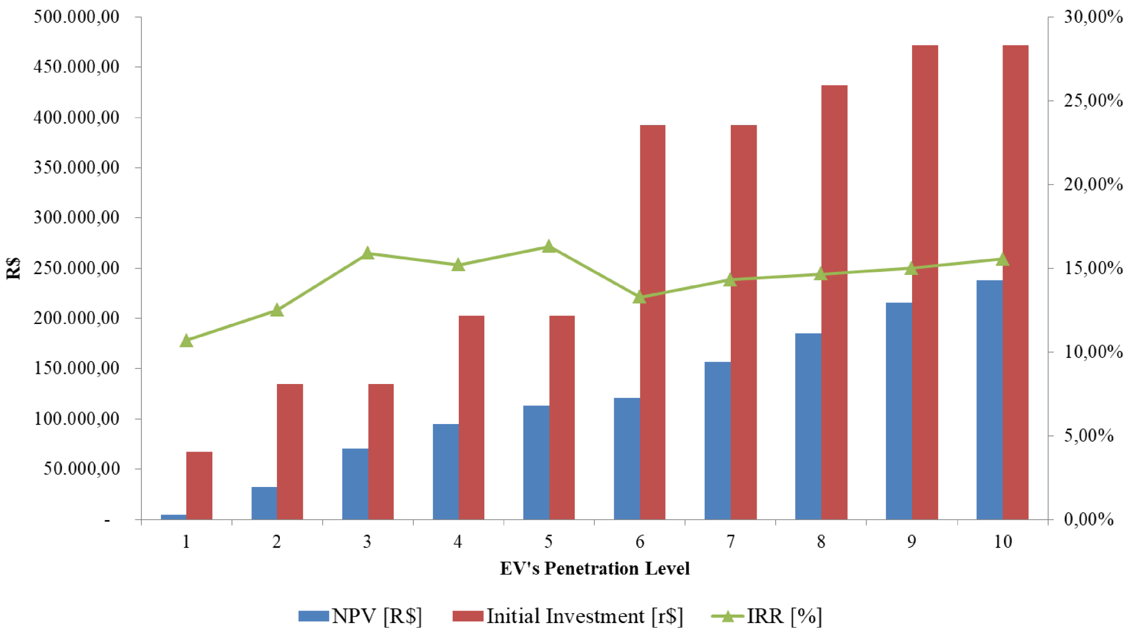


Source: Prepared by the author (2020).

Furthermore, the economic aspects determined for each penetration level (the Net Present Value (NPV) and the Internal Rate of Return (IRR)) reflect how profitable an investment might be. In this regard, it can be inferred that EVPL operations can be profitable if governments adopt policies that incentivize the increase of the EV penetration level.

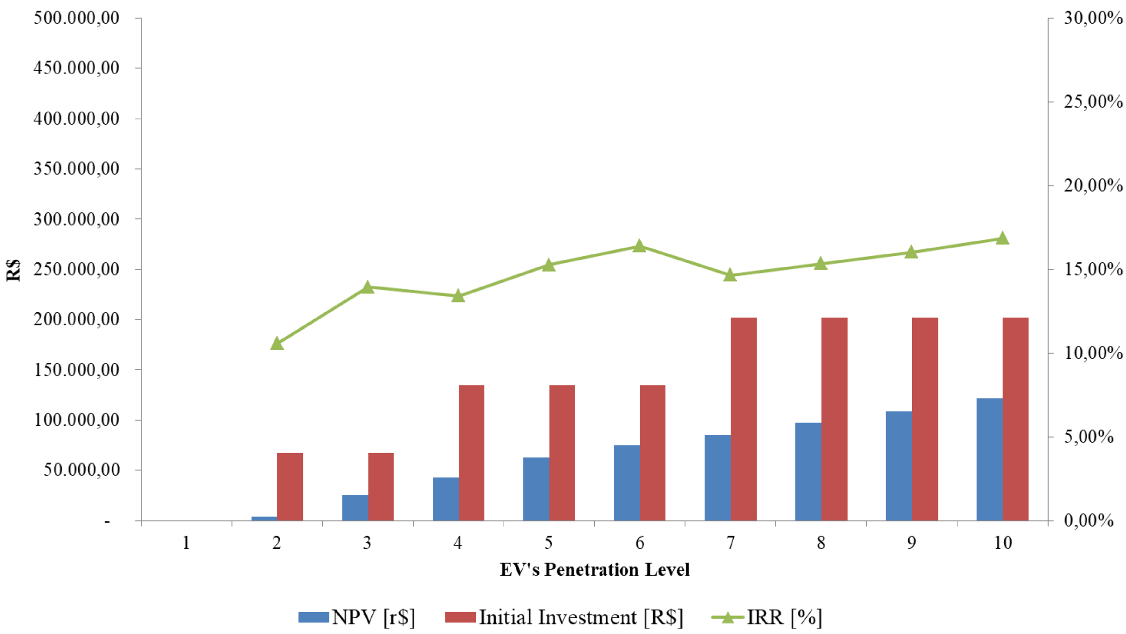
Graphs 7 and 8 show that the EVPL operation can be profitable in almost all cases. Although it is important to remark that as can be seen in Graph 7, for the "Strong Policy"curve, the profitability of the EVPL operation is very low at 1% EV penetration. Thus, as showed in Graph 8, for the "Slower Transition"curve, at 1% EV penetration there is no configuration that can be profitable and at the 2% level the profitability is very low. These results show that there is no linear correlation between the growth of the EV fleet and the growth of EVPL profitability.

Graph 7 – Economic results comparison in a "Strong Policy"scenario



Source: Prepared by the author (2020).

Graph 8 – Economic results comparison in a "Slower Policy"scenario



Source: Prepared by the author (2020).

From Graphs 7 and 8 it can also be seen that differently from the NPV, the IRR does not necessarily grow as the penetration level increases. This happens because, for some penetration levels, the initial investment is considerably higher than the previous one, but the NPV does not follow the same growth. For example, from 5% to 6% the initial investment, it increases almost twice, but the NPV hardly increases. Therefore, it is expected that the IRR for the 5% EV penetration level is bigger than the IRR for the 6% EV penetration level. Despite that, the NPV in both "Strong Policy"and "Slower Transition"scenarios tends to grow as the penetration level increases, but not linearly.

4.2.2 Scenario 2 - Battery only

In this scenario, the PV generation system is not installed. Therefore, the grid is the only way to charge the EVPL's ESS battery while both the grid and the batteries can be used to charge the EVs. Similar to Scenario 1, the penetration level varied from 1% to 10%, but it was only considered the "Strong Policy"curve. Table 4 summarizes the best configuration in each penetration level.

Table 4 – Scenario 2: best configuration for each EV penetration level and financial results - Strong Policy

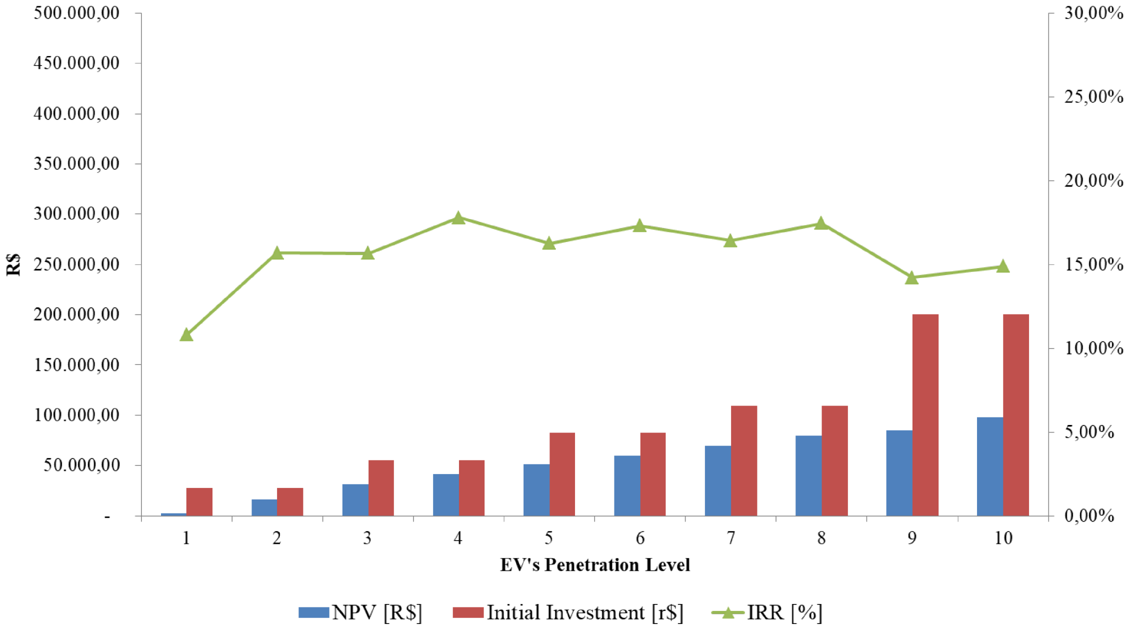
EV Penetration	Chargers [units]	ESS size [kWh]	PV size [kWp]	Initial Investment [R$]
1%	1	30	0	27,440
2%	1	30	0	27,440
3%	2	60	0	54,880
4%	2	60	0	54,880
5%	3	90	0	82,320
6%	3	90	0	82,320
7%	4	120	0	109,760
8%	4	120	0	109,760
9%	7	220	0	200,080
10%	7	220	0	200,080

Source: Prepared by the author (2020).

In this scenario, the initial investment is considerably low due to the high PV system cost, that is considered in Scenario 1. And this reflects on the IRR, since it can increase up to 4% when compared to the 6% penetration level case in Scenario 1, for example. Graph 9 shows the IRR for each penetration level.

On the other hand, this does not ensure that without PV generation the EVPL will be more profitable. As it can also be seen in Graph 9 the NPV in Scenario 2 is at least 2 times lower when compared to Scenario 1 (considering the same policy for the EV penetration level growth). Moreover, in some cases (i.e.: for 10% penetration) the NPV in the second scenario is lower than the result achieved under the "Slower Policy". This implies that, despite the operation of the EVPL it can be profitable even when not installing the PV system, and the final profit can be higher if more money could be invested to buy the PV generation system.

Graph 9 – Economic results under a Strong Policy curve - Scenario 2



Source: Prepared by the author (2020).

4.2.3 **Scenario 3 - PV only**

In this scenario, the battery is not included; therefore, the operation of the EVPL is made only through chargers, the PV panels and the distribution network. Therefore, it is not possible to store energy to be used when the tariff is higher (5pm to 8pm). Similar to Scenario 2, in this scenario it was considered only the "Strong Policy"curve. Table 5 summarizes the best configuration in each penetration level for Scenario 3. In this case from 1% up to 5% EV penetration level, it is not suitable to invest in an EVPL.

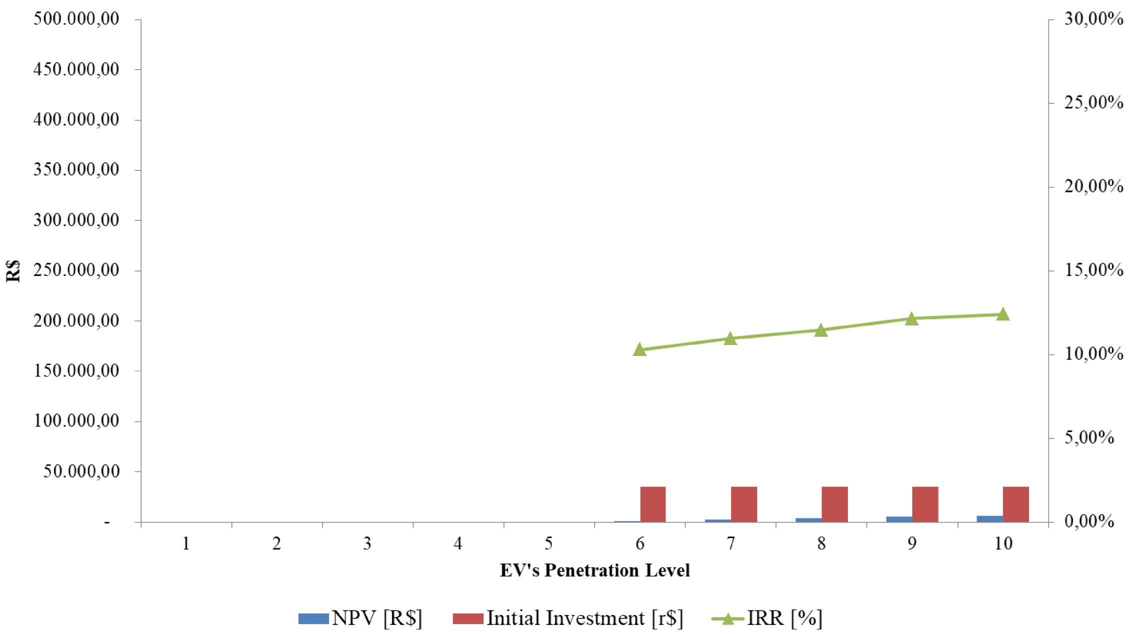
Table 5 – Scenario 3: best configuration for each EV penetration level and financial results

EV Penetration	Chargers [units]	ESS size [kWh]	PV size [kWp]	Initial Investment [R$]
1%	-	-	-	-
2%	-	-	-	-
3%	-	-	-	-
4%	-	-	-	-
5%	-	-	-	-
6%	1	0	8	35,440
7%	1	0	8	35,440
8%	1	0	8	35,440
9%	1	0	8	35,440
10%	1	0	8	35,440

Source: Prepared by the author (2020).

In Scenario 3, the profitability of the EVPL is jeopardized: the NPV was positive only from 6% EV penetration level and beyond, also the IRR was closer to the hurdle rate in all cases, except the one that the operation of the EVPL was not suitable (5% or lower EV penetration level). Thus, even considering the highest penetration level analyzed, the NPV was considerably lower than the presented in the previous results. This reinforces the importance of a storage system in the EVPL operation. Graph 10 shows the NPV, Initial Investment and IRR results for each penetration level in this scenario.

Graph 10 – Economic results under a Strong Policy curve - Scenario 3



Source: Prepared by the author (2020).

4.2.4 Scenario 4 - Chargers only

Scenario 4 considers the operation of an EVPL without PV system and ESS battery, only the chargers were installed and only the grid can be used to charge the EVs. In this case, it is not suitable to invest in an Electric Vehicle Parking Lot (EVPL), in any penetration level, since the operation will not be profitable. This result shows the importance of investing in PV generation and a storage system when working with electrical vehicle parking lots.

4.3 Results Compiled

Tables 6 and 7, where the black spaces indicate that for this penetration level there was no viable configuration, summarize the main results in each scenario and penetration level.

Table 6 – Summary of the NPV results

EV Penetration	Scenario 1 [Strong Policy]	Scenario 1 [Slower Policy]	Scenario 2	Scenario 3	Scenario 4
1%	4,558.58	-	2,400.54	-	-
2%	32,218.61	3,826.84	16,121.11	-	-
3%	70,698.07	25,261.77	31,102.55	-	-
4%	95,232.13	42,627.08	41,743.45	-	-
5%	113,325.22	62,969.08	51,310.12	-	-
6%	121,123.82	75,200.52	59,482.66	782.83	-
7%	156,773.86	85,332.58	69,730.70	2,572.31	-
8%	185,237.44	97,342.36	79,761.05	3,868.03	-
9%	215,770.99	108,661.86	85,055.09	5,648.26	-
10%	237,821.52	121,685.61	97,750.27	6,325.31	-

Source: Prepared by the author (2020).

Table 7 – Summary of the IRR (%) results

EV Penetration	Scenario 1 [Strong Policy]	Scenario 1 [Slower Policy]	Scenario 2	Scenario 3	Scenario 4
1%	10.67	-	10.80	-	-
2%	12.49	10.56	15.69	-	-
3%	15.89	13.94	15.66	-	-
4%	15.21	13.42	17.79	-	-
5%	16.30	15.26	16.25	-	-
6%	13.28	16.40	17.32	10.29	-
7%	14.30	14.64	16.42	10.96	-
8%	14.64	15.34	17.45	11.47	-
9%	14.99	16.03	14.23	12.15	-
10%	15.55	16.86	14.89	12.39	-

Source: Prepared by the author (2020).

4.4 SUMMARY OF THE CHAPTER

This chapter begins defining how the economic aspects will be evaluated and which parameters were considered in this study. Then, it presented the four scenarios that were considered in order to analyze the economic impact of PV generation, batteries and chargers in the EVPL operation. Furthermore, comparison between two policies that reflects the EV penetration growth was presented.

5 CONCLUSION

The Electric Vehicle Parking Lot (EVPL) might be a useful resource for governments that want to increase the penetration of electric vehicles in the country's fleet. This new fleet will bring great benefits to society (i.e.: less noise in the streets, reduction of urban pollution, reduction of the fossil fuel dependency). Moreover, if EVPLs adopt photovoltaic (PV) generation and an energy storage system (i.e.: batteries) the environmental benefits will increase; besides that, this generation can increase the benefits of the DG to the distribution system.

In order to achieve these benefits and ensure that EVPL operators will be able to have adequate profit, it is necessary to perform proper economic studies to determine the best configuration in each case, since it depends on several factors such as:

a) EV traffic flow characteristics;

b) EV owners charging behavior;

c) The Infrastructure technology of choice;

d) Location of the EVPL;

e) EV penetration level;

f) Energy costs.

Based on this, the work presented a methodology to determine the best configuration of an EVPL and to help in the planning of those EVPLs by governments and investors, considering a study case. Besides that, this methodology is based on the economic evaluation, considering the analysis of the return on investment of those structures. To do so, it considers two different scenarios, the "Slower Policies"and "Strong Policies"EV penetration scenarios.

The first observation is that the EV penetration level growth, on its own, is not a factor that will ensure an earlier payback of the investment made. It is very important to consider the policies adopted in order to estimate how they will interfere in the growth of the EV penetration level and then in the return of the investment. Furthermore, this work showed that there is no linear correlation between the EV penetration level growth and the EVPL Interest Rate of Return (IRR) nor its Net Present Value (NPV).

It was also observed that the investment in ESS batteries is a key aspect to make the EVPL profitable, since without this infrastructure, even in the best case the NPV and the IRR are lower when compared to the scenario with less government incentives to increase the EV penetration level.

Another interesting point is that, if the EVPL does not install a PV generation system, its operation might reach higher IRR, compared to the EVPL equipped with PV generation system, ESS and chargers.

On the other hand, an EVPL owner that decides to install a PV generation system, ESS and chargers might reach an NPV more than 2 times greater than EVPL without PV generation. Of course, this will require more investment by the EVPL owner.

Based on the results obtained in this work, it is important to highlight that, in order to have a reasonable return on the investment, the EVPL owner may have to consider investing, at least, in an ESS. However, the investment in a PV System could help to achieve higher profits. Furthermore, renewable generation, storage and EVs, merged with the well-defined policies, are very important in the path to reduce not only the greenhouse gas emissions but also the noise pollution in large cities and achieve the Paris Agreement goals worldwide. Based on this, EVs can play a major role since internal combustion engine (ICE) vehicles are greatly responsible for CO_2 emissions and replacing a part of the ICE vehicles fleet will considerably reduce CO_2 emissions.

However, in order to increase the EV penetration, it is of the utmost importance to provide a robust charging infrastructure. And it mainly depends on governments to define regulations that promote the acquisition of EVs as well as the installation of charging stations, specially the EVPLs.

Since the charging infrastructure is also important to increase the EV penetration and considering that if governments invest on public charging station, this represents a subside to EV owners. So, the private EVPLs can be an interesting alternative to improve the robustness of a region charging infrastructure. Therefore, it is very likely that the private sector and governments put in efforts to ensure the installation of EVPLs in large cities. One strategy is to adopt policies which favor companies or startups focused on the EV market. And those companies, along with the academia, must carry out studies and researches to ensure the installation of a robust charging infrastructure to meet the consumers expectations, as well as minimizing the impact of this structure on the power network.

The integration between governments, private sector and academia is a key solution to stop the vicious circle that disfavors the growth of the EV fleet. And, as presented in this work, if "Slower Transition"policies are adopted by governments, the potential investors will also be unmotivated to take part in the EVPL business. Then, the academia might not get incentives to research new technologies and strategies that will increase the effectiveness of EVPLs. So, this reinforces the importance of governments to taking the first step towards creating an efficient charging infrastructure that might favor the EV sales, increasing their penetration level such as presented in the "Strong Policy"curve, and also encouraging potential investors to contribute to this charging infrastructure and the academia to perform studies and researches.

In this regard, this work highlighted the importance of having in mind that renewables and storage must be taken into consideration when installing the charging infrastructure for EVs. Those three technologies – renewable generation, storage and EVs – are very important to the path to reduce not only the greenhouse gas emissions, but also pollution (e.g.: noisy) in large cities.

So, this work presented a first step in order to help the definition of the proper configuration of an electric vehicle parking lot. Some future works can be performed from this thesis such as:

a) Implementation of a Charging Controller in order to define when and for how long should an EV be charging;

b) Integrate this work with an algorithm that evaluate the impact of the EVPL in the grid. By doing so, it is possible to define the adequate location of the EVPL, reducing its impact on the distribution network;

c) Consideration of real and stochastic traffic data to better evaluate the profitability of the EVPL;

d) Use of other optimization methods (i.e.: meta-heuristics) to achieve the solution in less time;

e) Evaluate the economic results considering different electricity tariffs from other Brazilian distribution companies or even different tariff policies;

f) Assessment of the impact of feedin-tarif and net metering in the profitability of the EVPL.

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APPENDIX A – TECHNICAL ASPECTS

This appendix presents the most common batteries and EV chargers available in the market. The main features of each technology will be presented, as well as their pros and cons. The first part will set up a discussion on batteries, subsequently followed by the EV charger discussion.

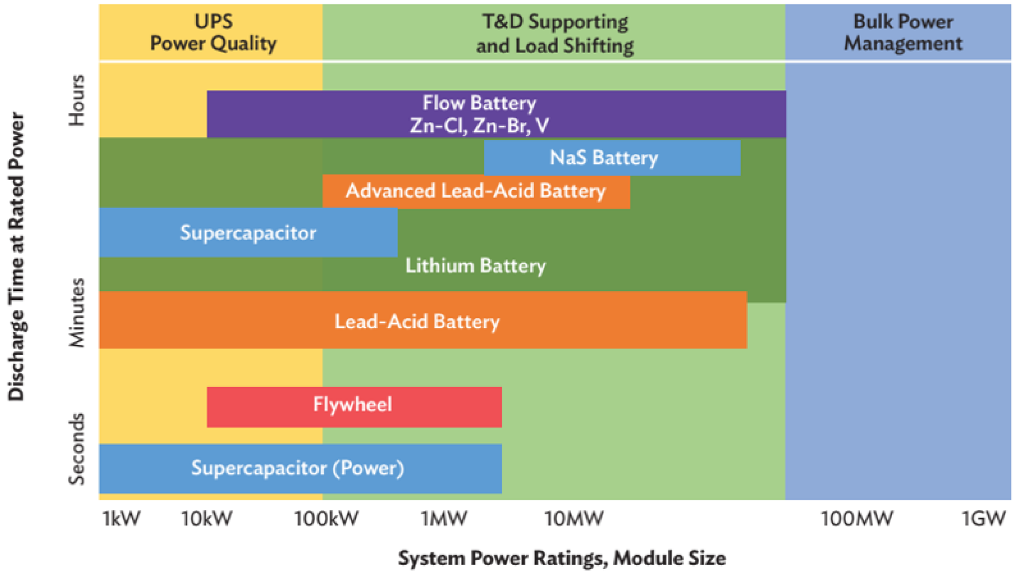
A.1 Batteries

The concern about the environmental issue is affecting the energy generation. Governments are giving more and more benefits to increase the penetration of RER, such as wind, photovoltaic and ocean waves. All of them can reduce fossil fuel energy generation, which might help countries achieve their goals of carbon dioxide (CO_2) reduction and also diversify the energy generation matrix.

Although the RER can provide cleaner energy, these sources are extremely intermittent and quite unpredictable. The uncontrollable increasing penetration of these sources might lead to problems that will negatively effect their integration and not provide all of their benefits. Among those problems, a few can be cited: the risk of overvoltage and undervoltage, frequency fluctuations, difficult to proper set a reliable protection scheme. In this regard, several strategies that combine RER and Energy Storage Systems (ESS) have seemed to be fruitful to mitigate the grid integration of these new generations sources, allowing more flexibility and control of the power systems operation (68).

The ESS can be categorized according to the storage technology used. They are divided into the following categories: mechanical, electrochemical, chemical, electrical and thermal devices. The ESS might apply to several duties such as: uninterruptible power supply (UPS), transmission and distribution (T&D) system support or large-scale generation. The ESS used in each case depends on the technology and storage capacity. According to (69), the technologies most commonly used in UPS and T&D are the reduction-oxidation (REDOX) flow, sodium-sulfur (Na-S), lead–acid and advanced lead-acid, super-capacitor, lithium, and flywheel batteries. Figure 1 compares the main technologies used in UPS and T&D system support considering the electrochemical, chemical and physical energy storage devices.

Figure 1 – ESS technologies comparison considering Power Output and Energy consumption



GW = gigawatt, kW = kilowatt, MW = megawatt, T&D = transmission and distribution, UPS = uninterruptible power supply, V = vanadium, Zn–Br = zinc–bromine, Zn–Cl = zinc–chlorine.

Note: With nominal discharge time ranging from seconds to hours. Both power output and energy consumption are expressed in logarithmic scales.

Source: (69).

Batteries are an ESS technology widely adopted and with a growing market share. This technology is a modular system that can be used to help integrate renewable generations since they can help provide various services (i.e.: frequency regulation, reduce curtailment of wind and solar generations, pick shaving, generation offset).

A comparison about some battery technologies for energy storage devices is presented in Figure 2, according to the following four main characteristics defined in (69):

a) Energy Density: The amount of energy stored in a single system per unit volume or per unit weight;

b) Charge and Discharge efficiency (round trip): performance scale used to assess battery efficiency;

c) Life span: Very important aspect with great impact in the economic efficiency of the battery;

d) Eco-friendliness: This aspect is more and more rising in importance with the growing concerning about environmental issue. So much so, an eco-friendly battery means that it is environmentally harmless and recyclable.

Figure 2 – Battery Characteristics Differentiation

	Energy density (kW/kg)	Round Trip Efficiency (%)	Life Span (years)	Eco-friendliness
Li-ion	1st (150-250)	1st 95	1st (10-15)	Eco-friendliness
NaS	2nd (125-150)	2nd (75-85)	3rd (10-15)	X
Flow	2nd (60-80)	2nd (70-75)	3rd (20-25)	X
Ni-Cd	4th (40-60)	4th (60-80)	4th (5-10)	X
Lead Acid	5th (30-50)	5th (60-70)	5th (3-6)	X

Li-ion = lithium-ion, Na-S = sodium-sulfur, Ni-Cd = nickel-cadmium.

Source: (69).

A.1.1 Lead-Acid (PbA) Batteries

This is the oldest battery technology and it is most commonly used in applications that require high load current values, such as starting internal combustion vehicles and backup power supplies (70). PbA batteries have been used since the middle of the 19^{th} century, therefore, this technology is quite mature and have some benefits when compared to new technologies (68):

a) Simple manufacture leading to a low capital cost;

b) Low self-discharge rate;

c) Low cost per watt-hour;

d) High specific power, capable of high discharge currents;

e) High tolerance of charging and discharging temperature.

On the other hand, this battery has some disadvantages:

a) Poor weight-to-energy ratio;

b) Need of periodic maintenance;

c) Slow charging (14-16 hours to fully charge);

d) Must be stored in charged condition to prevent sulfation;

e) Repeated deep-cycling reduces battery life;

f) Watering requirement for flooded type. This technology of Lead-Acid battery also suffers from transportation restrictions due to the risk of leaking;

g) Adverse environmental impact.

A.1.2 **Redox Flow Batteries**

Redox Flow Batteries (RFB) are one of the newest technologies under use. The charge and discharge of this battery is made up of oxidation-reduction reaction of ions of vanadium or other material used as electrolyte. They are commonly used in bulky energy storage systems with a large number of deep discharging cycles (70). According to (69), the three main types of RFB batteries and their characteristics are:

a) Vanadium Redox Battery: it has two vanadium electrolytes (V2+/V3+ and V4+/V5+). These electrolytes exchange hydrogen ions (H+) through the membrane of the battery in order to charge or discharge the battery;

b) Zinc-Bromine (Zn-Br): the electrodes are made up of a Zinc solution and a complex bromine compound;

c) Polysulfide-bromine (PSB): the electrolytes of this RFB are composed of sodium sulfide (Na_2S_2) and sodium tribromide ($NaBr_3$). Differently from the Vanadium Redox Battery, the ions that pass through the membrane when charging and discharging are the sodium ions (Na+).

Some advantages of the RFB are mainly related to the service life, safety and operation of those batteries:

a) Long service life with large number of cycles: nearly 20 years (69) and more than 10 thousand deep charge and discharge cycles (71);

b) Recent RFB systems use separated tanks for the anolyte and catholyte (72). Moreover, these batteries are not composed of combustible or flammable retardant materials (69), so the chance of a fire is very low. Based on this, flow batteries are inherently safer than conventional batteries (73);

c) Independence of the power and energy outputs: while power depends on the reactor's size, the energy stored is determined by the reactant type and concentration and also the size of reactor tanks (72) and (74).

Despite all the previous mentioned benefits, redox flow batteries have quite obvious drawbacks, since they are quite a new technology still under development:

a) Complexity: pumps, sensors, flow and power management systems are some of the equipment needed to build an RFB, which means this technology is more complicated than conventional batteries;

b) Low energy density compared to other battery technologies: around 25 to 35 W/kg (71);

c) Costs still considerably high, although the development of this technology will reduce them: around 500.00 US$/kWh (70).

A.1.3 **Sodium Sulfur (NaS) Batteries**

This is considered the first commercial battery developed, according to (68), it has been used in residential and industrial application since the 19^{th} century. The Sodium Sulfur (NaS) batteries work by transforming chemical energy in electrical energy when discharging. The charging process works on the other way (electrical into chemical energy).

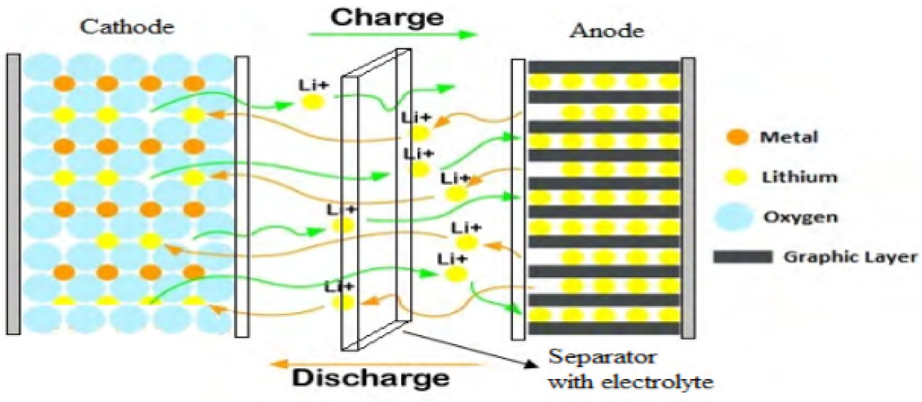
Due to the maturity of the Sodium Sulfur battery technology, they present significant advantages, such as great reliability and relatively low cost (75). They have also a long-life cycle, from around 10 to 12 years, and high charge/discharge efficiency, 89% to 92%. Since the NaS batteries are sealed and operate under high temperatures, their operation is less influenced by the environment.

However, the sodium polysulfides (that is part of the sodium sulfur batteries) is highly corrosive, also the metallic sodium (used in construction) is highly reactive and combustible when exposed to water. In this regard, this technology suffers from some transportation restrictions and requires extra construction costs to enclose the structure in order to prevent leakage. Other disadvantage of these batteries is that they need to be operated above 300°C besides that, the NaS batteries require stringent operation and maintenance (69).

A.1.4 **Lithium-ion (Li-ion) Batteries**

These batteries are increasing their market share year after year due to their superior characteristics and advanced technology (76). The Li-ion batteries are composed of four basic elements: cathode, anode, separator and electrolyte. Normally, the last two are put together as seen in Figure 3, which also summarizes the charge and discharge process.

Figure 3 – Li-ion battery composition and charging-discharging process



Source: (76).

The cathode is a lithium-metal-oxide powder that receives Lithium ions when the battery discharges and leaves lithium ions when it chargers. The anode is a graphitic carbon powder that works unlike cathode: giving lithium ions when the battery is discharging and receiving it when charging. The Li-ion battery chemical reaction is given (77) as follows:

$$LiMO_2 + C \rightleftharpoons Li_xC + Li_{1-x}MO_2$$

The Li-ion batteries are mostly used in electronic devices (i.e.: cameras, calculators, notebooks, mobile phones), and in the last decades it has been considerably increasing the use of this batteries for electric mobility (69). This wide possibility of adoption is related to the main advantages of the Li-ion batteries:

a) High voltage cell: The 3.6V provided by a single Li-ion cell is normally enough to numerous power applications requiring less cell compared to lead-acid or nickel-based batteries, for example;

b) High specific energy and power density;

c) High capacity, with low internal resistance;

d) Simple charge algorithm and reasonable short charge times;

e) Good charging and discharging efficiency;

f) Good performance in a wider temperature range.

Although Li-ion batteries seem to be quite superior to other battery technologies, there are some important drawbacks, such as: the possibility of explosion when charging, requiring protection and control circuits and also transportation regulation for large shipping; the reduction of the life span at high temperatures and when stored at high voltage; the impossibility of fast charge in freezing temperatures; and although it has been decreasing, the cost of Li-ion batteries are still quite high.

A.2 Electric Vehicle Chargers

The charging infrastructure is a key aspect to increase the Electric Vehicle (EV) sales. In this regard, it is extremely important for countries aiming at increasing the EV penetration to provide a proper charging infrastructure: well sited, sized and addressing the different EV chargers found in market.

In China (where the EV fleet is exponentially growing), according to the Chinese Electric Vehicle Charging Infrastructure Promotion Agency (EVCIPA), EV charger grew 80% from January/2018 to January/2019, reaching 880 thousand chargers (330 thousand of them are public). While, in the United States it is estimated that exists 500 thousand electric vehicle chargers, the majority of them being home chargers (78).

Different from gas stations, the chargers can be installed in a huge variety of places since they are much safer: at home, public parking lots, near colleges, shopping centers and so on. The main requests to install a charger station are access to the power grid and a place where the EV can reach. Of course, other requirements (grid and operation safety, for example) must be taken into account.

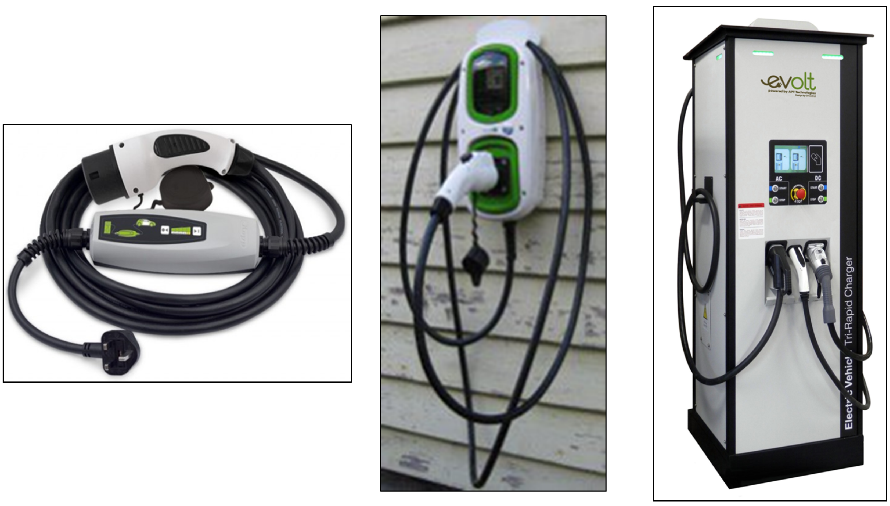
Before discussing the main connectors used by EV manufactures, it is important to address the charging modes existing in the literature. They can be summarized, according to (79) and (80), as follows in Board 4:

Board 4 – EV Charging Modes

Charging Mode	Description
Mode 1	- AC charging method, commonly used for light vehicles; - Chargers at a low current and plugged in common outlet; - Chargers convert alternate current (AC) into DC and controls battery charging; - No longer being used by manufactures;
Mode 2 Figure 4-A	- Temporary transition solution; - Also plugged in a normal outlet; - Has a control box that enhance the safety, compared to Mode 1; - Chargers convert AC into DC and control battery charging; - In general chargers at 2.4kW (10A);
Mode 3 Figure 4-B	- It has a dedicated wall-box with a control built-in; - AC method recommended for day-today charging; - Allows slow and fast charging; - Can charge the EV from 3.6kW (16A, single phase) up to 40kW (63A, 3 phase) - Chargers convert AC into DC and control battery charging; - Safer than Modes 1 and 2
Mode 4 Figure 4-C	- Recommended for fast charging; - The dedicated wall-box converts the AC current into DC current; - More expensive than the previous, but safer; - Able to provide from 5kW up to 150kW;

Source: Prepared by the author (2020).

Figure 4 – Charger Modes: A - Mode 2; B - Mode 3; C - Mode 4



(A) (B) (C)

Source: A and C (82); B (79).

In what concerns the EV charger standardization, throughout the world there are some standards to be followed, varying from region to region. According to (81), the main standards are:

a) Society of Automotive Engineers (SAE): defined the SAE J1772 connector (known as the J-plug). More common in North America EVs;

b) International Electrotechnical Commission (IEC): created the IEC62196 and the IEC61851 standards. The first is adopted in Europe, while the second was adopted in China;

c) Associação Brasileira de Normas Técnicas (ABNT): defined the ABNT NBR IEC 61851-1:2013 as the standardization for EV chargers in Brazil.

So, the EV industry must follow one of these standards when defining which connector will be used in each vehicle. The main connectors standards are:

a) **SAE J1772**: It is a North America standard set by SAE International in IEC 62196-2. This type of connector is also used in Japan. Known as J-plug, it only covers the single-phase AC (120V and 240V) charging, so it allows only slow-charging (type 1 and 2). This plug has a diameter of 43mm. Figure 5 shows one example of this plug.

Figure 5 – SAE J1772 plug

Source: (83).

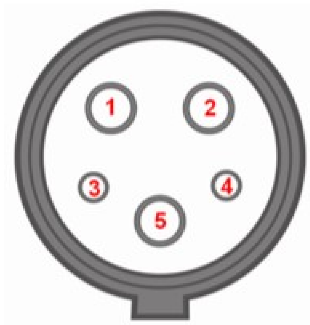
In what concerns the pins configuration, the J-plug has 5 pins, as can be seen in Figure 6. Bellow is the description of each pin showed in Figure 6 and some details:

- AC line 1;
- AC line 2;
- Control Pilot: it is a signal pin used to detect the presence of the vehicle, communicate the maximum allowable charging current and control charging. It is performed by a 1kHz square wave at +/-12 volts generated by the Electric Vehicle Supply Equipment (EVSE);

– Proximity Detection: prevents that the EV moves while charging;

– Ground.

Figure 6 – SAE J1772 pin layout



Source: (83).

b) **Mennekes**: The IEC 62196 Type 2 connector (also known as Mennekes) showed in Figure 7 is another plug that allows only AC charging. The difference for the J-plug is that this one allows single-phase charging (up to 16A) and also three-phase charging (up to 63A), providing power of 3.7kW and 44kW respectively (81). It is commonly used in Europe and the name Mennekes was given because this was the name of the first brand to commercialize this connector.

Figure 7 – Mennekes plug

Source: (84).

The Mennekes has 7 pins, as can be seen in Figure 8. The additional pins, compared to the J-plug, are the neutral pin and another AC line pin. Below is the description of each pin showed in Figure 8 and some details:

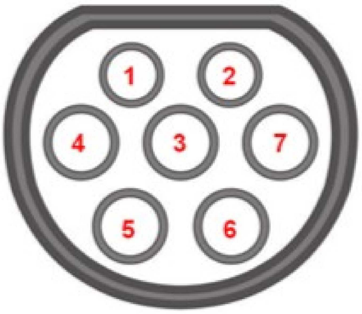
– Proximity Detection: prevents that the EV moves while charging;

– Control Pilot: it has the same function as the Control Pilot pin from the J-plug;

– Ground;

  - AC line 1
  - AC line 2;
  - AC line 3;
  - Neutral.

Figure 8 – Mennekes pin layout



Source: (84).

c) **CHAdeMO**: The name is an abbreviation of "Charge de Move"or in other words "move by charge". This is a DC fast charging pattern developed by the following Japanese companies: Tokyo Electric Power Company, Nissan, Mitsubishi, Toyota and Fujy Heavy Industries. This plug is widely adopted in Japan and USA.

   Differently from the previous chargers, the CHAdeMO allows direct current (DC) charging. The first version can provide power up to 62.5kW (81), but the CHAdeMO 2.0 protocol allows charging power up to 400kW at 1kV DC according to (85). Figure 9 shows an example of a CHAdeMO plug.

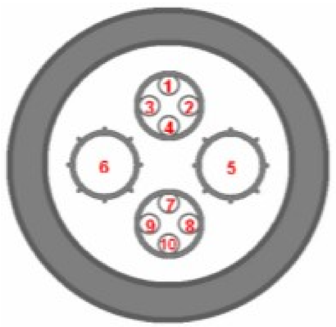
Figure 9 – CHAdeMO plug

Source: (86).

The CHAdeMO has 10 pins, as can be seen in figure 10, and the communication between the EV and the charger station is performed through the Controller Area Network (CAN) protocol. The description of each pin is summarized bellow:

– Ground;
– EV Control Relay 1: Charger start/stop 1;
– Not assigned;
– Charge Control: charging enable/disable;
– Power supply (-);
– Power supply (+);
– Proximity Detection;
– Communication - CAN Pin High;
– Communication - CAN Pin Low;
– EV Control Relay 2: Charger start/stop 2.

Figure 10 – CHAdeMO pin layout



Source: (87)

d) **Combined Charging System (CCS)**: This plug was developed by SAE and IEC and released in 2012. This plug allows both AC and DC charging. According to (88), eight companies adopted this pattern: Audi, BMW, Chrysler, Daimler, Ford, General Motors, Porsche and Volkswagen. The main goal of this pattern is to allow that the EV owners can use the majority of the existing charging stations. Figure 11 presents a CCS plug example.

Figure 11 – CCS Plug

Source: (88).

Due to the wide range of charging types, mainly type 1 (USA) and type 2 (Europe), the CCS plug is also available in two models: CCS Type 1 and CCS Type 2.

- CCS Type 1: The upper inlet is a J-Plug for AC charging levels 1 and 2 up to 19kW. The lower inlet of this plug has two DC inputs for DC fast charging allowing power up to 100kW;
- CCS Type 2: In this CCS plug, the upper inlet is a Mennekes type 2 pattern. The lower inlet is similar to the CCS Type 1.

e) GB/T: This plug standard was developed in China and is still adopted only in this country. "GB"stands for the a Chinese standard *Guobiao* and "T"comes from the chinese word *tuījiàn*, that means "recommended". The GB/T standard can be used for both AC and DC charging. Figure 12 shows an example of a GB/T plug.

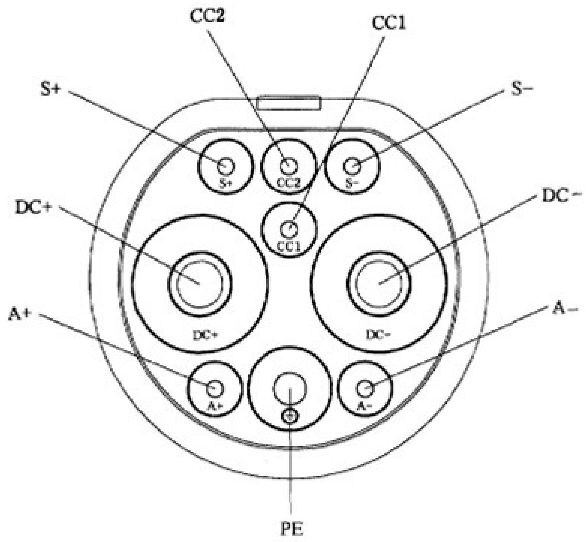
Figure 12 – GB/T plug

Source: (89).

This plug can charge up to 440V AC (63A at maximum) or 1kV DC (250A at maximum) according to (89). The communication between the EV and the charging station is made by the Controller Area Network (CAN) protocol. The pinout of the DC charging GB/T plug is presented in Figure 13 and the description of those pins are summarized below:

– CC1 and CC2: Connection pins 1 and 2;
– S+, S-: Charging communication pins (CAN-high and CAN-low);
– DC+ and DC-: Positive Negative DC power;
– A+ and A-: Positive and Negative low auxiliary power;
– PE: Protective ground pin.

Figure 13 – GB/T pin layout - DC charging



Source: (90).

APPENDIX B – TARRIFF STRUCTURES

Each country has its own tariff system according to the market structure adopted, energy policies, taxes, and social aspects. By definition, energy tariff is the price charged from consumers by the amount of energy they have requested from the grid during a specific time. The tariff also includes the generation, transmission and distribution costs, losses and also taxes (91).

According to (81), the most common tariff models applied worldwide are:

a) Flat rate;

b) ToU (Time of Use);

c) RTP (Real Time Pricing).

In the following sections those models will be briefly presented

B.1 Flat Rate

This model is characterized by a single price regardless of the time of consume. It is applied, in example, for the Brazilian residential consumers, called group B. The main advantage of this model is its predictability, since the consumer might know how much it will cost to use the energy regardless of the time. The drawback of this model is that it does not encourage the efficient energy consume (92).

B.2 ToU (Time of Use)

Different from the Flat Rate, the ToU model presents two or more different energy prices based on distinct periods of the day. Considering two levels, they are called peak period and off-peak period, based on the demand level during the day:

a) High demand levels increase the energy system costs, leading to higher tariffs. This is called **peak period**;

b) On the other hand, in the rest of the day, the electricity system demand is considerably lower than the peak period. So, the price is also lower. This is called **off-peak period**.

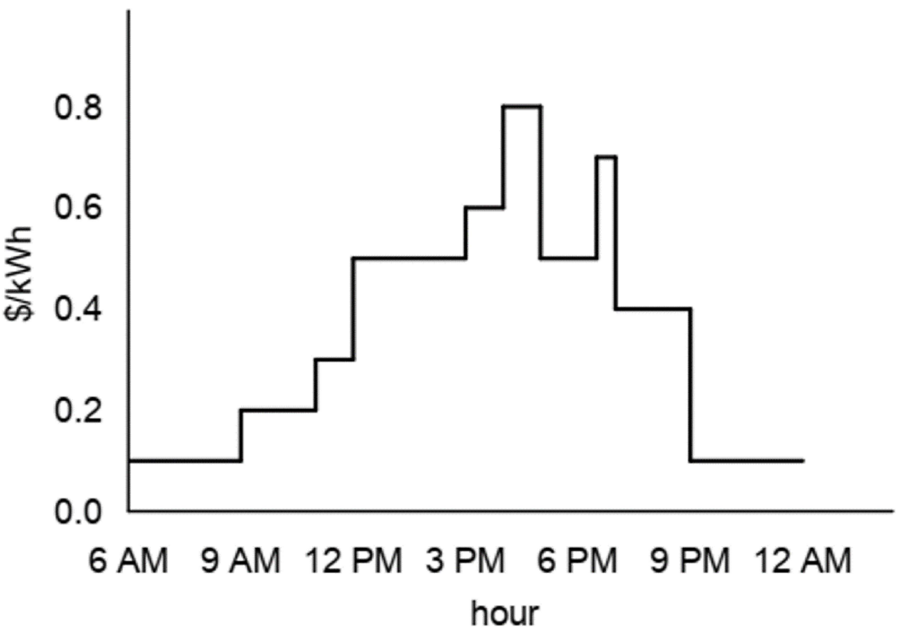
The main advantage of this model is exactly the main drawback of the Flat Rate. Since the energy price is higher during the period of the day when the electricity system faces the higher demand, hence presenting higher costs, the ToU model encourages the consumer to manage the energy consume through efficiency programs, adopting measures to avoid the consume during the time which is the worst to the electricity system. In Brazil, this model was first applied to the high voltage consumers. They are called Group A and they are mainly presented by heavy loads.

Since January 1^{st}, 2018, the Group B consumers have a ToU model option called *White Tariff* ("Tarifa Branca"). Firstly, it was applied for those who had a monthly consume higher than 500 kWh. In January $2nd$, 2019, this model was expanded for those who consume more than 250 kwh/month. The expectation is that in 2020 the "White Tariff"will be available to all Group B consumers. In Appendix C the *White Tariff* is detailed.

B.3 RTP (Real Time Pricing)

The greatest difference from this model to the previous one is that here the energy price is not predefined for any hour of the day. Therefore, the energy price varies during the day reflecting the wholesale market prices. Energy prices are released one day in advance (93). The United Kingdom, for instance, is a country that adopts this model. Graph 11 shows an example of the RTP model.

Graph 11 – Example of RTP model



Source: (93).

APPENDIX C – BRAZILIAN TARIFF SYSTEM

In Brazil the resolutions that describe the tariff system determined two major tariff groups: Group A and Group B. The main difference is that while the first is characterized by the binomial tariff structure, the second one follows the monomial tariff. There are two other differences between these groups: the voltage level and the demand of each consumer. While Group B consumers are supplied by low voltages (lower than 2.3kV, but in majority 127V or 220V), Group A consumers are those whose voltage supply is higher than 2.3kV.

Both groups are divided in subgroups, according to the supply voltage. The Group A consumers are classified in:

a) A1: Higher than 230kV;

b) A2: 88kV up to 138kV;

c) A3: 69kV;

d) A3a: 30kV up to 44kV;

e) A4: 2.3kV up to 25kV;

f) AS: Underground supply.

The Group B consumers are classified in:

a) B1: Higher than 230kV;

b) B2: 88kV up to 138kV;

c) B3: 69kV;

d) B4: 30kV up to 44kV.

C.1 Group A Tariff Systems

Group A consumers are, in general, big load supplied in high voltage. The tariff models adopted in this group are the Flat Rate and the ToU, presented in Appendix B. In the future, the Flat Rate model will be abandoned. The three tariff systems adopted in this group are detailed below.

C.1.1 **Conventional Tariff System**

In this tariff system, consumers pay a single price for the contracted demand and the energy consumed. This tariff system is restricted to those consumers who had a contracted demand lower than 300 kW, and in the past eleven months haven't had three consecutive or six alternated records of demand higher than 300 kW.

The total price payed at the end of the period of consume consists of three installments:

a) Energy Consume installment: Refers to the energy consumed during the measured time. It is calculated according to Equation C.1, where:

   - $Price\_Consume$ is the value payed to the energy consumed;
   - $\Pi_{consume}$ is the energy tariff;
   - $E_{Consumed}$ is the amount of energy consumed in the period.

$$Price\_Consume = \Pi_{consume} \times E_{Consumed} \tag{C.1}$$

b) Contracted Demand installment: Refers to the payment of the contracted demand. It is calculated according to the Equation C.2, where:

   - $Cost\_Demand$ is the value payed to the contracted demand;
   - Π_{demand} is the demand tariff and $D_{contracted}$ is the contracted demand.

$$Cost\_Demand = \Pi_{demand} \times D_{contracted} \tag{C.2}$$

c) Exceeded Demand installment: It is charged when the measured demand exceeds the contracted demand in 10% or more. It is calculated as presented in Equation C.3, where:

   - $Price\_Exceeded_Demand$ is the payment for the exceeded demand;
   - Π_{Exc_demand} is the tariff for exceeding the demand;
   - $D_{measured}$ is the demand measured;
   - $D_{contracted}$ is the demand contracted.

$$Cost_{Exce_Dem} = \Pi_{Exc\_demand} \times (D_{measured} - D_{contracted}) \tag{C.3}$$

The final price payed is composed by the three installments which were mentioned above, as presented in Equation C.4.

$$Total\_Price = Price\_Consume + Cost\_Demand + Cost_{Exce_Dem} \tag{C.4}$$

In the next tariff revision, the Conventional tariff system will be extinguished and consumers who adopt this system will have to move to the Seasonal Blue tariff or Season Green tariff systems (Group A) or to the Group B tariff system (94).

C.1.2 **Green Seasonal Tariff System**

This tariff system is restricted to the Group A consumers from subgroups A3, A4 and AS. The Green seasonal tariff system differs from the Conventional Tariff System from the point that in this system there is two energy tariffs, for the peak and off-peak periods. The demand installment is calculated the same way as presented in Equations C.2 and C.3. In this regard, the energy consumed price in the Green Seasonal Tariff System is calculated according to Equation C.5, where:

a) $Green_{Energ_Cons}$ is the price payed for the energy consume;

b) $\Pi_{peak_consume}$ and $\Pi_{off-peak_consume}$ are the energy tariff for peak and off-peak periods;

c) $E_{peak_consumed}$ and $E_{off-peak_consumed}$ are the measured energy consumed during the peak and off-peak periods.

$$Green_{Energ_Cons} = \Pi_{peak_consume} \times E_{peak\_consumed} + \Pi_{off-peak\_consume} \times E_{off-peak\_consumed} \tag{C.5}$$

According to (95), in the Green Seasonal Tariff System is allowed to the DSO to charge different prices for the humid and dry periods, which are defined by ANEEL RES.414/2010 (96).

Similarly, as far as the Conventional Tariff System is concerned, the final price payed is composed by three installments, as presented in Equation C.6.

$$Green_{Total\_Price} = Green_{Energ_Cons} + Cost\_Demand + Cost_{Exce_Dem} \tag{C.6}$$

C.1.3 **Blue Seasonal Tariff System**

Consumers from Group A, subgroups A1, A2 and A3 must adopt this tariff system. The other Group A consumers can adopt this tariff system, but it is not mandatory (94).

The energy cost is calculated as presented in Equation C.5. The difference from the Green to the Blue seasonal tariff is that in the Blue Seasonal Tariff consumers are charged for peak and off-peak contracted and/or exceeded demand.

In this way, the contracted demand cost is calculated as presented in Equation C.7, while the exceeded demand cost is presented in Equation C.8, where:

a) $Blue_{Cost\_Dem}$ and $Blue_{Cost\_Exce\_Dem}$ are the contracted and exceeded demand;

b) Π_{peak_demand} and $\Pi_{off-peak\_demand}$ are the peak and off-peak demand tariffs;

c) D_{peak_contr} and $D_{off-peak\_contr}$ are the peak and off-peak contracted demand;

d) $\Pi_{peak\_Exc\_dem}$ and $\Pi_{off-peak\_Exc\_dem}$ are the peak and off-peak exceeded demand tariffs;

e) D_{peak_meas} and $D_{off-peak\_meas}$ are the peak and off-peak demand measured.

$$Blue_{Cost\_Dem} = \Pi_{peak\_demand} \times D_{peak\_contr} + \Pi_{off-peak\_demand} \times D_{off-peak\_contr} \quad \text{(C.7)}$$

$$Blue_{Cost\_Exce\_Dem} = \left\{ \begin{array}{l} \Pi_{peak\_Exc\_dem} \times (D_{peak\_meas} - D_{peak\_contr}) + \\ +\Pi_{off-peak\_Exc\_dem} \times (D_{off-peak\_meas} - D_{off-peak\_contr}) \end{array} \right\} \quad \text{(C.8)}$$

Another difference from the previous tariff systems is that in the Blue Seasonal Tariff System the exceeded demand is charged when it exceeds 5% for the A1, A2 and A3 subgroups consumers, while for the others subgroups the limit allowed is 10% (94).

Similarly to the Green Seasonal Tariff System in the Blue Seasonal Tariff System also is allowed to the DSO to charge different prices for the humid and dry periods, also defined by ANEEL RES.414/2010 (96).

The final price payed by the consumers who adopt the Blue seasonal tariff is calculated as presented in Equation C.9.

$$Blue_{Total\_Price} = BlueEnerg\_Consume + Blue_{Cost\_Dem} + Blue_{Cost\_Exce\_Dem} \quad \text{(C.9)}$$

C.2 Group B Tariff Systems

Group B is mostly composed by the low voltage consumers. The tariff model used in this group is the Flat Rate and the ToU, detailed in Appendix B. The Flat Rate was the first tariff model adopted for Group B consumers, while the ToU model began to be adopted in 2018 through the *White Tariff*.

Despite the existence of the ToU tariff, most of the consumers still adopt the Flat Rate model. This tariff contains the energy costs and also the demand cost. So, there are not different tariffs for energy and demand, the tariff for the consumers is also the same regardless the time of the day. Equation C.10 presents how the final price is calculated for Group B consumers who adopt the Flat Rate Tariff, according to which:

a) $Total\_Price$ is the total cost of the energy consumption;

b) $\Pi_{flat\_rate\_Group\_B}$ is the Group B tariff;

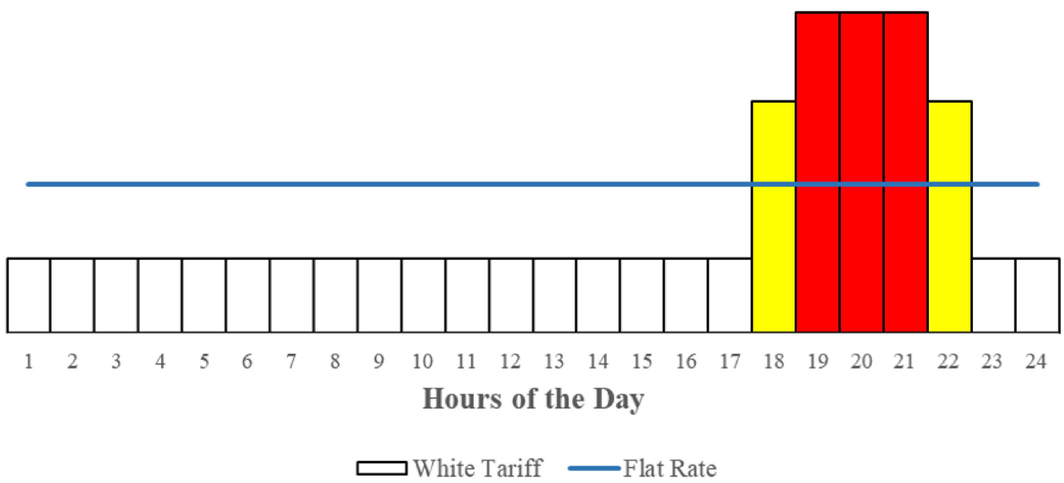
c) $E_{measured}$ is the energy consumption during the measured period.

$$Total\_Price = \Pi_{flat\_rate\_Group\_B} \times E_{measured} \quad \text{(C.10)}$$

C.2.1 **White Tariff**

In this model, during the week, there are three different levels, the previously defined peak and off-peak periods and the intermediate period. This new period is considered 1 hour after and 1 hour before the peak period, and its price is higher than the off-peak period, but lower than the peak-period. On weekends and holidays, the textitWhite Tariff price is the same as the off-peak period. Graph 12 is an example that compares the *White Tariff* and the Flat Rate models, during weekdays. For the *White Tariff*, the yellow hours represent the intermediate period, the red hours are the peak-period and the white ones are the off-peak period. The Blue line represents the Flat Rate.

Graph 12 – *White tariff* example compared to Flat Rate for a weekday



Source: Prepared by the author (2020), based in (97).

For those consumers who adopted the *White Tariff* system, the final price is calculated as presented in Equation C.11, where:

a) $White\_Total\_Price$ is the energy consumed price;

b) $\Pi_{white\_off-peak}$, $\Pi_{white\_intermediate}$ and Π_{white_peak} are the energy tariffs for off-peak, intermediate and peak periods, respectively;

c) $E_{off-peak\_measured}$, $E_{intermediate\_measured}$ and $E_{intermediate\_measured}$ are the energy consumed in during off-peak, intermediate and peak periods, respectively.

$$White\_Total\_Price = \left\{ \begin{array}{l} \Pi_{white\_off-peak} \times E_{off-peak\_measured} + \\ +\Pi_{white\_intermediate} \times E_{intermediate\_measured} + \\ +\Pi_{white\_peak} \times E_{intermediate\_measured} \end{array} \right\} \tag{C.11}$$