Parking lot operation management considering V2X and renewable generation

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Acknowledgments

I would like to thank my parents for their friendship, encouragement and caring over all these years, for always being there for me through thick and thin and without whom this project would not be possible. I would also like to thank my grandparents, aunts, uncles and cousins for their understanding and support throughout all these years.

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To each and every one of you – Thank you.

Resumo

O rápido crescimento do mercado de veículos elétricos (VE) enfatizou a necessidade de transporte sustentável como uma das soluções para reduzir as emissões de carbono e mitigar o impacto ambiental. O objetivo desta tese é explorar e avaliar os benefícios da utilização de um sistema solar e da tecnologia *Vehicle-to-Everything* (V2X) num parque de estacionamento com carregamento de VEs. O objetivo é melhorar o desempenho do parque, reduzir custos operacionais e aumentar a eficiência do carregamento de VEs. A pesquisa começa com uma revisão da literatura sobre as tendências atuais da indústria automóvel, com o foco na crescente popularidade dos veículos elétricos e na necessidade de infraestrutura adequada para suportar seu uso. Além disso, a importância da energia solar como fonte renovável e sustentável capaz de fornecer eletricidade limpa para produzir os mesmos ou melhores resultados no processo de carregamento de VEs, reduzindo a dependência de combustíveis fósseis. Além disso, será explorada a tecnologia V2X, que permite a troca bidirecional entre veículos elétricos e infraestrutura elétrica. Uma nova metodologia é proposta, permitindo a integração de recursos V2X no parque de estacionamento, permitindo a utilização de VEs como unidades de armazenamento de energia capazes de fornecer energia à rede ou às instalações do parque.

Palavras Chave

Carregamento de veículos elétricos (VE); Sistema de energia solar; Integração de energias renováveis; Otimização de carregamento; Vehicle-to-Everything (V2X).

Abstract

The rapid growth of the electric vehicle (EV) market has emphasized the need for sustainable transport as one of the solutions to reducing carbon emissions and mitigating environmental impact. The goal of this thesis is to explore and evaluate the benefits of using a solar system and Vehicle-to-Everything (V2X) technology in a parking lot with EV charging stations. The goal is to improve park performance, reduce operational costs, and increase the efficiency of EV charging.The research begins with a review of the literature on current trends in the automotive industry, with a focus on the growing popularity of electric vehicles and the need for adequate infrastructure to support their use. In addition, the importance of solar energy as a renewable and sustainable source capable of providing clean electricity to yield the same or better results in the EV charging process, while reducing reliance on fossil fuels. Aside from that, V2X technology will be explored, which allows for bidirectional communication between EVs and electric infrastructure. It will be proposed to integrate V2X resources into the parking lot, allowing electric vehicles to be used as energy storage units capable of providing power to the network or to the park's facilities.

Keywords

Electric vehicle; Parking lot; Solar Power system; Renewable energy integration; Charging optimization; Vehicle-to-Everything (V2X); V2X Discharge.

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Acronyms

BIPV	Building Integrated PV
CSP	Concentrated Solar Power
DR	Demand Response
EV	Electric Vehicle
EVPL	Electric Vehicle Parking Lots
ESS	Energy Storage System
GIS	Geographic Information System
IBGWO	Improved binary grey wolf optimizer
PEV	Plug-in Eletric Vehicle
PHEV	Plug-in Hybrid Eletric Vehicle
PLL	Peak Load Limiation
PLO	Parking Lot Operator
PLSPVS	Parking Lot Shaded Photovoltaic System
PV	Photovoltaic
MOCS	Multi-objective crow search
MOPSO	Multi-objective particle swarm optimisation
RES	Renewable Energy Source
SOC	State of Charge
STC	Standar Testing Conditions
TF	Time Factor
V2A	Vehicle-to-Anything
V2G	Vehicle to Grid
V2H	Vehicle-to-Home
V2L	Vehicle-to-Load
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

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Introduction

Contents

1.1 Motivation

The electric vehicle (EV) market has grown rapidly as the world is trying to prioritizes lowering carbon emissions to reduce the impact on the planet. Thus, the Greenplan 2050's was set in motion with the goal to lower carbon emissions by making EVs a viable alternative to today's internal combustion engine cars.

The expansion of the EV industry, along with the growing emphasis on mitigating carbon emissions, has prompted the investigation of inventive approaches to augment the sustainability and efficacy of electric transportation. Parking lots, being integral elements of urban infrastructure, possess significant potential for facilitating the extensive uptake of EVs. The integration of solar energy and Vehicle-to-Everything (V2X) reverse charging technologies within parking lots could offer a promising prospect for enhancing the management and utilisation of EVs, while concurrently exploiting sustainable energy sources.

The primary focus for investigating EV management in parking lots is to tackle the issue of charging infrastructure. The increasing prevalence of EVs necessitates the provision of easily accessible and convenient charging options. Urban areas are extensively equipped with public and private parking lots, which present a favourable opportunity for the installation of EV charging stations. Through the strategic incorporation of solar panels into parking structures, it is possible to harness sustainable and environmentally friendly energy sources in order to provide power for charging infrastructure. This not only diminishes reliance on the power grid but also substantially decreases the carbon emissions linked with EV charging.

Furthermore, the notion of V2X reverse charging amplifies the potential of EV management within parking facilities. V2X technology facilitates the exchange of energy between EVs and energy-consuming systems, such as the power grid, in a bidirectional manner. The V2X technology enables EVs to function as portable energy storage units, which can supply power to the grid or other energy-intensive applications during high-demand periods or emergency situations. The stationary and interconnected nature of parking lots can serve as central points for V2X infrastructure, thereby enabling the seamless integration of EVs into the larger energy ecosystem.

1.2 Objective

The objective of this thesis is to further dive into a previous optimization study, [1]. The goal was to optimize the charging process across all EVs by introducing penalization factors depending on the State-of-Charge (SOC) of the vehicle at the moment of arrival and during the charging process.

In this thesis the algoritm proposed in [1] will be updated to included renewable generation, solar photovoltaic in the present case, and the V2X capability in the EVs in order to increase the sustainability of the park and the power available to it. It will also be implemented a method of V2X discharge to study the benefit of the charging process of every vehicle on the park.

1.3 Thesis Outline

This dissertation is organized as follows: Chapter 1 is the introduction. Chapter 2 is the state-of-the-art where it is referenced and discussed correlated works in which the implementation of solar systems and parking rules to further improve general EV charging were considered. In chapter 3 is explained the methodology that is going to be used to calculate integrate the solar system in the parking optimization and also the integration of the V2X discharging method. Chapter 4 shows the numerical results that were obtained with the applied methodology regarding the F-Index (penalization index) comparison between them. Chapter 5 is a summary of the work done in this study is presented, along with some conclusions. Additionally is also made some suggestions for potential future developments related to this study.

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State of the Art

Contents

2.1 EV Charging in Parking Lots

Scheduled or smart charging of EVs can considerably reduce peak demand for electricity and avoid local grid congestion. The use of smart charging strategies will reduce the cost of providing accessible and affordable EV charging stations. As a result, one of the most significant barries to EV adoption is the absence of accessible charging stations. Smart charging can help increase the penetration of renewables in the mobility sector by aligning EVs charging with the availability of locally produce renewable energy (such as local energy provided by solar photovoltaics). Knowledge of future electricity demands and renewable energy production is required for EV charge scheduling schemes that aim to educe local peak demand and congestion.

The ability of a plug-in hybrid electric vehicle (PHEV) to connect to the power grid and operate as a vehicle-to-grid (V2G) makes it a unique subject for studying how EVs connect to the power grid. PHEVs have a power plug that lets them connect to the utility grid. This means that they can not only get power from the grid, but they can also send power back to the grid. With this ability, V2G can help power buildings with enough energy from their battery, which can be charged at a different location, [2]. V2G helps the power grid by storing energy as a backup when its battery pack is used to meet demand and lower system overload. It will do this by adding reactive and active power to the grid and not having to build new power plants. Previous research conducted on V2G control such as an autonomous distributed V2G control of grid connected PHEV and EV by coordinating battery condition, use for vehicle, and power system state. A Vehicle to grid concept can be seen in Figure 2.1.

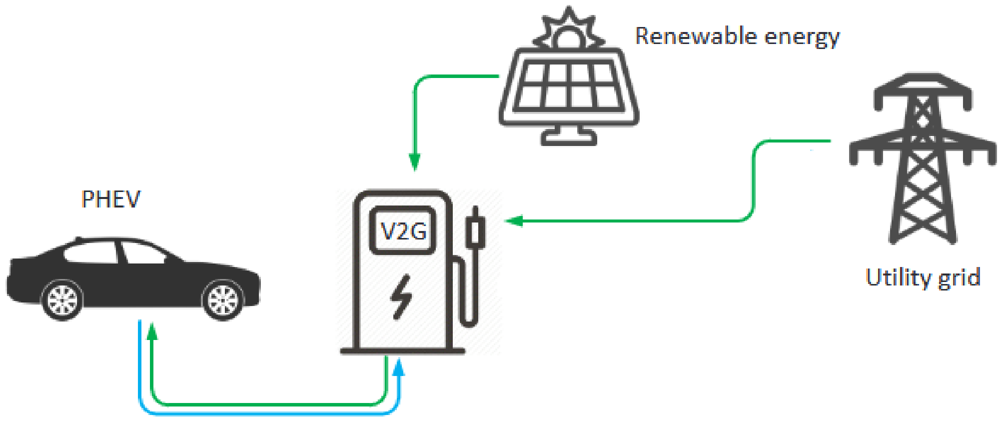

Figure 2.1: V2G Concept

2.2 EV management in parking lots

Several publications on the management of EVs have recently been published. Recently, in [3], an assessment of the vehicle-to-everything mode of operation of EVs was provided, which examined the integration of vehicles in electric grids, households, and between vehicles. However, there is no mention of parking lot integration or management. In [4], a framework for managing EVs in a parking lot is provided, taking into account the high degree of information shared between the EVs and the parking lot management system. The major purpose of the architecture proposed in [4] is to optimise the energy supplied to EVs based on their needs (energy for next travel). Parking lot management is also addressed in [5], which proposes three different methods: 1) first-come, first-served [6], 2) priority based on departure timetable [7], and 3) the authors' decision-making algorithm The choice is made using two decision levels: arrival time and an EV scoring system based on the difference between the necessary and actual level of SOC. In comparison to [4–7], the approach given in this study differs from those proposed in prior studies since the parking lot management system lacks information on departure time and energy requirements. This is an important aspect because this knowledge is not available in the real world. The fuzzy modelling of EV uncertainty and power market pricing uncertainties is modelled and integrated into the methods in [8]. [9] also addresses the optimal trading of plug-in electric automobiles in a market system. The investigation, however, is not limited to EVs connected to the same parking lot. In [10] is proposed an optimal stochastic scheduling of EVs, which is more focused on microgrids. In such instances, EVs can also be used as a mobile storage system to supply energy to microgrids in the event of a production outage.

In [11] the aim is to distribute available power resources efficiently among EVs to ensure customer satisfaction and minimize the impact on the power supply. The paper presents a model of an EV car park based on real data from a UK car park and simulates the traffic flow and charging behavior of EVs.

The model consists of two parts: traffic flow simulation and EV charging simulation. The traffic flow simulation uses real parking data to generate vehicle flow based on a probability density function. The EV charging simulation is based on the charging profile of the Nissan Leaf EV, considering rapid charging (level 3) with higher power capability.

Three power management strategies are proposed in [11] based on the available feeder power and EV SOC. The simulation results show that the feeder power can be effectively limited, and the impact of the power limit can be shared among all vehicles if desired. Additionally, a fourth method is derived from the observed features of the third method and further analyzed. The findings demonstrate the feasibility of limiting feeder power in EV car parks and the ability to manage the charging process based on SOC and available power. The research contributes to understanding the impact of EV charging on power supply and offers potential for future studies, such as simulating V2G scenarios and providing frequency response services through car parks acting as virtual power plants.

All of the papers mentioned above take into account the existence of parking lot central management administered by an aggregator or parking lot operator.

The majority of current research in the literature focuses on forecasting which parking lot will be available when the automobile arrives. The difficulty of getting a parking place in metropolitan locations is the driving force behind this. Traveling to locate parking places causes some traffic congestion, resulting in wasteful energy consumption and pollution. Off-street (parking spaces in private areas) and in-street versions are among the projects in this category (slots in the streets). According to [12], the real-time availability forecast method uses a combination of current (on-line) and historical data to anticipate parking facility availability in real time. This research employs an algorithm that works with both actual and simulated data. According to the [13], authors build a prediction model of parking occupancy based on Naive Bayes and machine learning methods such as decision tree, random forest, and regression analysis, and then predict subsequent parking availability using a matching-based allocation strategy to assign users to selected parking spaces. Many publications in the literature propose using deep learning to forecast parking occupancy. In [14], a deep learning model is used to forecast block-level parking occupancy 30 minutes in advance. The model uses a variety of data sources as input, such as parking, traffic, and weather.

2.3 Solar System in Parking EV Charging

Solar power, including photovoltaic (PV) and concentrated solar power (CSP) technologies, is a clean, free, and sustainable source of energy. The energy harvested by a solar plant during its full life cycle emits no greenhouse gases. Furthermore, as PV technology continues to progress, new uses emerge. These enhancements enable utility companies to diversify their energy portfolio by including a considerable portion of renewable electricity. PV uses described above include, but are not limited to: 1) ground mounted PV, 2) rooftop PV systems, 3) building integrated PV (BIPV), and 4) parking shaded PV [15]. Unfortunately, there are several downsides to solar energy harvesting that continue to concern utility companies, investors, and regulators. Inadvertence's in solar radiation are thus one of the key barriers to widespread use of solar energy. Photovoltaic efficiency is another barrier to broad usage of solar energy. Several studies have been undertaken in the past to investigate the effectiveness of grid-connected PV systems [15, 16]. Harvesting renewable energy is one of the ways to meeting rising electricity demand while also ensuring environmental sustainability. As a result, the current decline in the cost of PV panels in comparison to past years is encouraging the usage of this solar-dependent technology, which in turn helps to decarbonize the entire electrical sector [17].

By regulating insolation, solar shading is an engineering strategy that seeks to optimise heat gain to any physical structure entrenched in our environment. Garden shelters, window shades, and automobile parking sheds are examples of these buildings. It is important to remember that finding the greatest lots in terms of year-round solar heat gain might be difficult at times. In [18], a geographic information system (GIS)-based approach was created to locate not only available spaces, but also to select the ones ideal for PV shading deployment among various automobile parking lots. Furthermore, acquiring free land to build solar farms inside cities is getting increasingly challenging. Land prices in cities are greater than in rural areas, restricting the availability of enormous urban lands for various uses. Large-scale renewable energy technology were generally deployed in less populated rural areas rather than within a city's footprint [19]. There are many parking lots available around the world, which are seen as an untapped possibility for solar PV systems. The parking lot shaded PV system (PLSPVS) is more efficient than the typical ground-mounted PV system, and the former PV system's performance is not hampered by surrounding shading structures [20]. Solar shade for parking lots is thus an efficient use of space and can be implemented almost everywhere on the premises of load centres, such as workplaces, retail malls, hospitals, airports, industrial halls, and universities. As a result, using car parking area for solar shading is an efficient way to generate power while also providing shade [17]. In certain research, solar shading PV systems were optimally combined with EV fleets designs. This technology provided a dynamic and customizable charging of EV batteries based on converted solar radiation and the vehicles' current needs. It is also possible to respond to price signals from the spot market for electricity [17]. This strategy contributes to the decarbonization of the transportation industry.

Renewable energy sources have many benefits for the power system, but integrating them on a large scale may be hard, especially if EVs are added to the mix. This could make the power system less stable (in terms of voltage and frequency) and less flexible (due to conventional generation, energy flow, and grid limits), which could threaten the reliability of the power system, according to [21]. The main problems with PV are that it isn't always reliable and that it's hard to predict how much power it will produce. Also, EVs could lower the quality of the power and make the traditional power systems unstable by overloading them.

In [22] is explored the use of renewable energy in parking lot management. In this scenario, parking lot management is linked with solar generation from a rooftop PV system. The problem is examined from the standpoint of a distribution system, with the parking lot serving as a flexible load. Scheduling of EV charging and discharging with consideration for the influence on the distribution network is also examined in [23] , which proposes a decentralised management algorithm. The authors in [24] presents optimal scaling of hybrid renewable energy systems with EVs using two algorithms: multi-objective particle swarm optimisation (MOPSO) and multi-objective crow search (MOCS). [25] also includes an examination of a parking lot with a PV system with the goal of evaluating the solar energy potential in parking lots and maximising the usage of the energy generated by the PV system to charge the EV batteries. The methodology suggested in [25] assumes that excess PV energy may be stored in a centralised energy storage system, maximising the utilisation of PV energy. A financial assessment of the proposed solution is also presented, as is the required payback time. In [26] a real-time EV charging scheduling approach in parking lots with PV units and an energy storage system employing an improved binary grey wolf optimizer (IBGWO) method. The model proposes evaluating the parking time and charging demand requirements in order to schedule the charge (0/1) of each electric car while taking into account an objective function that minimises the cost of energy delivered by the main grid.

2.4 Solar System Economic Analysis

In [27] an energy economic model is developed to analyze the hourly energy availability, cash flow, and payback time for both the garage owner and the vehicle owner. The analysis also considers the impact of the PV-based charging facility on power grid emissions, taking into account carbon taxes. The analysis shows that vehicles are typically parked for a significant amount of time during the day, allowing for the utilization of solar energy without extensive energy storage.

In a previous study [28], a methodology utilising a geographic information system (GIS) was devised to not only determine appropriate locations, but also to select optimal car parking lots for the implementation of PV shading structures. Furthermore, the task of locating available land within urban areas for the construction of solar farms is proving to be increasingly challenging.

In [29] a potential approach for acquiring the energy return involves utilising the publicly available statistical information pertaining to the PV installations. The parameters that have been evaluated include the electrical energy output subsequent to the conversion process carried out by the inverter, which involves the transformation of direct current to low voltage alternating current. Additionally, the kilowatt peak (kWp) rating of the PV system that has been set up has also been taken into account. By utilising the module surface per installed peak power, it becomes feasible to compute the electrical output per unit area of the module. As per the Swiss energy statistics. At this juncture, it is imperative to establish the operational lifespan of a PV system. This statement necessitates an underlying assumption. At present, providers of PV installations typically estimate a lifespan of 30 years. However, the warranty for the materials is typically restricted to a period of 5 years.

Solar PV installations are considered an unexplored prospect in numerous parking lots worldwide. The PLSPVS exhibits superior efficiency compared to the conventional ground-mounted system, and its performance remains unaffected by the shading of its surroundings. In [30], the utilisation of solar shading in parking lots is a space-efficient approach that can be implemented in various locations within load centres, including but not limited to workplaces, shopping malls, hospitals, airports, industrial halls, and universities. As per the literature, the utilisation of parking spaces for solar shading is a productive strategy that enables the generation of electricity and provision of shade simultaneously [17].

2.5 Vehicle to Everything (V2X)

2.5.1 Applications

It can be inferred that a significant proportion exceeding 90% of EVs remain stationary at all times, [31], resulting in a substantial amount of energy being idle and unutilized. The energy in question can serve various purposes such as frequency balancing, peak demand management in the grid, or provision of electricity to residential, commercial, or other types of loads to ensure adequate power supply during periods of high demand.

The application of V2X holds significant importance in the realm of Cyber–Physical Power Systems, particularly for EVs that are utilised for personal, commercial, and public purposes. One potential solution for optimising the use of electric school buses is to integrate them with a local solar energy system in the school building. By utilising the solar energy system as a means of energy storage during periods of long-term parking, the buses can provide a more consistent power output throughout the day. Additionally, it has the capability to fulfil the energy requirements of educational institutions with minimal reliance on the power grid. The utilisation of fleet charging lots as a potential resource for the energy storage system (ESS) can be significant with the inclusion of public buses, construction, and agriculture machines. Additionally, the peak demand during the evening hours can be utilised to supply the grid.

The implementation of V2X technology enables the attainment of direct energy transfer among electric vehicles through the utilisation of on-board power exchange. Through the use of vehicle-to-vehicle (V2V) technology, EV owners have the ability to transfer energy from their own EVs to assist another EV that may be stranded on the road, enabling it to reach the nearest charging station. EVs owners have the potential to assist in fulfilling a building's energy requirements by collaborating with the building's solar energy infrastructure during their EVs stationary state within office premises. Therefore, the introduction of V2B technology enables the attainment of both charging and economic benefits. In an alternative scenario where the power grid is not accessible, the utilisation of vehicle-to-load (V2L) technology in our electric vehicle can offer substantial convenience in powering our electrical devices.

2.5.2 Vehicle-to-Everything (V2X) approaches in parking lots

V2X is the capability of the EVs exchange energy (consume and supply energy) with the environment were is connected. As environment, it is possible to refer, houses, buildings, energy communities, parking lots and directly with distribution network. According to [32], V2G can be managed by using optimization algorithms. The objective of the V2G scheduling is to minimize total running cost which includes mainly fuel cost and startup cost. In order to accomplish this some constraints have to be satisfied during the optimization process such as: charging-discharging frequency, system power balance, state of charge, efficiency and ramp rate.

The authors in [33] presented a comprehensive analysis of vehicle-to-anything (V2A) operations. They proposed a detailed framework and mathematical models for vehicle-to-home (V2H), V2G, and V2V operations. The utilisation of V2H, V2G, and V2V operations can effectively achieve objectives such as minimising costs, reducing power losses, mitigating peak loads, and providing reactive power support. The study conducted in [34] investigated the optimal operation of EV parking lots (EVPLs) through the utilisation of price-based and incentive-based demand response (DR) programmes. The researchers employed a stochastic programming approach in their analysis. In [35] was conducted an investigation on the role of EVs in mitigating voltage imbalances in low voltage distribution grids, while considering the presence of PV systems and V2G technology.

The study conducted [36] investigated the potential enhancement of system reliability through V2G technology in the case of failure of renewable energy source (RES) integrated distribution grids. In [37] have proposed an algorithm based on decision tree methodology, which considers the variability of weather conditions and dynamic loads. The objective of the algorithm is to minimise peak load by enabling coordinated charging in a household equipped with V2G capable EV, PV, and energy storage. The study conducted in [38] proposed a two-tiered model with the objective of reducing the cost incurred by the distribution system operator while simultaneously increasing the revenue generated by the EVPL manager. The model takes into consideration various factors such as the limitations of the distribution network, uncertainties associated with photovoltaic and wind power, and the behaviour of electric vehicle owners. Although the aforementioned studies investigated the impact of V2G technology on the distribution system and the potential synergies between V2G and PV systems, the convenience of EV owners is regarded as a fixed parameter during ancillary service operations. Nonetheless, practical implementations necessitate the deliberate consideration of supplementary services for the distribution system. This involves accommodating the fluctuating comfort requirements of EV owners across diverse grid operation modes, with the aim of incentivizing their participation in said services. Conversely, the operation of V2V communication holds significant potential in enhancing the comfort of EVs.

However, the aforementioned studies did not investigate the prospective function of V2V transactions. The V2V transaction is anticipated to play a crucial role in the charging of electric vehicles and improving their overall convenience. The authors in [39] aimed to decrease the expenses associated with charging EVs within a given region. This was achieved by means of transferring energy between the EVs during periods of high electricity prices. Nonetheless, the consideration of PV and peak load limitation (PLL) was omitted in the analysis, and the assumption was made that every EV attained the intended charge level at the time of departure. In [40] the authors sought to enhance user comfort by facilitating the attainment of the desired SOC level and minimising the frequency of energy transactions. To achieve this objective, the researchers employed a combination of V2G, V2V, PV technology, and supplementary backup batteries. The research conducted in [40] did not incorporate projections for PV and EV parking, nor did it incorporate PLL. The authors at [41] presented a V2V coordination approach aimed at facilitating energy transfer among EVs. Also EVs that have surplus energy and those that require charging were consolidated through aggregators. The objective of the study referenced as [41] was to reduce the charging expenses incurred by EVs requiring energy while simultaneously increasing the revenue generated by EVs that supply energy. However, the study did not take into account the potential contributions of PV systems and V2G technologies.

3

Parking lot management methodology

Contents

3.1 Previous Study

Given that this thesis bases itself upon a prior case study [1], it is imperative to present the initial values and proposed methodology in order to enhance comprehension of the present work. In this work the goal is to improve the previous by incorporating the solar energy as a way of charging the EV with clean energy and also using a V2X discharge method to improve the F-Index values by discharging higher SOC EV whenever we have low SOC EV in the park.

3.1.1 Parking lot constraints

All charging stations should have less power than the parking lot's capacity. The power transformer, cable thermal restrictions, or contractual capacity determine this capacity. Charging stations CS first apply the power limit to EVs.

$$\sum_{CS=1}^{N_{CS}} \frac{P_{maxCS(CS,T)}}{\eta_{CSt(CS)}} \leq P_{maxPark(t)} \forall t \in \{1,...,T\} \tag{3.1}$$

3.1.2 Charge Stations constraints

The charging station power should be lower than its maximum capacity (technical constraint) and lower than the upper-level energy management system's maximum power (particularly if integrated with buildings management). $X_{Place(EV,CS,t)}$ indicates if the EV is connected to the CS in period *t*. Since the same car might be linked to different charging stations, this value can be dynamic. In period *t*, the EV is not connected to a CS, hence its power charge ($P_{ch(EV,CS,t)}$) is 0. Charging stations have many outlets. Each plug provides the charging station's whole power. Modelling outlets requires no further limitations. $X_{Place(EV,CS,t)}$ is 0 for all periods when charging stations are unavailable due to technical reasons.

$$\sum_{EV=1}^{N_{EV}} P_{ch(EV,T)} \leq P_{maxCS(CS,t)} . X_{Place(EV,CS,t)} \forall CS \in \{1,...,N_{CS}\}; \forall t \in \{1,...,T\} \tag{3.2}$$

3.1.3 Electric Vehicles constraints

The power charge should be less than each EV's maximum power Eq. 3.3. The EV also prohibits power charges below Eq. 3.4. This figure can vary by EV and battery SOC. If the parking lot or charging station's power is less than the EV's minimal power ($P_{minCh(EV,t)}$), the variable $X_{Ch(EV)}$ will be 0, preventing infeasible solutions. The power charge is restricted by the energy needed by electric car batteries Eq. 3.5 to reach 100% SOC. Time Factor(TF) represents the power-energy relationship between one hour and each period *t*. TF is 1/60 for 1 min. Each EV's energy should be updated based on its prior condition (*t*-1) and the power charged in period *t*. Batteries should have less energy than the maximum.

The system receives SOC data when the EV arrives at the parking lot (*t* = 0). Because the parking lot management system has no EV journey history.

$$P_{ch(EV,T)} \leq P_{maxCh(EV,t)}.X_{Ch(EV,t)} \forall EV \in \{1,...,N_{EV}\}; \forall t \in \{1,...,T\} \tag{3.3}$$

$$P_{ch(EV,T)} \geq P_{minCh(EV,t)}.X_{Ch(EV,t)} \forall EV \in \{1,...,N_{EV}\}; \forall t \in \{1,...,T\} \tag{3.4}$$

$$P_{ch(EV,t)} \leq (1 - SOC_{EV,t}).\frac{E_{max(EV)}}{TF} \forall EV \in \{1,...,N_{EV}\}; \forall t \in \{1,...,T\} \tag{3.5}$$

$$E_{(EV,t-1)} + P_{ch(EV,t)}.TF = E_{(EV,t)} \forall EV \in \{1,...,N_{EV}\}; \forall t \in \{1,...,T\} \tag{3.6}$$

$$E_{(EV,t)} \leq E_{max(EV)} \forall EV \in \{1,...,N_{EV}\} \tag{3.7}$$

3.1.4 Parking rules constraints

Chargers and parking lots can be used fairly with few restrictions by applying weight penalties in order to establish rules so these can be used on the optimisation process. Starting with the Minimum Power Charge penalty ($PF_{MCP(EV,t)}$), Eqs. 3.8, 3.9 - The fundamental idea is to charge each EV with a minimal power ($P_{minMCP(EV,t)}$) at each instant *t*. Users (parking lot manager) can set this value for each car and period. If the energy needed to fully charge the EV is less than the minimum power, modify the value. The objective function will penalise the solution if the system cannot provide the minimal power charge ($P_{MCP(EV,t)}$) . State of Charge level penalties $PF_{SOCL(EV,t)}$ the SOC-level penalization factors prioritise low-SOC EVs. Consider three levels. Critical is 0–50$\%$ SOC. EVs with SOCs below level 1 should be prioritised. Level 3 (80–90$\%$ SOC) is low priority. EVs with SOCs above 3 have ample energy for daily use.

Level 2 is between 1 and 3. Before optimisation, calculate each level's EV power. The optimisation value should be 0 if the SOC level is higher than required. The parking lot manager accepts premium subscriptions. In such instance, VIPs (extremely important people) with privileged contracts will have priority over other users with similar SOC levels. Because of this, the power factor restrictions and objective function can be penalised.

$$P_{MCP(EV,t)} - PF_{MCP(EV,t)} \leq P_{ch(EV,t)} \forall EV \in \{1,...,N_{EV}\}; \forall t \in \{1,...,T\} \tag{3.8}$$

$$P_{MCP(EV,t)} = min\left(P_{minMCP(EV,t)}; (1 - SOC_{EV,t}).\frac{E_{max(EV)}}{TF}\right) \\ \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.9}$$

Eq. 3.10 limits active power for the sum of the three levels.

$$P_{SocL1(EV,t)} - PF_{SocL1(EV,t)} + P_{SocL2(EV,t)} - PF_{SocL2(EV,t)} + \\ P_{SocL3(EV,t)} - PF_{SocL3(EV,t)} \leq P_{ch(EV,t)} \\ \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.10}$$

Eqs. 3.11, 3.12, 3.13 define SOC levels. The formula define the charging power needed to reach each level based on present SOC and necessary SOC.

$$P_{SocL1(EV,t)} = max\left(0; (P_{SocL1max(Ev,t)} + P_{VIPL1(EV,t)} - SOC_{(EV,t)}).\frac{E_{max(EV)}}{t_{period}}\right) \\ \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.11}$$

$$P_{SocL2(EV,t)} = max\left(0; (P_{SocL1max(Ev,t)} + P_{VIPL2(EV,t)} - SOC_{(EV,t)}).\frac{E_{max(EV)}}{t_{period}}\right) \\ \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.12}$$

Eq. 3.13 caps each level's charging power at the EVs maximum. Maximum power charge variation $P_{FVarP(EV,t)}$.

$$P_{SocL3(EV,t)} = max\left(0; SOC_{(EV,t)}.\frac{E_{max(EV)}}{t_{period}}\right) \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.13}$$

Eq. 3.14, this penalty limits power charge changes in successive periods to prevent charging level fluctuations. Only charging power loss is limited.

$$P_{Ch(EV,t-1)} - P_{Ch(EV,t)} + PF_{VarP(EV,t)} \leq \Delta P_{Ch(EV,t)} \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.14}$$

SOC minimum $P_{FminSOC(EV,t)}$, Eq. 3.15, the minimum SOC of all EVs in the parking lot is penalised to prioritise vehicles with lower SOC. The previous punishment factor was Power-based, whereas this one is percentage-based. When two EVs arrive at the parking at the same time, the system will prioritise the one with the lower SOC. This penalization complements the SOC level penalization that favours some EVs over others with the same SOC level.

$$PF_{minSOC(t)} \leq SOC_{(EV,t)} \forall EV \in \{1, ..., N_{EV}\}; \forall t \in \{1, ..., T\} \tag{3.15}$$

This penalization element involves upper management (operational planning or real-time) setting a parking lot power operation setpoint. The upper level might be a complicated management tool or a basic specification of power operations levels based on electricity pricing. If the price exceeds a pre-defined figure, the maximum power setpoint ($P_{ParkingSet(t)}$), Eq. 3.16, can be lower than technical limits.

$$\sum_{CS=1}^{N_{CS}} P_{maxCSt(CS,t)} - PF_{PParking(t)} \leq P_{ParkingSet(t)} \forall CS \in \{1, ..., N_{CS}\} \forall t \in \{1, ..., T\} \tag{3.16}$$

3.1.5 Objective Function

Each period *t*, the target function minimises parking lot rule penalties to charge electric automobiles in a fairway.

$$\begin{aligned} f(t) = min \sum_{EV=1}^{N_{EV}} [PF_{MCP(EV,t)} \times PW_{MCP(EV,t)} + \\ PF_{SocL1(EV,t)} \times (PW_{SocL1(EV,t)} + PW_{VL1(EV,t)}) + \\ PF_{SocL2(EV,t)} \times (PW_{SocL2(EV,t)} + PW_{VL2(EV,t)}) + \\ PF_{SocL3(EV,t)} \times (PW_{SocL3(EV,t)} + PW_{VL3(EV,t)}) + \\ PF_{VarP(EV,t)} \times PW_{VarP(EV,t)}] - \\ PF_{minSOC(t)} \times PW_{minSOC(t)} + \\ PF_{PParking(t)} \times PW_{PParking(t)} \end{aligned} \tag{3.17}$$

3.1.6 F-Index

The suggested model's fairness index (F-Index), described in Eq. 3.18, can be calculated as the average of the SOC of EVs at departure time (t_{last}). Given that the system lacks knowledge on the SOC required by the EVs, in an ideal world, all of the EVs would have 100% SOC and the F-Index would be 1. Only EVs with a lower fairness level (50%) will be evaluated to avoid the impact of EVs with low energy requirements. To emphasise the EVs with lower SOC, a second term that comprised only the 10% EVs with lower SOC was introduced. This means that the F-Index is a quadratic function of the SOC of the EVs leaving the parking lot with the lowest SOC (in percentage).

$$F - Index = \frac{\Sigma_{EV=1}^{0.5\times N_{EV}} SOC_{(EV,t_{last})}}{N_{EV}} \times \frac{\Sigma_{EV=1}^{0.1\times N_{EV}} SOC_{(EV,t_{last})}}{N_{EV}} \tag{3.18}$$

3.2 V2X Discharge Method

In this section it was implemented the method V2X discharge where the EVs could discharge their batteries to charged adjacent EVs charging in the park. To implement this method a few changes had to be made to the objective function. First we have to check if the vehicles can discharge and that could only happen after having their SOC at least at 95%, then the vehicle could not discharge completely so a discharge threshold was set at 80% SOC. It is important to note that during the discharge process the vehicles cannot suddenly charge again, it can only discharge or charge, therefore when the SOC hits 80% the EV goes back to charging mode. As it is shown in Eq. 3.19

$$P_{maxDch(EV,t)} = (SOC_{(EV,t)} - DischargeBoundary) \times EV_{BatteryCapacity(EV,t)} \forall t \in 1, ..., T \tag{3.19}$$

It is important to understand that with this configuration in Eq. 3.19, the closer to 95% SOC, the faster the vehicle will discharge depending on his maximum charge/discharge rate and the closer it gets to the Discharge Boundary of 80%, the slower it discharges, until it stops.

Remember the goal is to optimize the F-Index result and have all the vehicles leave with higher SOC on t_{last}, which is the moment before leave the park.

The objective function which we want to minimize on the model also changes to take into account the discharge of the vehicle in the optimization model, as shown in Eq. 3.20

$$\begin{aligned} f(t) = min \sum_{EV=1}^{N_{EV}} [PF_{MCP(EV,t)} \times PW_{MCP(EV,t)} + \\ PF_{SocL1(EV,t)} \times (PW_{SocL1(EV,t)} + PW_{VL1(EV,t)}) + \\ PF_{SocL2(EV,t)} \times (PW_{SocL2(EV,t)} + PW_{VL2(EV,t)}) + \\ PF_{SocL3(EV,t)} \times (PW_{SocL3(EV,t)} + PW_{VL3(EV,t)}) + \\ PF_{VarP(EV,t)} \times PW_{VarP(EV,t)} + \\ PF_{Dch(EV,t)} \times PW_{PDch(EV,t)}] - \\ PF_{minSOC(t)} \times PW_{minSOC(t)} + \\ PF_{PParking(t)} \times PW_{PParking(t)} \end{aligned} \tag{3.20}$$

This new implementation of the objective function compared to the one is 3.17 now takes into account the penalization factor of the discharging EV in order optimize the charging for all EVs.

3.3 Solar System Implementation

In [42],the study evaluates the net value of installing PV panels on a solar parking lot over the lifetime of the panels, taking into account the presence or absence of energy storage. The analysis takes into account the expenses of purchasing PV panels and a battery, as well as the advantages of charging plug-in electric vehicles (PEV) with free energy from PV panels.

To simplify the approach the following equation was implemented to approximately calculate the solar production of a solar system with $SolarPowerOutput$ being (kW):

$$SystemPower = PV_{Power} \times Efficiency \tag{3.21}$$

$$SolarPowerOutput(t) = SystemPower \times \sin \frac{\pi \times t - dayStart}{dayEnd - dayStart} \qquad \forall t \geq 1, ..., T \tag{3.22}$$

The following graph serves as a visual representation of the system implemented regarding that it only starts producing energy at sunrise and stops at dawn.

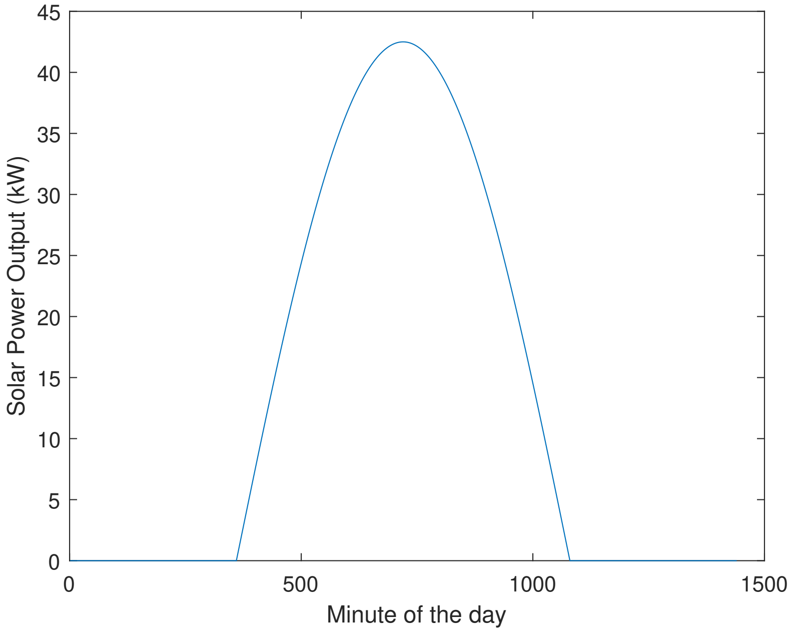

Figure 3.1: Solar Curve implemented for a random $SystemPower(kW)$.

To test how much can the solar system can improve the park F-Index three tests were conducted with different system powers of 50kWp, 100kWp, 150kWp, 200kWp, where all of them had 100 EVs.

3.4 Economical Study

To better evaluate if the solar system is reliable not only in terms of providing the charging capacity to the parking lot, it is proposed an economical study to evaluate the break-even point of installing a system like such.

Currently, silicon PV technology dominates the market. Silicon can be produced in either crystalline (expensive) or amorphous (cheap) form. The former technology might be either mono-crystalline or poly-crystalline. Mono-crystalline solar PV panels offer the maximum energy conversion efficiency, hence their premium price is justified. Single-crystalline PVs work well even in hot regions with adequate natural ventilation, making them suited for the Middle East. Standard testing conditions (STC), were used to measure these criteria. The STCs are as follows: 1) 25℃ cell temperature, 2) 1000 W/m^2 irradiance, and 3) an air mass of 1.5 spectrum.

According to [43], mono-crystalline solar panels have a good ratio of efficiency per m^2 therefore were chosen for this study. Since this study is for a parking lot, the use of carports seem the best solution to accommodate the parking spaces along side with providing shade and solar energy, although their quite expensive.

As such here are the conditions of the proposed solar system, taking into account that the amount of panels will increase according to the case. Furthermore, it has been proposed that the PLSPVS be implemented as a fixed-tilt, non-tracking system oriented at a 20-degree southern tilt angle to optimise its ability to capture solar irradiance throughout the year, we have the following general configuration in Tables 3.1 and 3.2.

Table 3.1: Solar Module Parameters

Peak Power (Wp)	500
Area (m^2)	2.58
Price per watt (€/W)	0.23

PV arrays often generate power output that is lower than their STC rating, primarily due to variations in real-world conditions that differ from those specified under STC. Possible real-world scenarios that may affect photovoltaic cell performance include elevated cell temperatures, reduced irradiance levels, and accumulation of dirt or other contaminants on the module surface. Upon factoring in the projected energy losses, it can be inferred that the photovoltaic system proprietor will experience an operational output of approximately 85$\%$ of the standard test conditions rating. Given the persistent nature of these losses, it is possible to oversize the photovoltaic (PV) array beyond the power rating of the inverter.

Table 3.2: General PV System configuration

System Parameters				
Azimuth	180º			
Inclination	20º			
System Efficiency	85%			
Nº of Panels	115	230	345	460
Peak Power (kWp)	57.5	115	172.5	230
Output Power (kW)	50	100	150	200

Given that a single carport has the capacity to accommodate 100 modules and can provide parking space for 25 electric vehicles, it is proposed to augment the number of carports by one in each instance of peak power testing, which would result in an associated increase in cost.

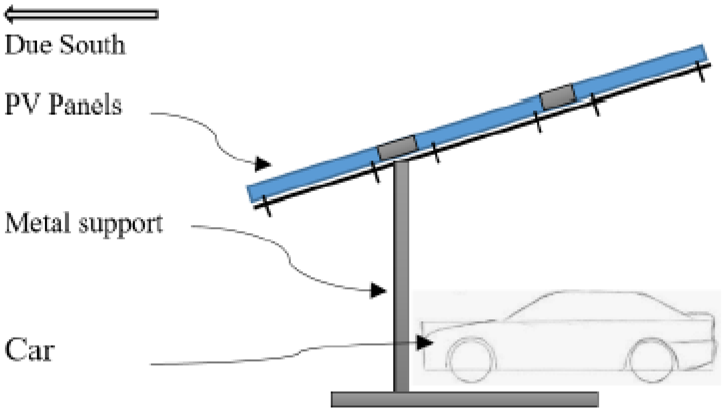

Figure 3.2: Example of a Side-view of the PLSPV system (Tilt angle is 20°).

In addition, in order to have a better understanding of the extent to which the park will profit from the installation of a solar power system, an analysis of how much energy the park was consuming daily was taken into account by simply summing the power used by each station through the day, as shown in Eq. 3.23.

$$DailyPowerConsumption = \sum_{CS=1}^{100} \frac{P_{ch(EV,t)}}{60} \forall t \in 1, ..., T \tag{3.23}$$

Also we have to take into account the daily power generated by the solar system taking into consideration that it was set to have sun for 12h a day and that can be achieved in Eq. 3.24 using the results from Eq. 3.23.

$$DailySolarProduction = \sum \frac{SolarPowerOutput(t) \times 12}{60 \times 24} \forall t \in 1, ..., T \tag{3.24}$$

To calculate the break-even point in Eq. 3.26 it was taken into the account that the electricity tariff is around 0.17€/kWh and the price per kWp for a solar system with carports would be around 1.1€/Wp. With this and using Eq. 3.25, we can calculate the yearly energy production from out solar system, in €.

$$YearlyProduced = DailySolarProduction \times 365. \tag{3.25}$$

$$BreakEvenPeriod = \frac{TotalCost}{YearlyProduced \times ElectricityPrice} \tag{3.26}$$

4

Numerical Results

Contents

4.1 Base Study Results for comparison

In this section, we present the numerical results obtained from the study, utilizing the program developed in [1], using MATLAB and the optimization program GAMS. Our aim was to establish a baseline of comparison for evaluating the effectiveness of integrating solar energy and V2X discharge in parking lots. To ensure a fair assessment, we focused on analyzing the power capacity of the parking lots, limiting the grid power of the park to a maximum of 100 kW, and just like the previous study there will be 100 EV charging in the parking entering and leaving at different time periods.

To ensure comprehensive analysis, we considered four distinct cases representing varying CS configurations. These cases are as follows:

1. Case 1: In this scenario, we examined a parking lot equipped with 100 charging stations, each capable of delivering a maximum output of 7.2 kW.

2. Case 2: The second case focused on a parking lot featuring 20 charging stations, each with a maximum output of 22 kW.

3. Case 3: We explored a scenario where the parking lot consisted of only three high-power charging stations, each capable of delivering a maximum output of 120 kW.

4. Case 4: Finally, we investigated a single charging station with a maximum output of 250 kW.

Figures 4.1 and 4.2, along with Table 4.1, serve as the foundational benchmarks for comparison in the subsequent sections. In these sections, we will provide a comprehensive analysis of the numerical results, emphasising the significant findings and implications for each case.

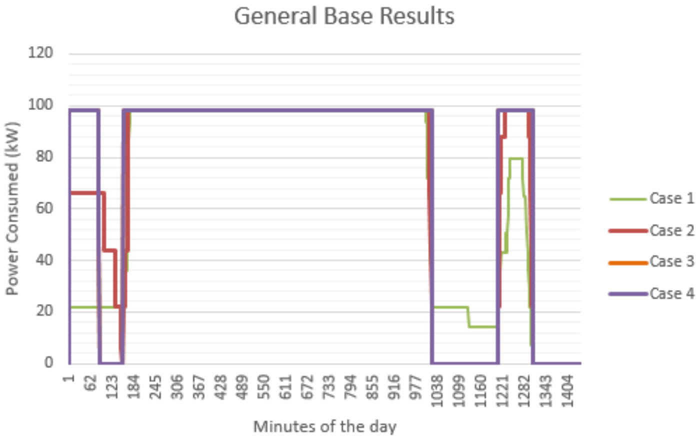

Figure 4.1: Base of comparison for Consumed Power for every single case to be applied.

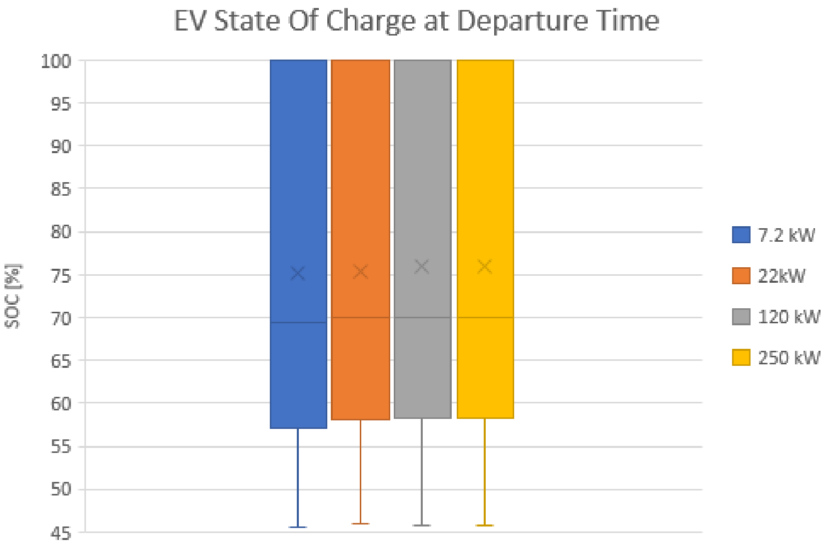

Figure 4.2: EV State of Charge at Time of Departure

Table 4.1: F-Index results for each base case

CS	F-Index
7.2 kW	0.2691
22 kW	0.2874
120 kW	0.2861
250 kW	0.2861

4.2 Solar System Implementation

Four distinct solar power systems were implemented for each case, with varying capacities. The study under consideration analysed solar power capacities of 50 kW, 100 kW, 150 kW, and 200 kW. With this we can analyse the effects of varying solar power capacities on the charging performance, energy consumption, and grid interaction across different scenarios. Through the assessment of charging behaviour and energy dynamics in response to diverse solar power conditions, the viability and efficacy of incorporating sustainable energy sources in parking lot charging facilities can be ascertained.

Figures 4.3,4.4,4.5 and 4.6 represents the EV with lowest SOC at each minute of the day present in the park for each case this method was implement. In appendix A, Figures A.4, A.5, A.6 and A.7, represent the power consumption of adding the four distinct solar power system for each case.

Figure 4.3: Minimum SOC with only solar power added, along the day for case 1.

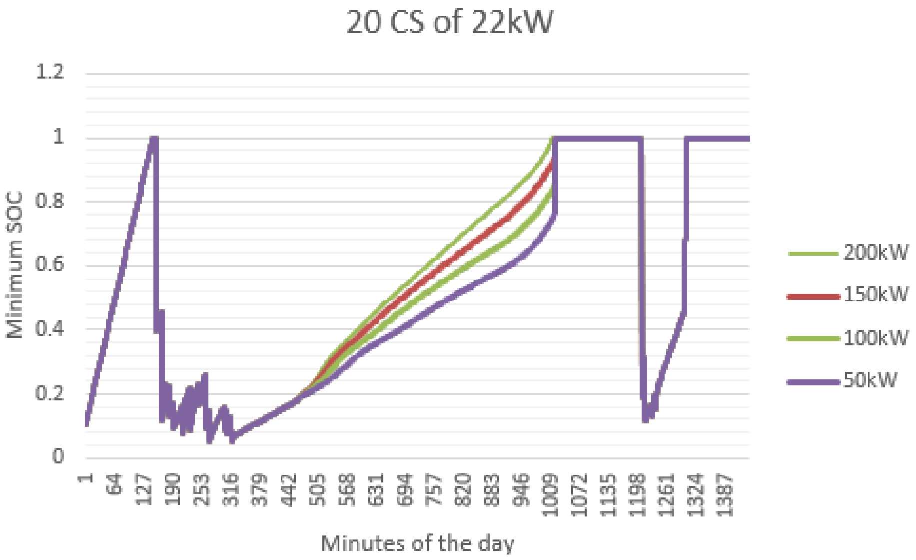

Figure 4.4: Minimum SOC with only solar power added, along the day for case 2.

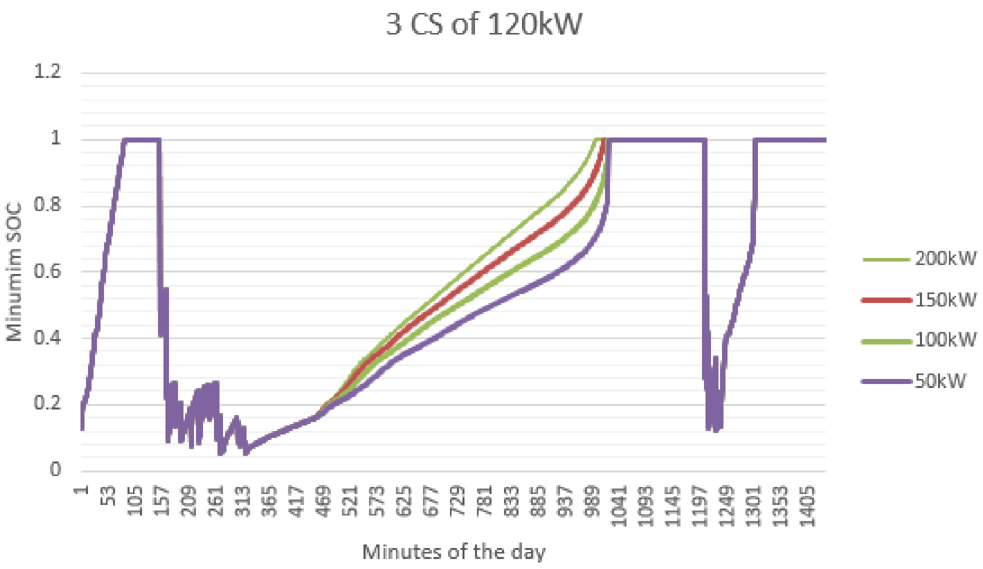

Figure 4.5: Minimum SOC with only solar power added, along the day for case 2.

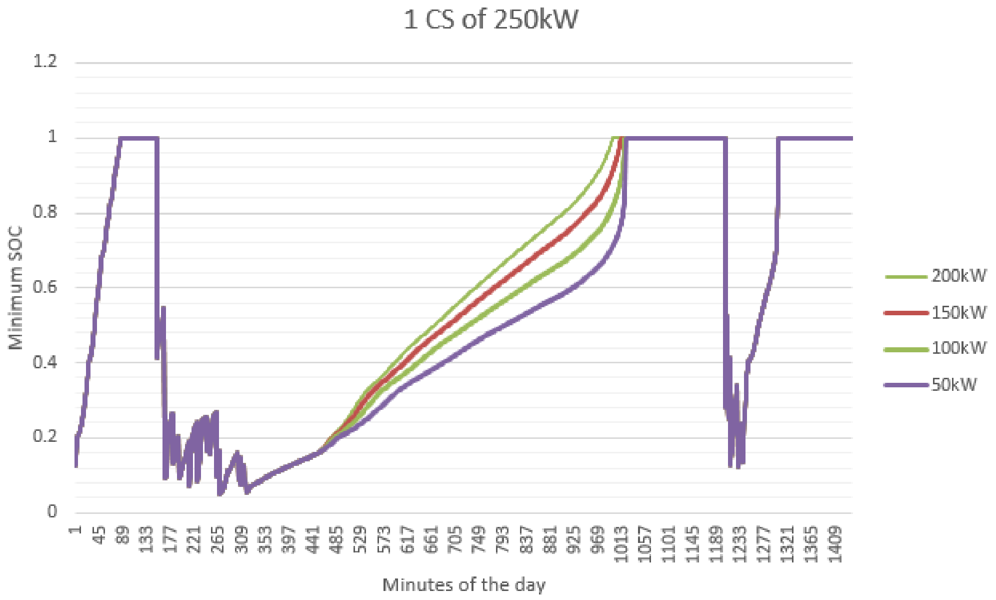

Figure 4.6: Minimum SOC with only solar power added, along the day for case 2.

To better visualise the results we just obtained the following Figure 4.7 shows the EVs state of charge at departure time for every single case refered with the 4 solar power implementations.

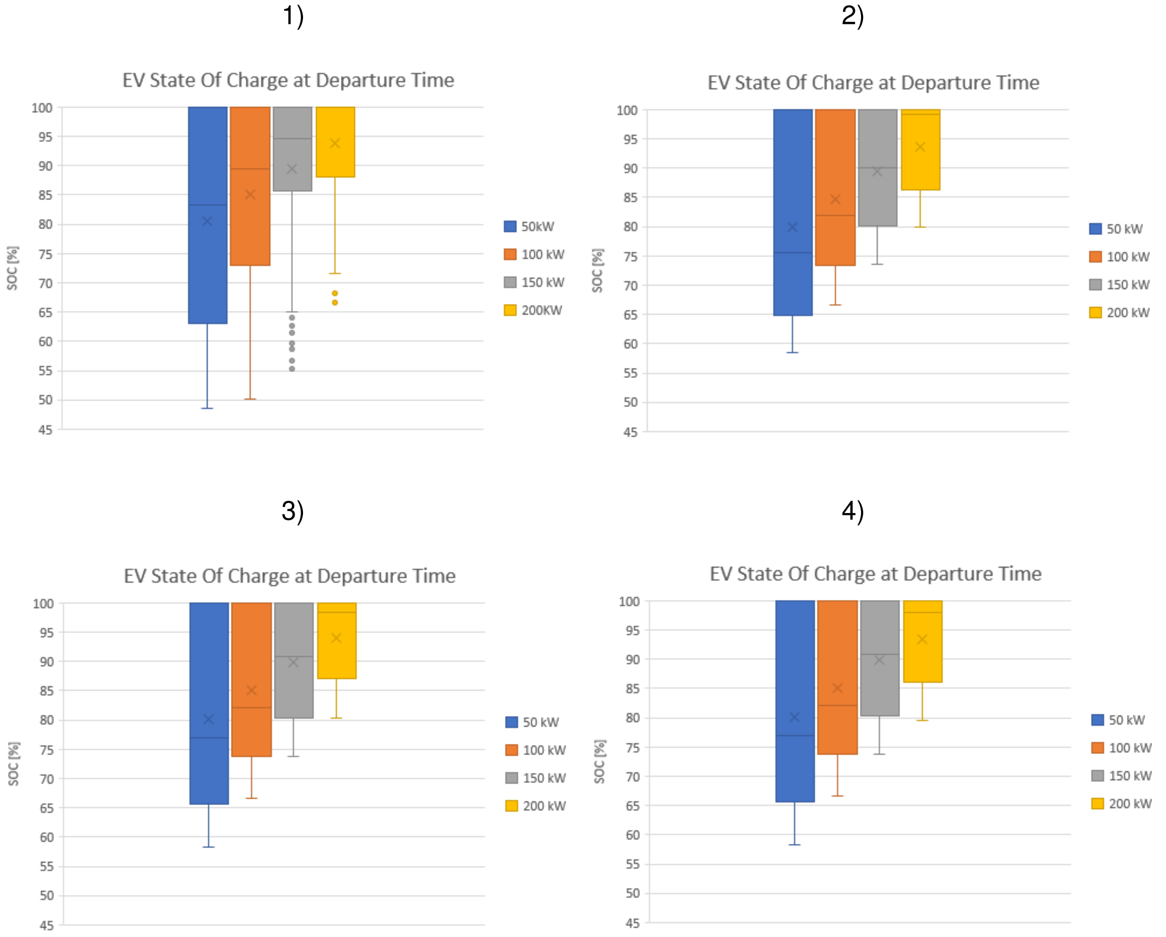
1) 2) 3) 4)

Figure 4.7: EV State of Charge at Departure time for each solar system implemented: 1) Is for case 1; 2) is for case 2; 3) is for case 3; 4) is for case 4.

As such the results for F-Index evaluation each case are represented in Table 4.2

Table 4.2: F-Index results for each case with the four implementations of solar power.

Solar Power (kW)	Case 1	Case 2	Case 3	Case 4
50	0.3320	0.3912	0.3911	0.3911
100	0.3968	0.4930	0.4972	0.4972
150	0.4735	0.5982	0.6030	0.6030
200	0.6457	0.7085	0.7158	0.7005

The results that are shown in Table 4.2 make one thing abundantly clear: the superiority of the outcomes is directly proportional to the rate at which the vehicle may be charged. In the first scenario, we are only able to see EVs leaving with a full charge in Figure 4.3 after installing a solar system with a peak power of one hundred kilowatts. In the other circumstances, given that the station itself has a far greater amount of power available, the vehicle itself will be the limiting factor.

All of these tests take into consideration a perfect daily solar generation without any bad weather interference, so it stands to reason that the more power we add to the solar system, the better it will be. This is due to the fact that we will be able to accomplish fast charging much sooner if the energy is accessible (there is sun), and the station will be able to give it with relative ease. This is demonstrated in Figures 4.5 and 4.6.

4.3 Economic Evaluation

Table 4.3: Daily Power Consumption without Solar

Case	Power Consumption (kWh)
1	2620.97
2	2739.08
3	2739.08
4	2740.18

To calculate the break-even point we first need to know how much solar energy our system if going to produce. Accurately determining the appropriate size of a PV array for connection to an inverter necessitates the ability to forecast the power output that will be generated throughout a full year.

As a result, the input rating of the solar power inverter was selected to be equivalent to that of the PV array in order to ensure secure and effective operations for the grid-tied PV system. On Table 4.4 it represents the daily energy production of sun with each type of implementation.

Table 4.4: Solar Energy Production

Solar Power (kw)	Daily(kWh)	Yearly (kWh)
50	142	51.830
100	416	151.840
150	624	227.760
200	821	299.665

As a consequence of this, in order to determine the point at which each scenario becomes profitable, and since we concluded that the required energy for every case is mostly the same it will only be considered case one, which leads to the following results:

Table 4.5: Break-Even Point for each case for a system power.

System Power (kW)	Cost (€)	Break-Even (years)
50	55.000	3.12
100	110.000	2.16
150	165.000	2.16
200	220.000	2.16

According to the example presented and the data in Table 4.5, it appears that the break-even point stabilises. However, it should be noted that this analysis does not take into account the decreasing prices as the kWp installed increases, which would likely result in a faster break-even point. Moreover, the analysis fails to account for the partial absorption of energy by the park, as there exist periods during the day when the energy is not exclusively allocated towards charging electric vehicles, but rather directed towards the grid.

4.4 V2X discharge and Solar Power

4.4.1 V2X discharge Without Solar Power

Prior to examining the outcomes pertaining to the solar system, it is imperative to inspect the impact of V2X discharge on the SOC of the vehicles. It is noteworthy to reiterate that the park maximum power is presently set at 100kW for the entire day. Nevertheless, it should be noted that the aggregate energy consumption may still increase, given the incorporation of localised solar energy into the park's energy supply as opposed to relying solely on grid-based sources.

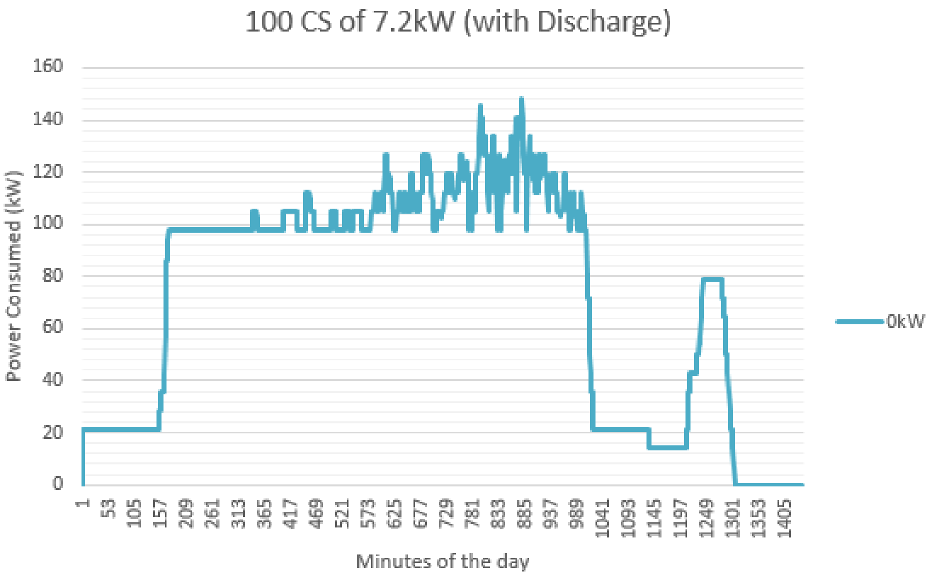

Figure 4.8: Power Consumed for one hundred 7.2kW CS with V2X discharge.

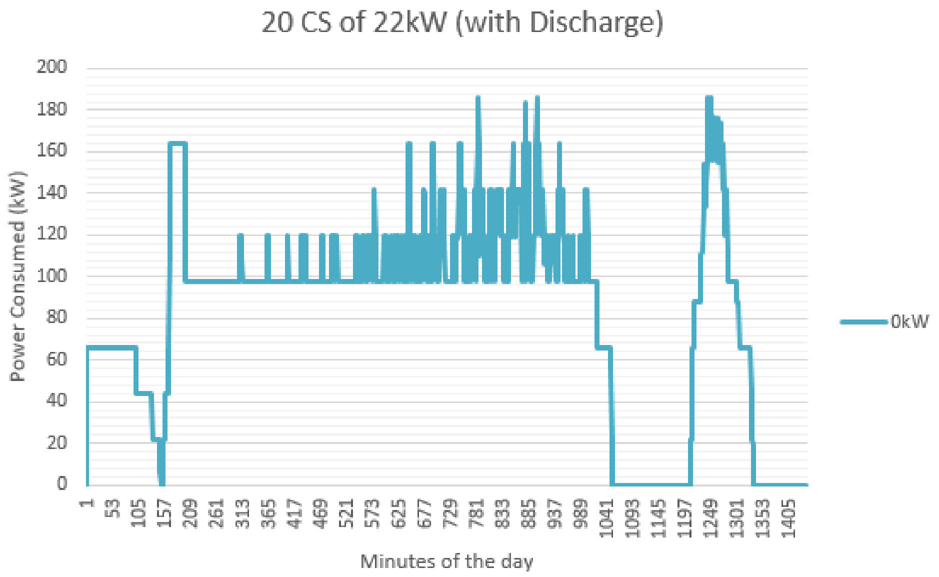

Figure 4.9: Power Consumed for twenty 22kW CS with V2X discharge.

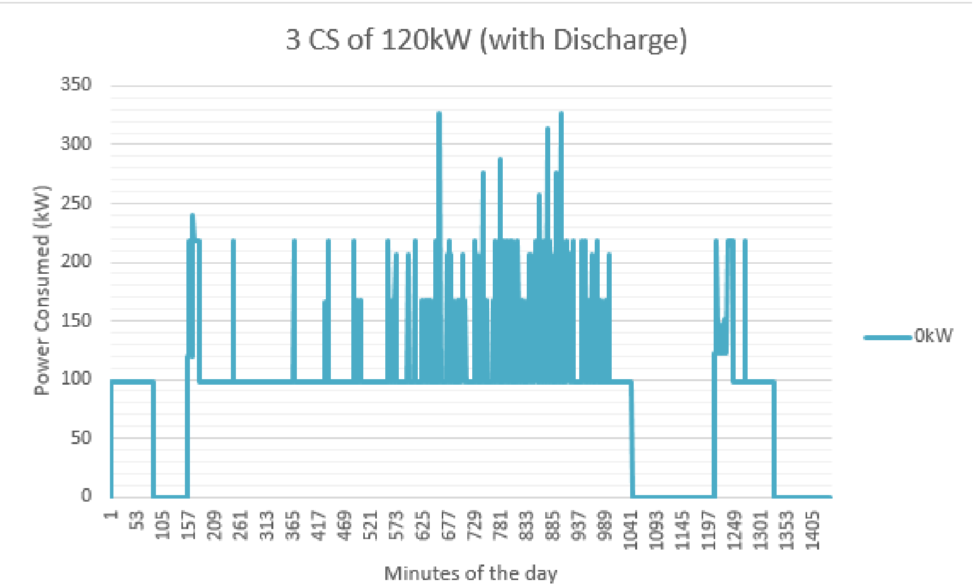

Figure 4.10: Power Consumed for three 120kW CS with V2X discharge.

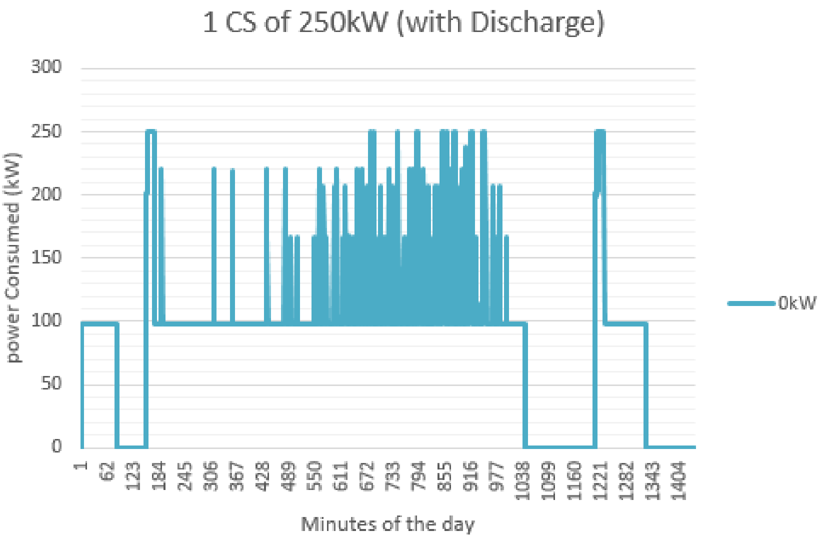

Figure 4.11: Power Consumed for one 250kW CS with V2X discharge.

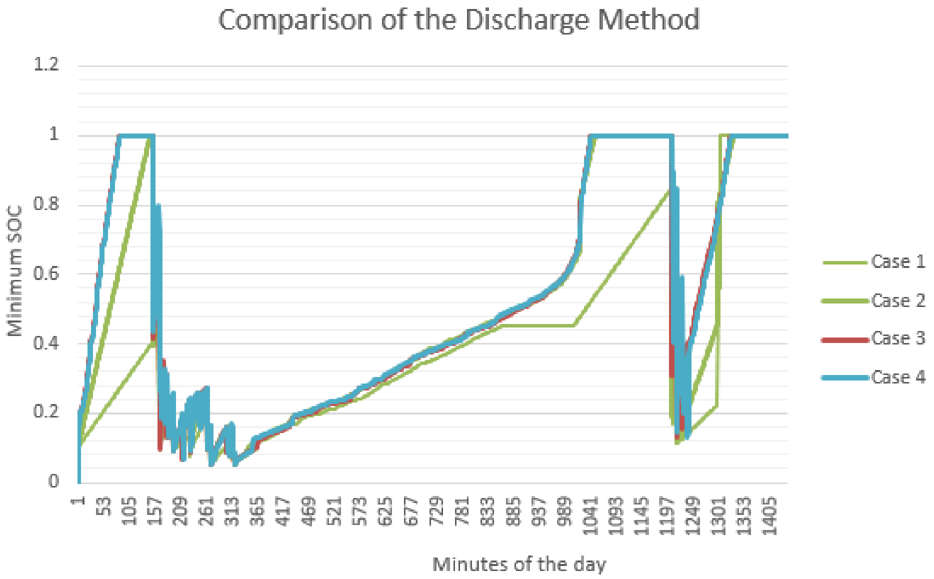

Figure 4.12: Comparison between the 4 cases of V2X discharge without any solar power added.

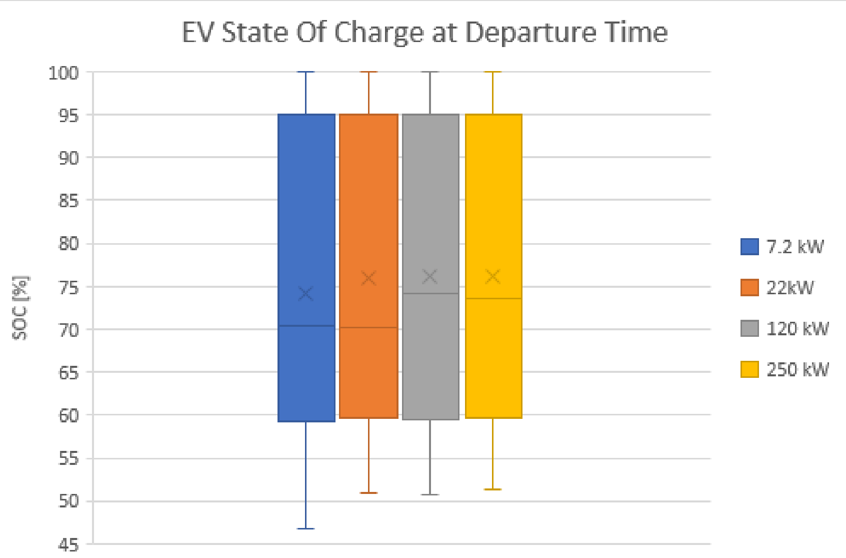

Figure 4.13: Comparison between the 4 cases of V2X discharge without any solar power added.

Table 4.6: F-Index results for each case of V2X discharge without solar power.

Case	F-Index
1	0.2859
2	0.3210
3	0.3231
4	0.3258

As illustrated in Figure 4.12, the utilisation of the V2X discharge method in Case 1, as shown in Figure 4.8, did not yield satisfactory results. This can be attributed to the insufficient power supply of the charging stations, resulting in prolonged charging times that prevent EVs from reaching full 100% SOC. Consequently, these EVs cannot discharge as they are superseded by other vehicles with higher charging priority.

In contrast, it can be observed that cases 3 and 4, as depicted in Figures 4.10 and 4.11 correspondingly, exhibit similar F-Index outcomes and nearly identical trends as illustrated in Figure 4.12, this has to do with the database that is used, because if for example we were to add more EVs with higher charging rate, or with bigger battery capacity we could notice a difference in these 2 cases as they could take more advantage of these high power stations.

4.4.2 V2X discharge With Solar Power

In our study, we incorporated V2X discharge capabilities in conjunction with the solar power systems for each case examined. The investigation was conducted to examine the impact of V2X discharge on the overall performance of the EV charging infrastructure and the utilisation of solar energy. The subsequent Figures 4.14,4.15,4.16 and 4.17 illustrates once again the EVs that possess the minimum SOC within the park at each minute throughout the day. In appendix B, the results of the power consumption for each independent test can be found.

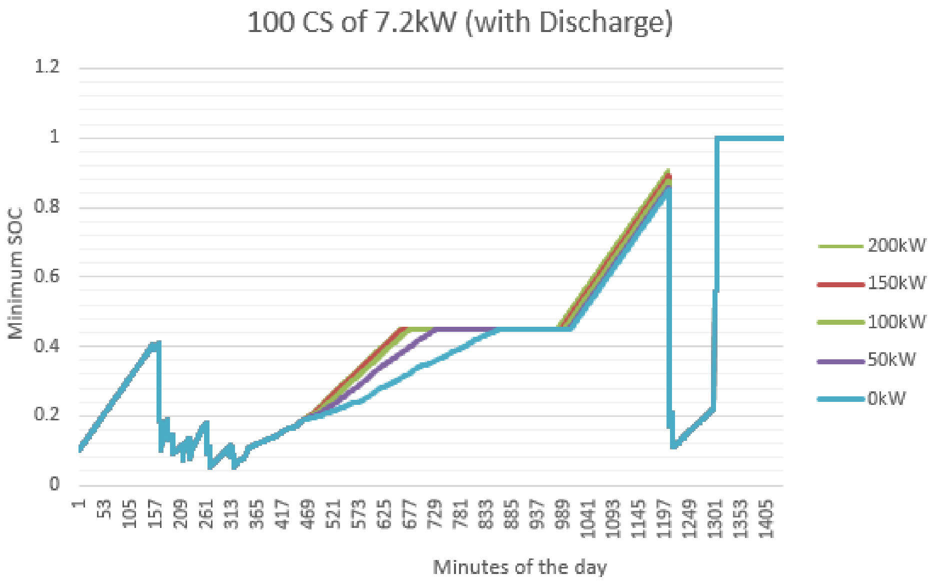

Figure 4.14: Minimum SOC of EVs throughout the day for one hundred 7.2kW CS with solar and V2X discharge.

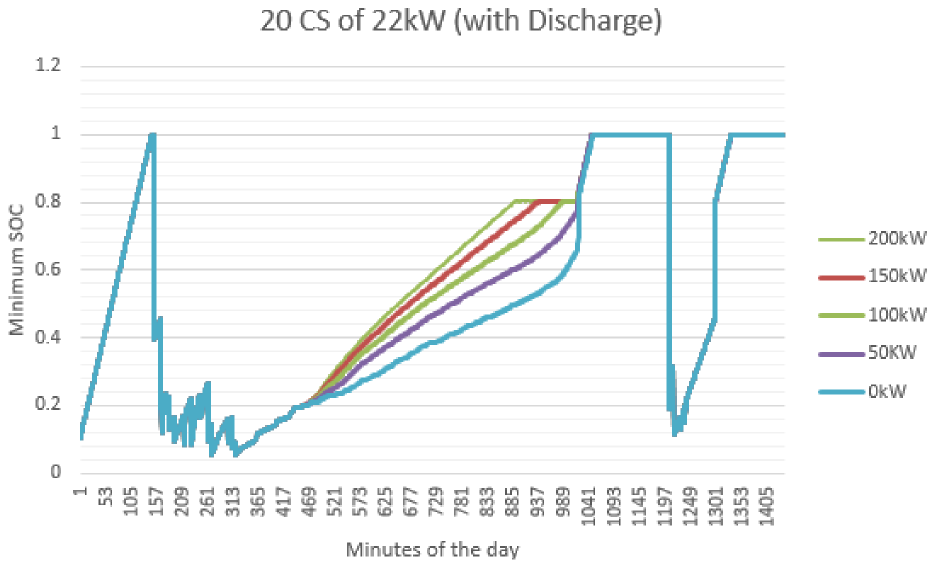

Figure 4.15: Minimum SOC of EVs throughout the day for three 120kW CS with solar and V2X discharge.

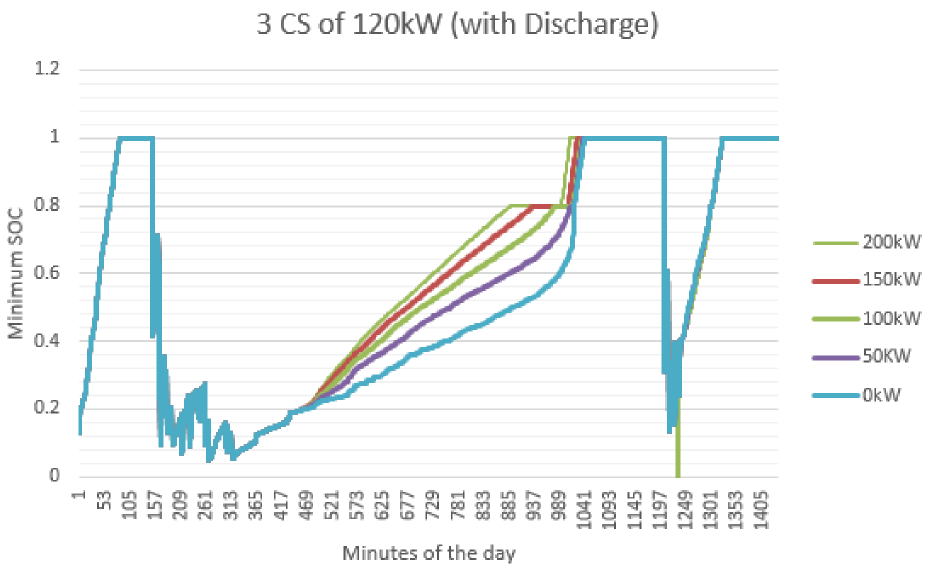

Figure 4.16: Minimum SOC of EVs throughout the day for three 120kW CS with solar and V2X discharge.

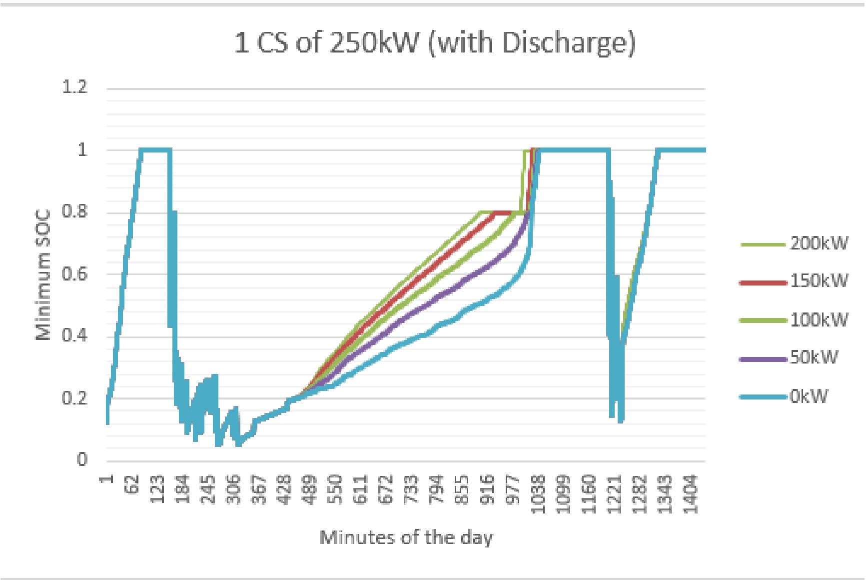

Figure 4.17: Power Consumed for one 250kW CS with 200kW of solar and V2X discharge.

Again to better visualise the results we just obtained the following Figure 4.18 shows the EVs state of charge at departure time for every single case refered with V2x discharge and the 4 solar power implementations.

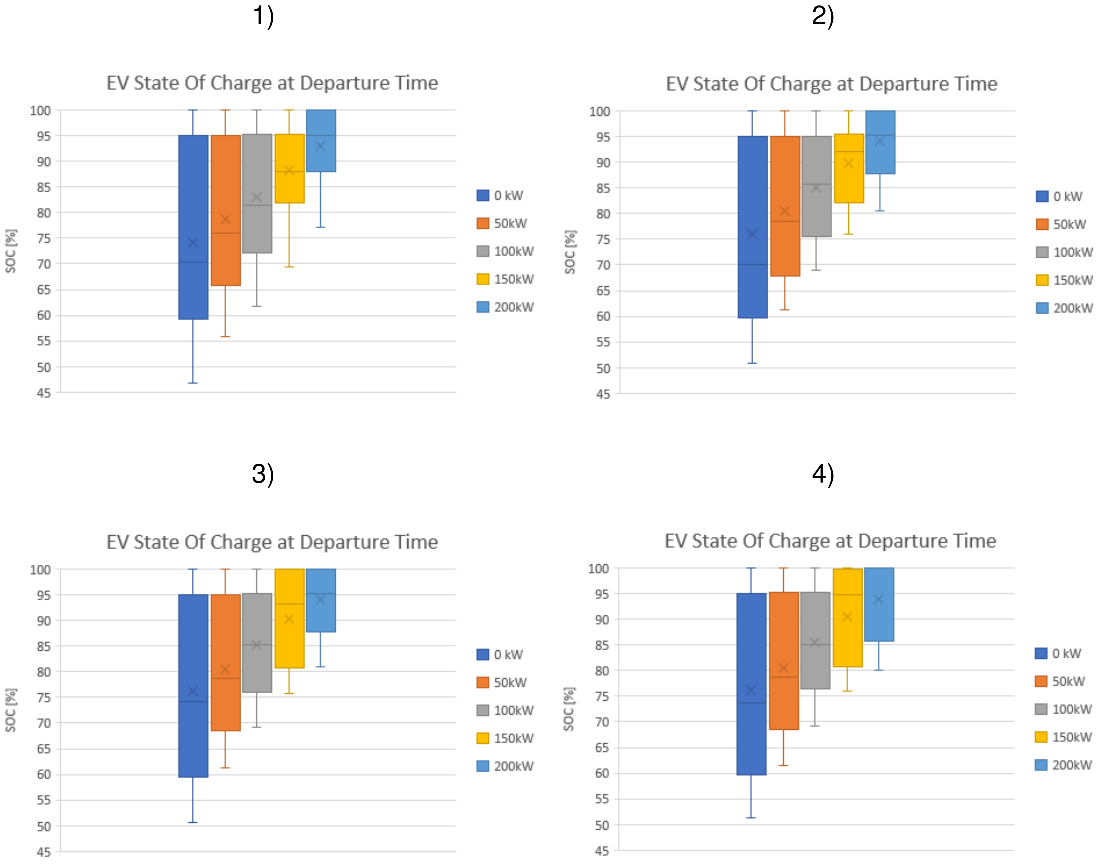
1)
2)
3)
4)

Figure 4.18: EV State of Charge at Departure time for each solar system implemented and V2X discharge: 1) Is for case 1; 2) is for case 2; 3) is for case 3; 4) is for case 4.

Table 4.7: F-Index results for each case of V2X discharge with the four implementations of solar power.

Solar Power (kW)	Case 1	Case 2	Case 3	Case 4
0	0.2859	0.3210	0.3231	0.3258
50	0.3865	0.4247	0.4277	0.4296
100	0.4718	0.5280	0.5340	0.5337
150	0.5800	0.6354	0.6336	0.6350
200	0.7159	0.7353	0.7393	0.7090

It should be noted that the discharge capability of vehicle batteries has resulted in earlier vehicles receiving greater benefits from charging alongside with the solar charging, even with a robust 200kW solar system, compared to the results shown in Table 4.2, vehicles that remain parked for extended periods of time do not experience significant improvements in their F-Index value.

The evaluation of the F-Index optimisation for the scenario without solar power exhibited a decline in performance, as indicated in Table 4.6, owing to the occurrence of V2X discharge, which is in contrast to the outcomes presented in Table 4.7. As anticipated, the incorporation of solar power resulted in a marginal increase in the F-Index.

Interestingly case 2 and 3 present very similar results all across Tables 4.5 and 4.7, this shows that having fewer CS with higher power can lead to better power management through the park, but on the other hand case 4, that is one CS of ”only” 250kW does not manage well with this much power, as expected.

In the forth scenario, the 250kW CS is being utilised to its maximum capacity. However, the excessive implementation of solar power with V2X discharge proves to be counterproductive and fails to yield significant benefits. This is particularly evident when comparing the index values of case 3 and 4 of Table 4.7, as they exhibit minimal differences.

Thus, it can be inferred that an excessive amount of local power generation does not provide substantial benefits. It should be noted that the system consistently draws the maximum power of 100 kW from the grid. Decreasing the income value has the potential to significantly decrease monthly billing expenses. However, it is also crucial to consider the necessity of this value. As depicted in Figure 4.11 and in comparison to the F-Index value presented in table 4.6, relying solely on V2X discharge is insufficient.

4.5 Best Results

Upon analysing the F-Index values of the 2 methods presented in Tables 4.2, 4.7, it was found that Case 3 yielded the most favourable results. This conclusion is due to the higher F-Index score obtained in comparison to the other cases. It is important to note that the F-Index evaluates the lowest 10% and 50% of SOC vehicles, and a value closer to 1 indicates a lower degree of penalization, which in turn suggests that the SOC of the vehicles is closer to 100%.

It is important to acknowledge that case 3 does have more CS power in general, a total of 360 kW in CSs, as such leaving to an overall better score. In certain scenarios, such as Case 4, reducing the overall park power may lead to more favourable outcomes. Conversely, in Case 1 and 2, increasing the park power may also result in improved results.

5

Conclusion

Contents

5.1 Achievements

The research done in this thesis indicate that the charging rate has a direct impact on the results of electric vehicle charging. The swifter charging rates of EVs lead to a more rapid attainment of full charge, thereby demonstrating a clear correlation between charging rate and charging outcomes.

Enhancing the power capacity of the solar system has a beneficial effect on the charging results. A solar system with greater capacity facilitates expedited charging during periods of solar energy availability, thereby enhancing the station's ability to furnish energy with greater ease. As a consequence, there is an enhancement in the outcomes of the charging process.

According to the economic analysis, the point at which the cost of installing a solar power system is equal to the savings generated by the system stabilises at a power output of 100 kW. It is possible that further augmentation of power may not yield advantageous outcomes unless there is a corresponding increase in the park's energy consumption. Nonetheless, this analysis fails to take into account the energy that is returned to the grid during periods when vehicles do not necessitate charging.

The assessment of V2X discharge in the absence of solar power indicates suboptimal charging and protracted charging durations, impeding electric vehicles from attaining complete charge. The integration of solar power in conjunction with reverse charging results in marginally superior outcomes.

Of the cases that were assessed, it was found that case 4, which encompasses three charging stations with a capacity of 120 kW each and utilises solar power, produced the most advantageous outcomes. The F-Index score exhibits a higher value in this instance, suggesting a reduced level of penalization and a greater proximity of SOC to 100$\%$ for the electric vehicles.

The study concludes that it is crucial to take into account the charging rate, integrate solar power, and optimise the power capacity of charging stations to achieve efficient electric vehicle charging. It is imperative to consider these factors during the design and implementation of charging infrastructure in order to optimise charging outcomes, reduce charging duration, and enhance overall efficiency.

5.2 Future Work

Future research could involve the assimilation of Smart Grid Technologies. The investigation of the amalgamation of smart grid technologies that has the potential to facilitate improved synchronisation and correspondence among the charging infrastructure, solar power generation, and the electrical grid. The implementation of this approach can potentially enhance load management, demand response, and grid balancing tactics, thereby resulting in heightened efficacy in the utilisation of solar energy, decreased peak demand, and enhanced stability of the grid.

Additionally, conducting economic and policy analyses in order to evaluate the financial feasibility, efficiency, and regulatory structures of EV charging infrastructure powered by solar energy. The aforementioned tasks encompass the analysis of various financing mechanisms, assessment of the ROI, and investigation of prospective incentives or regulations aimed at promoting the uptake of solar-powered charging infrastructures.

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A

Base and Solar System implementation results

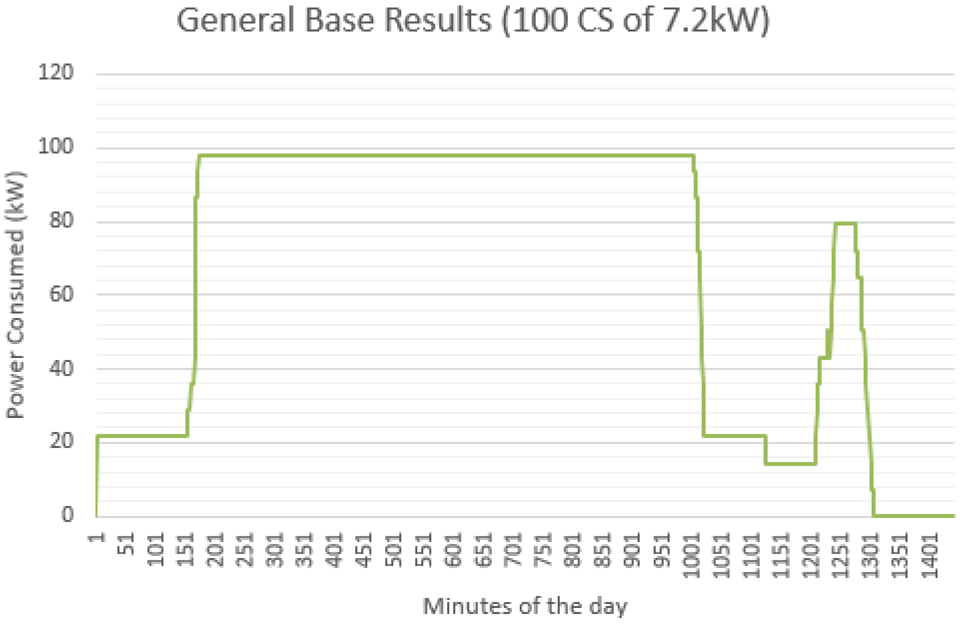

Figure A.1: Base of comparison for Consumed Power, this example was made using case 1

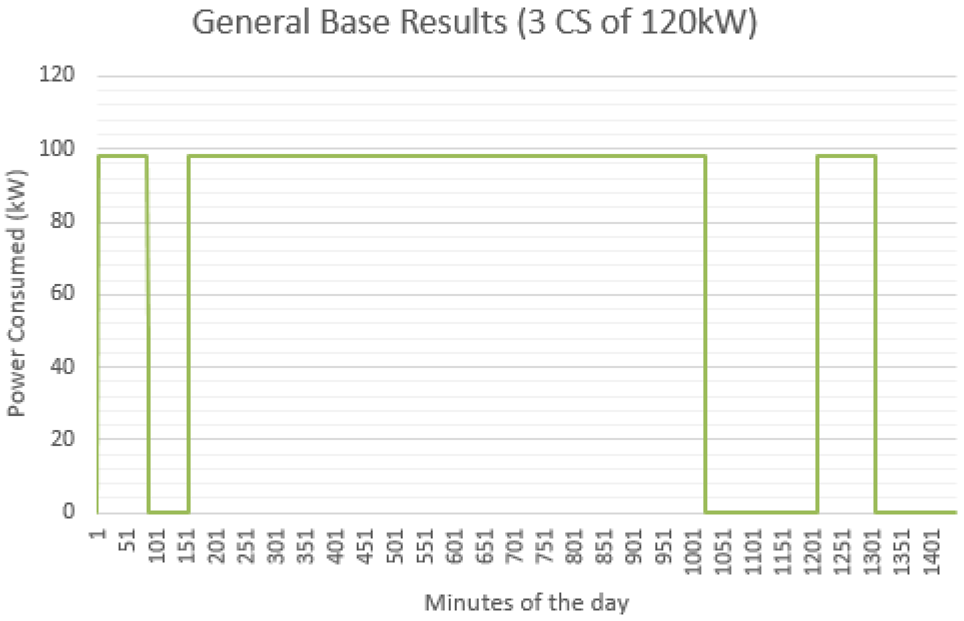

Figure A.2: Base of comparison for Consumed Power, this example was made using case 3

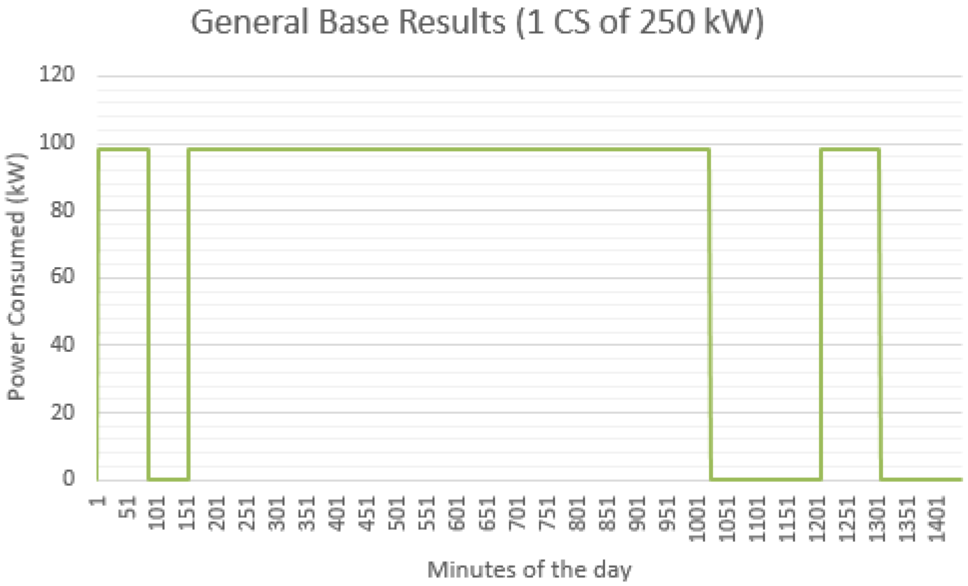

Figure A.3: Base of comparison for Consumed Power, this example was made using case 4

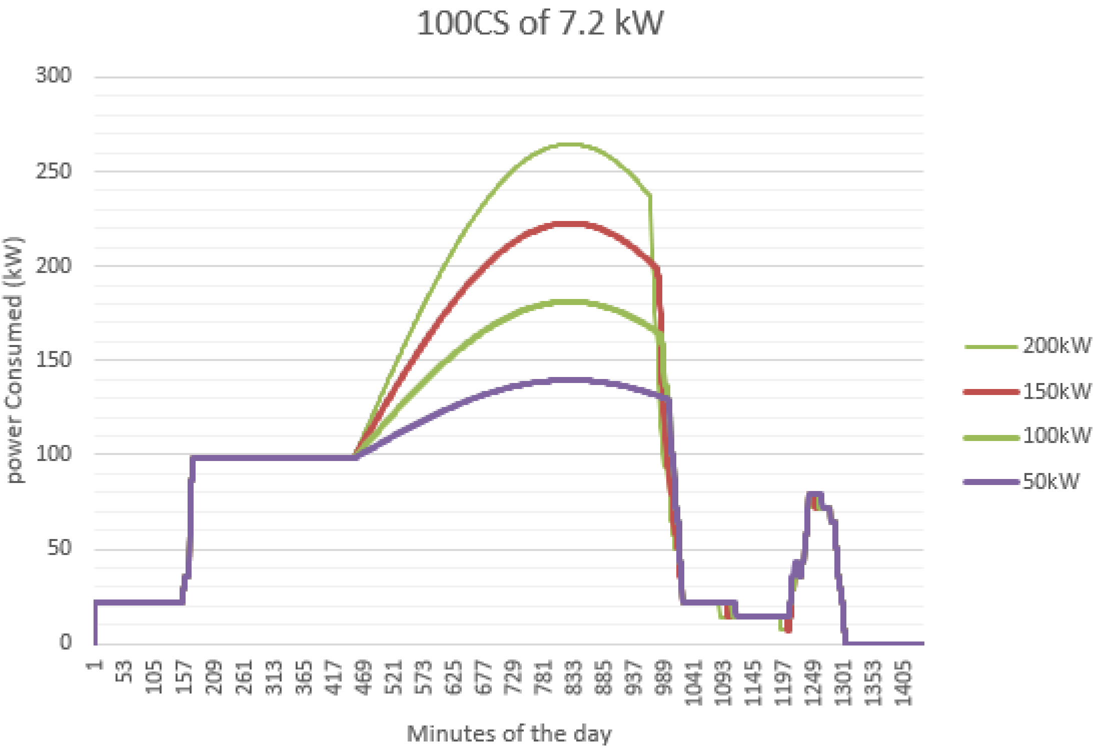

Figure A.4: Solar power added to 100 CS of 7.2 kW.

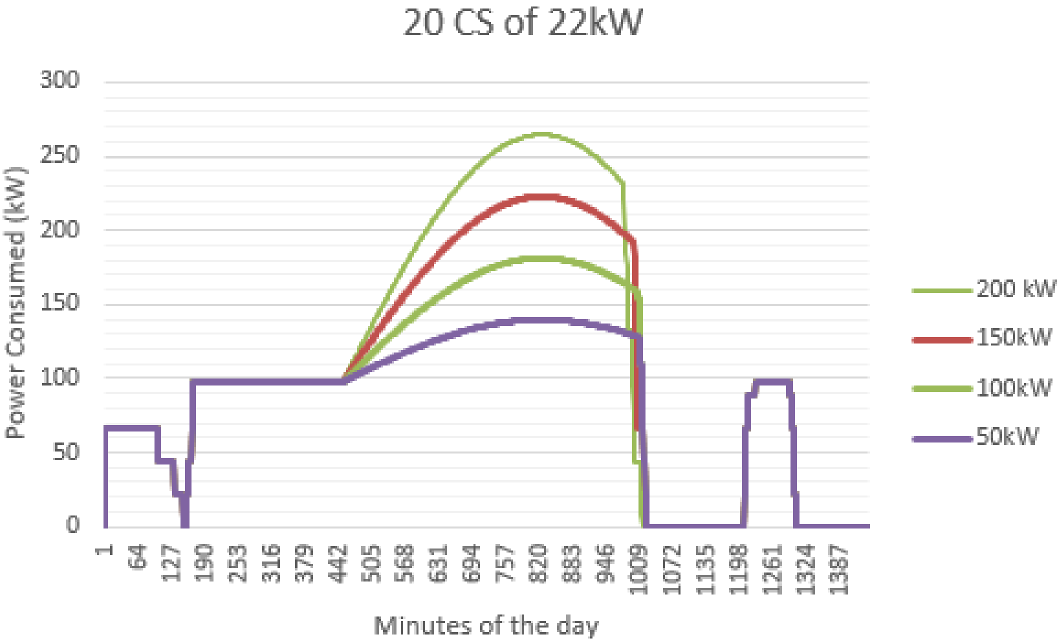

Figure A.5: Solar power added to 20CS of 22 kW.

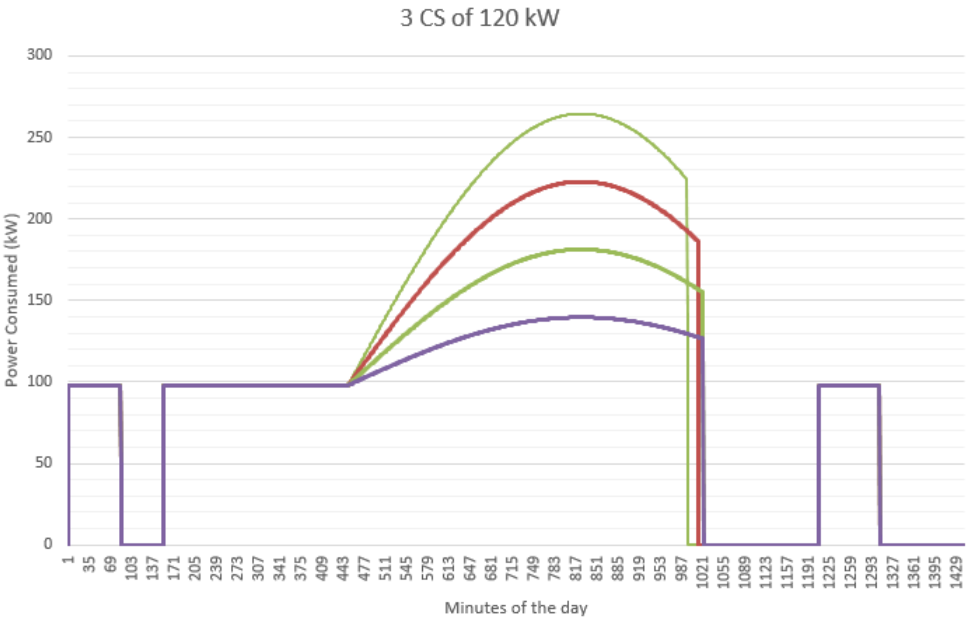

Figure A.6: Solar power added to 3CS of 120 kW.

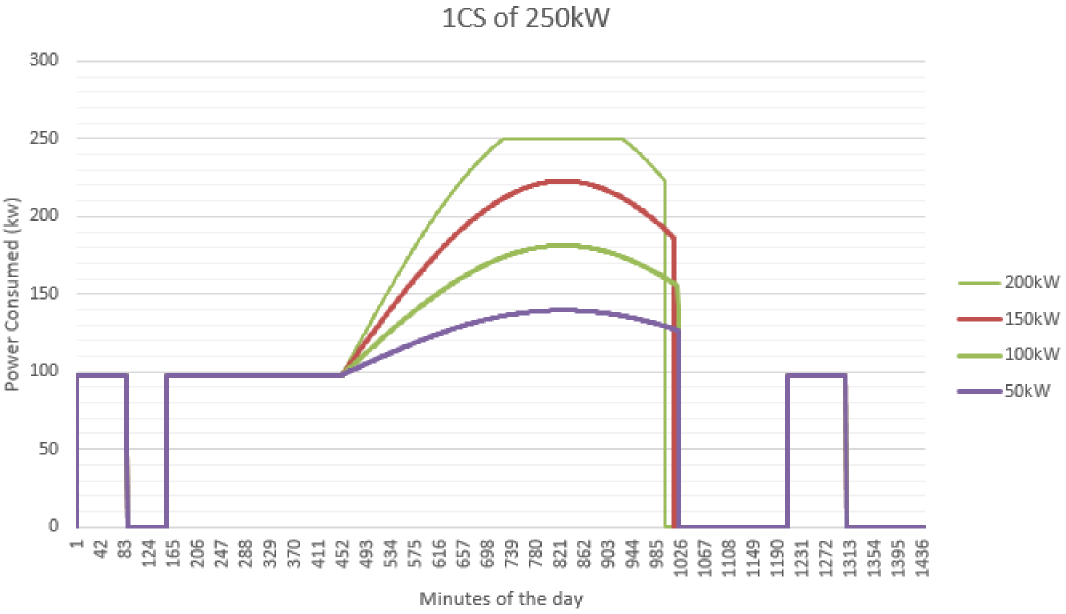

Figure A.7: Solar power added to 1CS of 250 kW.

B

V2X Discharge and Solar System results

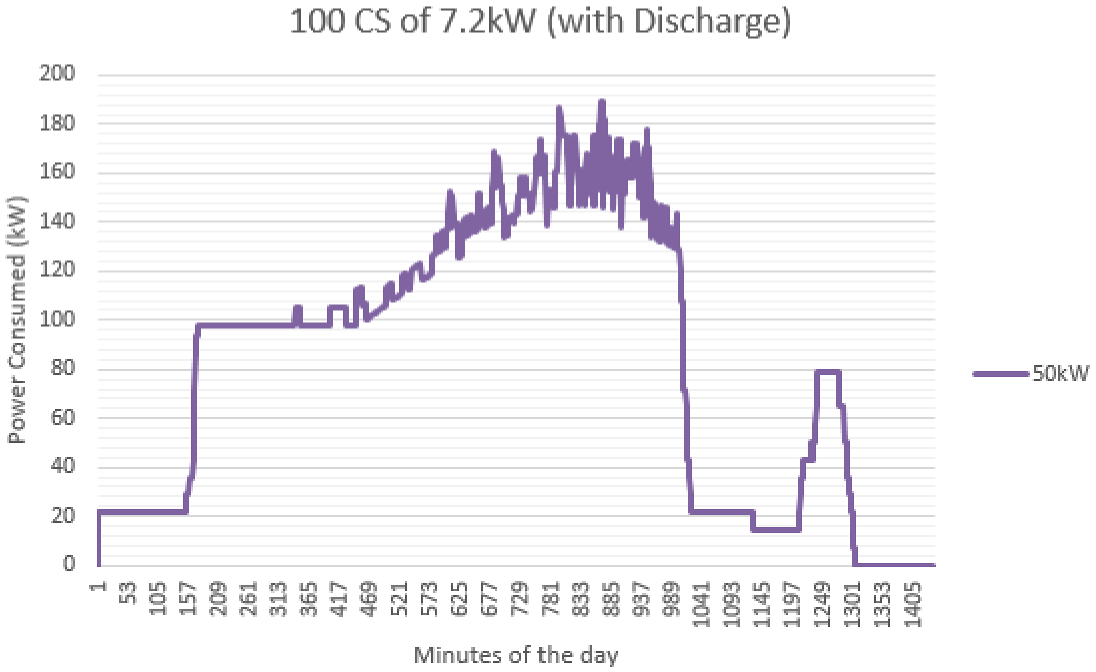

Figure B.1: Power Consumed for one hundred 7.2kW CS with 50kW of solar and V2X discharge.

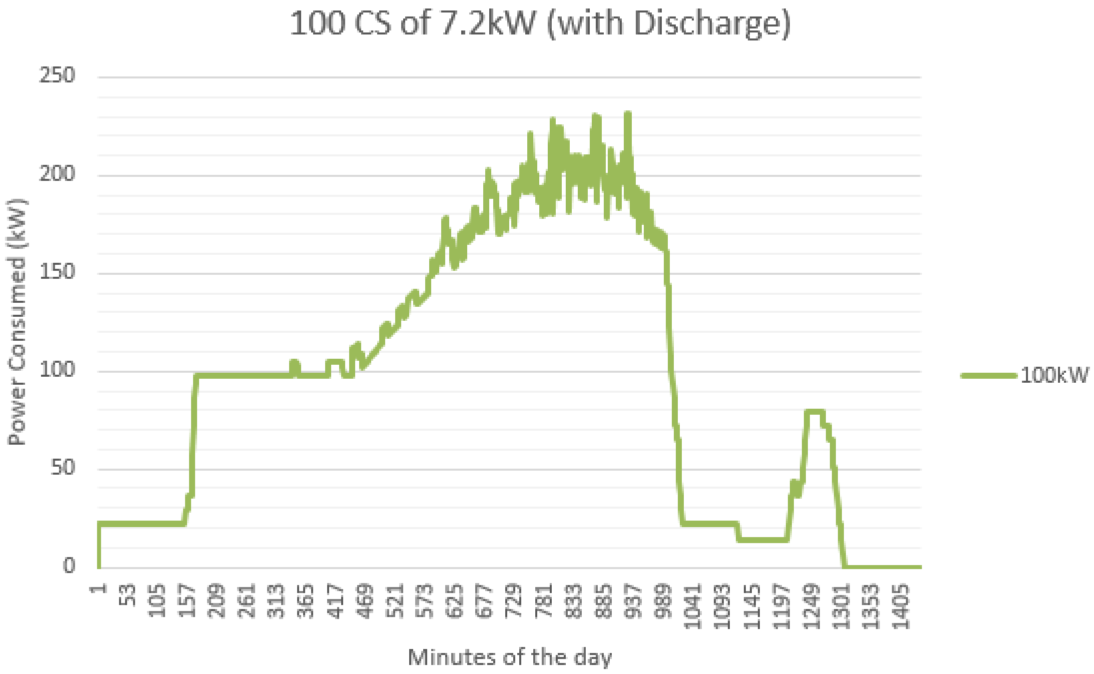

Figure B.2: Power Consumed for one hundred 7.2kW CS with 100kW of solar and V2X discharge.

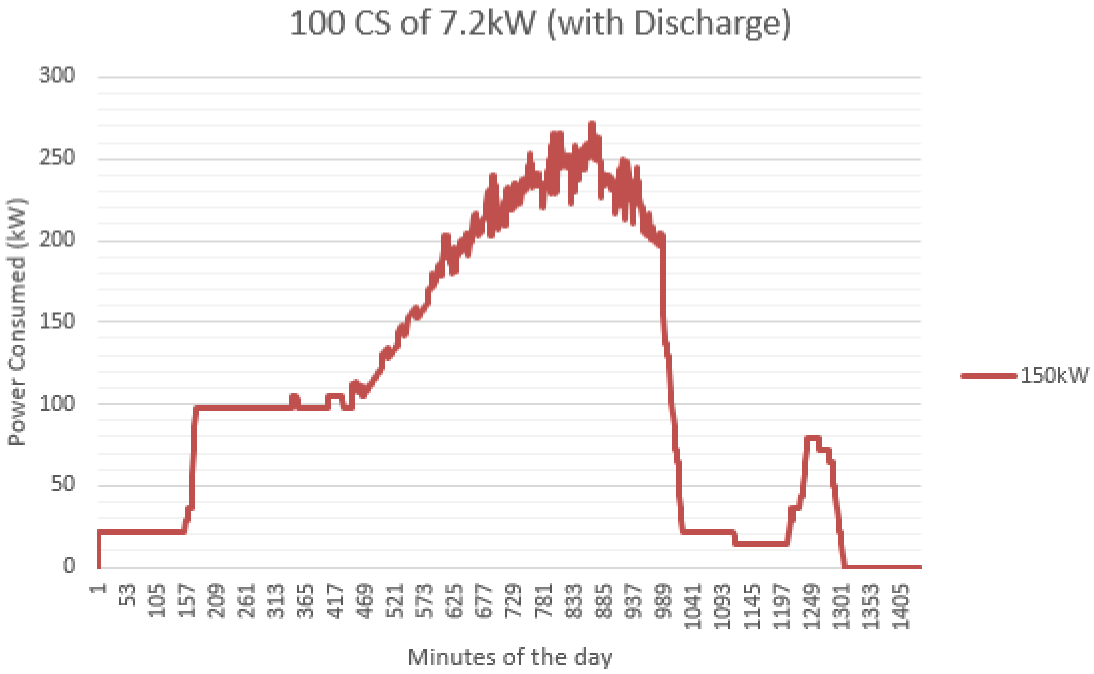

Figure B.3: Power Consumed for one hundred 7.2kW CS with 150kW of solar and V2X discharge.

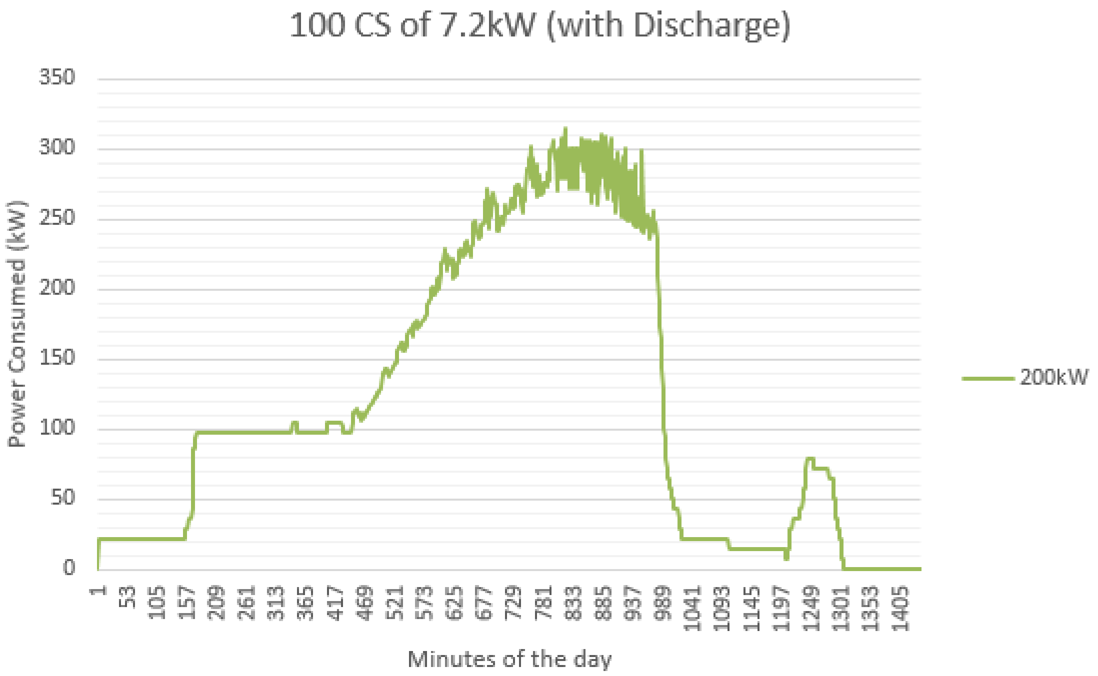

Figure B.4: Power Consumed for one hundred 7.2kW CS with 200kW of solar and V2X discharge.

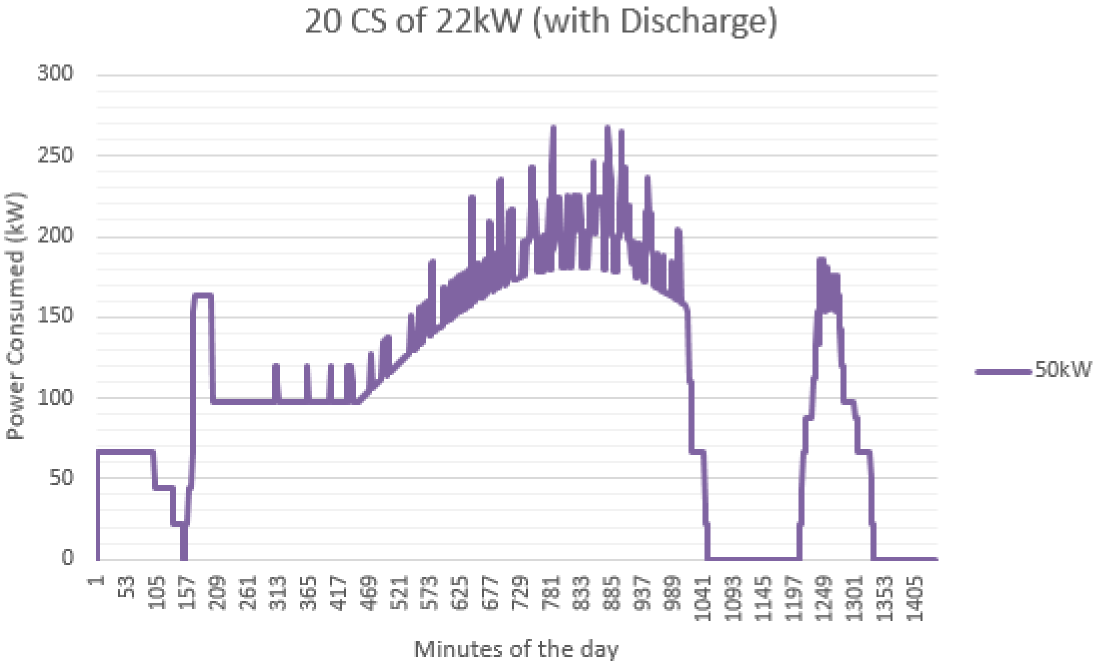

Figure B.5: Power Consumed for three 120kW CS with 50kW of solar and V2X discharge.

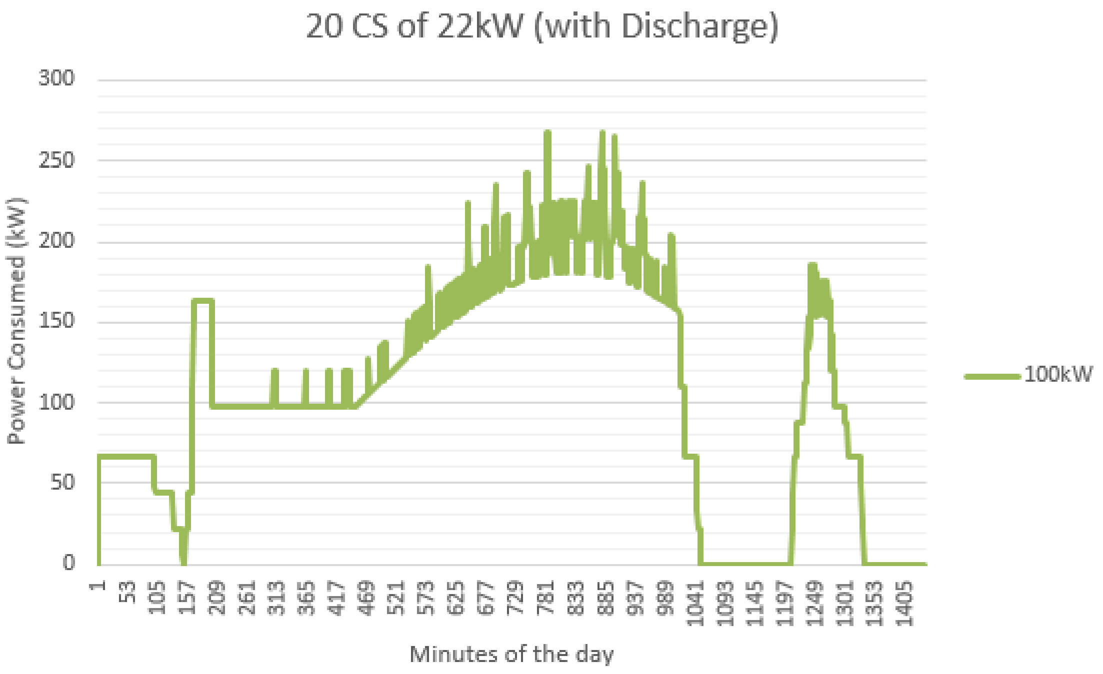

Figure B.6: Power Consumed for three 120kW CS with 100kW of solar and V2X discharge.

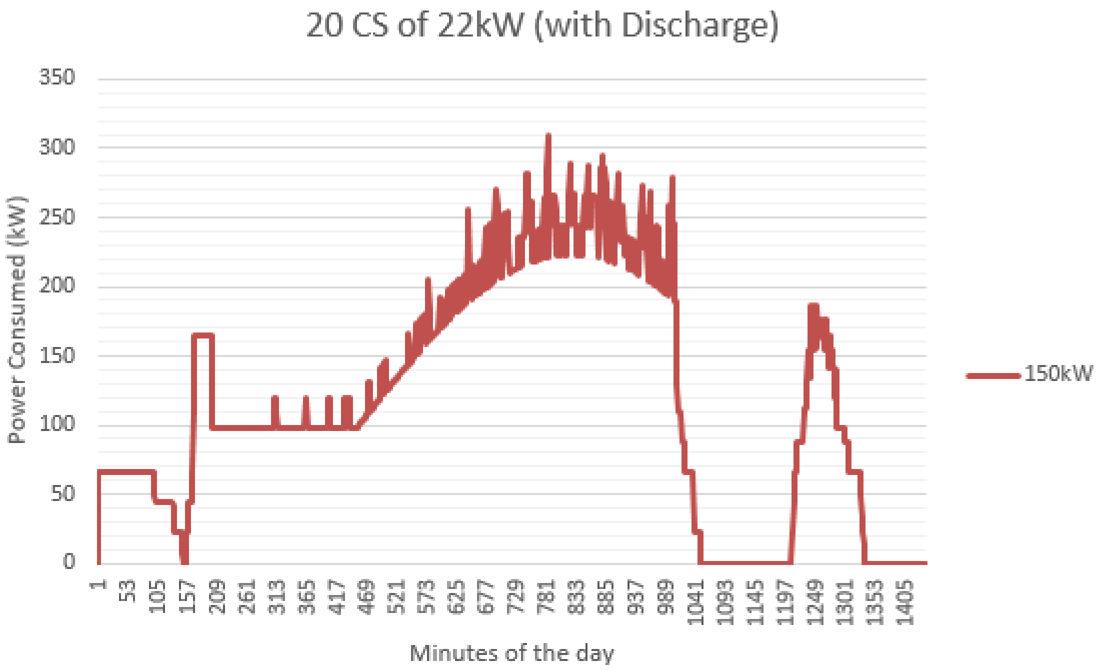

Figure B.7: Power Consumed for three 120kW CS with 150kW of solar and V2X discharge.

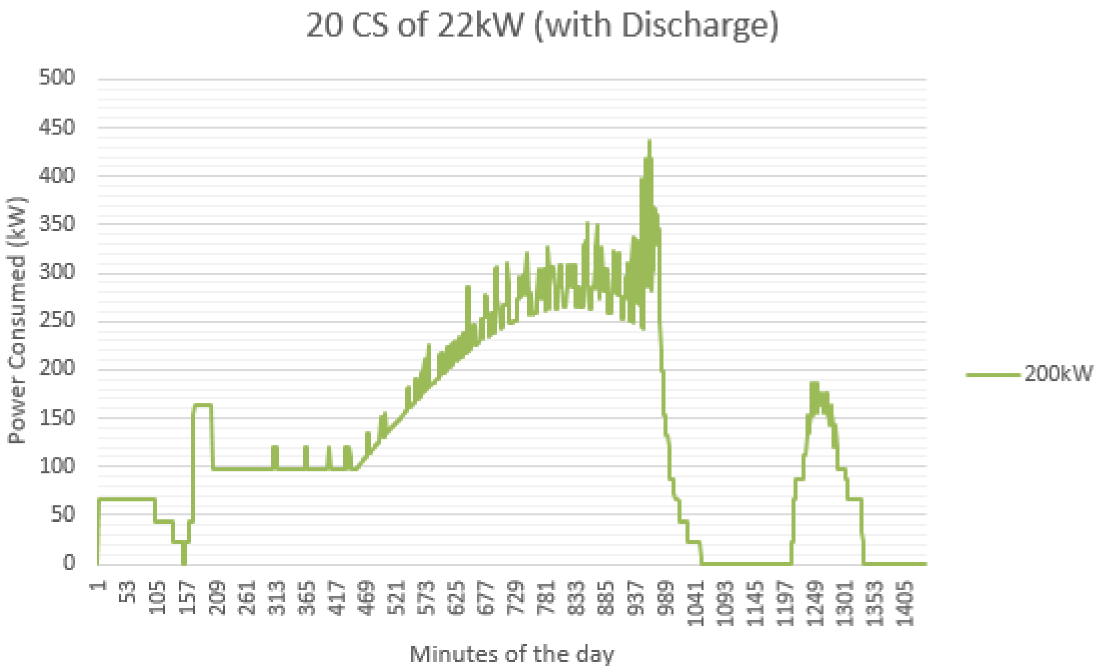

Figure B.8: Power Consumed for three 120kW CS with 200kW of solar and V2X discharge.

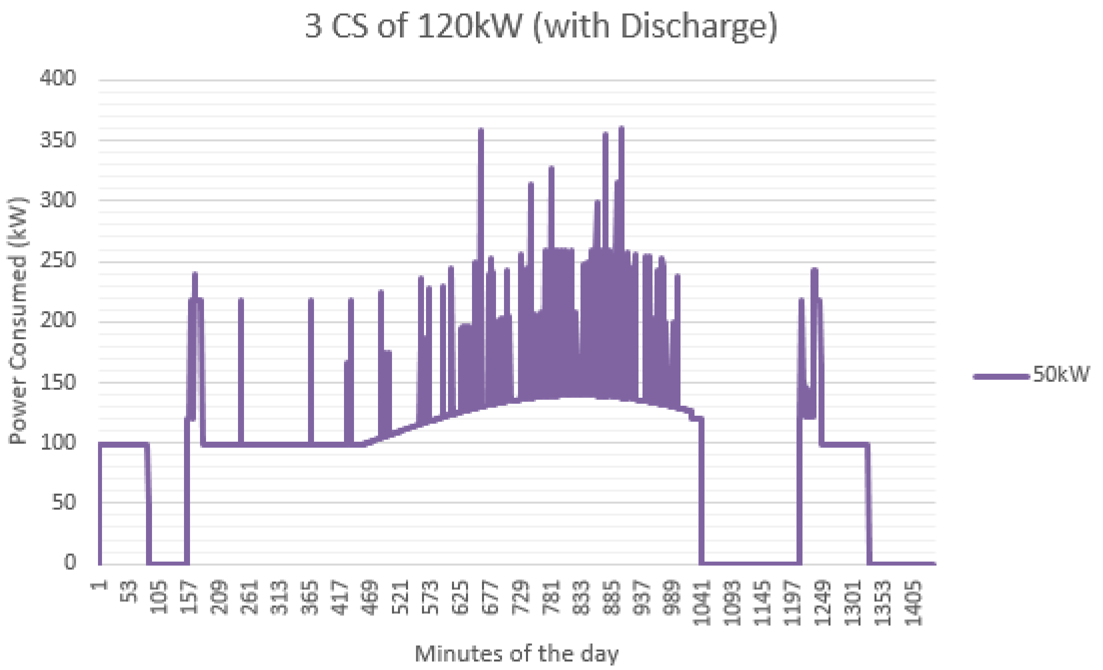

Figure B.9: Power Consumed for three 120kW CS with 50kW of solar and V2X discharge.

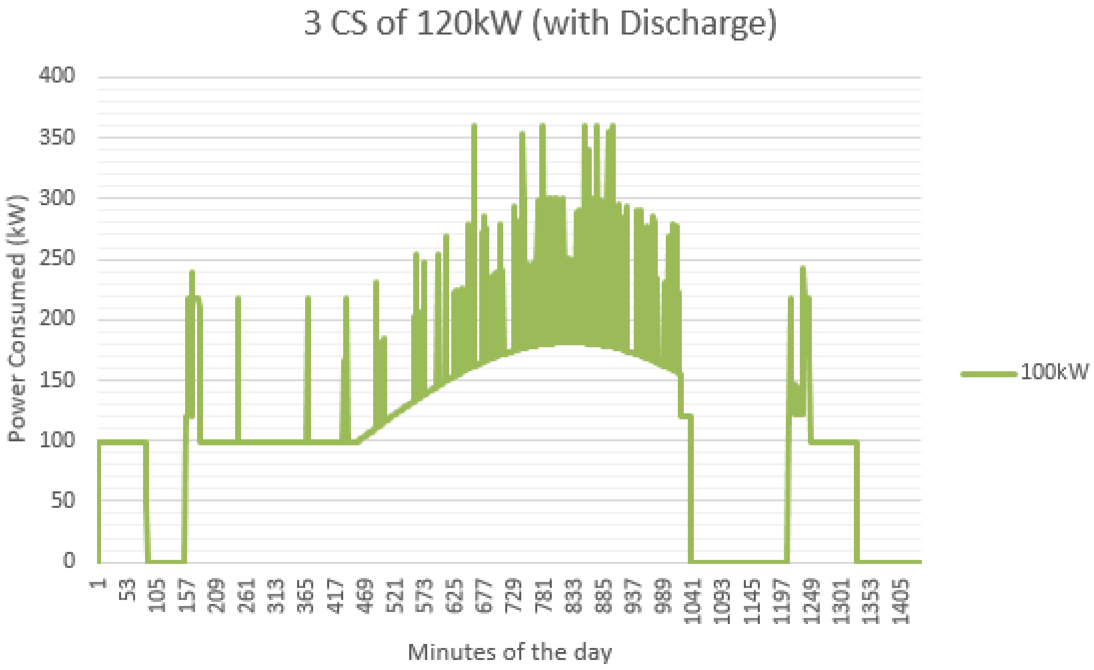

Figure B.10: Power Consumed for three 120kW CS with 100kW of solar and V2X discharge.

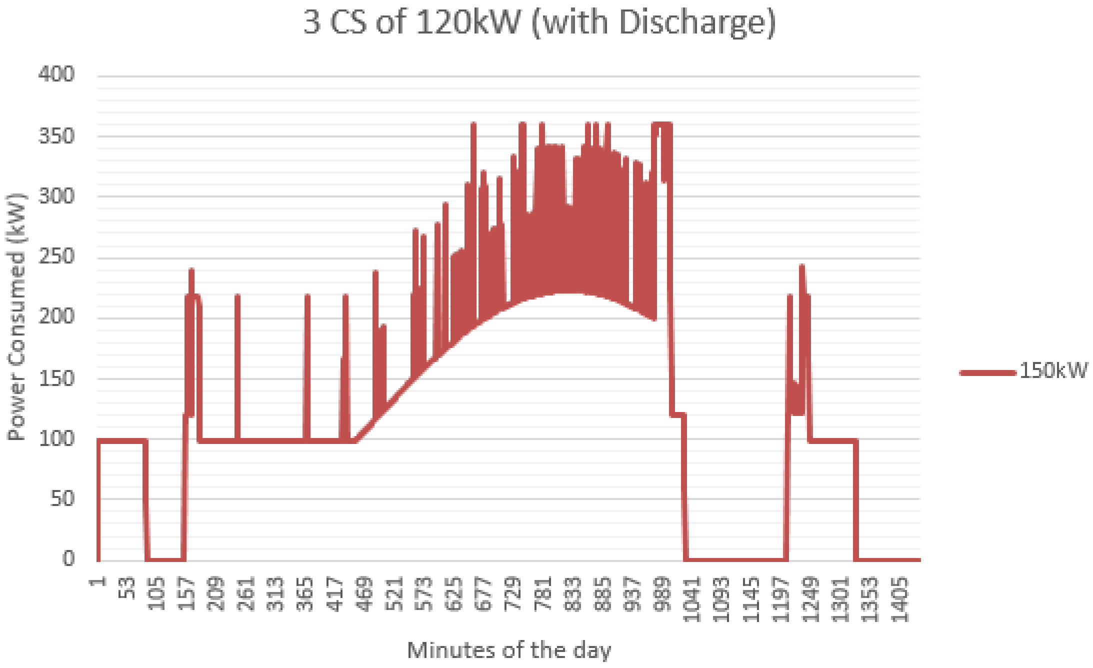

Figure B.11: Power Consumed for three 120kW CS with 150kW of solar and V2X discharge.

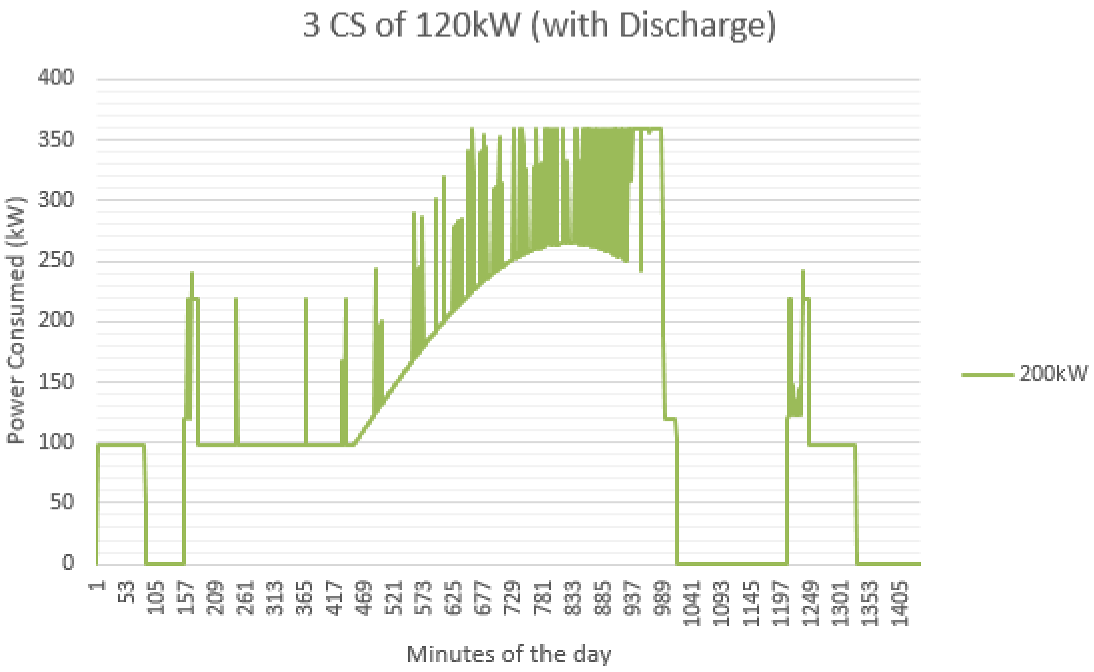

Figure B.12: Power Consumed for three 120kW CS with 200kW of solar and V2X discharge.

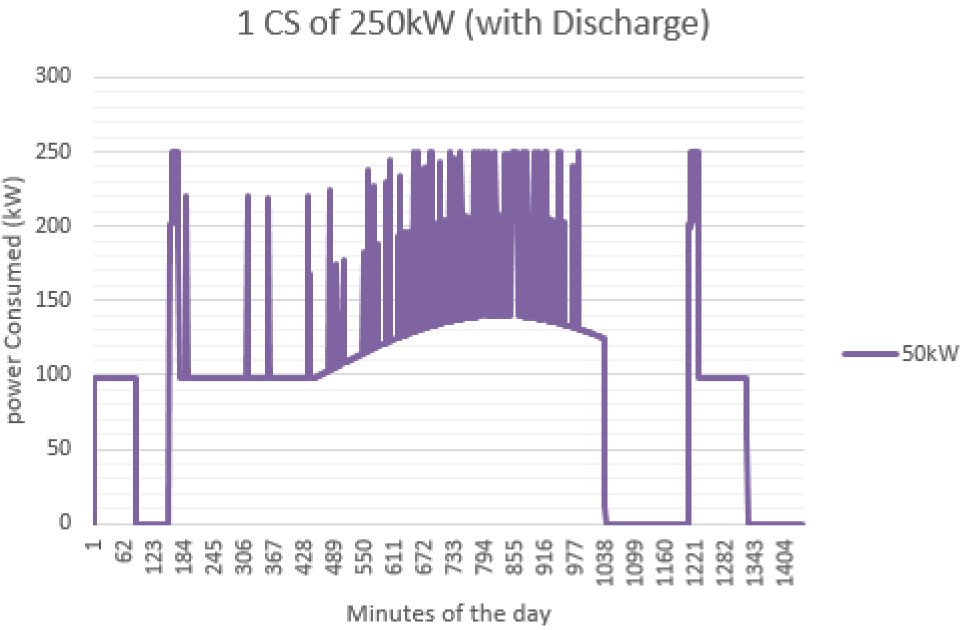

Figure B.13: Power Consumed for one 250kW CS with 50kW of solar and V2X discharge.

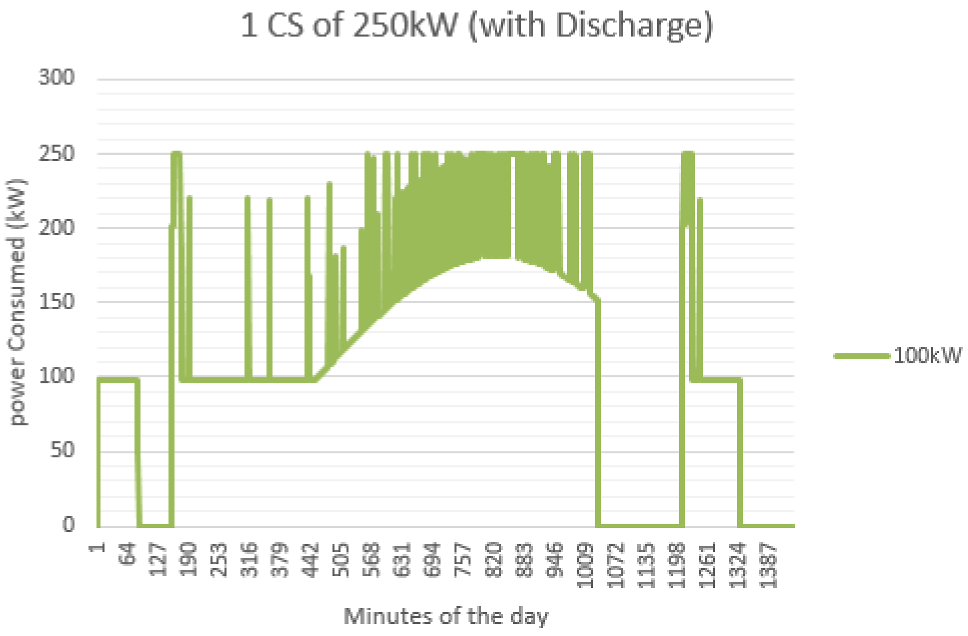

Figure B.14: Power Consumed for one 250kW CS with 100kW of solar and V2X discharge.

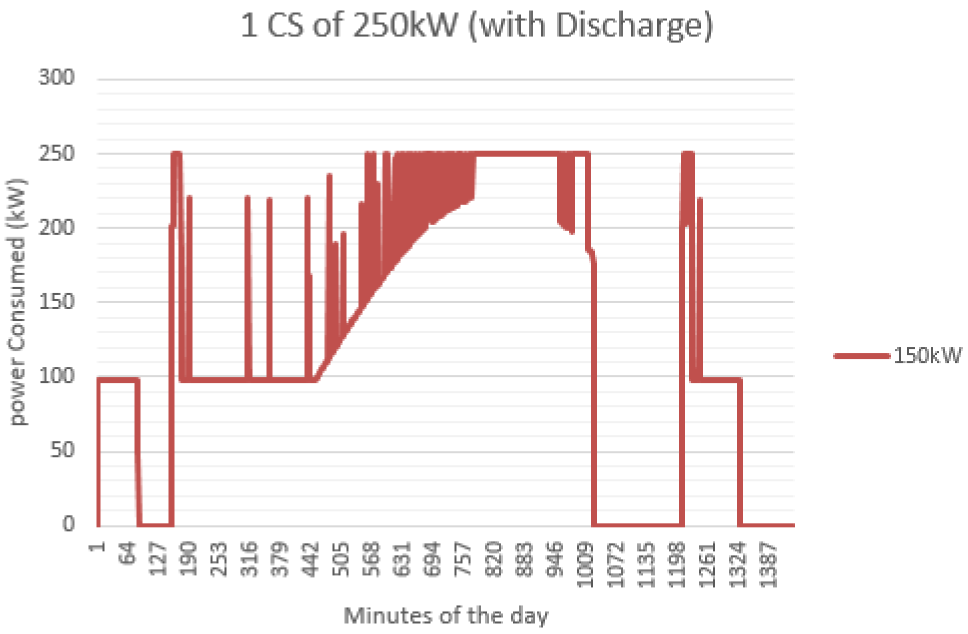

Figure B.15: Power Consumed for one 250kW CS with 150kW of solar and V2X discharge.

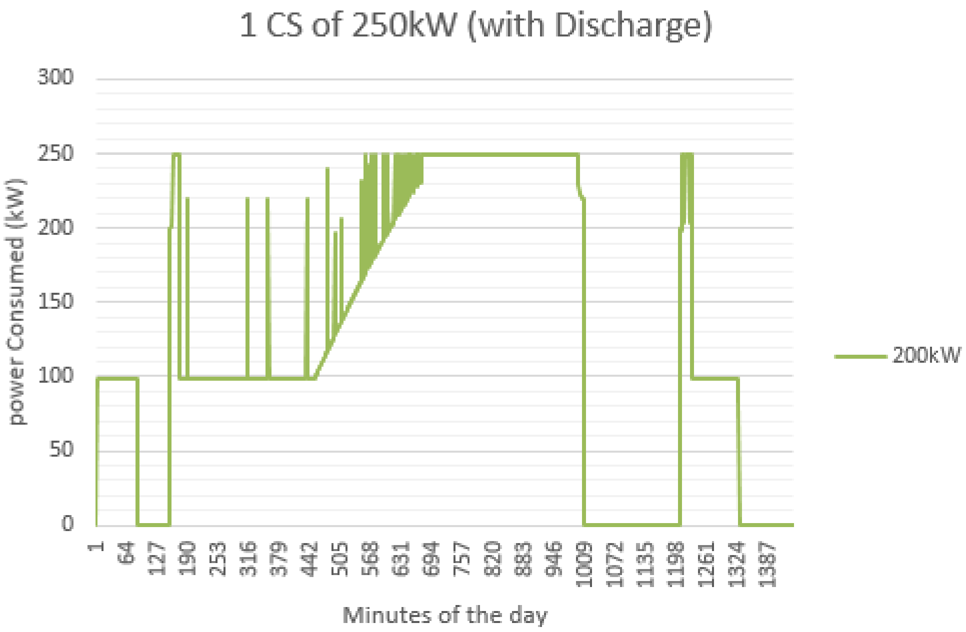

Figure B.16: Power Consumed for one 250kW CS with 200kW of solar and V2X discharge.