Planning and Operation of Smart EV Parking Lots

PLANNING AND OPERATION OF SMART EV PARKING LOTS

by

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Dedication

To my dear father, To my beloved mother, and to my dear brother and sister, in recognition of your endless love, support, and encouragement.

Abstract

Aiming to reduce Green House Gas (GHG) emissions and to increase resources security, renewable resources and electric vehicles (EVs) are gaining a lot of global interest. Promoting the use of EVs for consumers requires proper charging infrastructure adding a considerable amount of load on the grid. Aiming to accommodate this extra load economically, proper planning and operation studies have to be implemented avoiding grid overloading severe consequences. The smart coordination of EV charging via the demand side management and local generation from Photovoltaic panels can efficiently reshape the EV charging load to ensure seamless integration with the grid. Therefore, this research focuses on the development of new methodologies to facilitate accommodating high penetration of EVs. The research work will be achieved through two main stages, namely the planning stage and the operation stage. One of the main pillars of smart grids is the implementation of two-way communication with customers. Therefore, in both research stages, it is assumed that smart signals can be exchanged between the EV and the dispatch center. Planning stage starts with the development of new models to describe the effects of EVs charging as an electric load. The output of the proposed planning scheme will include several implementation decisions such as configuration of the charging stations, types, and number of EV chargers, the local generation by phtovoltic units and the expected profit, among other information. The operation stage proposes an innovative approach for day ahead load scheduling for smart charging/discharging management for EV charging stations. The main target of this approach is to maximize both customer satisfaction and stakeholder's profit.

Keywords: ***coordinated charging; electric vehicles; photovoltaic; smart grid; bidirectional power flow; vehicle-to-grid.***

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Nomenclature

Acronyms

AC	Alternating current
AER	All Electric Range
CC	Control and Communication
DC	Direct Current
DSM	Demand Side Management
ETA	Estimated Time of Arrival
EV	Electric Vehicle
FCEV	Fuel Cell Vehicle
FIT	Feed-In Tariff
G2V	Grid to Vehicle
GHG	Green House Gasses
MDOD	Maximum Depth of Discharge
PV	Photovoltaic
PVF	Present Value Formula
SOC	State of Charge
V2G	Vehicle to Grid

Indices

d	Index of days that represent the entire year
h	Index of candidate slots in the parking
t	Index of time segments
pi	Index of candidate parking lots
c	Index of customer

Sets

$\mathbb{T}$ Set of time segments $\mathbb{T} = \{1,2, \dots ,24\}$

$\mathbb{D}$ Set of days $\mathbb{D} = \{1,2, \dots ,8\}$

$\mathbb{H}$ Set of candidate slots in the parking lot $\mathbb{H} = \{1,2, \dots . , CHNO\}$

$\mathbb{P}$ Set of candidate parking lots considered in operation $\mathbb{P} = \{1,2\}$

$\mathbb{C}$ Set of candidate EV charging requests $\mathbb{C} = \{1,2. ,100\}$

Subsets

we Subset of weekends $we \subset \mathbb{D},\ we = \{1,2,3,4\}$

wd Subset of weekdays $wd \subset \mathbb{D},\ wd = \{5,6,7,8\}$

Parameters

C^{L1} The capital cost of a single unit of type 1 EV charger ($/kW)

C^{L2} The capital cost of a single unit of type 2 EV charger ($/kW)

C^{PV} The capital cost of the installed PV ($/kW)

$\mathrm{EV}_{\mathrm{h,d,t}}^{\mathrm{Logic}}$ Availability of EV in the parking lot

$\mathrm{EV}_{\mathrm{c,t}}^{\mathrm{Logic\_day}}$ Availability of EV in the parking lot

$\mathrm{FIT}^{\mathrm{PV}}$ Feed-In-Tariff (FIT) for PV generated energy ($/kWh)

$\mathrm{PVF}^{\mathrm{EV}}$ Present value function of EV (years)

$\mathrm{PVF}^{\mathrm{PV}}$ Present value function of PV (years)

$\mathrm{PV}_{\mathrm{d,hr}}^{\%}$ PV output power as a fraction of the capacity

$\mathrm{PV\_day}_{\mathrm{hr}}^{\%}$ PV output power as a fraction of the capacity

$\mathrm{Pload}^{\mathrm{MAX}}$ The maximum load connected to the grid (kW)

$\mathrm{Prated}^{\mathrm{L1}}$ EV charger type 1 maximum power (kW/Unit)

$\mathrm{Prated}^{\mathrm{L2}}$	EV charger type 2 maximum power (kW/Unit)
$\mathrm{Prated}^{\mathrm{PV}}$	PV single unit rated power (kW/Unit)
$\mathrm{Prated}^{\mathrm{TF}}$	Distribution transformer maximum power rating (kW)
$\mathrm{SOC}_{\mathrm{h,d}}^{\mathrm{I}}$	Initial SOC of EV at arrival time (%)
$\mathrm{SOC}_{\mathrm{h,d}}^{\mathrm{MAX}}$	Maximum requested EV SOC before departure (%)
$\mathrm{SOC}_{\mathrm{c}}^{\mathrm{I}}$	Initial SOC of EV at arrival time (%)
$\mathrm{SOC}_{\mathrm{c}}^{\mathrm{MAX}}$	Maximum requested EV SOC before departure (%)
$\rho\mathrm{FX}^{\mathrm{Grid}}$	Fixed grid supply monthly cost ($/Month)
$\mathrm{BAT}_{\mathrm{h}}^{\mathrm{CAP}}$	EV battery capacity (kWh) for each candidate channel
$\mathrm{BAT}_{\mathrm{c}}^{\mathrm{CAP}}$	EV battery capacity (kWh) for each candidate customer
Cheff	EV Battery charging efficiency (%)
CHNO	Parking lot maximum capacity (Unit)
Dcheff	EV Battery discharging efficiency (%)
MDOD	Maximum depth of discharge (%)
$\mathrm{Pload}_{\mathrm{d,hr}}$	Active connected load as a fraction of total connected load
$\mathrm{Pload\_day}_{\mathrm{hr}}$	Active connected load as a fraction of total connected load
$\mathrm{Pmax}_{\mathrm{h}}^{\mathrm{CH}}$	EV battery maximum charging power (kW)
$\mathrm{Pmax}_{\mathrm{h}}^{\mathrm{DCH}}$	EV battery maximum discharging power (kW)
$\mathrm{Pmax}_{\mathrm{c}}^{\mathrm{CH}}$	EV battery maximum charging power (kW)
$\mathrm{Pmax}_{\mathrm{c}}^{\mathrm{DCH}}$	EV battery maximum discharging power (kW)
$\mathrm{SOC}_{\mathrm{h,d}}^{\mathrm{DIFF}}$	Requested SOC change during the availability time (%)
$\mathrm{SOC}_{\mathrm{c}}^{\mathrm{DIFF}}$	Requested SOC change during the availability time (%)
$\mathrm{SOC}^{\mathrm{PrMIN}}$	The minimum ratio between requested and achieved SOC (%)

ev^{MAX}	Maximum EV charging cost margin ($/kWh)
ev^{MIN}	Minimum EV charging cost margin ($/kWh)
$extra_{sell}$	V2G cost margin ($/kWh)
$\rho_{d,hr}^{Grid}$	Grid supplied energy cost ($/kWh)
$\rho\_day_{hr}^{Grid}$	Grid supplied energy cost ($/kWh)
ev_day_{t}	EV hourly charging cost margin

Variables

CC^{PV}	PV annual capital cost
CC^{EV}	EV chargers annual capital cost
CE^{EVCH}	Annual income of EV charging process
CE^{EVDCH}	Annual cost of EV discharging process
CE^{Grid}	Annual grid supply cost involved in the EV charging process
CE^{PV}	Annual income of solar energy selling to the grid
CE^{EVCH_day}	Daily income of EV charging process
CE^{EVDCH_day}	Daily cost of EV discharging process
CE^{Grid_day}	Daily grid supply cost involved in the EV charging process
CE^{PV_day}	Daily income of solar energy selling to the grid
$E_{h,d,t}^{CH}$	Energy consumed by EV during charging
$E_{h,d,t}^{DCH}$	Energy delivered to grid from EV during discharging
$E_{c,t}^{CH}$	Energy consumed by EV during charging
$E_{c,t}^{DCH}$	Energy delivered to grid from EV during discharging
N^{PV}	Number of allocated PV units

$\mathrm{SOC}_{h,d,t}^{Finish}$	SOC at the end of each hour segment
$\mathrm{SOC}_{h,d,t}^{Start}$	SOC at the beginning of each hour segment
$\mathrm{SOC}_{h,d}^{Delta}$	Total achieved SOC through the day
$\mathrm{SOC}_{c,t}^{Finish}$	SOC at the end of each hour segment
$\mathrm{SOC}_{c,t}^{Start}$	SOC at the beginning of each hour segment
SOC_{c}^{Delta}	Total achieved SOC through the day
b_{h}^{L1}	Placement decision for type 1 charger
b_{h}^{L2}	Placement decision for type 2 charger
$r_{h,d}^{L1}$	Routing decision for type 1 charger
$r_{h,d}^{L2}$	Routing decision for type 2 charger
$r_{pi,h,c}^{L}$	Routing decision for candidate EV
$x_{h,d,t}^{CH}$	Charging decision for each candidate channel
$x_{h,d,t}^{DCH}$	Discharging decision for each candidate channel
$x_{c,t}^{CH}$	Charging decision for each candiate customer
$x_{c,t}^{DCH}$	Discharging decision for each candiate customer
$\mathrm{PL1}_{h,d,t}^{CH}$	Power consumed by type 1 charger during charging
$\mathrm{PL1}_{h,d,t}^{DCH}$	Power consumed by type 1 charger during discharging
$\mathrm{PL2}_{h,d,t}^{CH}$	Power consumed by type 2 charger during charging
$\mathrm{PL2}_{h,d,t}^{DCH}$	Power consumed by type 1 charger during discharging
$\mathrm{PL}_{c,t}^{CH}$	Power consumed by type 1 charger during charging
$\mathrm{PL}_{c,t}^{DCH}$	Power consumed by type 1 charger during discharging
$\mathrm{Pnet}_{d,t}^{EV}$	Net EV chargers power flow

$\mathrm{Pnet}_{\mathrm{d,t}}^{\mathrm{TF}}$	Net power flow through the distribution transformer
$\mathrm{Pnet}_{\mathrm{pi,t}}^{\mathrm{EV}}$	Net EV chargers power flow
$\mathrm{Pnet}_{\mathrm{pi,t}}^{\mathrm{TF}}$	Net power flow through the distribution transformer
$\mathrm{SOC}_{\mathrm{h,d}}^{\mathrm{Pr}}$	The ratio between requested and achieved SOC change
$\mathrm{SOC}_{\mathrm{c}}^{\mathrm{Pr}}$	The ratio between requested and achieved SOC change
Z	The objective function (Net annual revenue).
Z^{day}	The objective function (Net daily revenue).
$ev_{d,t}$	EV hourly charging cost margin

Chapter 1. Introduction

In this chapter, we provide a short introduction about primary energy resources and the encountered problems of Green House Gas (GHG) emissions influenced by fossil fuel consumption. Then, we present the alternative option to replace fuel-powered passenger vehicles with electric vehicles (EVs), followed by the problem investigated in this study as well as the thesis contributions. Finally, the general organization of the thesis is presented.

1.1. Overview

Energy is considered as one of the main necessities for the humankind. There have been a variety of primary resources of energy, such as fossil fuel (natural gas, oil, and coal), nuclear, biofuel, and hydro energy. However, these energy sources are diverse in nature. They are not used equally and have different contributions shared with the worldwide energy supply. The International Energy Agency report shows the world total primary energy supply to be 160 PWh in 2016 [1]. The major three resources of energy are oil, coal and natural gas. They represent more than 80% of primary energy resources and they are all non-renewable limited resources. Considering the use of these energy resources in different life aspects, Figure 1.1 shows the total world final energy consumption in 2016 considering different fuel. Fossil fuels still have the biggest share of energy consumption as these resources represent more than 80% of total fuel consumption around the world.

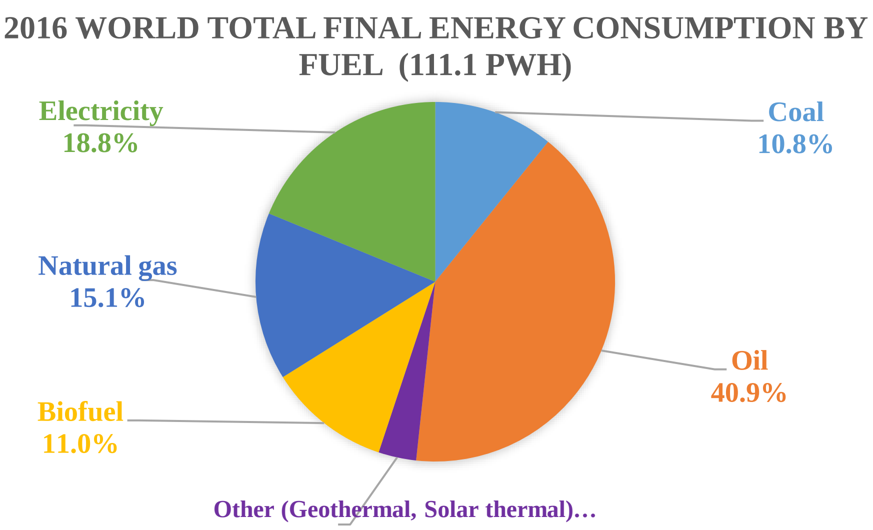

Figure 1.1: World total final energy consumption by fuel in 2016 [2]

These energy resources are used in different major aspects such as electricity generation, transportation, industry, commercial and public, residential and agriculture [2]. Figure 1.2 shows the different energy consumption share of each sector in 2016 [2].

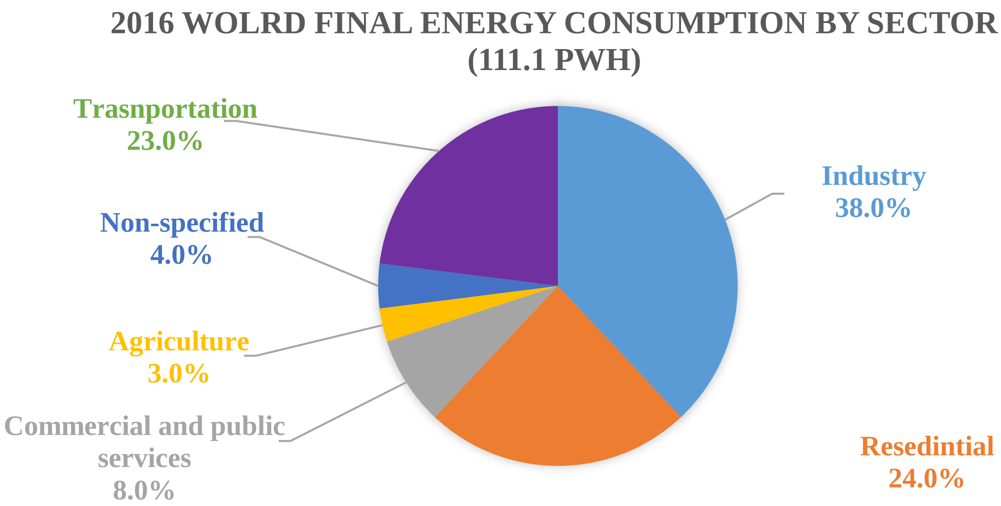

Figure 1.2: World energy consumption by sector in 2016 [2]

On the other hand, many studies have focused on the environmental harm of fossil fuel consumption due to its by-products and its impacts on the environment. The main downside of the consumption of fossil fuel consists of Green House Gasses (GHG) emissions. GHG is a term entitled for different gaseous emissions such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and various hydrofluorocarbons (HFCs). However, CO_2 has the largest impact factor compared to other GHG due to the high volume emissions. In 2016, CO_2 emissions around the world estimated to be 32.3 Giga metric ton [3]. The majority of CO_2 emissions are driven by the consumption of fossil fuel as shown in Figure 1.3. To minimize CO_2 emissions, there should be better solutions to minimize the consumption of fossil fuels. In order to achieve that, the main contributors of CO_2 emissions should be targeted. Figure 1.4 shows the contribution share of different sectors in CO_2 emissions in 2016. It is noticed that more than 65% of the total CO_2 emissions are due to transportation and electricity generation sectors [3]. Aiming to reduce CO_2 emissions in the electricity generation sector, the use of renewable energy resources is the best option, which also helps in reducing the dependency on fossil fuel power generators [4], [5].

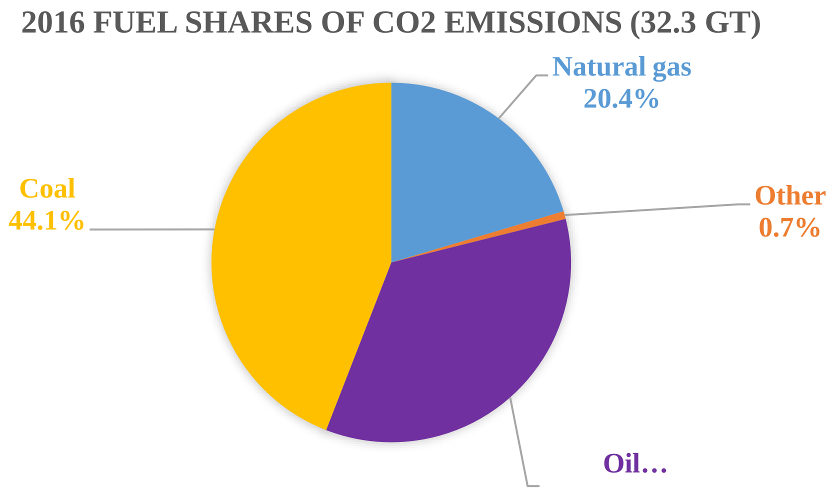

Figure 1.3: Fuel shares of CO_2 emissions from fuel combustion in 2016 [3]

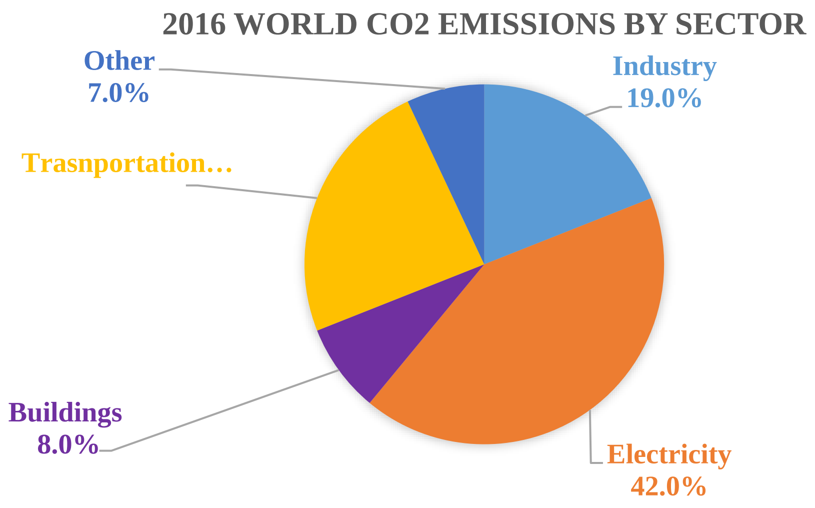

Figure 1.4: World CO_2 emissions by sector in 2016 [3]

Moving to the second biggest contributor to CO_2 emissions, the transportation sector is divided into different transportation methods. Light-duty vehicles represent the biggest contribution percentage of GHG emissions due to its enormous population. In addition, other methods are influencing the transportation sector GHG emissions with less impact comparing to light-duty vehicles such as rails, ships, boats, aircraft, and medium and heavy-duty trucks. In Figure 1.5, the contribution percentages of different sources of CO_2 emissions in USA transportation sectors are shown with total CO_2 emissions of 1,854 Million Metric Tons of CO_2 equivalent [6]. The US Environmental Protection Agency estimated the annual GHG emissions from a typical light-duty vehicle to be 4.6 metric tons of CO_2 equivalent [7].

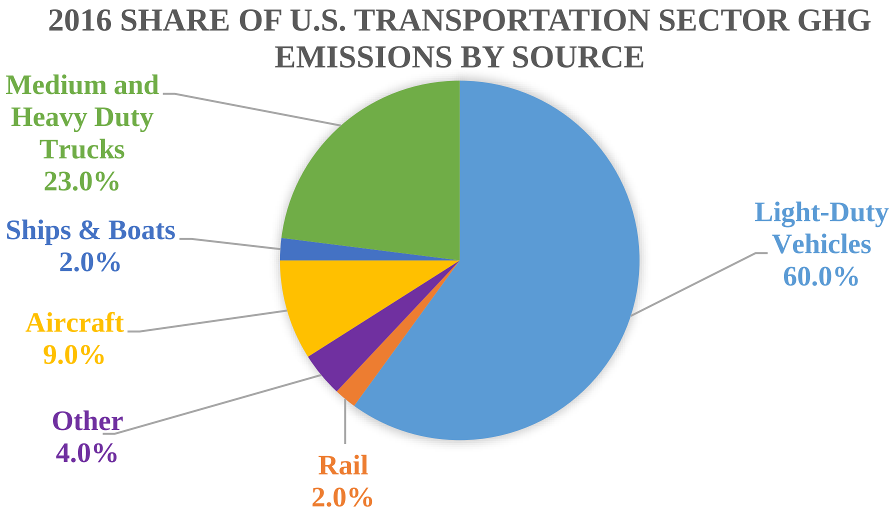

Figure 1.5: Share of U.S.A transportation sector GHG emissions by source in 2016 [6]

In order to reduce GHG emissions, light-duty vehicles should move towards low-emission or zero-emission vehicles. Currently, there are two available technologies in the market that can achieve this aim:

- Fuel Cell Electric Vehicles (FCEVs)
- Battery Electric Vehicles

FCEVs require hydrogen input in order to generate electricity without any GHG emissions. Despite the environmental benefits of FCEVs, the adaptation of FCEVs faced many issues due to its high cost, as the technology of fuel cells are complex. In addition, adopting FCEVs will require new infrastructure, as hydrogen storage, distribution and refilling stations [8]. In addition, hydrogen storage is considered as one of the main concerns due to safety and cost issues, as it is insecure to use hydrogen storage for high temperature areas and it is expensive compared to other fuel storage methods.

Looking into the second solution, Battery EVs (referred to as EV for the rest of the work) proved to be more promising, as they need fewer infrastructure changes in comparison with FCEVs. The EV charging process is done by connecting the vehicle to the electricity distribution grid, which is available everywhere, through different types of EV chargers. However, the extra load imposed on the electric grid by the EVs charging is expected to have severe consequences on the grid if not managed properly. The extra load can lead to thermal overloading, overcurrent relays tripping, transformer degradation, higher power loss, and voltage profile deterioration.

One of the major approaches to enable high penetration of EVs is the coordinated charging under the paradigm of a smart grid, where two-way communication can be utilized to coordinate the charging and discharging of the EVs. Moreover, before installing EV charging stations, a detailed planning approach has to be implemented to maximize the profit for the investor and ensure customer satisfaction, in addition to respecting all the grid technical limits.

Since smart coordination of the charging process is viable and beneficial for both grid operators and EV owners, EV charging coordination has to be implemented in real-time operation of the charging stations and also in the planning phase of the EV charging stations.

1.2. Thesis Objectives

Driven by the developing interest in big scale EV integration in the transportation sector and the aim of providing alternative options of consumers away from the conventional combustion engine vehicles, this research focuses on developing approaches to accommodate high penetration of EVs through two stages: planning stage and operation stage for EV charging infrastructure.

1.3. Research Contribution

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

- Propose a new resource allocation approach to allocate EV charging stations in conjunction with renewable energy sources. The proposed approach considers different levels of EV chargers and considers smart routing signals for EV drivers inside the parking lot.
- Propose a new EV charging/discharging coordination approach for real-time operation of EV charging stations. The approach includes smart routing signals and customer satisfaction index.

1.4. Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 provides background about EV charging technology and recent techniques used for EV charging and demand side management and discusses related research. Chapter 3 discusses the models and methods used to represent different EV charging aspects along with other system component models. Chapter 4 presents the proposed approach for planning and operation of an EV parking lot considering optimization technique and defining the major variables and their constraints. Chapter 5 presents different versions of a case study to examine, evaluate, and to validate the proposed planning approach. Chapter 6 presents different versions of a case study applying the proposed operation approach. Finally, Chapter 7 concludes the thesis and outlines the main contribution and outcomes of both planning and operation approaches along with the proposed future work.

Chapter 2. Background and Literature Review

This chapter introduces a brief background of EVs and their charging infrastructure. Then, we explain the demand side management concept and its various techniques followed by the related research work in the field of EV charging planning. Finally, the drawbacks in previous work are highlighted and discussed.

2.1. Background of Electric Vehicles

EVs are mainly powered by batteries that have different capacities and charging abilities that vary based on the EV model. As EV model and brand varies, different battery, motor, charging technologies are used aiming to enhance the EV performance via increasing the distance covered with a fully charged battery with considerable recharge time. The enormous advancements in the battery technologies have pushed EV development further by making the charging process faster and the battery capacity larger with less weight and cost.

2.1.1. EV categories. Looking into many details of EV battery capacity, charging power, motor torque and power consumption can be confusing for customers. Therefore, the best way to compare these EVs is the All-Electric Range (AER), which refer to the distance the EV can travel depending on the battery-stored 100% state of charge (SOC). Figure 2.1 presents different models of EV and their AER showed as a scaled distance. Accordingly, EVs can be divided into three main categories based on its AER:

- Small range EVs that have AER less than 75 miles (120 km) such as Chevrolet Spark EV.
- Medium range EVs are characterized by an AER in the range of 75-150 miles (120-241.5 km) such as Nissan Leaf.
- Large range EVs come with AER above 150 miles (241.5 km) such as Tesla different models.

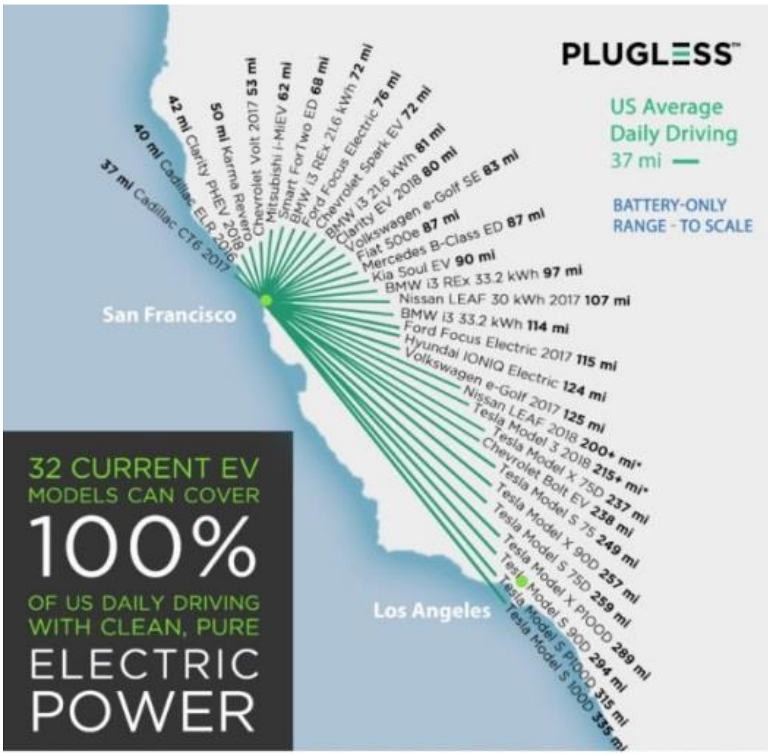

Figure 2.1: AER for different models of EV presented in miles [9]

2.1.2. EV sales. During the last few years, EVs have shown promising potential in the global market. Many governments offer incentives for the consumer to buy an EV instead of conventional vehicles. This incentive was reflected in the number of sold EVs around the world. Annual EVs sales between 2011 and 2016 are shown in Figure 2.2. The data from the figure demonstrates the significant growing interest in EVs, which indicates the necessity of a proper EV charging infrastructure to support this growing interest.

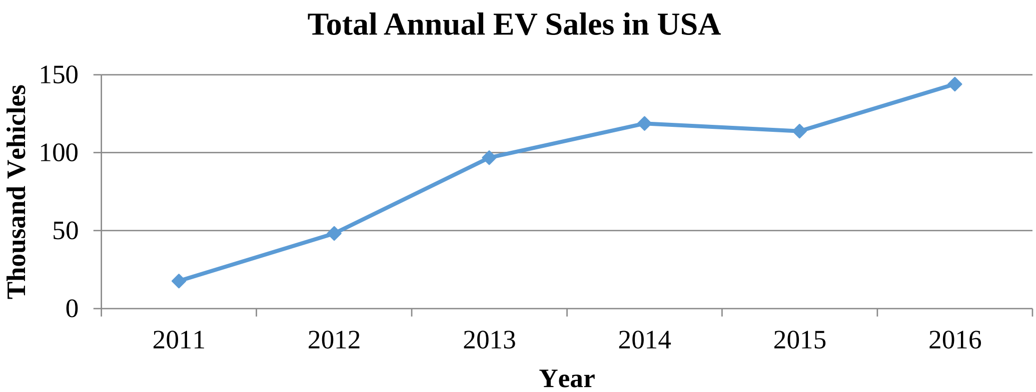

Figure 2.2: Total annual EV sales in USA between 2011-2016 [10]

2.1.3. EV charging requirements. As mentioned previously, the EV battery has to be charged from grid supply through a charging station, which is available in different technologies and capabilities. Table 2.1 shows the different levels of EV chargers and their power delivery rating [8].

Table 2.1: EV charging station power delivery capabilities based on the level [8].

Type	**Specifications**
Level 1	110/120 V, 3.3 kW, AC Does not require installation and can use a standard electrical outlet Typical charging time: 8-12 hours
Level 2	208-240 V, 7 to 11 kW, AC Requires special installation Typical charging time: 3-8 hours
Level 3	Known as “DC fast charging” 20 kW or higher Requires special installation Typically charges 50% of EV battery in less than 30 minutes

Although there are different levels of EV charger power. Not all EVs can use advanced level of charging as charging rate is limited to the maximum power the EV battery can handle during charging and discharging. In some cases, a charging power limit is caused by the onboard AC charging converter in EV. This limit is noted in cases of level I and II as the charger supply is converted to DC supply through the onboard power converter and controller in the EV, in order to supply the suitable DC supply to charge the EV battery. In contrast, Level 3 DC charging has a higher power limit due to the fact that on-board AC-DC converter is bypassed and the energy is directly supplied to the battery as shown in Figure 2.3 and Figure 2.4. This shows the difference between level I, II charger and level III DC charger. Table 2.2 presents the different battery capacities and maximum power rates for charging and discharging of the listed commercial EVs available in the US market between 2011-2016.

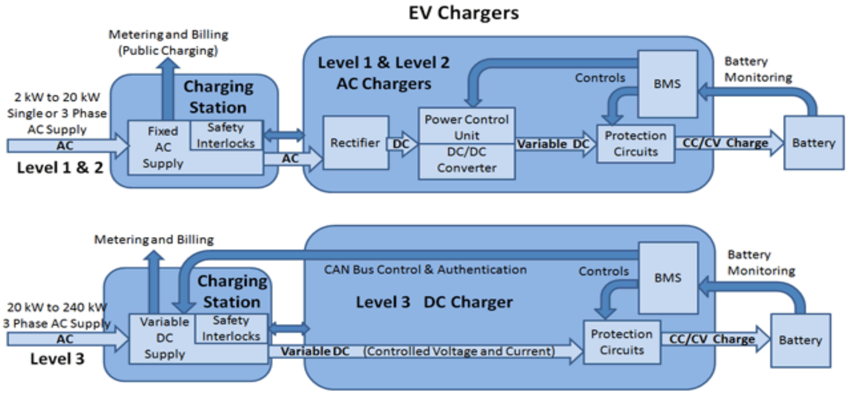

Figure 2.3: Internal structure of different levels of EV charger [11]

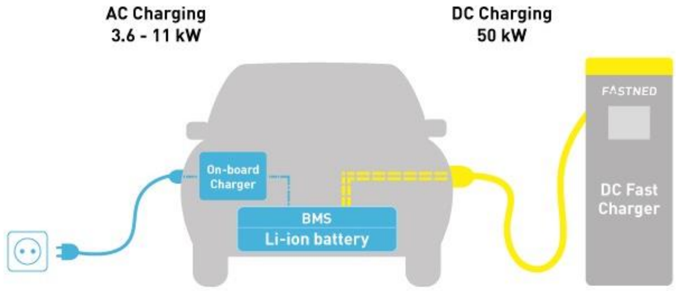

Figure 2.4: The difference between AC and DC EV charging power flow [12]

Table 2.2: List of EVs sold in the US market between 2011-2016 and their battery specifications [10], [13]

Model	Units sold in USA between 2011-2016	Battery Capacity (kWh)	AC Charging Rating (kW)	DC Charging rate (kW)
Mitsubishi i-MiEV	2098	16	3.6	44
Smart forTwo EV	5698	16.5	7.2	22
Honda Fit EV	1071	20	6.7	40
Chevrolet Spark	7369	21	3.3	50
Ford Focus EV	6839	23	6.6	50
Fiat 500E	10229	24	6.6	50
Kia Soul EV	2993	27	6.6	50
Mercedes B-Class Electric	3312	28	10	50
BMW Active E	965	32	6.4	-
BMW i3	24721	33	7.7	50
VW e-Golf	4589	36	7.2	40
Nissan LEAF	103578	40	6.6	50
Toyota RAV4 EV	2399	42	10	45
Tesla Model S	93277	100	22	90
Tesla Model X	18236	100	22	120

2.1.4. EV charging control. In consideration of EV charger control, EV charging stations have different Control and Communication (CC) levels that vary from the uncontrolled case (level 0cc) and ending with a fully controlled charging station (level 3cc). Figure 2.5 presents the capabilities of each different levels of EV charger communication and control [8]. Table 2.3 presents different samples of commercial EV chargers with different CC levels.

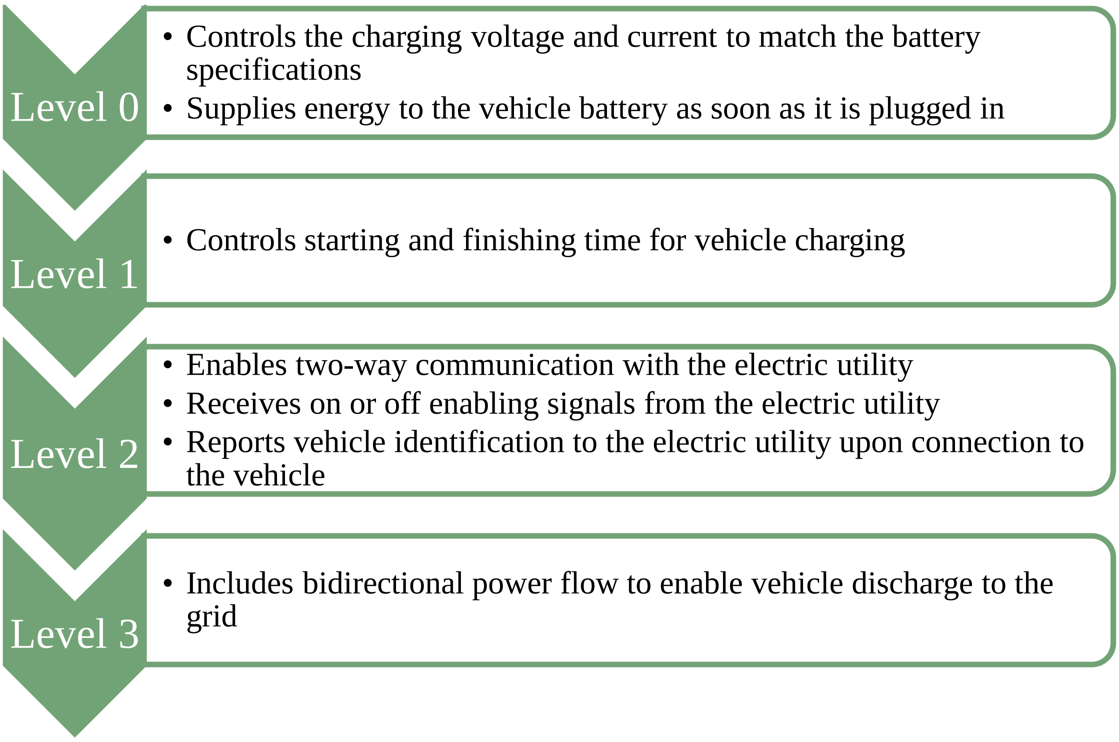

Figure 2.5: EV charger control and communication levels and their capabilities [8]

Table 2.3: Samples of commercial EV chargers with different levels of CC [14]–[18]

CC level	**0CC**	**1CC**	**2CC**	**3CC**
Charger name	EVoCharge EVoInnovate	Siemens VersiCharge	JuiceBox Pro 40	Nuvve EVSE-B-P3-H1
Image				

2.1.5. Charging economy. There are different economic aspects involved in EV parking lot planning and operation as the charging process can be studied as supply and demand. In this study, the supply side consists of both grid supply and photovoltaic (PV) supply. On the other hand, the demand side consists of EVs charging. EV charging is associated with several costs, which can be categorized as capital and operation costs.

2.1.5.1. ***Charging capital costs.*** Capital costs consist of equipment cost and the installation cost for EV chargers and PV units. In order to develop a better understanding of EV charging as an investment, the capital costs should be annualized, i.e. converted to equal annual payments. Therefore, we define the present value function (PVF), which represents the present value of a series of n equal annual payments in the future, considering the discount rate d and escalation factor e. The PVF is calculated as in (1,2).

$$PVF(d',n) = \frac{(1+d')^n - 1}{d'(1+d')^n} \tag{1}$$

$$d' = \frac{d-e}{1+e} \tag{2}$$

Assuming n to be the lifetime of the equipment, the annualized capital cost can be calculated as in (3).

$$Annualized\ Capital\ Cost = \frac{Capital\ Cost}{PVF(d',n)} \tag{3}$$

2.1.5.2. ***Charging running costs***. The encountered running costs involved in the process of EV charging include:

- Cost of energy bought from the power distribution grid
- Cost of energy bought from EV discharging batteries
- Maintenance costs for both EV chargers and PV units

2.2. Demand Side Management

Demand side management (DSM) is considered one of the main objectives of the utility company to avoid high energy demand during peak hours by influencing users' consumption behaviors. Utility company tends to apply different techniques to encourage users to reduce power consumption during peak hours. One of DSM techniques tends to control major connected loads in the grid via commands. Another technique of DSM is to provide different energy prices throughout the day. This means to divide power prices into three main categories; high price for peak hours, moderate price for normal hours and low price for low hours of power consumption. This technique affects the overall power profile to make it flatter as some consumers will reduce their power consumption during peak hours and use the high power devices only during low energy price hours aiming to minimize their energy bills [19]. Figure 2.6 presents the different techniques used by the utility company to apply DSM [19].

In EV charging case system load shifting is a major consideration in order to charge the connected EVs with the cheapest possible price and to avoid any overloading problems due to high power demand through the network. In order to optimize the EV charging process, prior knowledge of the connected loads is necessary as EV charging is limited to the power that can be supplied from the grid. In the case, the hourly power demand profile through the grid is collected from the historical data and is used to decide the allowed power supply to EV chargers as overall power flow is constrained.

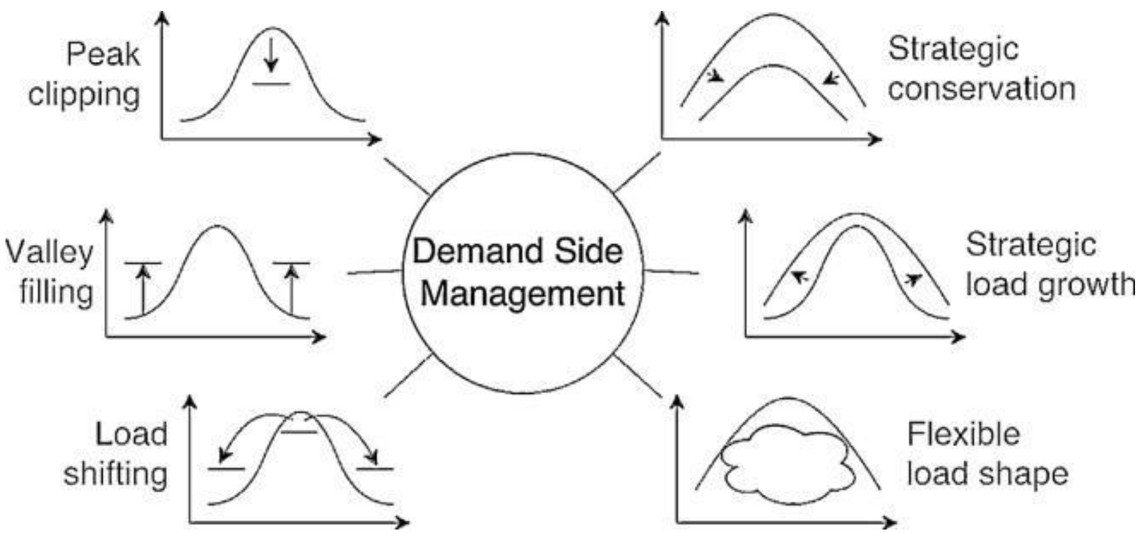

Figure 2.6: Different Demand Side Management techniques applied by power distribution utility [19]

2.3. Literature Review

Mainly, approaches in EV chargers allocation are divided into two categories: uncoordinated and coordinated EV chargers. Uncoordinated EV chargers have level 0 of communication and control which are capable of controlling voltage and current level to abide by battery charging requirements. In [20], different scenarios were studied of EV charging in public and domestic EV charger abiding the power and voltage grid requirements in order to obtain the EV load performance on the grid in different demand hours. However, this study was focused on load performance and it neglected to consider the DG and BESS allocation. In [21], EV chargers allocation is studied with the support of different location capacitor banks installation is considered to examine the impact of capacitor banks in enhancing voltage amplitude and reducing power loss. In [22], DG allocation is used to reduce the stress caused by the high penetration of uncoordinated EV charging in the network. In [23], the usage of different types of BESS is studied and showed that level 0 controlled EV chargers are optimally allocated with the support of BESS to store Energy from off-peak hours to be used during high demand hours. In [24], [25], the allocation of uncoordinated EV charger is linked with the allocation of PV units aiming to reduce any overload on the transmission grid. Moreover, [26]–[29] considered the allocation of BESS, PV, and uncoordinated EV chargers and presented how this will help to reduce stress on the grid during peak hours. In addition, [30] focused more toward the allocation and sizing of different levels of uncoordinated EV chargers within different buses in the grid, considering different cases of allocating PV, wind turbine, and BESS in different distributed buses within the grid. The main objective of these different cases was to maximize the allocated units and minimize the power losses within the grid. However, the study in [31] was based on fixed EV charging profiles and did not consider different charging behaviors. In [29], the allocation process finds one optimum LV bus suitable for multiple EV chargers, PV, and BESS allocation with the consideration of voltage and power constraint of the LV bus without the consideration of the other loads connected to the LV bus. Some other studies focused more on the allocation of EV chargers, PV and BESS with the main objective of maximizing the profit of EV charging from the PV generated power and to minimize the capacity of the allocated BESS [31]. [31] aimed to maximize the charging profit through the lower cost of the renewable generated energy in comparison with the grid cost. However, this study neglected the allocated

BESS battery cycle life and only considered EV uncontrolled charging. Some studies focused on allocation optimization to consider the minimal cost of charging along with the power and voltage requirements [32]. As a result of this optimization, the allocation decision and its optimum sizing for EV charger, PV, and BESS are found to be allocated within the same bus to avoid any power overload. However, various aspects were not considered; such as grid cost profile, EV arrival and departure timings, and charging pricing.

Moving toward coordinated EV charger allocation, [33] introduced the allocation of controlled EV charger within the gird buses considering getting the maximum output power possible abiding the grid power and voltage constraint. In [34], [35], the studies purposed a real-time coordination algorithm to enable and disable EV charging based on demand response to avoid high grid tariff and respond to grid curtailment during peak hours. Uncontrolled EV charging showed to have a major negative impact on the grid as it requires frequent grid components replacement due to overload. In contrast, EV controlled charging process avoided grid component overload which will extend its duty lifecycle [35]. In [34], [35] the allocation approaches were based on binary optimization with constant output power equivalent to the maximum battery power rating. In [36], the study solved an optimization problem to allocate DGs and BESS in the grid along with the EV chargers to abide by the grid power constraints and to apply maximum profit. The case study presented in this paper showed both uncoordinated chargers case which required having BESS and DGs in the grid and coordinated chargers case with DGs only which show that BESS allocation is not required in case of coordinated EV chargers.

Moving toward a more coordinated type of EV charger, some papers introduced discharging option to EV charger to discharge the EV battery in necessary situations as Vehicle to Grid (V2G). In [37], V2G option is purposed to solve planning and operation challenges in EV chargers allocation into the existing power system by considering the power system loads. In [38], coordinated EV charger can discharge the EV battery and use it as an energy storage device to supply the grid in case of power regulation is needed. Moreover, in [39], V2G is used in order to apply voltage regulation by injecting reactive power from the vehicle battery to grid. In both [38], [39], V2G concept is applied by the grid operator in order to maintain the grid quality considering the EV battery as a reserve or a storage unit to use over a short time. In [40], V2G option is considered to assist power system operations as it is considered as a BESS to be used over high demand hours. This discharging process is constrained by the ability of the charger to fully charge the EV before departure time. In [38]–[40] the discharging process is studied only one allocated charger and did not consider multiple EV chargers. In [41], V2G is considered simultaneously with the Grid to Vehicle (G2V) mode during the allocation study done to allocate DGs and EV parking lots with multiple charging stations in the grid abiding the grid constraints. This study had the originality in coordinating each individual charger based on the connected EV SOC and the grid situation, so some chargers in the parking lot are controlled to be on V2G mode while the remaining chargers are on G2V mode depending on the grid current situation. However, this paper was based on fixed charging and discharging power rates assigned based on EV chargers ratings and did not consider dynamic power delivery.

It is noted that all the previous research did consider a few aspects of EV allocation and focused on proposing new updates. One of the main mess considerations is ignoring the difference in EV battery specifications among different EV models. As all previous studies were based on the EV battery model based on the same battery capacity and power rating which does not represent the real EV population. Also, it is noted that many studies did not consider the charging pricing along with the planning process as it was assumed to be fixed charging cost margin added to the grid supply cost. In addition, previous researches were based on the assumption that EV battery has the same charging ability which is not close to the real case as there is a variety of EV charging abilities based on the used battery technology. Moreover, this variety is not considered as the main influence in EV charger power level. Therefore, this thesis research proposes:

- Allocation PV panels and EV charger with a dynamic range of power exchange
- Making the decision between different types of EV chargers
- Finding the best prices for EV charging and discharging (V2G)
- Modeling multi parking lot operation system to receive EV charging requests and process them achieving maximum daily profit

Chapter 3. Modeling

In this chapter, we present the different model used in the purposed planning and operation approach for an EV parking lot. These models focus on different aspects of the grid component and its data scenario if it is needed.

3.1 Grid Original Load Model

Currently, active connected load is considered as one of the main considerations regarding planning and operation of EV charging as the grid is designed to withstand the power demand of all the connected loads operating simultaneously. In reality, it is very rare for all the loads to be active with its full capacity. Also, grid connected loads are affected by the pattern of user power consumption as not all loads are used for the full day. In addition, power consumption pattern is different as some loads are only used in limited days like offices which operate only during weekdays.

Due to all this variation in grid connected loads operation, consideration of different scenarios of connected load is essential in order to define the gird power limitation around the hour. Figure 3.1 presents the time based scenario representation of the active original load as 1 year is represented by 4 seasons and each season is represented by 1 weekday wd and 1 weekend we and each day is represented by 24 time segments as each time segment is 1 hour long. Also, it is noted that the current grid construction is limited in case of bidirectional power flow as the maximum power flow is limited to the distribution grid power rating for both power flow direction.

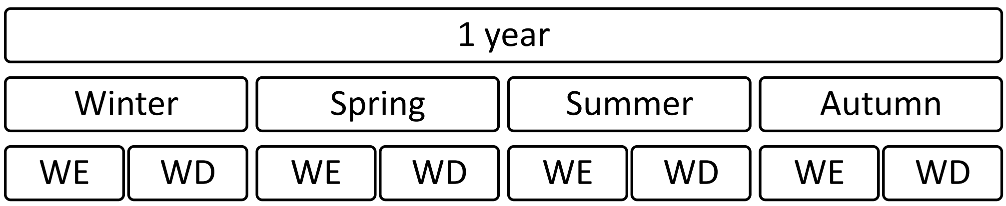

Figure 3.1: Time based scenarios representation of active connected load

3.2 PV Model

PV model is mainly dependent on two physical characteristics: ambient temperature T^{A} ($°C$) and solar irradiance $S^{IR}(W/m^{2})$[42]. PV performance is affected by T^{A} and S^{IR} variation as seen in (4), where T^{cell} is the PV cell temperature ($°C$) and $NOCT$ is the normal operating cell temperature ($°C$). PV output current $I^{PV}(A)$ is mainly influenced by solar irradiance S^{IR} as seen in (5), where I^{SC} is the short-circuit current

(A) and K^{i} is the current temperature coefficient ($A/°C$). Moreover, the PV output voltage V^{PV} (V) is negatively proportional with T^{cell} as seen in (6), where V^{OC} is the open –circuit voltage (V) and K^{v} is the voltage temperature coefficient ($V/°C$). In consideration of maximum power point tracking (MPPT), PV output current and voltage after MPPT are I^{MPP} (A) and V^{MPP} (V) respectively. Fill Factor $PV_{d,t}^{FF}$ (%) is defined as the ratio between the output power after MPPT and the multiplication of $I^{SC}$and V^{OC} as seen in (7). The normalized output power of a single PV unit $PV_{d,t}^{\%}$(%) is seen in (8), where $Prated^{PV}$is the rated output power of a single PV unit (kW). The total output power of PV units $P_{d,t}^{PV}$ (kW) is seen in (9), where N^{PV} is the number of allocated PV units.

$$T_{d,t}^{cell} = T_{d,t}^{A} + S_{d,t}^{IR} \times \left(\frac{NOCT - 20}{0.8\ kW/m^{2}}\right) \tag{4}$$

$$I_{d,t}^{PV} = S_{d,t}^{IR} \times \left(I^{SC}\left(1 + K^{i}\left(T_{d,t}^{cell} - 25\right)\right)\right) \tag{5}$$

$$V_{d,t}^{PV} = V^{OC}\left(1 - K^{v}\left(T_{d,t}^{cell} - 25\right)\right) \tag{6}$$

$$PV^{FF} = \frac{V^{MPP} \times I^{MPP}}{V^{OC} \times I^{SC}} \tag{7}$$

$$PV_{d,t}^{\%} = \frac{V_{d,t}^{PV} \times I_{d,t}^{PV}}{Prated^{PV}} \tag{8}$$

$$P_{d,t}^{PV} = PV_{d,t}^{\%} \times Prated^{PV} \times N^{PV} \tag{9}$$

Based on this model, the main decision variable for PV allocation is the number of PV units N^{PV}. The inputs to this model are the PV panel parameters and the historical irradiance and temperature readings. The output of this model is the PV generated power scenarios, which are influenced by historical data and are divided into 4 days as each day represent one season and each day is segmented into 24 segments and each segment is 1 hour. Figure 3.2 presents the input $PV_{d,t}^{\%}$ scenarios division. In order to set a common time-based scenarios, two copies of each season scenario is set as input that represents weekdays and weekends.

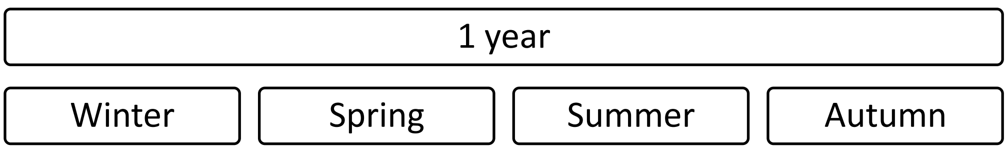

Figure 3.2: Time based scenarios representation for PV

3.3 EV Model

In this task, we will work on EV consumption modeling as a time-varying load. Modeling the EV charging load requires: modeling the EV battery considering power flow and efficiencies, modeling the EV charging at one instant of time for power flow analysis, and modeling the EV charging as it varies with time.

3.3.1 EV battery model. EV battery can be considered as a dispatchable BESS available only when there is an EV connected to an EV charger. Mainly, stored energy in EV can be represented by battery State-of-Charge (SOC) as it describes the percentage of stored energy from the overall capacity of the battery. It is noted that all batteries have Maximum Depth of Discharge (MDOD) which refer to the minimum SOC required for the battery to be rechargeable. Through time battery SOC is either increasing or decreasing based on charging and discharging operation. SOC_t^{Finish} is calculated at the end of time t based on the SOC state at the beginning of time t SOC_t^{Start} in (10), where E_t^{CH} is the energy supplied to the EV charger through the charging process (kWh), E_t^{DCH} is the energy received by the EV charger through the discharging process (kWh), $Cheff$ is the charging efficiency(%), $Dcheff$ is the discharging efficiency (%) and $BAT^{CAP}$is the battery capacity(kWh).

$$SOC_t^{Finish} = SOC_t^{Start} + \left(\frac{100}{BAT^{CAP}} \times \left((E_t^{CH} \times Cheff\,) - \frac{E_t^{DCH}}{Dcheff} \right) \right) \qquad (10)$$

3.3.2 EV charger load model. A simple model that was developed previously by one of the studies considered EV charging for power flow analysis [43]. In other words, how the EV charging load can be modeled at a certain time. Generally, there are three types of loads: constant power, constant impedance, and constant current. Also, EV chargers harmonics contributions in the power flow analysis are considered. It is noted that EV charger harmonics contribution is negligible in case of high switching frequency converters are used which are based on power electronics. The EV charging system usually consists of two converters: AC/DC converter on the grid side, and a DC/DC converter on the battery, as shown in Figure 3.3.

For the EV charging load at any instant, the battery side converter (DC-DC) controls the delivered power to the battery, while the grid side converter (AC-DC) controls the charging power factor to unity. Therefore, it is ensured that any variation in the grid voltage will not affect the battery charging power at any instant of time as the power electronics converters act as a buffer between the grid side and the battery. Consequently, for power flow analysis studies in the grid, the EV charging could be modeled as a normal constant power load which can be connected in any power load bus.

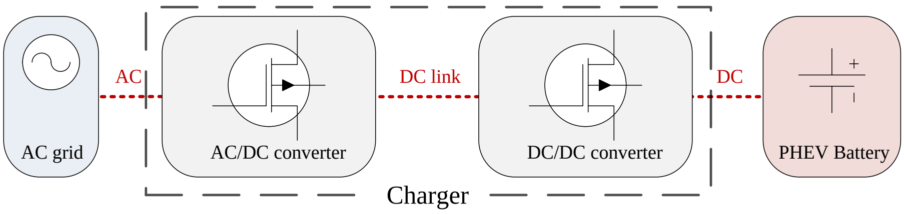

Figure 3.3: Structure of an Electric Vehicle batteries charging system [43]

3.3.3 EV charger load model variation through time. The proposed model relies on Monte-Carlo simulation to build virtual scenarios of EV trips, based on historical data of conventional vehicles travel patterns. represents the year with 8 days: weekday and weekend for each of the four seasons. The proposed model mainly consists of several stages. The outcome of this model can be described as virtual scenarios for each of the 8 days representing the year. Each scenario has a probability of occurrence. Each scenario consists of the hourly status of EV charger which is either connected or disconnected.

The model is composed of two sub-models. In the first model, the batteries of the EVs are depleted through the trip; then, in the second model, the battery is charged by one of the following schemes:

a) Coordinated charging to optimize single or multiple objectives.
b) Coordinated charging/discharging to optimize single or multiple objectives.

3.3.4 EV charging price model. In consideration of EV charging cost, a dynamic margin is considered to be added to the grid hourly price in order to cover operation and maintenance costs of EV chargers and PV with considerable profit. This margin has minimum and maximum values that are seen to influence customer behavior. The requested amount of energy by the EV owner is negatively proportional to the overall charging cost as higher charging cost will lead to less charging energy requested. This model is mainly set on demand theory as the higher product price will lead to less quantity demand. Figure 3.4 shows the relation between charging cost and requested energy graphically, where $Ꝑ^{MAX}$ is the maximum charging price margin ($\$/\text{kWh}$), $Ꝑ^{MIN}$ is the minimum charging price margin ($\$/\text{kWh}$) and E^{MAX} is the maximum requested energy by EV owner (kWh). In this model, the relation between charging price and requested energy is assumed to be linear [36].

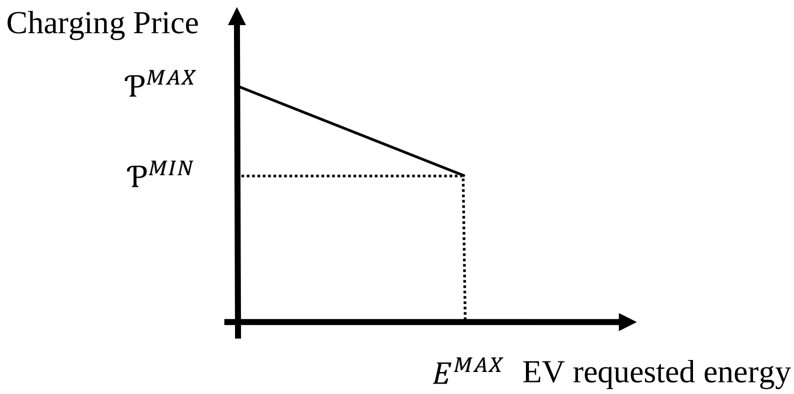

Figure 3.4: Linear relation between charging cost and energy demand [36]

Chapter 4. Proposed Approach

In this chapter, we present problem formulation for planning and operation proposed approaches in the format of an optimization problem with consideration of the objective function and constraints. Figure 4.1 shows the general structure of the parking lot.

Figure 4.1: EV Parking lot prototype

4.1. Planning

Planning study is approached through optimization of Mixed Integer Nonlinear Problem (MINLP). Solving this MINLP will provide the optimum case that satisfies the optimization objective function to maximize the net annual revenue through the allocation of PV, EV charger units and controlling EV charging/discharging operation. In order to solve this MINLP, Branch-And-Reduce Optimization Navigator (BARON) solver is used from the general algebraic modeling system (GAMS) software [44]–[46]. The planning approach inputs and outputs summary is given in Figure 4.2. The main contribution in the planning approach consists of considering a variety of EV battery specifications that represent EV population.

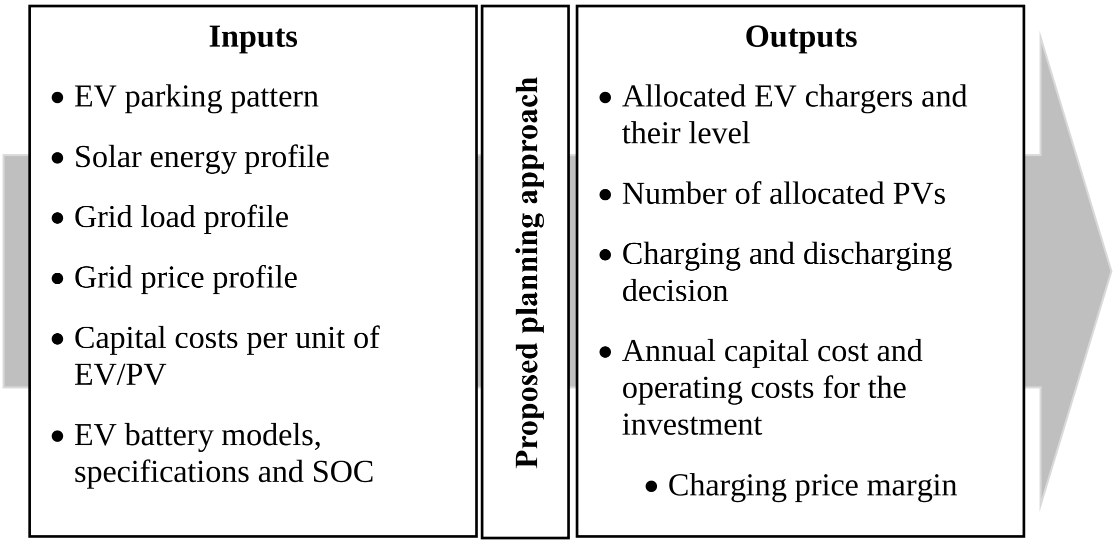

Figure 4.2: Summary of planning approach inputs and outputs

4.1.1 Optimization objective functions. The optimization objective function aims to maximize the net annual revenue Z as in (11) with respect to the vector of decision variables X. X contains the main decision variables of: number of allocated PV units $\mathrm{N^{PV}}$, type 1 charger placement decision $\mathrm{b_h^{L1}}$, type 2 charger placement decision $\mathrm{b_h^{L2}}$, charging decision $x_{\mathrm{h,d,t}}^{CH}$, discharging decision $x_{\mathrm{h,d,t}}^{DCH}$, and EV charging cost margin $ev_{d,t}$ (\$/kWh) as shown in (12). The net annual revenue Z is composed mainly of capital, operational, costs and incomes as in (13).

$$OBJECTIVE \rightarrow \max_{X}(Z) \tag{11}$$

$$X = [N^{PV}, b_h^{L1},\ b_h^{L2}, x_{\mathrm{h,d,t}}^{CH}, x_{\mathrm{h,d,t}}^{DCH}, ev_{d,t}\ ] \tag{12}$$

$$Z = CE^{PV}\ +\ CE^{EVCH} - CC^{PV} - CC^{EV} - CE^{Grid} -\ CE^{EVDCH} \tag{13}$$

There are two types of capital costs involved in Z. The first capital cost is the cost of PV units CC^{PV}, which is defined in (14), where $\mathrm{C^{PV}}$is PV capital cost per kW rated power (\$/kW) and $PVF^{PV}$is PVF applied for PV (years). The second capital cost is the cost of EV units $\mathrm{CC^{EV}}$, which is defined in (15), where both of C^{L1} and C^{L2} are the capital cost of type 1 and type 2 chargers respectively as a ratio of rated power (\$/kW) and both of $Prated^{L1}$ and $Prated^{L2}$ are the rated output power for type 1 and type 2 chargers respectively (kW).

$$CC^{PV} = \frac{N^{PV}\ \times Prated^{PV}\ \times C^{PV}}{PVF^{PV}} \tag{14}$$

$$CC^{EV} = \sum_{h} \frac{b_h^{L1} \times C^{L1} \times Prated^{L1}}{PVF^{EV}} + \sum_{h} \frac{b_h^{L2} \times C^{L2} \times Prated^{L2}}{PVF^{EV}} \quad (15)$$

There are two types of operational costs. The first operational cost is the cost of energy supplied from the grid CE^{Grid} , which is defined in (16), where ρFX^{Grid} is the fixed monthly cost of grid energy supply services ($/Month), $\rho_{d,t}^{Grid}$ is the hourly grid supply energy cost ($/kWh) and $Pnet_{d,t}^{EV}$ is the hourly net power flow due to EVs charging and discharging process (kW), which is defined in (17), where $PL1_{h,d,t}^{CH}$ and $PL2_{h,d,t}^{CH}$ are the output power of type 1 and type 2 chargers respectively during charging (kW) and $PL1_{h,d,t}^{DCH}$ and $PL2_{h,d,t}^{DCH}$ are the received power from type 1 and type 2 chargers respectively during discharging (kW). The second operational cost is the cost of energy supplied from EV through discharging CE^{EVDCH}, which is defined in (18), where $extra_{sell}$ is the extra cost margin added for V2G process ($/kWh) and $E_{h,d,t}^{DCH}$ is the hourly energy received from EV through discharging process for each candidate channel (kWh) which is calaulcated in (19).

$$CE^{Grid} =$$

$$\begin{aligned} rhoFX^{Grid} \times 12 + \left(\frac{365 \times 5}{7 \times 4}\right) \times \sum_{t} \sum_{wd} \left(rho_{d\in wd,t}^{Grid} \times Pnet_{d\in wd,t}^{EV}\right) \\ + \left(\frac{365 \times 2}{7 \times 4}\right) \times \sum_{t} \sum_{we} \left(rho_{d\in we,t}^{Grid} \times Pnet_{d\in we,t}^{EV}\right) \end{aligned} \quad (16)$$

$$Pnet_{d,t}^{EV} = \sum_{h} \left(PL1_{h,d,t}^{CH} + PL2_{h,d,t}^{CH} - PL1_{h,d,t}^{DCH} - PL2_{h,d,t}^{DCH}\right) \quad (17)$$

$$CE^{EVDCH} =$$

$$\begin{aligned} \left(\frac{365 \times 5}{7 \times 4}\right) \times \sum_{t} \sum_{wd} \left(\left(rho_{d\in wd,t}^{Grid} + extra_{sell}\right) \times \sum_{h} E_{h,d\in wd,t}^{DCH} \right) \\ + \left(\frac{365 \times 2}{7 \times 4}\right) \times \sum_{t} \sum_{we} \left(\left(rho_{d\in we,t}^{Grid} + extra_{sell}\right) \times \sum_{h} E_{h,d\in we,t}^{DCH} \right) \end{aligned} \quad (18)$$

$$E_{h,d,t}^{DCH} = x_{h,d,t}^{DCH} \times \left(\left(b_h^{L1} \times PL1_{h,d,t}^{DCH}\right) + \left(b_h^{L2} \times PL1_{h,d,t}^{DCH}\right) \right) \quad (19)$$

Finally, there are two operational incomes. The first operational income is the income of energy supplied from the grid to EV through charging $\mathrm{CE}^{\mathrm{EVCH}}$, which is defined in (20), where $ev_{d,t}$ is the hourly EV charging cost margin ($/kWh) and $\mathrm{E}_{\mathrm{h,d,t}}^{\mathrm{CH}}$ is the hourly energy consumed by EV through the charging process for each candidate channel (kWh) which is calculated in (21). The second operational income is the income of energy supplied from PV to grid $\mathrm{CE}^{\mathrm{PV}}$, which is defined in (22), where FIT^{PV} is the feed-in-tariff for PV generated energy ($/kWh) and $PV_{d,t}^{FF}$ is the output power ratio to the rated power.

$$CE^{EVCH} =$$

$$\left(\frac{365 \times 5}{7 \times 4}\right) \times \sum_{t} \sum_{wd} \left(\left(rho_{d \in wd,t}^{Grid} + ev_{d \in wd,t}\right) \times \sum_{h} E_{h,d \in wd,t}^{CH} \right) + \left(\frac{365 \times 2}{7 \times 4}\right) \times \sum_{t} \sum_{we} \left(\left(rho_{d \in we,t}^{Grid} + ev_{d \in we,t}\right) \times \sum_{h} E_{h,d \in we,t}^{CH} \right) \tag{20}$$

$$E_{h,d,t}^{CH} = x_{h,d,t}^{CH} \times \left(\left(b_h^{L1} \times PL1_{h,d,t}^{CH}\right) + \left(b_h^{L2} \times PL2_{h,d,t}^{CH}\right) \right) \tag{21}$$

$$CE^{PV} =$$

$$\left(\frac{365 \times 5}{7 \times 4}\right) \times \sum_{t} \sum_{wd} \left(FIT^{PV} \times PV_{d \in wd,t}^{\%} \times N^{PV} \times Prated^{PV}\right) + \left(\frac{365 \times 2}{7 \times 4}\right) \times \sum_{t} \sum_{we} \left(FIT^{PV} \times PV_{d \in we,t}^{\%} \times N^{PV} \times Prated^{PV}\right) \tag{22}$$

4.1.2 Constraints. In this part, we define the main system constraints as there are minimum and maximum limits for each variable in order to avoid any solution out of the given options.

Considering allocation constraints, the total allowed units of PV is limited by the available area of the parking lot roof as defined in (23). It is estimated that 1kW PV unit covers 10 square meters area.

$$0 \le N^{PV} \le \frac{parking\ lot\ roof\ area}{10 \times Prated^{PV}} \tag{23}$$

Beside PV allocation constraint, EV chargers allocation process is limited by the capacity of the parking lot. It is considered that one EV charger can serve one EV only and vice versa. Therefore, each candidate EV is examined for charger allocation as the decision will be either to allocate type 1 charger, type 2 charger or no charger as defined in (24). The total number of allocated chargers should not exceed the total number of candidate parking slots as defined in (24), where $CHNO$ is the number of parking slots in the parking lot.

$$0 \leq (b_h^{L1} + b_h^{L2}) \leq 1 \tag{24}$$

$$0 \leq \sum_h (b_h^{L1} + b_h^{L2}) \leq CHNO \tag{25}$$

Considering system power constraints, the overall system power flow $Pnet_{d,t}^{TF}$ should not exceed the transformer rated power $Prated^{TF}$ as defined in (26). $Pnet_{d,t}^{TF}$ is calculated in (27) where $Pload_{d,t}$ is the percentage of the active load (%) and $Pload^{MAX}$ is the maximum connected load.

$$-Prated^{TF} \leq Pnet_{d,hr}^{TF} \leq Prated^{TF} \tag{26}$$

$$Pnet_{d,t}^{TF} = \left(Pload_{d,t} \times Pload^{MAX}\right) - \left(PV_{d,t}^{\%} \times N^{PV} \times Prated^{PV}\right) + Pnet_{d,t}^{EV} \tag{27}$$

EV chargers charging and discharging power are limited by both charger and EV battery capabilities as seen in (28-35), where $Pmax_h^{CH}$ is the EV battery maximum charging power (kW) and $Pmax_h^{DCH}$ is the EV battery maximum discharging power (kW).

$$PL1_{h,d,t}^{CH} \leq Pmax_h^{CH} \tag{28}$$

$$PL2_{h,d,t}^{CH} \leq Pmax_h^{CH} \tag{29}$$

$$PL1_{h,d,t}^{DCH} \leq Pmax_h^{DCH} \tag{30}$$

$$PL2_{h,d,t}^{DCH} \leq Pmax_h^{DCH} \tag{31}$$

$$PL1_{h,d,t}^{CH} \leq Prated^{L1} \tag{32}$$

$$PL2_{h,d,t}^{CH} \leq Prated^{L2} \tag{33}$$

$$PL1_{h,d,t}^{DCH} \leq Prated^{L1} \tag{34}$$

$$PL2_{h,d,t}^{DCH} \leq Prated^{L2} \tag{35}$$

Considering, charging operation, charging and discharging processes cannot occur at the same time as seen in (36). In addition, charging and discharging decisions are taken based on the availability of EV in the parking lot as seen in (37). It is considered that a parking slot is set to be used by one EV per day which is defined in the EV parking pattern.

$$x_{\mathrm{h,d,t}}^{CH} + x_{\mathrm{h,d,t}}^{DCH} \leq 1 \tag{36}$$

$$if\ EV_{h,d,t}^{Logic} = 0 \ \rightarrow \quad x_{\mathrm{h,d,t}}^{CH} = x_{\mathrm{h,d,t}}^{DCH} = 0 \tag{37}$$

Charging cost margin is limited within maximum cost margin ev^{MAX} and minimum cost margin ev^{MIN} as seen in (38).

$$ev^{MIN} \leq ev_{d,t} \leq ev^{MAX} \tag{38}$$

Considering EV battery constraints, SOC maximum is limited to 100% and SOC minimum value is decided based on $MDOD$ as seen in (39). In addition, SOC at the beginning of each time segment $SOC_{h,d,t}^{Start}$ is the same as SOC at the end of the previous time segment $SOC_{h,d,t-1}^{Finish}$ as seen in (40) and (41), where $SOC_{h,d,t}^{Start}$ at $t = 1$ is defined as EV SOC upon arrival $SOC_{h,d}^{I}$ (%).

$$100\% - MDOD \ \leq SOC_{h,d,t}^{Finish} \leq 100\% \tag{39}$$

$$SOC_{h,d,t}^{Start} = SOC_{h,d,t-1}^{Finish}\ \forall\ \mathrm{hr} \geq 2 \tag{40}$$

$$SOC_{h,d,t=1}^{Start} = SOC_{h,d}^{I} \tag{41}$$

The total change in SOC $SOC_{h,d}^{Delta}$ is calculated as seen in (42). This value should satisfy the customer charging request as seen in (43), $SOC_{h,d}^{DIFF}$ represents the customer requested change in SOC and $SOC_{h,d}^{Pr}$ is the achieved percentage of customer request. $SOC_{h,d}^{Pr}$ has minimum limit $SOC_{h,d}^{PrMIN}$ to insure customer satisfaction as seen in (44).

$$SOC_{h,d}^{Delta} = \quad \left(SOC_{h,d,t=24}^{Finish} - SOC_{h,d,t=1}^{Start}\right) \tag{42}$$

$$SOC_{h,d}^{Delta} = \ SOC_{h,d}^{Pr} \times SOC_{h,d}^{DIFF} \times (b_h^{L1} + b_h^{L2}) \tag{43}$$

$$SOC_{h,d}^{PrMIN} \leq SOC_{h,d}^{Pr} \leq 100\% \tag{44}$$

4.2. Operation

In this phase of the study, the consideration of customers' charging requests will be received a day ahead. Then, the proposed approach will decide which customer is eligible for charging and will decide the suitable charger that can fit his charging requirements. In addition, the consideration of different parking lots is going to take place as multiple parking lots are distributed around the city and the optimization approach will be capable of assigning the best available parking lot location based on the charging traffic and the expected arrival time of the EV. Figure 4.3 presents the summary of operation approach inputs/outputs. The main contribution in operation approach consists of considering routing of customer EV to assign the parking lot and the EV charger suitable to serve the customer EV.

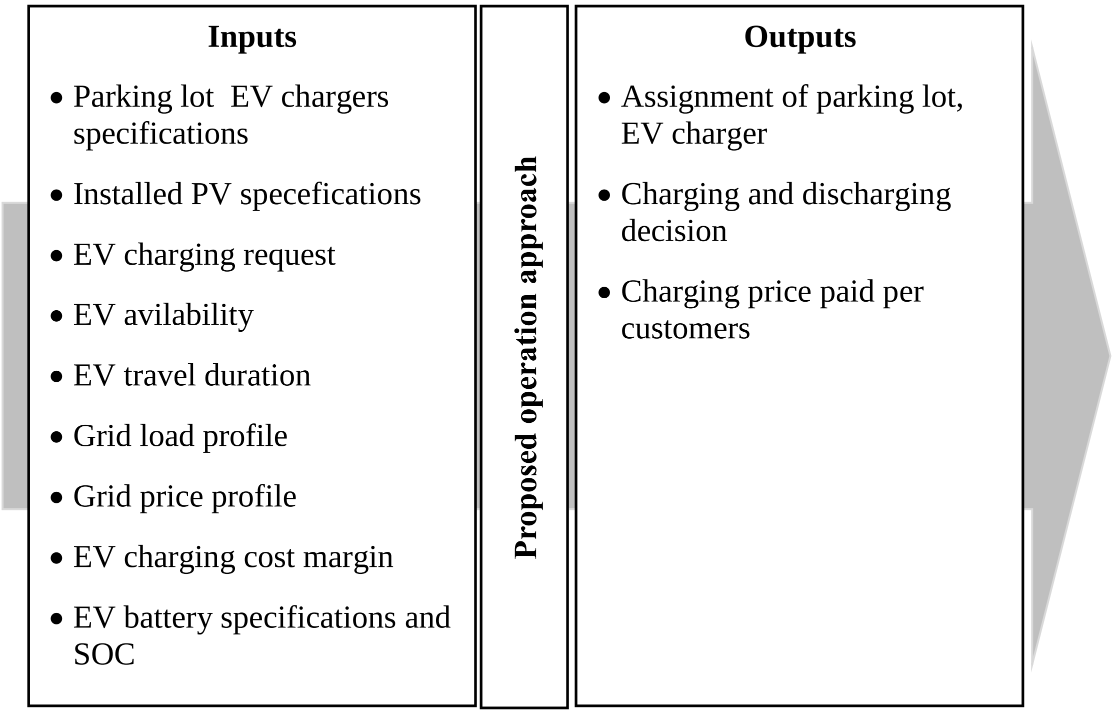

Figure 4.3: Summary of operation approach inputs and outputs

4.2.1 Optimization objective functions. The optimization objective function aims to maximize the net daily revenue Z_{day} as in (45) with respect to the vector of decision variables X. X contains the main decision variables of : customer routing decision $r^{L}_{pi,h,c}$, customer EV charging decision $x^{CH}_{\mathrm{c,t}}$ and customer EV discharging decision $x^{DCH}_{\mathrm{c,t}}$ as shown in (46). The net daily revenue Z_{day} is composed mainly of daily operational costs and incomes as in (47).

$$OBJECTIVE \rightarrow \max_{X}(Z_{day}) \tag{45}$$

$$X = [r^{L}_{pi,h,c},\ x^{CH}_{\mathrm{c,t}},\ \ x^{DCH}_{\mathrm{c,t}}] \tag{46}$$

$$Z_{day} = CE^{PV\_day} + CE^{EVCH\_day} - CE^{Grid\_day} - CE^{EVDCH\_day} \tag{47}$$

There are two types of daily operational costs. The first operational cost is the cost of energy supplied from the grid CE^{Grid_day}, which is defined in (48), where $rho\_day_t^{Grid}$ is the hourly grid supply energy cost ($/kWh) and $Pnet_{pi,t}^{EV}$ is the hourly net power flow due to EVs charging and discharging process (kW) per parking lot, which is defined in (49), where $PL_{c,t}^{CH}$ is the output power of EV charger respectively during charging (kW) and $PL_{c,t}^{DCH}$ is the received power from EV during discharging (kW). The second operational cost is the cost of energy supplied from EV through discharging CE^{EVDCH_day}, which is defined in (50), where $extra_{sell}$ is the extra cost margin added for V2G process ($/kWh) and $E_{c,t}^{DCH}$ is the hourly energy received from EV through the discharging process for each candidate customer (kWh). $E_{c,t}^{DCH}$ is calculated in (51).

$$CE^{Grid\_\text{day}} = \sum_t \sum_{pi} \left(rho\_day_t^{Grid} \times Pnet_{pi,t}^{EV} \right) \tag{48}$$

$$Pnet_{pi,t}^{EV} = \sum_h \sum_c r_{pi,h,c}^{L} \times \left(PL_{c,t}^{CH} - PL_{c,t}^{DCH} \right) \tag{49}$$

$$CE^{EVDCH\_day} = \sum_t \left(\left(rho\_day_t^{Grid} + extra_{sell} \right) \times \sum_c E_{c,t}^{DCH} \right) \tag{50}$$

$$E_{c,t}^{DCH} = \sum_{pi} \sum_h r_{pi,h,c}^{L} \times x_{c,t}^{DCH} \times PL_{c,t}^{DCH} \tag{51}$$

Finally, there are two operational incomes for the parking lot investor. The first operational income is the income of energy supplied to EV through charging CE^{EVCH_day}, which is defined in (52) and (53), where ev_day_t is the hourly EV charging cost margin ($/kWh) and $E_{c,t}^{CH}$ is the hourly energy consumed by EV through the charging process for each candidate customer (kWh). The second operational income is the income of energy sold from the PV local generation to the grid CE^{PV_day}, which is defined in (54), where N^{pi} is he number of the parking lot, FIT^{PV} is the feed-in-tariff for PV generated energy ($/kWh), $PV\_day_t^{\%}$ is the output power ratio to the rated power $Prated^{PV}$, $N^{PV}$is the number of PV units allocated at each parking lot rooftop and N^{pi} is the number of EV parking lots.

$$CE^{EVCH\_day} = \sum_{t} \left(\left(rho\_day_t^{Grid} + ev\_day_t\right) \times \sum_{c} E_{c,t}^{CH} \right) \quad (52)$$

$$E_{c,t}^{CH} = \sum_{pi} \sum_{h} r_{pi,h,c}^{L} \times x_{c,t}^{CH} \times PL_{c,t}^{CH} \quad (53)$$

$$CE^{PV\_day} = N^{pi} \times \sum_{t} \left(FIT^{PV} \times PV\_day_t^{\%} \times N^{PV} \times Prated^{PV}\right) \quad (54)$$

4.2.2 Constraints. In this part, we define the main system constraints. Considering routing constraints, every charger can serve only one customer at a time as defined in (55), where $evlogic\_day_{c,t}$ is the EV avilability status per customer and $delay_{pi,c,t}$ is the time delay of the custimer EV to reach to parking lot pi. In addition, one customer is routed to one charger only as defined in (56).

$$\sum_{c} r_{pi,h,c}^{L} \times \left(EV_{c,t}^{Logic\_day}\right) \leq 1 \quad (55)$$

$$\sum_{pi} \sum_{h} r_{pi,h,c}^{L} \leq 1 \quad (56)$$

Considering system power constraints, the overall system power flow $Pnet_{pi,t}^{TF}$ should not exceed the local transformer rated power $Prated^{TF}$ as defined in (57). $Pnet_{pi,t}^{TF}$ is calculated in (58), where $Pload_{d,t}$ is the percentage of the active load (%), $Pload^{MAX}$ is the maximum connected load (kW), and $Pnet_{pi,t}^{EV}$ is the net power transfer as culculated in (59).

$$-Prated^{TF} \leq Pnet_{pi,t}^{TF} \leq Prated^{TF} \quad (57)$$

$$Pnet_{pi,t}^{TF} = \left(Pload_{d,t} \times Pload^{MAX}\right) - \left(PV_{d,t}^{\%} \times N^{PV} \times Prated^{PV}\right) + Pnet_{pi,t}^{EV} \quad (58)$$

$$Pnet_{pi,t}^{EV} = \sum_{h} \sum_{c} r_{pi,h,c}^{L} \times ((x_{c,t}^{CH} \times PL_{c,t}^{CH}) - (x_{c,t}^{DCH} \times PL_{c,t}^{DCH})) \quad (59)$$

EV chargers charging and discharging power are limited by both charger and EV battery capabilities as seen in (60-63), where $Pmax_c^{CH}$ is the EV battery maximum charging power (kW), $Pmax_c^{DCH}$ is the EV battery maximum discharging power (kW), $Pmax_h^{CH}$ is the charger maximum charging power (kW) and $Pmax_h^{DCH}$ is the EV charger maximum discharging power (kW).

$$PL_{c,t}^{CH} \le Pmax_{c}^{CH} \tag{60}$$

$$PL_{c,t}^{DCH} \le Pmax_{c}^{DCH} \tag{61}$$

$$PL_{c,t}^{CH} \le \sum_{pi}\sum_{h} r_{pi,h,c}^{L} \times Pmax_{h}^{CH} \tag{62}$$

$$PL_{c,t}^{DCH} \le \sum_{pi}\sum_{h} r_{pi,h,c}^{L} \times Pmax_{h}^{DCH} \tag{63}$$

Considering, EV charger operation, charging and discharging processes cannot occur at the same time as in (64). In addition, an EV can be charged/discharged if it exists in the parking lot as in (65). It is considered that a parking slot is set that can be used by one EV per day which is defined in the EV parking pattern.

$$x_{\mathrm{c,t}}^{CH} + x_{\mathrm{c,t}}^{DCH} \le 1 \tag{64}$$

$$if\ EV_{c,t}^{Logic\_day} = 0 \ \rightarrow \quad x_{\mathrm{h,d,t}}^{CH} = x_{\mathrm{h,d,t}}^{DCH} = 0 \tag{65}$$

Considering EV battery constraints, maximum SOC is limited to 100% and minimum SOC value is decided based on $MDOD$ as in (66). In addition, the EVs' SOC at the beginning of each time segment $SOC_{c,t}^{Start}$ is the same as SOC at the end of the previous time segment $SOC_{c,t-1}^{Finish}$ as in (67) and (68), where $SOC_{c,t}^{Start}$ at $t = 1$ is defined as the SOC upon arrival SOC_{c}^{I} (%).

$$100\% - MDOD \le SOC_{c,t}^{Finish} \le 100\% \tag{66}$$

$$SOC_{c,t}^{Start} = SOC_{c,t-1}^{Finish}\ \forall\ \mathrm{hr} \ge 2 \tag{67}$$

$$SOC_{c,t=1}^{Start} = SOC_{c}^{I} \tag{68}$$

The total change in the SOC SOC_{c}^{Delta} is calculated as in (69). This value should satisfy the customer charging request as in (70), where SOC_{c}^{DIFF} represents the customer requested change in SOC and SOC_{c}^{Pr} is the achieved percentage of customer request. SOC_{c}^{Pr} has minimum limit SOC^{PrMIN} to insure customer satisfaction as in (71).

$$SOC_{c}^{Delta} = \left(SOC_{c,t=24}^{Finish} - SOC_{c,t=1}^{Start}\right) \tag{69}$$

$$SOC_{c}^{Delta} = SOC_{c}^{Pr} \times SOC_{c}^{DIFF} \times \sum_{pi}\sum_{h} r_{pi,h,c}^{L} \tag{70}$$

$$SOC^{PrMIN} \le SOC_{c}^{Pr} \le 100\% \tag{71}$$

Chapter 5. Planning Approach Case Study

In this chapter, we present the simulation results achieved for the proposed planning approach showing the optimum allocation of EV chargers and PV in different situations. This optimum solution will be evaluated and compared with other situations solutions.

5.1. Case Study Description

In the presented case study, all the optimization problem solving are based on the same input data and constraints as the main focus of this study to compare the different approaches of EV planning. The parking lot fixed input data is represented in table 5.1.

Table 5.1: Planning case study fixed inputs

Input	Value	Unit	Input	Value	Unit
$Prated^{TF}$	1600	kW	C^{PV}	3500	\$/kW
$Pload^{MAX}$	1500	kW	C^{L1}	450	\$/kW
$CHNO$	50	Unit	C^{L2}	550	\$/kW
$Prated^{L1}$	7.2	kW/unit	PVF^{EV}	1.994	Year
$Prated^{L2}$	24	kW/unit	PVF^{PV}	13.638	Year
$Prated^{PV}$	1	kW/unit	FIT^{PV}	0.33	\$/kWh
$Cheff$	96	%	ρFX^{Grid}	32	\$/month
$Dcheff$	96	%	ev^{MIN}	0.25	\$/kWh
$MDOD$	80	%	ev^{MAX}	0.4	\$/kWh
$SOC_{h,d}^{PrMIN}$	80	%	$extra_{sell}$	0.4	\$/kWh
parking lot roof area	1300	m^2			

In addition, time based inputs of the optimization problem are the same for all the cases. Figure 5.1 presents the input of active connected loads in kW. Figure 5.2 presents the grid supply prices for different seasons' weekday and weekend in $/kWh. Figure 5.3 presents a sample of EV parking pattern as EV presence is shown for one day duration.

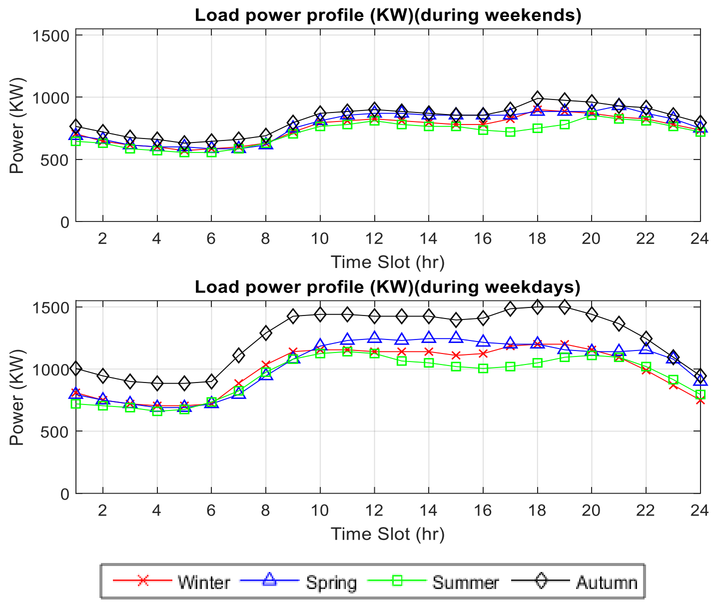

Figure 5.1: Original active load profile

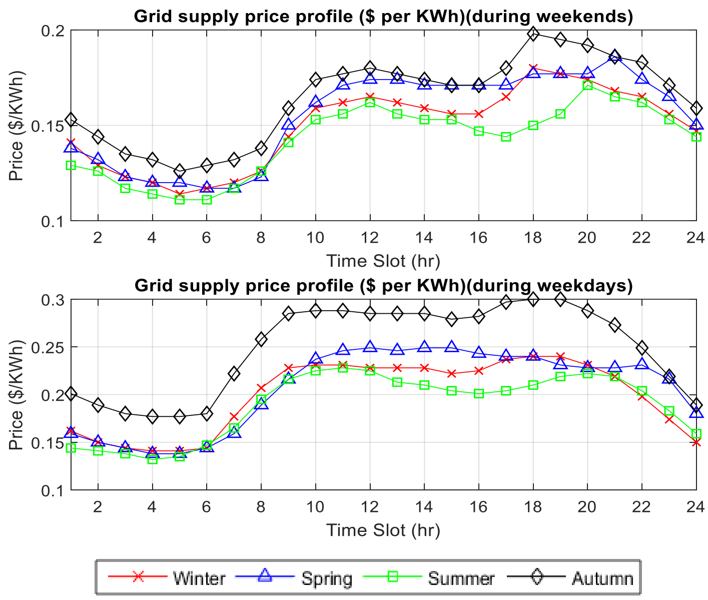

Figure 5.2: Grid supply price profile

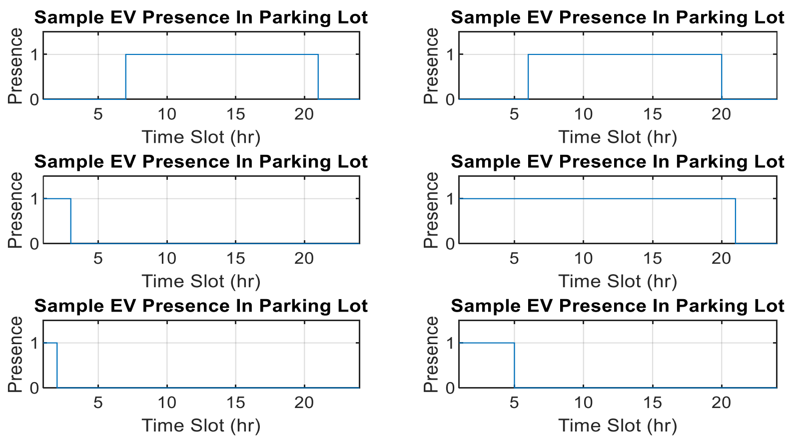

Figure 5.3: Sample of EV arrival and departure scenarios

5.2. Case Study Versions

In order to develop the EV planning approach, an initial version is used with basic control and data (Version 0.0). Afterward, other versions with a higher level of control are presented. Table 5.2 presents the different versions of the planning case study and their consideration for allocation. It is noted that the only variation in input data is EV battery specifications as optimization it is not feasible in early versions with different EV battery specifications. Therefore, for early versions of the case study, standard battery specifications are assigned. The standard battery has a capacity of 60kWh and charging/ discharging rate of 20kW.

Table 5.2: Case study versions and their considerations

Case study version	V0.0	V0.1	V0.2	V0.3	V0.4	V0.5	V0.6
PV	Yes						
Type 1 charger (7.2kW)	Yes						
Type 2 charger (24kW)	No	No	Yes	Yes	Yes	Yes	Yes
Discharging	No	Yes	Yes	Yes	Yes	Yes	Yes
Battery	Standard				Variable		
Routing	No	No	No	No	Yes	Yes	Yes
EV population	50	50	50	50	50	50	100

5.2.1. Version 0.0: Allocation of one type of EV charger without discharging considering 50 standard EVs. In this version of the case study, type 1 EV chargers allocation are considered with the assistance of PV units allocation with standard EV battery and without discharging. Table 5.3 presents the optimization outputs.

Table 5.3: Optimization output for V0.0 case study

Output	Value	Unit
Z: Net annual revenue	122,425	\$ / year
$\mathrm{CC}^{\mathrm{PV}}$: PV annual capital cost	33,362	\$ /year
$\mathrm{CC}^{\mathrm{EV}}$: EV annual capital cost	45,374	\$ / year
$\mathrm{CE}^{\mathrm{EVCH}}$: EV charging cost	192,656	\$ / year
$\mathrm{CE}^{\mathrm{EVDCH}}$: EV discharging cost	0	\$ / year
$\mathrm{CE}^{\mathrm{Grid}}$: Grid supply energy cost	71,105	\$ / year
$\mathrm{CE}^{\mathrm{PV}}$: PV energy cost	79,611	\$ / year
Total number of allocated type 1 chargers	28	Unit
Total number of allocated type 2 chargers	0	Unit
N^{PV}: Total number of allocated PV units	130	Unit
The rated output power of allocated PV panels	130	kW

It is noted that some candidate EVs did not have EV charger allocation as it is seen as an inefficient solution. It is seen that additional EV charger will have less charging income than the extra capital and operation costs. In addition, some candidate EVs did not have EV charger allocated due to infeasibility as EV charger is not able to satisfy the customer request due to short availability duration. On the other hand, it is noted that the optimum number of PV allocated unit is set to the maximum limit. PV energy income CE^{PV} surplus the annual capital cost of PV CC^{PV} abiding the power costraints. It is noted that in all the versions of the planning approach case study, PV allocation results are the same. Figure 5.4 presents the PV output power profile in kW.

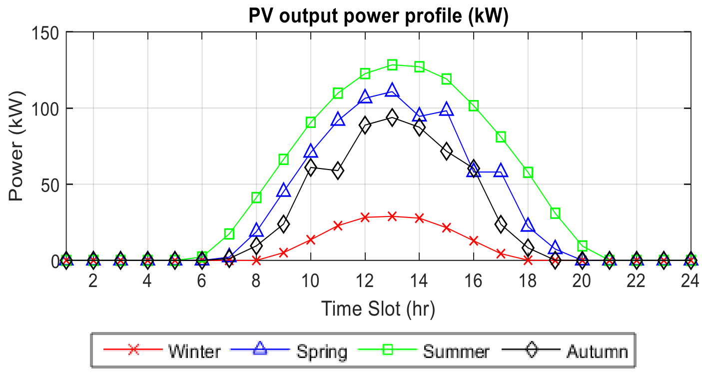

Figure 5.4: PV output power profile

Figure 5.5 presents the overall transformer power flow $Pnet_{d,t}^{TF}$ which shows that power flow constraints are met. It is noted that in the middle of the day the net power flow is low due to high incoming power from the allocated PV units. PV power supply reduces the net demanded power from the grid in some cases and sends back energy to the grid in case of low local power demand as seen in summer weekeknd. Figure 5.6 presents the profile of net power consumed by EV chargers $Pnet_{d,t}^{EV}$. Generally, charging requests are more during weekdays than weekends. This point is seen clearly as $Pnet_{d,t}^{EV}$ is lower during weekends than $Pnet_{d,t}^{EV}$ during weekdays. Capturing a sample of EV charger operation, Figure 5.7 presents a samples of EV charger operation. It is seen that EV charger operation is only enabled in case an EV is connected to the charger and charging operation is controlled to deliver a certain amount of power which is reflected in EV battery SOC increase.

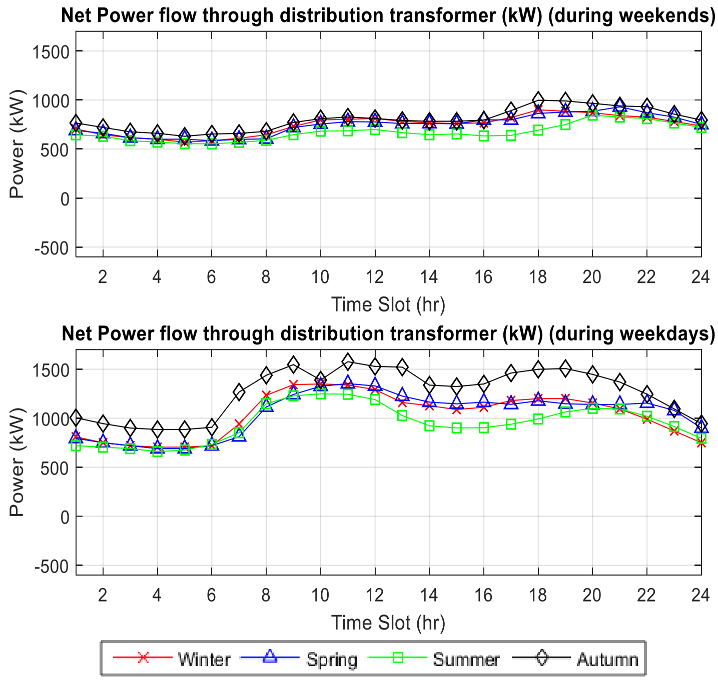

Figure 5.5: V0.0 case study overall power flow

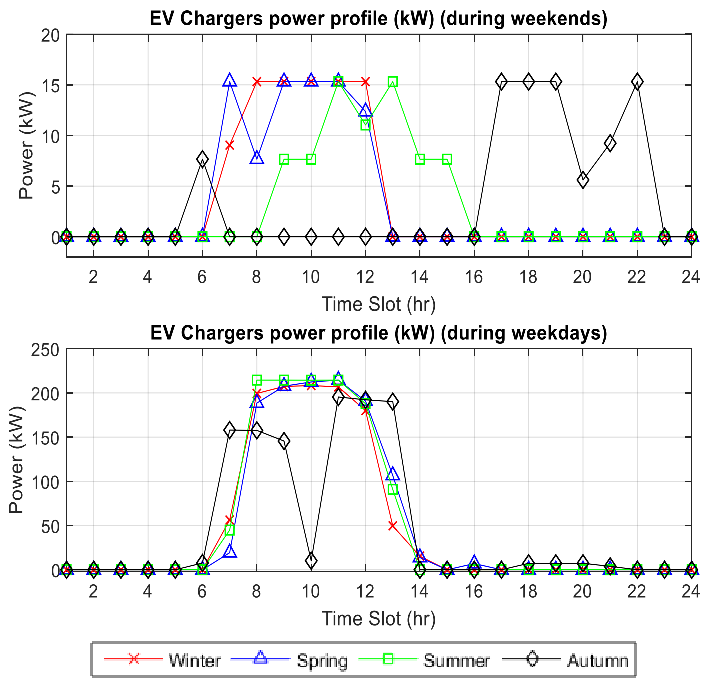

Figure 5.6: V0.0 case study net EV chargers power profile

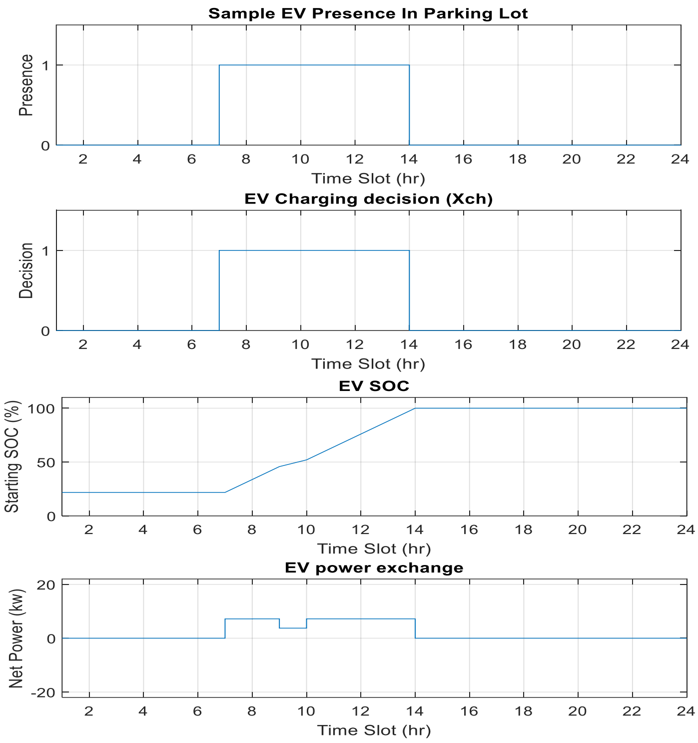

Figure 5.7: V0.0 case study sample of the EV charging operation

5.2.2. Version 0.1: Allocation of one type of EV charger with discharging considering 50 standard EVs. In this version of the case study, discharging option is introduced as EV can be considered as dispatchable BESS system. The discharging option was applied abiding customer satisfaction constraints as $SOC_{h,d}^{PrMIN}$ is set to 80%. Table 5.4 presents the optimization outputs. It is seen that introducing the discharging option have increased the annual revenue. Figures 5.8 and 5.9 present the overall power flow and net power flow for all allocated EV chargers respectively.

Table 5.4: Optimization output for V0.1 case study

Output	Value	Unit
Z: Net annual revenue	125,260	$ / year
CC^{PV}: PV annual capital cost	33,362	$ /year
CC^{EV}: EV annual capital cost	45,374	$ / year
CE^{EVCH}: EV charging cost	228,038	$ / year
CE^{EVDCH}: EV discharging cost	32,026	$ / year
CE^{Grid}: Grid supply energy cost	71,627	$ / year
CE^{PV}: PV energy cost	79,611	$ / year
Total number of allocated type 1 chargers	28	Unit
Total number of allocated type 2 chargers	0	Unit
N^{PV}: Total number of allocated PV units	130	Unit
The rated output power of allocated PV panels	130	kW

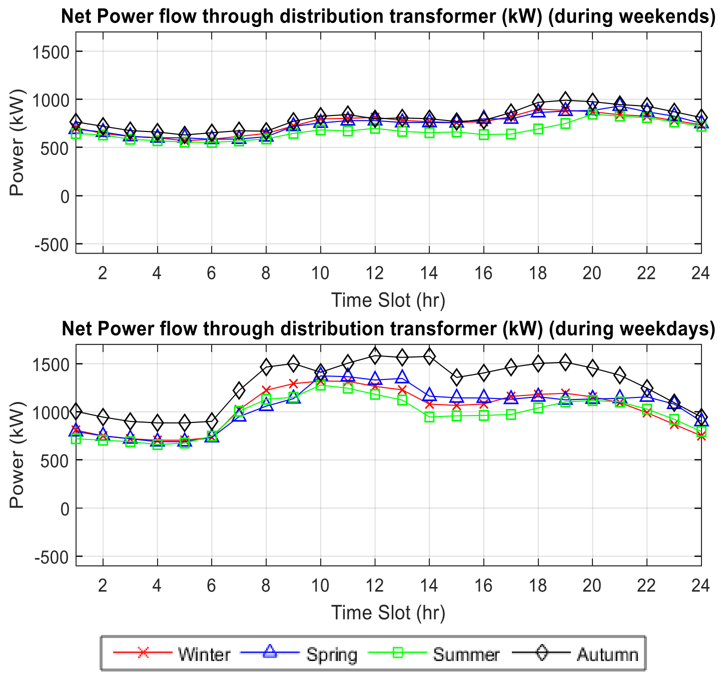

Figure 5.8: V0.1 case study overall power flow

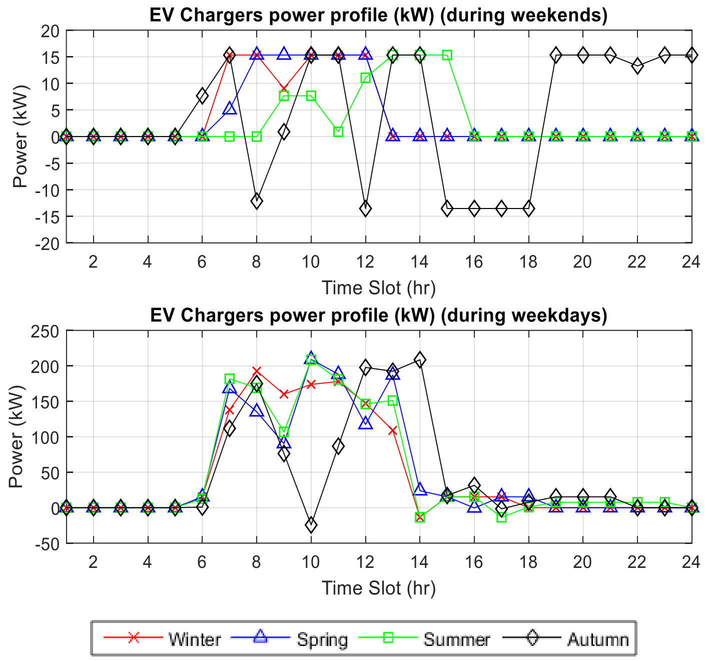

Figure 5.9: V0.1 case study net EV chargers power profile

Capturing samples of EV charger operation, Figures 5.10 and 5.11 present two samples of EV charger operation. It is seen that enabling dischargingg have enabled more EV chargers to be allocated and these chargers are managed and coordinated to achieve the mission of EV charging with the highest possible revenue. As seen from Figure 5.10, the EV is connected for a long duration is optimized to charge and discharge on different hour segments with varying power exchange rate achieving the connected EV charging request within the allowed satisfaction rates and acting as a dispatchable BESS during the EV discharging hours. On the other hand, some EVs are available for a short duration as seen in Figure 5.11. In this case, the EV charger will not consider EV discharging as this will not achieve the minimum EV charging satisfaction rate prior the EV departure.

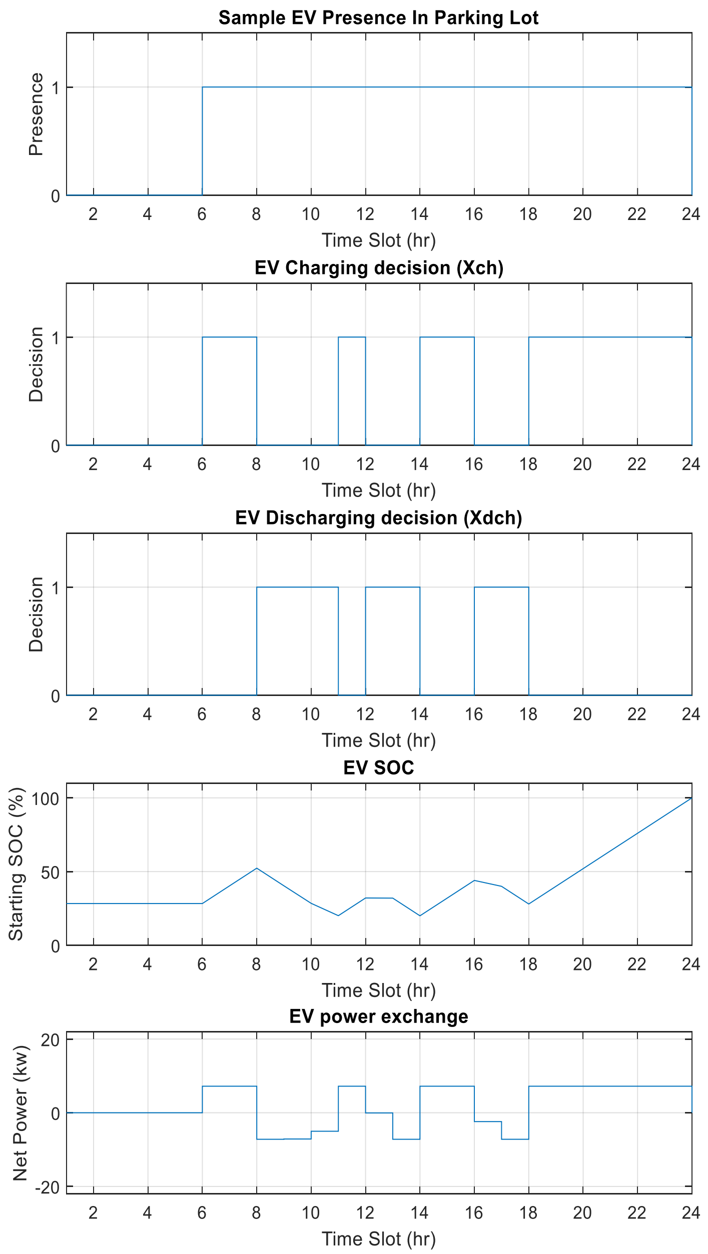

Figure 5.10: V0.1 case study sample 1 of the EV charging operation

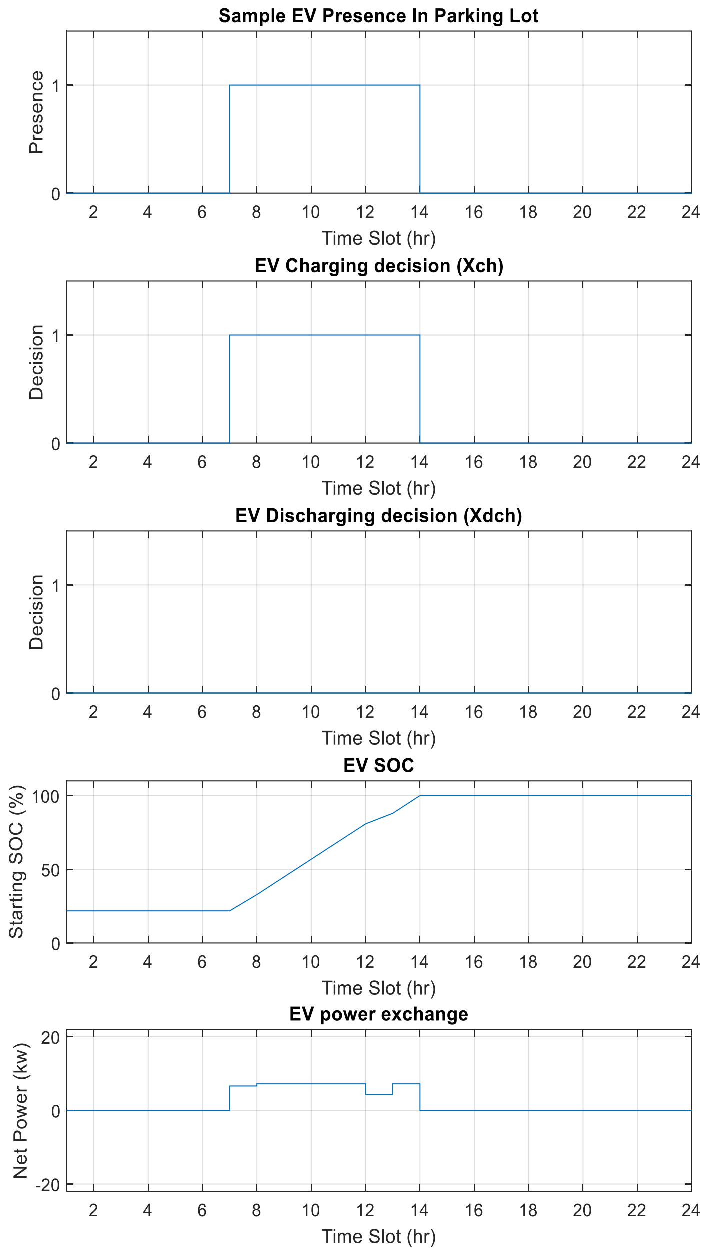

Figure 5.11: V0.1 case study sample 2 of the EV charging operation

5.2.3. Version 0.2: Allocation of two types of EV chargers with discharging considering 50 standard EVs. In this version of the case study, two types of EV chargers are considered for allocation with standard EV battery and discharging. Table 5.5 presents the optimization outputs. It is seen that introducing another option of EV charger increased the annual revenue and increased the number of served EVs. Figures 5.12 and 5.13 present the overall power flow and net power flow for all allocated EV chargers respectively.

Table 5.5: Optimization output for V0.2 case study

Output	Value	Unit
Z: Net annual revenue	133,420	$ / year
$\mathrm{CC}^{\mathrm{PV}}$: PV annual capital cost	33,362	$ /year
$\mathrm{CC}^{\mathrm{EV}}$: EV annual capital cost	117,995	$ / year
$\mathrm{CE}^{\mathrm{EVCH}}$: EV charging cost	549,899	$ / year
$\mathrm{CE}^{\mathrm{EVDCH}}$: EV discharging cost	232,671	$ / year
$\mathrm{CE}^{\mathrm{Grid}}$: Grid supply energy cost	112,061	$ / year
$\mathrm{CE}^{\mathrm{PV}}$: PV energy cost	79,611	$ / year
Total number of allocated type 1 chargers	28	Unit
Total number of allocated type 2 chargers	11	Unit
N^{PV}: Total number of allocated PV units	130	Unit
The rated output power of allocated PV panels	130	kW

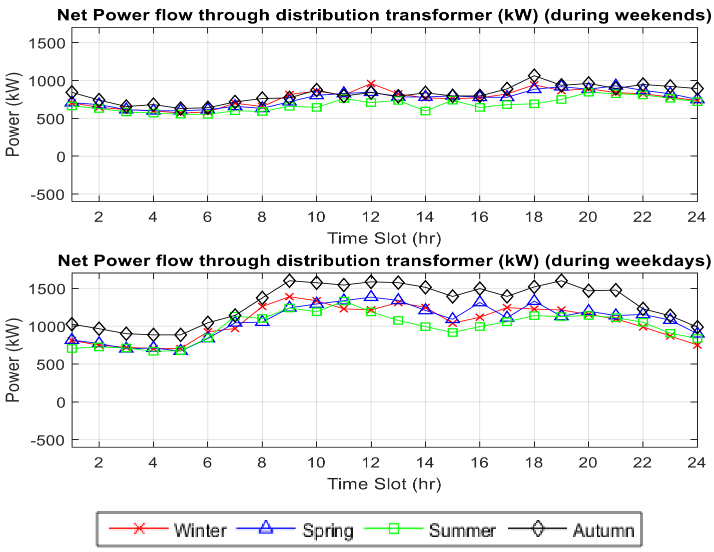

Figure 5.12: V0.2 case study overall power flow

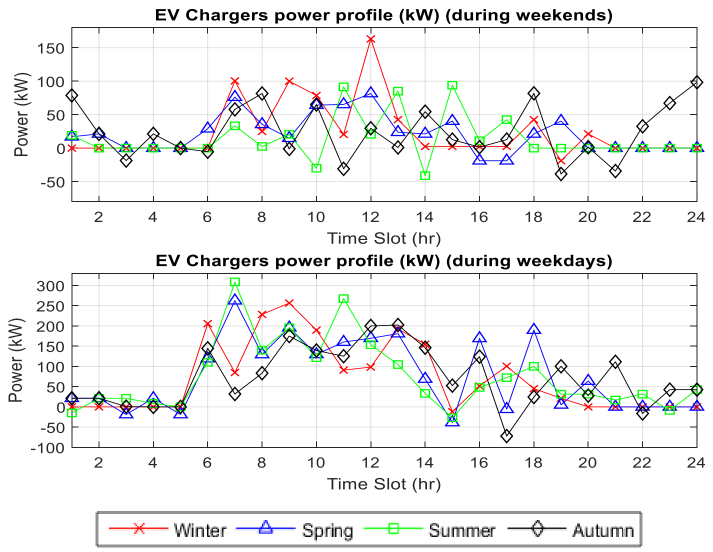

Figure 5.13: V0.2 case study net EV chargers power profile

Capturing samples of EV charger operation, Figures 5.14 and 5.15 present samples EV chargers operation. As seen in Figure 5.14, type 1 EV charger is used to achieve the charging request as it is seen as an optimum option. Moving toward Figure 5.15, type 2 EV charger is seen to be more optimum to satisfy the available EV charging request as it has higher power exchange capabilities for both charging and discharging abiding the connected EV standard battery power exchange limits.

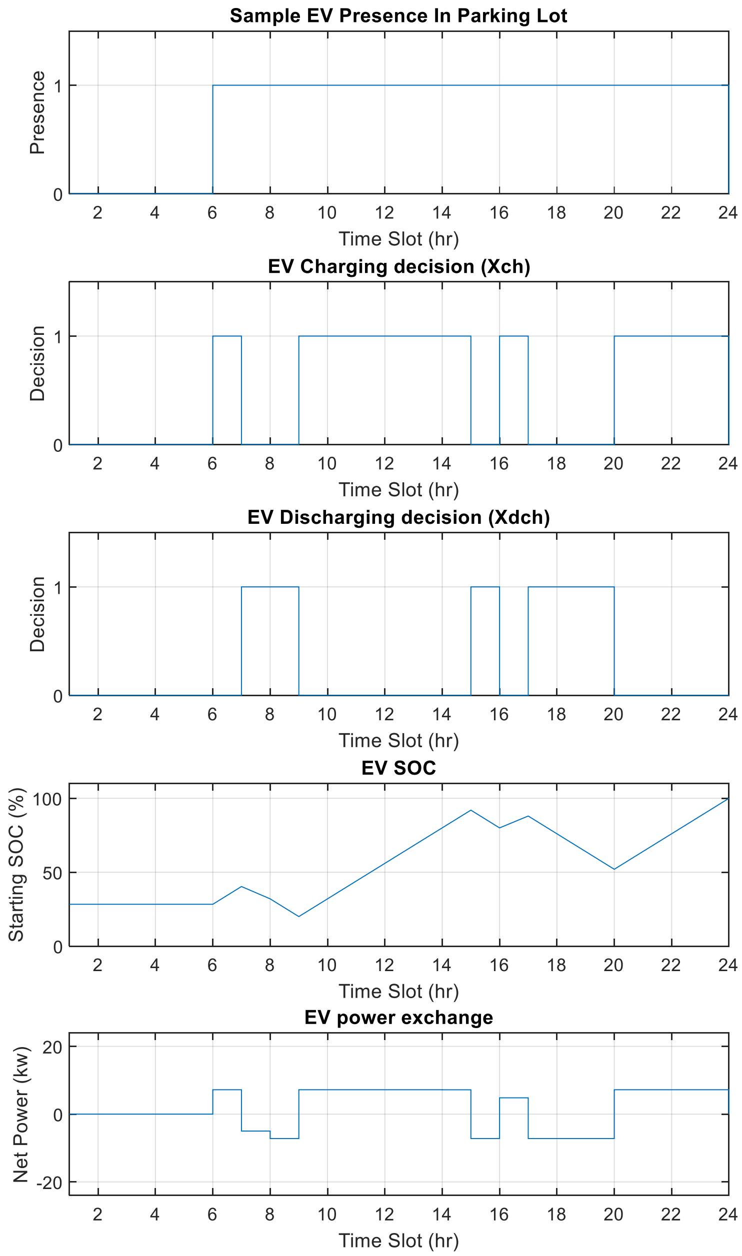

Figure 5.14: V0.2 case study sample 1 of the EV charging operation

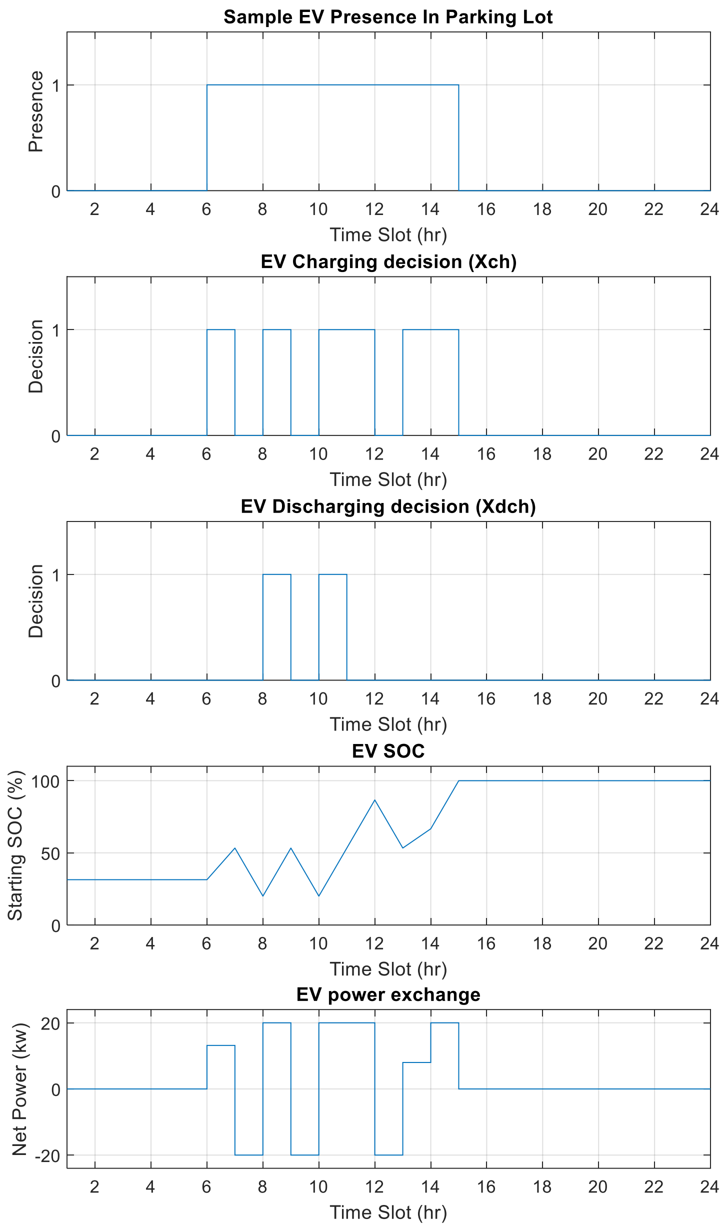

Figure 5.15: V0.2 case study sample 2 of the EV charging operation

5.2.4. Version 0.3: Allocation of two types of EV chargers with discharging considering 50 different EVs. This version is similar to Version 0.2; however, different battery specifications are used to reflect the realistic variation of EV charging requirements. Table 5.6 presents the optimization outputs. It is seen that introducing a variety of EV batteries have changed the optimization output due to the high percentage of lower EV battery capacity compared to the standard battery used in previous versions of the case study. In addition, not all the EVs have the same charging rate which impacted the allocation decision. Figures 5.16 and 5.17 present the overall power flow and net power flow for all allocated EV chargers respectively.

Table 5.6: Optimization output for V0.3 case study

Output	Value	Unit
Z: Net annual revenue	95,031	$ / year
CC^{PV}: PV annual capital cost	33,362	$ /year
CC^{EV}: EV annual capital cost	136,421	$ / year
CE^{EVCH}: EV charging cost	414,350	$ / year
CE^{EVDCH}: EV discharging cost	125,773	$ / year
CE^{Grid}: Grid supply energy cost	103,373	$ / year
CE^{PV}: PV energy cost	79,611	$ / year
Total number of allocated type 1 chargers	19	Unit
Total number of allocated type 2 chargers	16	Unit
N^{PV}: Total number of allocated PV units	130	Unit
The rated output power of allocated PV panels	130	kW

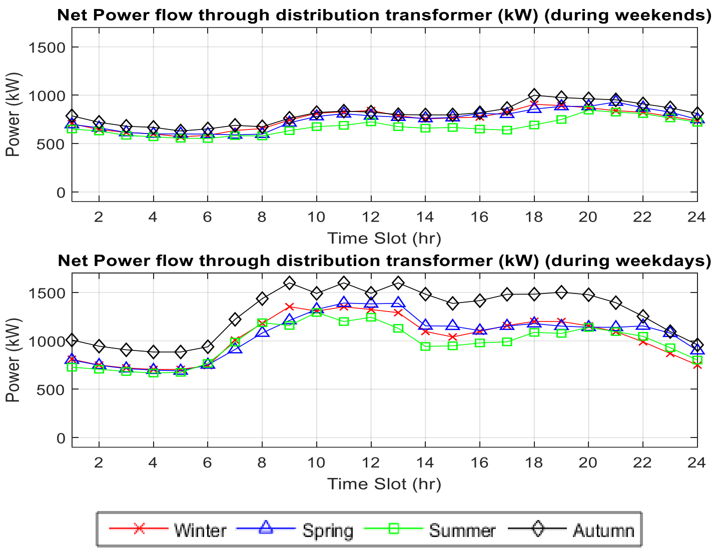

Figure 5.16: V0.3 case study overall power flow

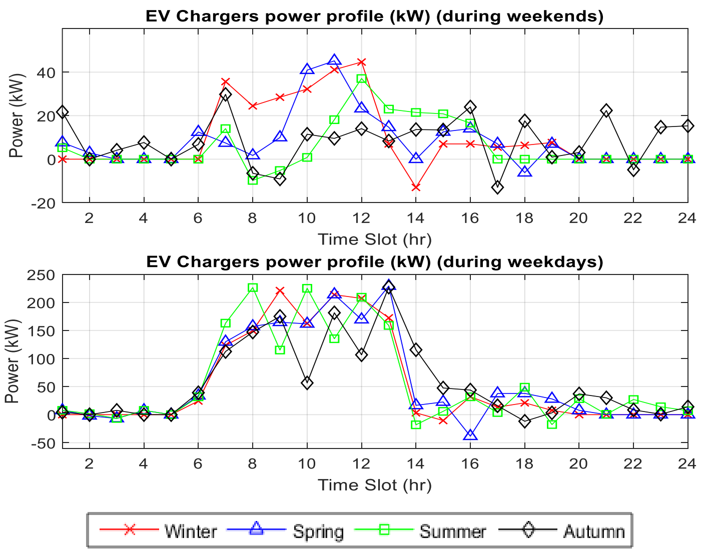

Figure 5.17: V0.3 case study net EV chargers power profile

Capturing samples of EV charger operation, Figures 5.18 and 5.19 present samples EV charger operation. It is seen that considering variable EV battery specifications are reflected into power exchange limit as EV charger abided the connected EV battery specifications to apply suitable charging/discharging power. In Figure 5.18, type 1 EV charger is allocated as it is suitable for the connected EV. Considering Figure 5.19, type 2 EV charger is allocated and controlled to not exceed the connected EV charging rate (10 kW).

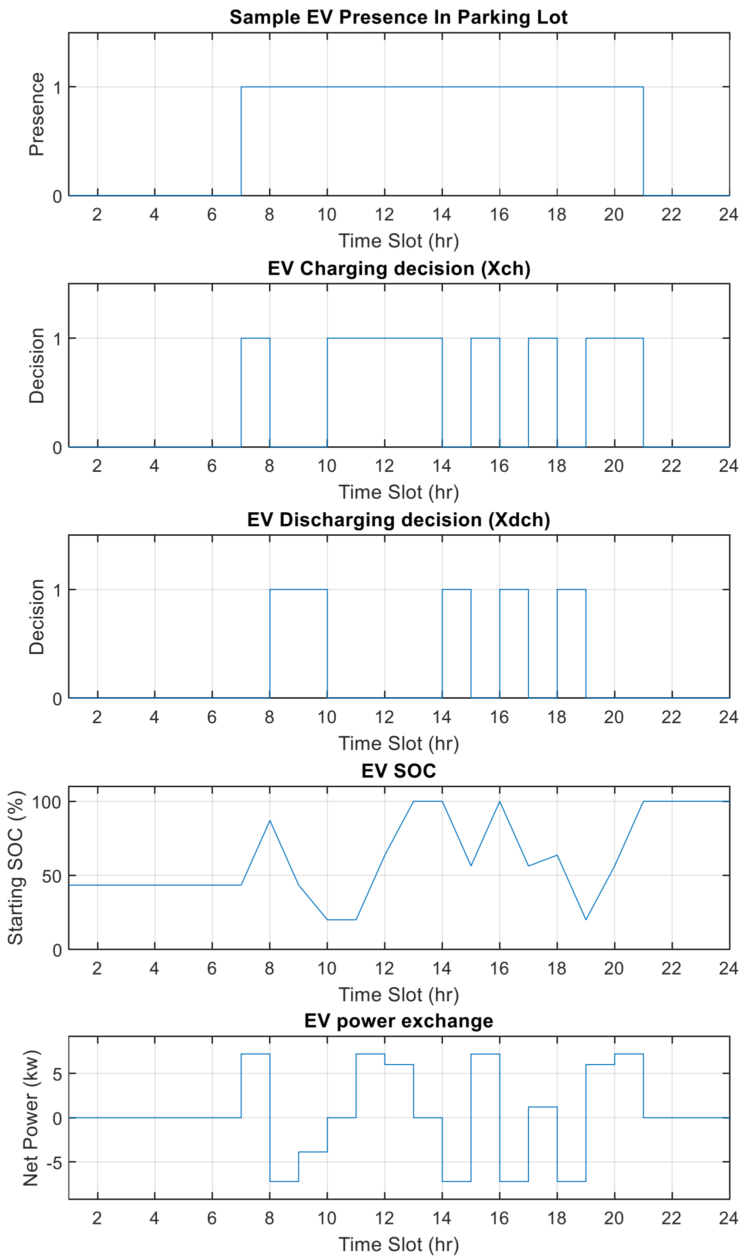

Figure 5.18: V0.3 case study sample 1 of the EV charging operation

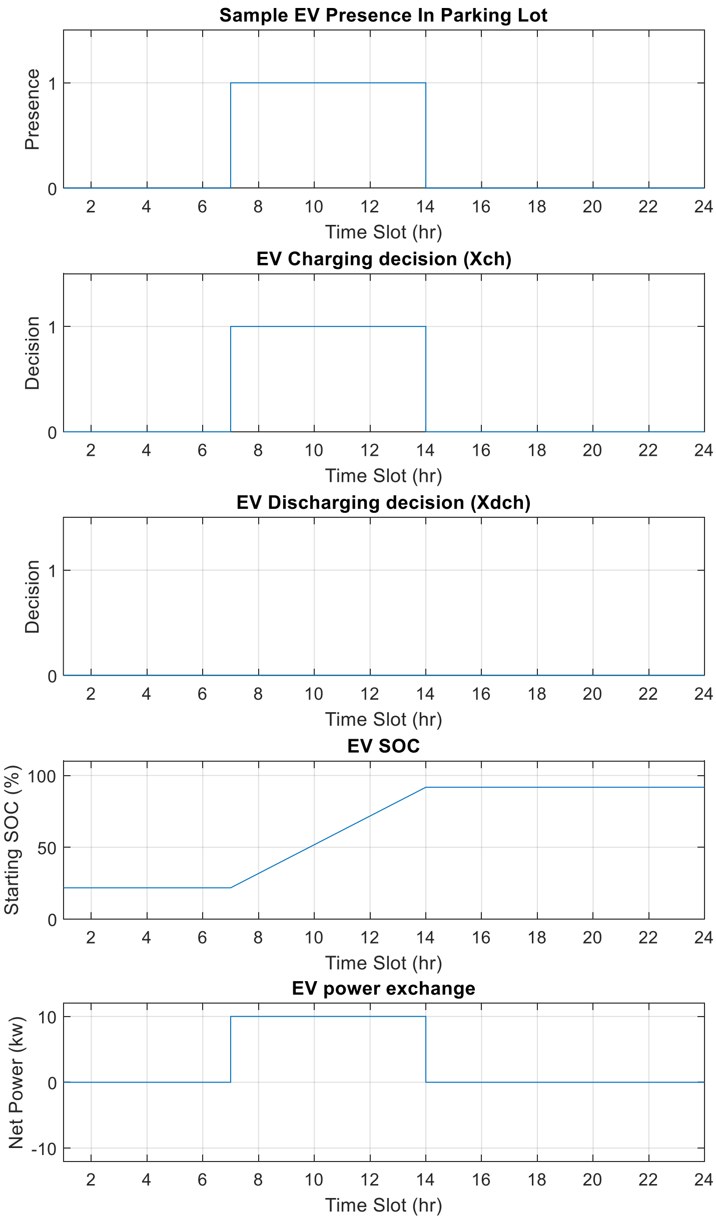

Figure 5.19: V0.3 case study sample 2 of the EV charging operation

5.2.5. Version 0.4: Allocation of two types of EV chargers with discharging and routing considering 50 different EVs. In addition to the capabilities of Version 0.3, routing option is introduced in this version as previously EVs were assumed to be assigned to the same slot every day which is considered as a weak point in planning approach. Routing is introduced for both types of chargers as $r_{h,d}^{L1}$ and $r_{h,d}^{L2}$ are the routing for type 1 and type 2 chargers respectivly. Consideing routing, new constraints are introduced as defined in (72-73) as the number of routed EVs shouldnot exceed the allocated number of EV chargers for each type of charger. In addition, a single channel cannot be routed for both channels as defined in (74).

$$\sum_h b_h^{L1} = \sum_h r_{h,d}^{L1} \tag{72}$$

$$\sum_h b_h^{L2} = \sum_h r_{h,d}^{L2} \tag{73}$$

$$r_{h,d}^{L1} + r_{h,d}^{L2} \leq 1 \tag{74}$$

After considering routing in the optimization, we can have a different EV for each day in the same slot. Table 5.7 presents the optimization outputs. It is noted that introducing EV routing have increased optimization output. Figures 5.20 and 5.21 present the overall power flow and net power flow for all allocated EV chargers respectively.

Table 5.7: Optimization output for V0.4 case study

Output	Value	Unit
Z: Net annual revenue	134,576	$ / year
$\mathrm{CC}^{\mathrm{PV}}$: PV annual capital cost	33,362	$ /year
$\mathrm{CC}^{\mathrm{EV}}$: EV annual capital cost	116,135	$ / year
$\mathrm{CE}^{\mathrm{EVCH}}$: EV charging cost	477,822	$ / year
$\mathrm{CE}^{\mathrm{EVDCH}}$: EV discharging cost	157,938	$ / year
$\mathrm{CE}^{\mathrm{Grid}}$: Grid supply energy cost	115,420	$ / year
$\mathrm{CE}^{\mathrm{PV}}$: PV energy cost	79,611	$ / year
Total number of allocated type 1 chargers	35	Unit
Total number of allocated type 2 chargers	9	Unit
N^{PV}: Total number of allocated PV units	130	Unit
The rated output power of allocated PV panels	130	kW

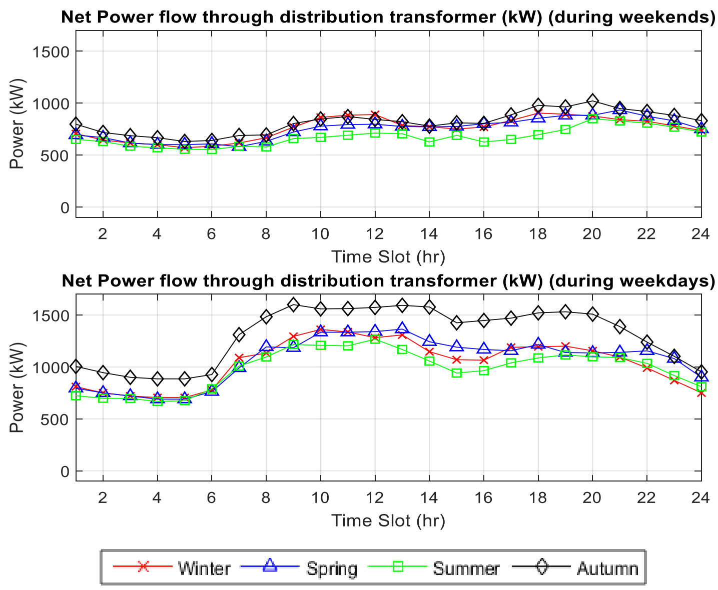

Figure 5.20: V0.4 case study overall power flow

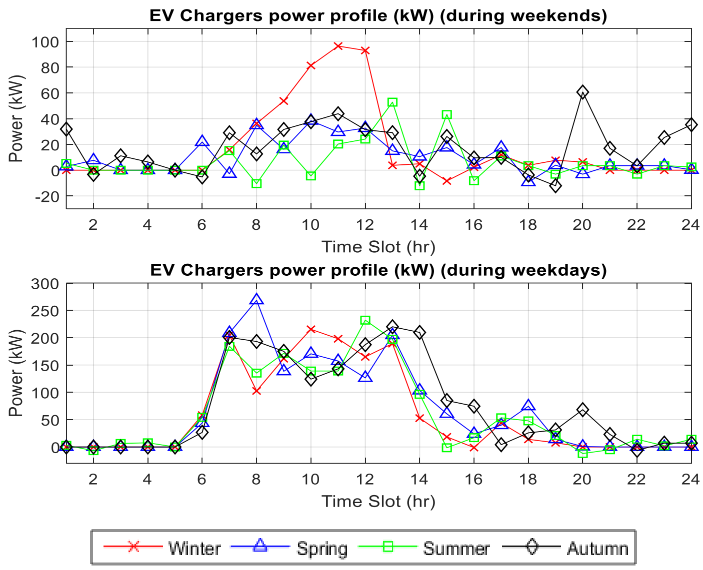

Figure 5.21: V0.4 case study net EV chargers power profile

5.2.6. Version 0.5: Allocation of two types of EV chargers with discharging and routing considering 100 different EVs. In this version of the case study, the routing concept is used with bigger EV population than the parking lot capacity. Inputs of 100 different EV are used for EV chargers allocation with a maximum of 50 EV chargers. Table 5.8 presents the optimization outputs. As shown in Table 5.8, introducing more EVs have impacted the optimization output compared to moderate EV population used in previous versions of the case study. Figures 5.22 and 5.23 present the overall power consumption and net power flow for all allocated EV chargers respectively.

Table 5.8: Optimization outputs for V0.5 case study

Output	Value	Unit
Z: Net annual revenue	141,821	\$ / year
CC^{PV}: PV annual capital cost	33,362	\$ /year
CC^{EV}: EV annual capital cost	145,784	\$ / year
CE^{EVCH}: EV charging cost	479,985	\$ / year
CE^{EVDCH}: EV discharging cost	100,514	\$ / year
CE^{Grid}: Grid supply energy cost	138,114	\$ / year
CE^{PV}: PV energy cost	79,611	\$ / year
Total number of allocated type 1 chargers	37	Unit
Total number of allocated type 2 chargers	13	Unit
N^{PV}: Total number of allocated PV units	130	Unit
The rated output power of allocated PV panels	130	kW

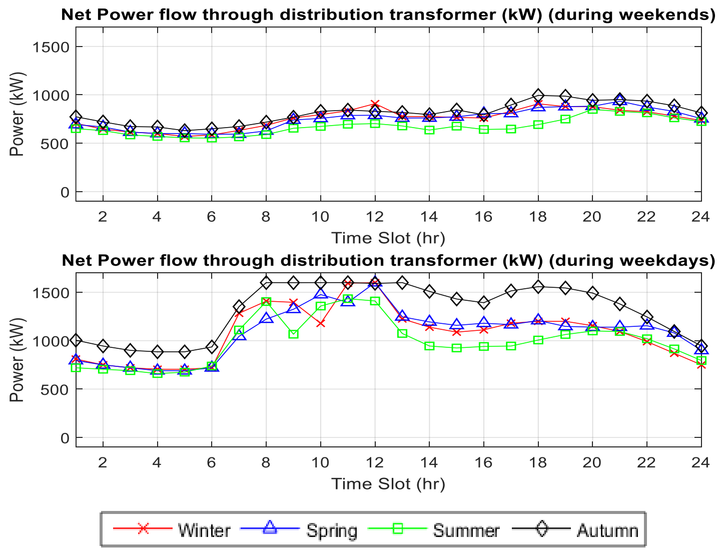

Figure 5.22: V0.5 case study overall power flow

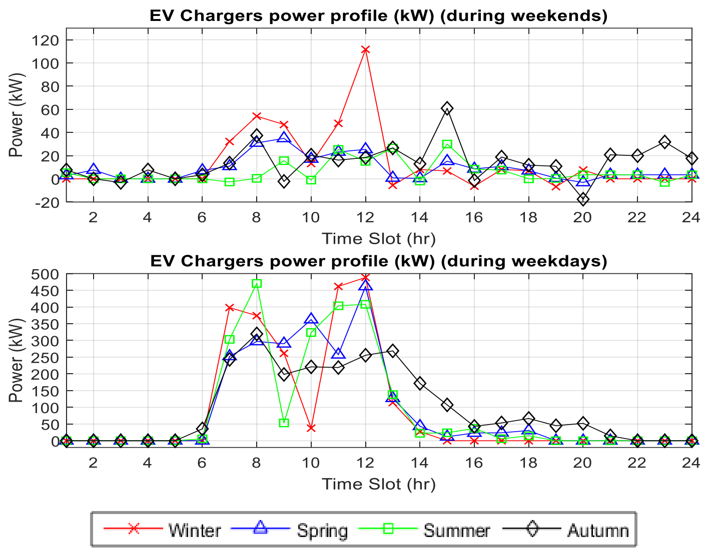

Figure 5.23: V0.5 case study net EV chargers power profile

5.3. Planning Case Study Versions Comparison

As explained before, 6 different versions of the planning case study have been tackled in this research. Table 5.9 presents outcomes for all the case study different versions. It is noted that all the versions have the same PV allocation decision which is the maximum allowed number of PV units limited by the parking lot roof available area. Overall, it is seen that V0.5 of the case study has the highest net annual revenue. In additions, V0.4 and V0.5 are most realistic in case of commercial EV charger as parking lot are not private for each candidate EV as one EV can be assigned to different parking slots in different days depending on the EV charging request, availability, and battery specifications.

Table 5.9: Optimization outputs comparison between different planning case study versions

Output	V0.0	V0.1	V0.2	V0.3	V0.4	V0.5	Unit
Z: Net annual revenue	122,425	125,260	133,420	95,031	134,576	141,821	$ / year
$\mathrm{CC}^{\mathrm{PV}}$: PV annual capital cost	33,362	33,362	33,362	33,362	33,362	33,362	$ /year
$\mathrm{CC}^{\mathrm{EV}}$: EV annual capital cost	45,374	45,374	117,995	136,421	116,135	145,784	$ / year
$\mathrm{CE}^{\mathrm{EVCH}}$: EV charging cost	192,656	228,038	549,899	414,350	477,822	479,985	$ / year
$\mathrm{CE}^{\mathrm{EVDCH}}$: EV discharging cost	0	32,026	232,671	125,773	157,938	100,514	$ / year
$\mathrm{CE}^{\mathrm{Grid}}$: Grid supply energy cost	71,105	71,627	112,061	103,373	115,420	138,114	$ / year
$\mathrm{CE}^{\mathrm{PV}}$: PV energy cost	79,611	79,611	79,611	79,611	79,611	79,611	$ / year
Total number of allocated type 1 chargers	28	28	28	19	35	37	Unit
Total number of allocated type 2 chargers	0	0	11	16	9	13	Unit
EV population	50	50	50	50	50	100	Unit

5.4. EV Discharging Price Margin Effect On EV Charger Allocation

In this version of the case study, the routing concept is used with different incentive prices for EV discharging. This version will examine the effect of EV discharging in allowing more EV chargers to be allocated. EV charger allocation is mainly connected to the availability of spare power to be utilized either from PV panels, grid supply or EV discharging. Different price margins were considered as the standard cost is considered to be 0.4 $/ kWh which is same as the maximum charging energy price margin. Table 5.10 presents the optimization outputs for different EV discharging price margins. As shown in Table 5.10, a higher discharging margin would decrease the amount of energy to be discharged from EVs reducing the overall number of allocated EV chargers. On the other hand, lower discharging energy price margin has increased the amount of discharged energy as CE^{EVDCH} has a lower value. this case the EV discharging cost is less is more competative compared to grid prices in some situations the optimization output compared.

Table 5.10: Optimization outputs planning case study with different EV discharging price margin considering variable EV batteries, discharging, and EV routing

Output	Value	Value	Value	Value	Unit
$\mathrm{extra}_{\mathrm{sell}}$: Discharging price margin	0.35	0.4	0.45	0.50	$/kWh
Total discharged energy	140,930	138,380	123,680	0	kWh
Z: Net annual revenue	148,602	134,576	124,540	118,038	$ / year
$\mathrm{CC}^{\mathrm{PV}}$: PV annual capital cost	33,362	33,362	33,362	33,362	$ /year
$\mathrm{CC}^{\mathrm{EV}}$: EV annual capital cost	121,116	116,135	102,931	89,727	$ / year
$\mathrm{CE}^{\mathrm{EVCH}}$: EV charging cost	492,613	477,822	435,248	253,695	$ / year
$\mathrm{CE}^{\mathrm{EVDCH}}$: EV discharging cost	150,483	157,938	145,819	0	$ / year
$\mathrm{CE}^{\mathrm{Grid}}$: Grid supply energy cost	118,660	115,420	108,206	92,178	$ / year
$\mathrm{CE}^{\mathrm{PV}}$: PV energy cost	79,611	79,611	79,611	79,611	$ / year
Total number of allocated type 1 chargers	34	35	35	35	Unit
Total number of allocated type 2 chargers	10	9	7	5	Unit

Chapter 6. Operation Approach Case Study

In this chapter, we present the simulation results for the proposed operation approach for different distributed parking lots. The outcomes will be demonstrated and discussed in the following sections.

6.1. Case Study Description

In the presented case study, all the simulations are based on the same parameters and constraints as the base case for the sake of comparison. The parking lot input data is presented in Table 6.1.

Table 6.1: The simulation parameters of the operation case study

Input	Value	Unit	Input	Value	Unit
$Prated^{TF}$	1600	kW	N^{PV}	130	Unit
$Pload^{MAX}$	1500	kW	FIT^{PV}	0.33	\$/kWh
$Prated^{L1}$	7.2	kW	$\text{extra}_{\text{sell}}$	0.4	\$/kWh
$Prated^{L2}$	24	kW	$Cheff$	96	%
$Prated^{PV}$	1	kW	$Dcheff$	96	%
N^{L1}	10	Unit	$MDOD$	80	%
N^{L2}	10	Unit	SOC^{PrMIN}	80	%

In addition, time based inputs are the same for all cases. Considering input power profiles, Figure 6.1 presents the profile of active connected loads in kW and Figure 6.2 presents the profile of PV output power in kW. Considering energy pricing profiles, Figure 6.3 presents the grid supply prices in \$/kWh and Figure 6.4 presents the EV charging cost margin in \$/kWh. A sample of EV availability status is shown duration in Figure 6.5.

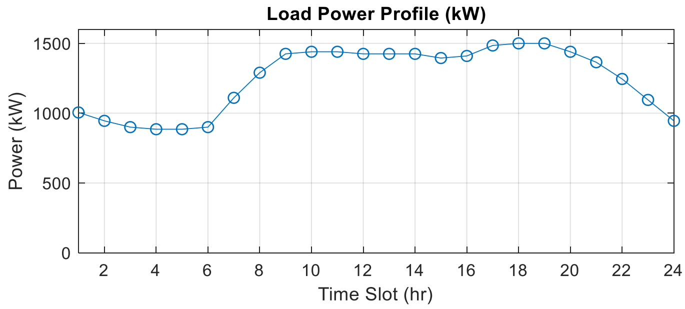

Figure 6.1: Original active load profile for one day

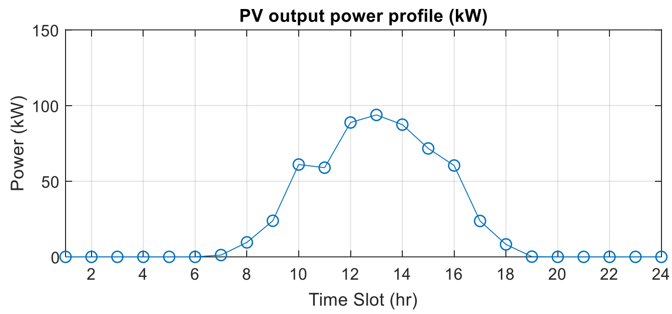

Figure 6.2: PV output power profile for one day

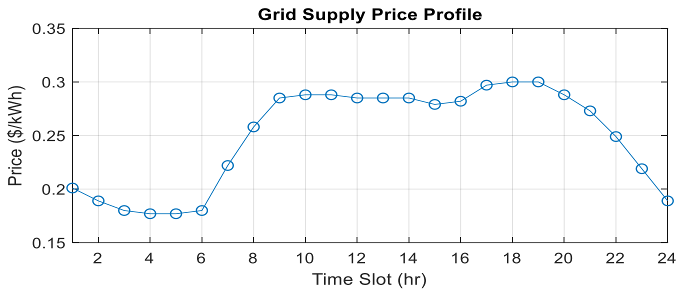

Figure 6.3: Grid supply price profile for one day

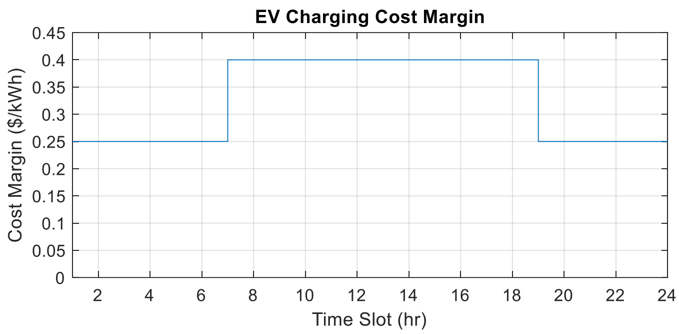

Figure 6.4: EV charging cost margin price profile for one day

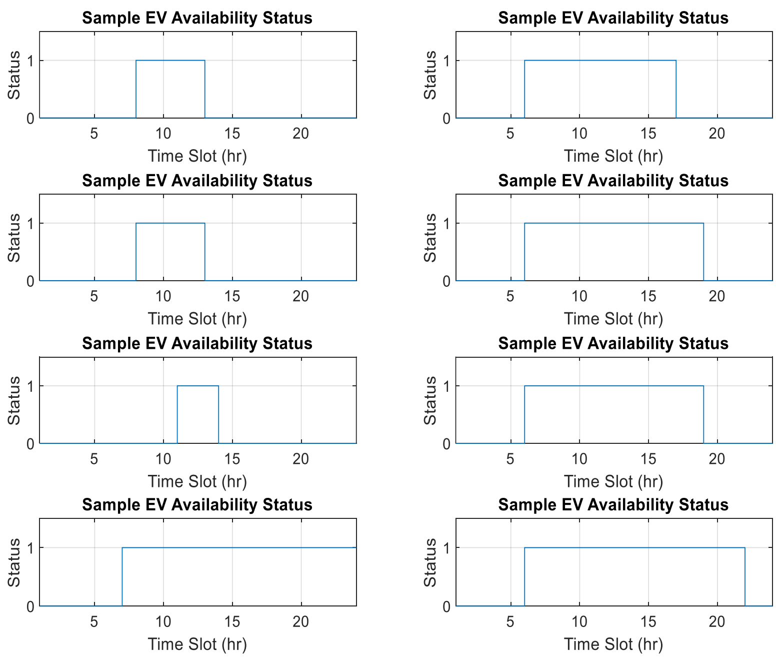

Figure 6.5: Sample of incoming EVs availability status for one day

6.2. Case Study Versions

In order to develop the EV operation approach, an initial version is used with the basic data (Version 0.0). Afterward, other versions are presented. Table 6.2 presents the different versions of the operation case study and their considerations. Moreover, all the versions of this case study will consider using two types of EV chargers as each type of charger is installed in 10 parking slots specified as shown in Table 6.3. It is noted that all used types of EV chargers have level 3 of communication and control with the ability to charge and discharge the connected EV with controlled power rate.

Table 6.2: Case study versions and their considerations

Case study version	V0.0	V0.1	V0.2
Number of parking lots	1	2	2
Consideration of EV travel time delay	No	No	Yes
EV population considered	100	100	100

Table 6.3: Charger types and their corresponding slots assignment

EV charger type	Maximum power transfer rate (kW)	Parking slots
Type 1	7.2	1,2,…10
Type 2	24	11,12,…20

6.2.1. Version 0.0: Operation of one parking lot considering 100 charging requests. In this version of the case study, operation of one parking lot is considered as the customers EV charging requests are given one day ahead then the optimization will decide which customer is eligible to use the parking lot for charging via assigning an available parking slot and providing the suitable charging and discharging decisions with their corresponding power rates to achieve customer charging request and abide the grid power limit. Table 6.4 provide the optimization results for version 0.0. It is seen that the one EV charger is able to serve more than one customer per day as 21 customers were served by 20 EV chargers with the main requirement of EV charger serving one customer at a time. The total customer satisfaction rate is seen as the ratio of the total requested energy for served customer versus the total supplied energy for served customers.

Table 6.4: Optimization output for V0.0 operation case study

Output	Value	Unit
Z^{day}: Net daily revenue	669	$
$\mathrm{CE}^{\mathrm{EVCH\_day}}$: EV charging cost	947	$
$\mathrm{CE}^{\mathrm{EVDCH\_day}}$: EV discharging cost	141	$
$\mathrm{CE}^{\mathrm{Grid\_day}}$: Grid supply energy cost	331	$
$\mathrm{CE}^{\mathrm{PV\_day}}$: PV energy cost	194	$
Number of served customers by parking lot 1	21	-
Number of served customers by parking lot 2	0	-
Total requested energy for served customers	1,127.8	kWh
Total supplied energy for served customers	1,094.4	kWh
Total customers satisfaction rate	97.04	%

6.2.2. Version 0.1: Operation of two parking lots considering 100 charging requests. In this version of case study, operation of two parking lots are considered as the customers EV charging requests are given a day ahead and the optimization will decide which customer is eligible to use each parking lot for charging via assigning an available EV charger and providing the suitable charging and discharging decisions with their corresponding power rates to achieve customer charging request and abide the grid power limit. Table 6.5 provide the optimization results for version 0.1. It is seen from the optimization output that an additional EV parking lot help ed to serve more customers gaining more net daily revenue via serving more customers.

Table 6.5: Optimization output for V0.1 operation case study

Output	Value	Unit
Z^{day}: Net daily revenue	1,227	$
$\mathrm{CE}^{\mathrm{EVCH\_day}}$: EV charging cost	1,836	$
$\mathrm{CE}^{\mathrm{EVDCH\_day}}$: EV discharging cost	398	$
$\mathrm{CE}^{\mathrm{Grid\_day}}$: Grid supply energy cost	600	$
$\mathrm{CE}^{\mathrm{PV\_day}}$: PV energy cost	389	$
Number of served customers by parking lot 1	21	-
Number of served customers by parking lot 2	20	-
Total requested energy for served customers	1,919.6	kWh
Total supplied energy for served customers	1,900.6	kWh
Total customers satisfaction rate	98.97	%

6.2.3. Version 0.2: Operation of two parking lots considering 100 charging requests and customers' EV travel delay. In this version of the case study, customer travel delay will be considered in operation optimization. In this case, the customer estimated time of arrival (ETA) will be considered for both parking lots as this will reduce the EV availability in the parking lot based on the distance and the traffic status between the EV location and the nearby parking lot. Figures 6.7 and 6.8 provide a sample of how the travel delay affects the availability of a sample EV in the corresponding parking lot. Considering EV travel delay, two constraints need to be redefined as shown in (75) and (76).

$$\sum_{c} \mathrm{r}^{\mathrm{L}}_{\mathrm{pi,h,c}} \times \left(EV_{c,t}^{Logic\_day} - delay_{pi,c,t}\right) \leq 1 \quad (75)$$

$$if\ (EV_{c,t}^{Logic\_day} - delay_{pi,c,t}) = 0 \ \rightarrow \ x_{\mathrm{c,t}}^{CH} = x_{\mathrm{c,t}}^{DCH} = 0 \quad (76)$$

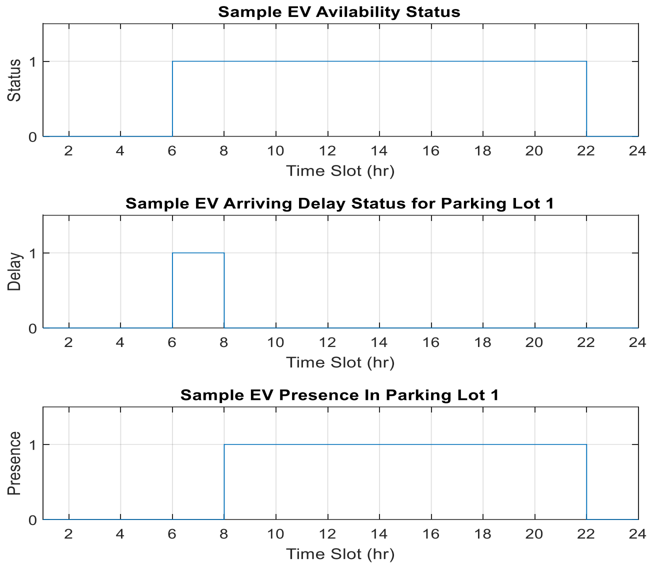

Figure 6.6: Sample of EV travel delay and its effect in EV presence parking lot number 1

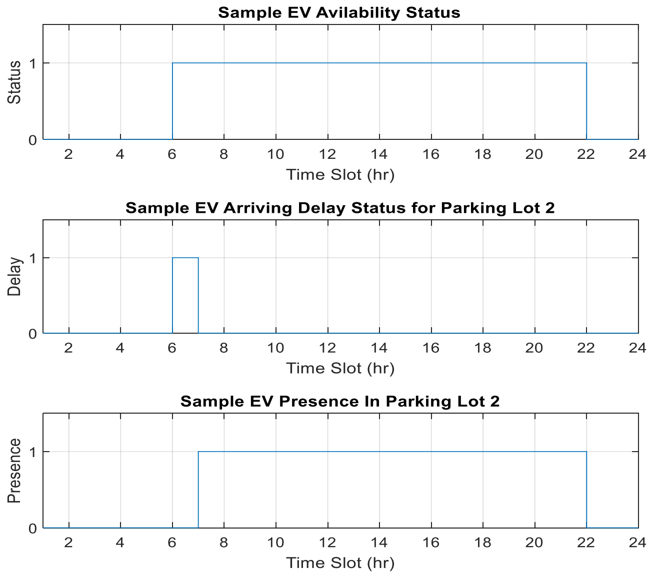

Figure 6.7: Sample of EV travel delay and its effect in EV presence parking lot number 2

Considering travel delay into operation optimization, Table 6.6 presents the optimization output of version 0.2 of operation optimization case study. It is seen that consideration of EV travel delay has impacted the EV chargers operation decisions as the number of served customers and the total requested energy for served customers have decreased slightly reducing the net daily revenue.

Table 6.6: Optimization output for V0.2 operation case study

Output	Value	Unit
Z^{day}: Net daily revenue	1,180	$
$\mathrm{CE}^{\mathrm{EVCH\_day}}$: EV charging cost	1,637	$
$\mathrm{CE}^{\mathrm{EVDCH\_day}}$: EV discharging cost	275	$
$\mathrm{CE}^{\mathrm{Grid\_day}}$: Grid supply energy cost	570	$
$\mathrm{CE}^{\mathrm{PV\_day}}$: PV energy cost	389	$
Number of served customers by parking lot 1	20	-
Number of served customers by parking lot 2	20	-
Total requested energy for served customers	1,818.3	kWh
Total supplied energy for served customers	1,808.8	kWh
Total customers satisfaction rate	99.48	%

6.3. Case Study Versions Summary

Table 6.7 presents the optimization outputs for all operation case study versions. It is noted that all the versions met the power constraint. Overall, it is seen that V0.1 of the case study has the highest net daily revenue. In additions, V0.2 is the most realistic as considering traffic and travel delays in EV chargers scheduling and operation will reduce errors and uncertainties.

Table 6.7: Optimization output comparison between different operation case study versions

Output	V0.0	V0.1	V0.2	Unit
Z^{day}: Net daily revenue	669	1,227	1,180	$
$\mathrm{CE}^{\mathrm{EVCH\_day}}$: EV charging cost	947	1,836	1,637	$
$\mathrm{CE}^{\mathrm{EVDCH\_day}}$: EV discharging cost	141	398	275	$
$\mathrm{CE}^{\mathrm{Grid\_day}}$: Grid supply energy cost	331	600	570	$
$\mathrm{CE}^{\mathrm{PV\_day}}$: PV energy cost	194	389	389	$
Number of served customers by parking lot 1	21	21	20	-
Number of served customers by parking lot 2	0	20	20	-
Total requested energy for served customers	1,127.8	1,919.6	1,818.3	kWh
Total supplied energy for served customers	1,094.4	1,900.6	1,808.8	kWh
Total customers satisfaction rate	97.04	98.97	99.48	%

Chapter 7. Conclusion and Future Work

In this Thesis, EV parking lot planning is approached using Matlab for data entry and representation and BARON solver from GAMS software to find the optimum solution for MINLP. In addition, different models were used to represent the different aspects of the system. The planning approach considered the allocation of two types of EV chargers with V2G capabilities supported by PV panels allocation. It is shown that in comparison with simpler EV charging planning approaches, the annual revenue is higher which prove the benefit of V2G and different types of EV chargers to fulfill the customers EV charging demand and to maintain higher revenue satisfying the variety of EVs in the market. In addition, planning of EV parking lot is considered with a bigger population than the parking lot capacity with EV routing option and showed to be beneficial to choose eligible EVs with highest operation income via routing procedure.

Moving toward EV parking lot operation, the operation of two parking lots is considered to optimizing the incoming EV charging requests per day. The optimization succeeded to create the most profitable charging scheduling for each available EV charger in two different located parking lots achieving highest net daily revenue and abiding Grid power constraint. Customer EV travel delay is considered to find the most optimum parking lot and EV charger suitable for each candidate EV as less availability customers are given higher priority to be assigned to higher power delivery EV charger.

Considering future work in EV chargers operation approach, the day ahead results will be tuned in real-time considering smaller time divisions and operation updates around hour time frame. Also, traffic model would be considered to have a better representation of EV travel delay for different times of the day. Moreover, the possibility of the customer not showing up to complete the charging request will be considered and a penalty would be charged in that case.

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