REPUBLIC OF TÜRKİYE
MUĞLA SITKI KOÇMAN UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

THE MOST ECONOMICAL USE OF VEHICLE-TO-GRID CHARGING TECHNOLOGY IN ELECTRICITY DISTRIBUTION NETWORKS

DOCTORAL THESIS

ABDULLAH KÜRŞAT AKTAR

JUNE 2023
MUĞLA

A. KÜRŞAT AKTAR DEPT. OF ELECTRICAL AND ELECTRONICS ENGINEERING PhD THESIS MUĞLA 2023

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THESIS ACCEPTANCE APPROVAL

The thesis, submitted by ABDULLAH KÜRŞAT AKTAR, entitled "THE MOST ECONOMICAL USE OF VEHICLE-TO-GRID CHARGING TECHNOLOGY IN ELECTRICITY DISTRIBUTION NETWORKS" has been accepted on 14/06/2023 in fulfilment of Doctor of Philosophy in the Department of ELECTRICAL AND ELECTRONICS ENGINEERING by the thesis committee listed below.

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I declare; all results, documents, information and files that I gained and presented as part of this thesis, were obtained by me within the study of this thesis and those are fines by scientific and academic ethic rules. Also, I declare; all original information and results belong to someone else that were not achieved within the study of this thesis were referenced by ethic rules of academy and science.

Abdullah Kürşat AKTAR
14/06/2023
(İmza)

ÖZET

ELEKTRİK DAĞITIM ŞEBEKELERİNDE ARAÇTAN ŞEBEKEYE ŞARJ TEKNOLOJİSİNİN EN EKONOMİK KULLANIMI

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Haziran 2023, 63 sayfa

Günümüz teknolojileri birçok farklı disiplini birleştirerek büyümeye devam etmektedir. Elektrikli araçların (EA) da dahil olduğu elektrik enerjisi sisteminin geliştirilmesi için elektrik, elektronik, mekanik ve bilgi teknolojileri arasındaki iş birliği bir gerekliliktir. Hem yük taleplerinin hem de yenilenebilir enerji üretiminin değişken olması nedeniyle elektrik güç sistemlerinde enerji arzı ve talebi arasındaki dengeyi korumak daha zor hale geldiğinden, EA bataryaları belirli bir süre için bu dengeyi desteklemede kritik bir rol oynayabilir. Bu fikirden yola çıkarak, bu tezde araçtan şebekeye şarj teknolojisi (V2G), EA filosu ve batarya donanımlı mobil şarj istasyonu kullanımı bağlamında değerlendirilmektedir. Tasarlanan iki farklı algoritma, dağıtım şebekesi operatörü ve EA kullanıcıları için hem operasyonel hem de ekonomik faydaları hedeflemektedir.

İlk yöntemde, "Şebeke için Araç" (VfG) kavramı olarak adlandırılan sistem operatörleri tarafından birden çok EA'nın mobil enerji depolama sistemleri olarak kullanıldığı teknolojinin sağlayacağı faydaları değerlendirmek için karışık tam sayılı doğrusal programlamaya dayalı bir optimizasyon algoritması kullanılmaktadır. Özellikle pik enerji dönemlerinde şebeke üzerindeki yük talebinin hafifletilmesi amaçlanmaktadır. Farklı özelliklere sahip iki tip EA'nın yer aldığı sisteme ait sonuçlar, sisteme entegre edilecek optimum EA sayısı ve özellikleri belirlendiğinde ekonomik ve operasyonel faydaların maksimize edilebileceğini göstermektedir. Her biri 200 kWh kapasiteli 15 EA'nın kullanıldığı en iyi senaryoda, yük eğrisinin pik/ortalama güç oranı %6.56 azalmaktadır.

İkinci yöntemde ise yakın gelecekte yardımcı hizmet olarak yaygın bir şekilde kullanılması beklenen mobil şarj istasyonlarının EA kullanıcılarının aldığı hizmet kalitesi üzerindeki etkisini incelemek için kısıtlı bir optimizasyon algoritması geliştirilmiştir. Sonuçlar, artan şarj taleplerini karşılamak için kalıcı şarj istasyonlarının genişletilmesine kıyasla mobil şarj istasyonu kullanımının hem operasyonel hem de ekonomik faydalar sağladığını göstermektedir.

Anahtar Kelimeler: Elektrikli Araç, Şebeke için Araç, Araçtan Şebekeye Şarj, Mobil Şarj İstasyonu, Enerji Depolama

ABSTRACT

THE MOST ECONOMICAL USE OF VEHICLE-TO-GRID CHARGING TECHNOLOGY IN ELECTRICITY DISTRIBUTION NETWORKS

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Doctoral Thesis (PhD)
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June 2023, 63 pages

Today's technologies continue to grow by merging many various fields. The collaboration between electrical, electronic, mechanical and information technology is a necessity to re-evaluate the electrical energy system for including electric vehicles (EVs). As it becomes more challenging to maintain the balance between energy supply and demand in electric power systems due to the stochasticity of both load demands and renewable power generation, EV batteries can play a critical role in supporting this balance for a given period. Based on this idea, in this thesis vehicle-to-grid (V2G) energy transfer technology is evaluated in the context of EV fleet and battery-equipped mobile charging station (MCS) utilization. The two different algorithms designed aim at both operational and economic benefits for the distribution network operator and EV users.

In the first method, an optimization algorithm based on mixed integer linear programming is used to evaluate the economic and technical benefits of EVs when they are used as mobile energy storage systems by system operators, which is called the concept of "Vehicle for Grid" (VfG). It is particularly aimed to alleviate the load demand on grid during the peak energy periods. The results obtained for two types of EVs with different characteristics show that the economic and operational benefits can be maximized when the optimum number and specification of EVs to be integrated into the system are determined. In the best-case scenario in which 15 EVs each with a capacity of 200 kWh are used, the peak-to-average power ratio of the load curve decreases by 6.56%.

In the second method, a constrained optimization algorithm is developed to examine the impact of mobile charging stations, which are expected to be widely used as an auxiliary service in the near future, on the service quality received by EV users. The results show that the use of MCS provides both operational and economic benefits compared to the expansion of permanent charging stations (PCSs) for increasing charging demands.

Keywords: Electric Vehicle, Vehicle for Grid, Vehicle-to-Grid Charging, Mobile Charging Station, Energy Storage

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my advisor, Assoc. Prof. Dr. Akın TAŞCIKARAOĞLU, for his unwavering support and guidance throughout my doctoral studies. His invaluable insights and expertise have been instrumental in shaping my research and helping me to develop as a scholar.

I am also indebted to my committee members, Prof. Dr. Sırrı Sunay GÜRLEYÜK, and Prof. Dr. Ozan ERDİNÇ, for their invaluable feedback and constructive criticism during my research. Their diverse perspectives and areas of expertise have greatly enriched my work and helped me to achieve a more comprehensive understanding of my field.

My sincere thanks also go to my family for their unwavering support, encouragement, and love.

Finally, I would not have been able to complete this journey without the patience, understanding and belief in me of my life partner and precious wife, Firdevs AKTAR, to whom I owe special thanks.

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A	Vehicle frontal area (m^2).
B_l	Susceptance of line l (pu).
C_d	Aerodynamic drag coefficient.
C_{rr}	Coefficient of rolling resistance.
CE^{ESS}	Charging efficiency of the ESS battery.
CE^{EV}	Charging efficiency of the EV battery.
CE^{MCS}	Charging efficiency of the MCS battery.
CS	Number of charging and discharging socket of buses.
CS^{MCS}	Number of charging and discharging socket of MCS.
CS^{PCS}	Number of charging and discharging socket of PCS.
DE^{ESS}	Discharging efficiency of the ESS.
DE^{EV}	Discharging efficiency of the EV battery.
DE^{MCS}	Discharging efficiency of the MCS battery.
EC^{EV}	Energy consumption of EV (kWh).
EC^{MCS}	Energy consumption of MCS (kWh).
$F_{v,tt}^{a}$	Aerodynamic drag force of EV in time interval tt ($kg.m/s^2$).
$F_{v,tt}^{ac}$	Acceleration force of EV in time interval tt ($kg.m/s^2$).
F_{tt}^{g}	Gravity force of EV in time interval tt ($kg.m/s^2$).
F_{tt}^{r}	Rolling friction force of EV in time interval tt ($kg.m/s^2$).

$F_{v,tt}^{t}$	Total traction force of EV in time interval tt (kg.m/s^2).
f_m	Mass factor.
g	Gravity of earth (m/s^2).
M^{EV}	Mass of EV (kg).
M^{MCS}	Mass of MCS (kg).
$m_{i,t}^{EV}$	Binary variable (1 if the EV is connected to bus i in time interval t; 0 otherwise).
$M_{i,l}^{F}$	Coefficient is 1 if line l of bus i is receiving end; 0 if line l of bus i is sending end; 0 if it is not both.
$M_{i,l}^{L}$	Coefficient is 1 if line l of bus i is sending end; 0 if it is not.
$M_{l,i}^{W}$	Coefficient that belongs to bus i and line l is obtained from transpose of $M_{i,l}^{F}$ matrix.
$m1_{i,t}$	Binary variable (1 if the MCS is connected bus i in time interval t; 0 otherwise).
$m2_{t}$	Binary variable (1 if the MCS is on travel in time interval t; 0 otherwise).
$m3_{i,t}$	Binary variable (1 if the MCS leaves the bus i during time interval t; 0 otherwise).
$m4_{i,t}$	Binary variable (1 if the MCS is connected to the bus i during time interval t; 0 otherwise).
N	Sufficiently large positive constant.
$P_{i,t}^{BM}$	Active power generation by biomass power plant at bus i in time interval t (kWh).

$P_{i,t}^{CPD}$	Charging power demand of bus i in time interval t (kWh).
$P_{i,t}^{ESS,ch}$	Charging power by ESS that is connected to bus i in time interval t (kWh).
$P_{i,t}^{ESS,dis}$	Discharging power by ESS that is connected to bus i in time interval t (kWh).
$P_{i,t}^{EV,ch}$	Charging power by EV that is connected to bus i in time interval t (kWh).
$P_{i,t}^{EV,dis}$	Charging power by EV that is connected to bus i in time interval t (kWh).
$P_{i,t}^{G}$	Total active power of bus i in time interval t (pu).
$P_{i,t}^{L}$	Total power demand of bus i in time interval t (pu).
$P_{i,t}^{L,total}$	Active power demand of bus i in time interval t (pu).
$P_{l,t}^{\mathrm{loss}}$	Total active power loss of line l in time interval t (pu).
$\hat{P}_{l,t}^{\mathrm{loss}}$	Model variable to represent total active power loss of line l in time interval t (pu).
$P_{i,t}^{MCS,ch}$	Charging power by MCS that is connected bus i in time interval t (pu).
$P_{i,t}^{MCS,dis}$	Discharging power by MCS that is connected bus i in time interval t (pu).
$P_{i,t}^{PCS,PD}$	Charging power by PCS to charge EVs in the queue at bus i in time interval t (pu).
$P_{i,t}^{S}$	Total power flowing from transformer to bus i in time interval t (pu).
$P_{l,t}^{r}$	Total active power of line l in time interval t (pu).

$P_{v,tt}^{ve}$	Electrical power demand of EV/MCS in time interval tt (W).
$P_{v,tt}^{vm}$	Mechanical power demand of EV/MCS in time interval tt (W).
$P_{i,t}^{W}$	Active power generation by wind farm at bus i in time interval t (kWh).
$Price_{t}$	Electricity price in time interval t (€/kWh).
$Q_{i,t}^{G}$	Total reactive power of bus i in time interval t (pu).
$Q_{i,t}^{L}$	Reactive power demand of bus i in time interval t (pu).
$Q_{l,t}^{\text{loss}}$	Total reactive power loss of line l in time interval t (pu).
$Q_{l,t}^{r}$	Total reactive power of line l in time interval t (pu).
$R_{i}^{ESS,\text{ch}}$	Charging rate limit of ESS that is connected to bus i (kW).
$R_{i}^{ESS,dis}$	Discharging rate limit of ESS that is connected to bus i (kW).
$R_{i}^{EV,\text{ch}}$	Charging rate limit of EV that is connected to bus i (kW).
$R_{i}^{EV,dis}$	Discharging rate limit of EV that is connected to bus i (kW).
$R_{i}^{MCS,\text{ch}}$	Charging rate limit of MCS that is connected bus i (kW).
$R_{i}^{MCS,dis}$	Discharging rate limit of MCS that is connected bus i (kW).
$R_{i}^{PCS,PD}$	Discharging rate limit of PCS that is connected bus i (kW).
R_{l}	Resistance of line l (pu).
$SOE_{i,t}^{ESS}$	SOE of the ESS is connected to bus i in time interval t (kWh).
$SOE_{i}^{ESS,ini}$	Initial SOE of the ESS that is connected to bus i (kWh).
$SOE_{i}^{ESS,max}$	Maximum SOE of the ESS that is connected to bus i (kWh).

$SOE_i^{ESS,min}$	Minimum SOE of the ESS that is connected to bus i (kWh).
$SOE_{i,t}^{EV}$	SOE of the EV battery is connected to bus i in time interval t (kWh).
$SOE_{i,j,m}^{EV,ini}$	Initial SOE of the EV (kWh).
$SOE_{i,j,m}^{EV,max}$	Maximum SOE of the EV (kWh).
$SOE_{i,j,m}^{EV,min}$	Minimum SOE of the EV (kWh).
SOE_t^{MCS}	SOE of the MCS battery in time interval t (kWh).
$SOE^{MCS,ini}$	Initial SOE of the MCS (kWh).
$SOE^{MCS,max}$	Maximum SOE of the MCS (kWh).
$SOE^{MCS,min}$	Minimum SOE of the MCS (kWh).
$T_{i,j}$	MCS travel time interval t from bus i to bus j.
$u_{i,t}^{ch}$	Binary variable (-1 if the EV/MCS is charging in time interval t; 0 otherwise).
$u_{i,t}^{dch}$	Binary variable (1 if the MCS is discharging in time interval t; 0 otherwise).
$V_{i,t}$	Voltage magnitude of bus i in time interval t (pu).
V_{max}	Permitted maximum voltage level of buses (pu).
V_{min}	Permitted minimum voltage level of buses (pu).
$V_{v,tt}^{EV}$	EV speed (m/s).
$V_{v,tt}^{MCS}$	MCS vehicle speed (m/s).
$V_{v,tt}^{W}$	Wind speed (m/s).

$W_{i,t}$	Equivalent of cosine term of power flow equation on line (i,j) in time interval t (pu).
$W_{r,t}$	Square of voltage magnitude at receiving end bus r $(r \in i)$ in time interval t (pu).
X_l	Reactance of line l (pu).
α	Acceleration (m^2/s).
η_d	Driving efficiency.
ρ	Air density (kg/m^3).
θ	Road slope angle (°).
$\Delta L_{j,m}$	Distance to point j through route m (km).
ΔT	Time period (min).
ED	Energy Drawn.
ESS	Energy Storage System.
EV	Electric Vehicle.
MCS	Mobile Charging Station.
RES	Renewable Energy Source.
SOE	State-of-Energy.
VfG	Vehicle for Grid.
$V2G$	Vehicle to Grid.

1. INTRODUCTION

1.1. Electric Vehicle Types

The imminent depletion of fossil fuels, global warming, the climate crisis, and political developments in different regions of the world are forcing the related fields to change. The story of the internal combustion engine (ICE), which has been in widespread use for nearly two centuries and has been presented as the machine that changed the world, is coming to an end. While the transformation has started with the integration of a small-scale electric motors into vehicles in addition to ICE, various studies are being carried out on different options (Singh, Singh, and Vaibhav 2020).

Electric vehicles (EVs) with different operating principles are divided into two categories: hybrid electric vehicles (HEVs) and all electric vehicles (AEVs) (H. S. Das et al. 2020). The concept of HEV is often used only as the first step in the evolution from ICE to EV. The structure is very similar to conventional vehicles, but with the addition of an electric motor as an auxiliary power unit. While the vehicle's main power source comes from fossil fuels, an electric motor powered by the vehicle's internal system is used to make fuel consumption more efficient.

As a next level, plug-in hybrid electric vehicles (PHEVs) have a grid-chargeable battery in complement to the ICE and a larger electric motor than a PEV. Longer range is provided in the PHEV version by a bigger battery capacity and a stronger electric motor (Wu et al. 2007). PHEVs are classified into series, parallel and power-split versions, depending on the connection way of powertrain to the ICE and electric motor (Tarlak and İşen 2018). In a series PHEV, as shown in Figure 1.1, the propulsion power is provided by the conversion of energy from the battery into mechanical energy by the electric motor. The series PHEV configuration is very similar to the AEV structure, with the difference that the energy needed to charge the battery is generated from fossil fuels.

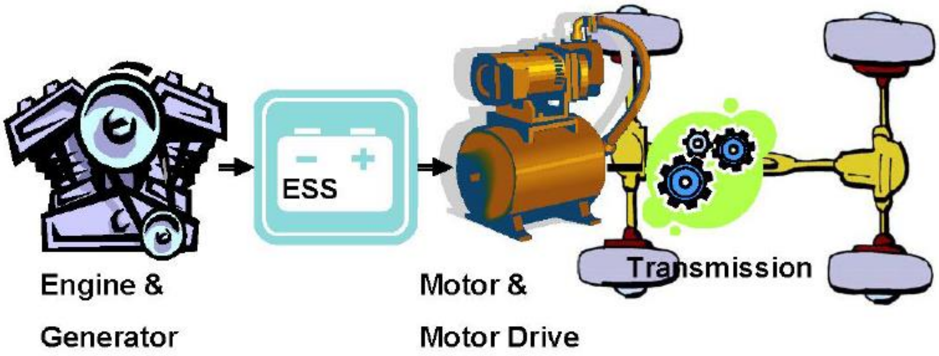


Figure 1.1. Structure of series PHEV (Tarlak and İşen 2018)

The PHEV in parallel configuration is propelled by the sum of the power provided by ICE and electric motor. Moreover, in the power-split type of PHEV, series and parallel configurations can be preferred thanks to the planetary gearing, aiming to combine the advantages of the two configurations (Tarlak and İşen 2018). Thus, the power required for the vehicle can be supplied only with ICE or with electric motor or both. The parallel and power-split PHEV structures are shown in Figure 1.2 and Figure 1.3 respectively.

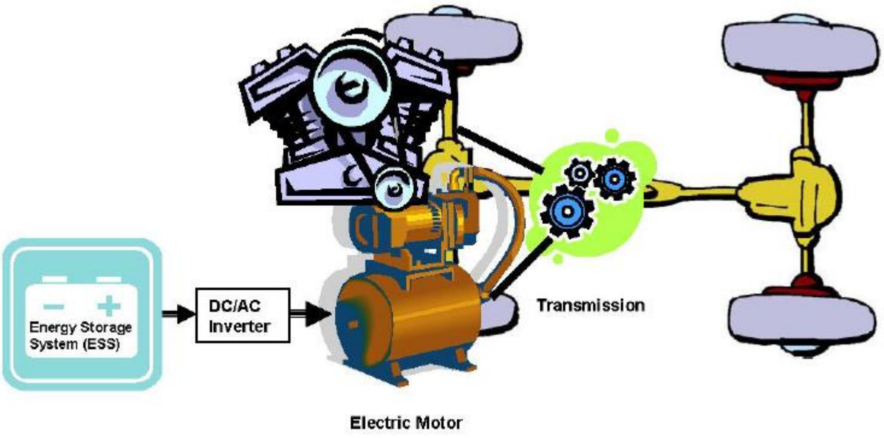


Figure 1.2. Structure of parallel PHEV (Tarlak and İşen 2018)

AEVs, whose widespread use is increasing day by day, are of two types: battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) (H. S. Das et al. 2020). BEVs, which can be shown as the future of the vehicle industry, run entirely by electric motors, and can be charged from the grid in different ways depending on the model.

The driving distance of BEVs varies according to the energy storage capacity of the battery. With the developing technology, prices are decreasing to affordable levels. Besides, FCEVs presents a different structure with both electric power usage and the fuel cell as an alternative of the ICE. Difficulties in the production and storage of hydrogen gas can be highlighted as obstacles to the development of this technology.

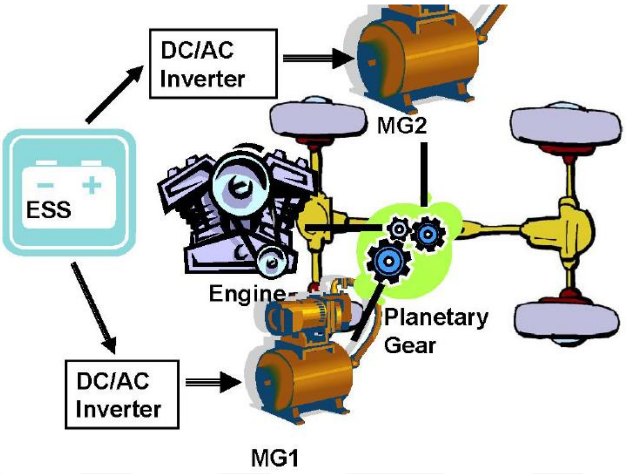


Figure 1.3. Structure of power-split PHEV (Tarlak and İşen 2018)

As a conclusion, studies on electric vehicle components and operations, such as the battery, the main energy source and the powertrain, may enable different options to develop.

1.2. Electric Vehicle Battery Charging Technologies

The necessity for charging stations (CSs) is increasing in parallel with the increase in the use of EVs. CSs are available in a variety of forms such as home chargers to public charging infrastructure placed in parking lots, streets, and commercial areas. Besides, CSs are equipped with different charging levels, including Level 1 (standard household outlets), Level 2 (AC charging stations), and Level 3 (DC fast chargers) (Boulanger et al. 2011);(Mohammed et al. 2022).

CSs are frequently defined in the literature as a device that can charge 2 EVs at the same time, while areas where multiple CSs are located together are called EV parking lot. In addition, the concept of permanent charging station (PCS) in this thesis refers to a charging zone formed by the cluster of 5 CSs. As a further option, mobile charging stations (MCSs) for EVs are portable units that provide on-the-go charging capabilities for EVs (Abdullah Kursat Aktar, Tascikaraoglu, and Catalao 2022). Unlike conventional stationary CSs, MCSs are designed to be flexible and can be easily moved to different locations as needed. Besides, MCSs are equipped with a high-capacity battery, charging cables and sockets that can deliver power output to meet the needs of many EV models (Beyazıt and Taşcıkaraoğlu 2023). They can be installed temporarily during periods of high demand in areas where permanent charging infrastructure is inadequate, or in other locations where EV charging is needed such as at events, in parking lots, etc.

Battery swapping stations (BSSs) can be an ideal option if the EV users do not have the time to wait for the required time for charging. At a BSS, the depleted battery of EVs is removed by automated machines or personnel and replaced with a fully charged battery (Revankar and Kalkhambkar 2021). This kind of stations can be placed at strategic points along main transportation routes to offer EV users an additional option and reduce concerns about driving ranges. However, the main drawback of this operation can be shown as the EV manufacturers use various types of batteries in different models, which limits the service scope of the BSS.

The main idea in all the mentioned charging methods is to charge the battery in a way that meets the user's demands. The increasing number of batteries that need to be charged makes the management of grid-to-vehicle energy (G2V) transfer operations a necessity. In the most general terms, the energy transfer from the EV to external systems and devices is expressed as vehicle-to-X (V2X) (H. S. Das et al. 2020). The operation is named depending on where the energy is transferred, such as Vehicle-to-Grid (V2G), to buildings (V2B), to other vehicles (V2V), and to the load (V2L). Within the scope of this thesis, especially the effectiveness of V2G technology on the EV fleet, MCS, PCS systems is examined. In a V2G operation, EVs can discharge electricity from their batteries back to the grid during peak demand periods or when there is an additional energy need for extraordinary circumstances. This enables EVs to serve as mobile energy storage units, providing valuable grid services such as load balancing, load shifting, effective usage of renewable energy sources and frequency regulation (Beyazıt, Taşcıkaraoğlu, and Catalão 2022). Moreover, EVs that belong to the distribution system operator (DSO) can be used to provide technical and economic benefits in the concept of vehicles for the grid (VfG).

1.3. Objective of the Thesis

While animal power was widely used in transportation before the industrial revolution, the invention of engines powered by fossil fuels revolutionized transportation and shaped the development of humanity. Recent technological developments in the field of electricity and electronics are forcing the transportation sector to change its shell again. The use of electric motors for the main power supply in vehicles is a new milestone. EVs offer a wide range of opportunities for all stakeholders, as they are environment friendly, more energy efficient, provide more comfortable driving experience and require less maintenance costs (Singh, Singh, and Vaibhav 2020). However, the need for electric energy of the EV poses challenges that must be overcome as the number of EVs in use increases. These situations encourage electricity system operators and scientists to conduct research and development on new grid dynamics (Alsharif et al. 2021).

For the grid operators, the problem of meeting the energy demand of the EVs in a way that does not harm the grid and controlled charging has emerged (Sourav Das, Acharjee, and Bhattacharya 2021). The institutions and organizations involved in solving this problem state that it is possible in the near future to discharge EVs to meet the needs of the grid, taking into account the speed of technological developments (Naik and Vyjayanthi 2021). Thanks to the grants and incentive provided/to be provided by the relevant institutions, the companies are working on the development of the technology called V2G which enables the transfer of the desired amount of energy from battery to the grid via bidirectional charging stations (Hannan et al. 2022);(Alalwan et al. 2021). Thus, through agreements between grid operators and EV users, users can gain various advantages while having a better electricity grid in terms of reliability, power quality, etc. (Alghsoon, Harb, and Hamdan 2017). Moreover, while V2G technology can be realized by each individual EV user connecting the EV to the grid under the conditions they decide, it can also be realized through companies that create some power reserves in agreement with many EV users called aggregator (ur Rehman, Riaz, and Wani 2021).

The majority of studies on V2G technology in the literature have focused on EVs owned by individual users. Within the scope of the agreements made with each user, it is aimed to meet the peak load demand of the grid by taking into account constraints such as battery State-of-Charge level and the hours allowed for V2G, as well as to increase power quality and to maximize the operating profit (Qi, Li, and Lei 2021; Xu et al. 2021). The fact that the users can include EVs in the system at their own convenience or allow the aggregator to do so at specific periods through agreements limits the desired benefits for the grid. For this reason, the idea that the distribution system operator should own the EVs (called Vehicle-for-Grid) to be used for the grid, has emerged. Studies that focus on the VfG concept, which has been mentioned in many studies to increase the benefits that EVs can provide, are very limited in the literature (Rahmani-Andebili 2019; Zhong et al. 2015).

Besides, from a different perspective, mobile charging stations (MCSs) owned by the distribution system operator can be used to provide energy support to the grid independently of EV users (Beyazit and Tascikaraoglu 2022). The station, which can also provide off-grid charging services at many locations with its mobile energy storage system, can ensure significant benefits in V2G and V2V energy transfer operations (Afshar et al. 2021). Therefore, the results of the studies involving the VfG concept and MCSs are of great importance in order to determine the most precise improvements to be made in the grid.

For the aforementioned reasons, this thesis addresses the issue of the distribution system operator's contribution to maximize the charging service quality for EV user and to maintain the balance between energy supply and demand in the system by using the EVs and MCS, especially when the demand power is high. By utilizing charging-discharging stations and parking lots, the most economical operation is determined by considering the required time and amount of energy to travel the connection bus node at the peak energy demand of the grid.

In two different energy management systems designed in this thesis, algorithms are developed to provide a flexible operation on the electrical grid and reduce energy costs. The components within the system such as the EV, MCS, permanent charging station and the electricity grid are modeled in accordance with the determined objectives. In order for the algorithms to perform the optimal system management, the parking areas and charging/discharging station points where the EVs and MCS should be located are determined. The findings of the study highlight the benefits of VfG and MCS technology and the issues that need to be considered in the implementation process and provide insights for future works.

2. LITERATURE REVIEW

2.1. A Framework for Dispatching of an Electric Vehicle Fleet using Vehicle-to-Grid Technology

Under the conditions of the Covid-19 pandemic, similar to the other sectors, the electricity sector has deviated from its growth path. With the increase in the normalization rate, it is expected to reach the estimated growth rates rapidly. In meeting the global energy needs, electrical energy is anticipated to continue to rise to the top in the long run. Also, with the increase in the world population, there will be a rise in the necessities, thus it will be necessary to use more electrical energy, especially from the Renewable Energy Sources (RESs). While renewable energy plays an important role in reducing CO2 emissions, which is one of the most important environmental concerns, it is expected to meet 21% of the world energy consumption in 2030 according to International Energy Agency (Cozzi et al. 2020). Currently, the transportation in the world is provided in two ways: electrical energy and fossil fuel. While the energy demand continues to increase in both cases, the transportation energy demand of non-OECD countries is expected to increase by 77% until 2050 (EIA. 2019). Besides, the International Energy Outlook shows that global transport sector energy use will increase around 50% between 2012 and 2040 (EIA 2016).

The electrification of transportation, which has been first started with the hybrid vehicles and continued with the plug-in hybrid electric vehicles, is a new situation for the world that has to overcome. The growth in the number of EVs has considerably increased the demanded power in distribution grids at the last decade. Managing the charging operations of EVs has become therefore crucial to avoid grid failures and distribute resources efficiently (Bayram et al. 2015).

When the controlled and uncontrolled charging situations of EVs are compared, it has been clearly revealed that the controlled charging state is much better in terms of losses and overloading (Verzijlbergh et al. 2012). It is, however, obvious that smart charging systems might only provide a temporary solution to the rapidly increasing capacity of EVs. To this end, the Vehicle-to-Grid (V2G) operation, which implies the energy flow from EV battery to grid for a more economic and flexible operation, has come into prominence recently. This technology shows that the need for energy storage and power regulation brought about by the increase in RES can be eliminated by using EV batteries to meet the frequency balancing, power quality and system reliability conditions (Lehtola and Zahedi 2016; Naik and Vyjayanthi 2021). In (Alghsoon, Harb, and Hamdan 2017), it is mentioned that V2G operations at high charging rates do not cause any negative effects in terms of system reliability and power quality. Moreover, with the simplest use of V2G technology, the difference between the minimum and maximum values in the consumption curve could be easily reduced (Xu et al. 2021).

The V2G and G2V technologies have the potential to support the sustainability of the distribution systems provided that the necessary improvements in the system infrastructures are implemented. However, the increasing number of EVs with different usage patterns makes the management of the system more challenging (Soumyabrata Das et al. 2022). The value and necessity of V2G operations is better understood when it is considered that 30% of the distribution transformers will face overload situation with the increase of 5 kW in the energy consumption of the houses in Norway (Hannan et al. 2022). The first work on the V2G concept was done in Japan for the peak shaving and load shifting (Ravi and Aziz 2022). A large-scale study was also conducted in (Ravi and Aziz 2022) for the arbitrage transaction in the UK between 2018 and 2021 with 320 sockets.

It has been stated that 600 GW of capacity can be used flexibly thanks to the V2G operations in various studies conducted in China, India, EU and USA (Hannan et al. 2022). Being able to use this amount of energy at peak hours may bring many operational advantages. According to the 2030 projection, the total capacity of energy in the EVs batteries will be about 20 TWh, which is equivalent to 27% of the daily global electricity production (Qin et al. 2022). The mentioned capacity could be obtained through contracts that can be made in many ways, such as using EVs in V2G operations in exchange for free charging (Qi, Li, and Lei 2021).

Energy transfer from an EV to grid does not only provide benefits to network, but also offers opportunities to users who include their EV in the system for this purpose. It can be expressed as an incentive situation to share the EV during the parking time to support the network and gain financial advantages in return (Karfopoulos, Panourgias, and Hatziargyriou 2016). From a different point of view, it has also been put forward that the benefits obtained will increase with the use of EVs not individually but collectively (such as a fleet) in the system, which provides more predictable power management and advanced smart charging systems (D. Guo and Zhou 2018). The study in (ur Rehman, Riaz, and Wani 2021) showed that profit maximization could be achieved while prioritizing grid stability by performing V2G operations in markets that have different characteristics. In another study, it was aimed to maximize income for both the aggregator and EV owners by creating pools of private and commercial EVs.

In addition, it has been revealed that the differences in the working styles of commercial enterprises with more than one EV such as cargo companies and the usage habits of private EV owners bring opportunity to create mixed pools and have a positive effect on income up to seven times (Tepe et al. 2022). In another study that supports the same idea, in order to reduce the fluctuations caused by the EVs with high demand and to minimize the operating costs, it was aimed to control the charge-discharge periods of EVs by using the TOU pricing mode. However, the optional participation of EVs in the V2G operation and not being in the system as a fleet limited the exploitation of the EVs in the cost minimization (S. Guo et al. 2021). Besides, in a study that examines seasonal changes, it was stated that the operational benefits might be higher in the winter period with the increase in incentives (Sourav Das, Acharjee, and Bhattacharya 2021). In the study aiming to increase the benefits with the coordinated charging operations, the potential impacts of ESS and RES on the benefits have not been considered.

As mentioned above, while the number of EV users involved in the system increases, the system management becomes more challenging. Also, the constraints such as the personal driving preferences of the EV users, the arrival and departure times of the EVs to/from the parking area, and the State-of-Energy (SOE) limitations of the EV battery have an impact on the efficiency of the system management (Wei, Liu, and Mei 2016). Nonetheless, the support of an EV fleet on the crucial power system operations such as valley filling and peak shaving was not discussed in (Wei, Liu, and Mei 2016). In order to have a more efficient system, the idea of the VfG, which is a new perspective that takes into account the EVs to be used only in line with the needs of the grid, has been put forward recently in the literature. In a study conducted with the EVs moving between different regions as a fleet owned only by the grid operator, it is stated that an economic management can be achieved by taking the electricity unit price, demand level and SOE of the battery into account (Zhong et al. 2015). In another study, it was stated that working together to reduce the system losses and operating costs of companies with EVs belonging to generation and distribution companies provides remarkable benefits for both parties (Rahmani-Andebili 2019). At the same time, it might be possible to reduce the new investment costs with the increase in the system efficiency by the control of peak-energy time. However, the energy consumption of the EVs was not taken into account in (Zhong et al. 2015) and (Rahmani-Andebili 2019), and only the mass movement of the EV fleet was considered in these studies, which might decrease the benefits compared to the case where the fleet can be distributed if necessary.

2.2. Optimal Charging and Discharging Operation of Mobile Charging Stations

The increase in the world population, technological developments and environmental concerns force the energy sector to change at a macro level. One of the major changes is the electrification of vehicles in the transport sector. By 2030, it is estimated that there will be more than 110 million EVs worldwide and these EVs will demand a total energy of 500 TWh (Cozzi et al. 2020). Moreover, the energy demand of the transportation sector will reach 11% of the global demand by 2040 (Cozzi et al. 2020).

The proliferation of decentralized energy systems and increase in the number of prosumers necessitate advanced management systems in electrical power systems.

Considering the diversity of instruments in the system, it is obvious that it would not be sufficient to meet the demand simply by establishing more centralized power plants. There is a need to optimally manage such a large system by using different technologies such as bidirectional EV energy flows, demand side management strategies and EV charging stations, and by making use of information technologies (Alsharif et al. 2021).

Today's power systems include EVs, renewable energy sources, energy storage systems, energy markets with various price mechanisms and smart homes. It is possible to operate this system more efficiently if the data collected from all instruments of the system are processed effectively (Ouramdane et al. 2021). By doing so, all the system stakeholders can gain significant economic advantages. While the distribution system operator controls the peak energy period, the energy demand becomes more flexible with the incentives given to the consumers. Additionally, in terms of the commitments made by the countries in the climate agreement, it will create an opportunity for political executives (Panda and Paterakis 2021).

In a decentralized system, many consumers can have their own power production units and EV charging facilities and equip them with smart home devices to gain economic benefits if it is allowed by system operators. Besides, storing the energy produced by different energy sources and shifting some flexible loads from the peak energy period to a different time might provide significant economic benefits to consumers (Taik et al. 2021). Also, private companies and electrical system operators develop their own solutions in order to provide a more reliable service.

Mobile charging stations (MCSs), which can be easily dispatched according to the energy demand for charging, stand out in terms of providing fast solutions and preventing very high investments (Afshar et al. 2021). It is possible to serve alongside the fixed charging stations during peak energy periods, and it is also possible to provide energy in suitable areas in off-grid mode (Saboori, Jadid, and Savaghebi 2021). Moreover, instead of deciding the location of mobile charging operations according to the regional charge service demand, it could be possible to provide safe charging services to EV users anywhere with IoT-based applications (Chen et al. 2021). Among the studies for mobile charging, in (Raboaca et al. 2020) it was aimed to place the minimum number of MCS for both safe and economical management of the system operator, while in (Chauhan and Gupta 2018) and (El-fedany, Kiouach, and Alaoui 2021) additional MCS capacity was defined to reduce the waiting times of EV users. From a different perspective, the effect of MCS on reactive power capability and voltage quality was investigated in (Jeon and Choi 2021). Also, the challenges in various areas, such as financial, battery life, energy transfer efficiency, socket types and wireless energy transfer were reviewed in detail in (Afshar et al. 2021).

2.3. The Contributions of the Thesis

In this thesis, two different constrained optimization algorithms are developed to investigate the evolving technologies and operations of different types associated with the increasing number of EVs in use. In the first method (A Framework for Dispatching of an Electric Vehicle Fleet using Vehicle-to-Grid Technology), an EV fleet, which is free from time and location constraints for the VfG operation, is considered to be deployable to the appropriate bus nodes. In the second method (Optimal Charging and Discharging Operation of Mobile Charging Stations), the use of mobile charging stations (MCSs), which is expected to be one of the important components of the future energy systems, is considered to improve the satisfaction of EV users and an optimization algorithm is proposed to use MCS to minimize the quantity of the EVs that were not served.

Besides, in both methods, a more effective and economical operation of the electricity grid is aimed with V2G and/or B2G applications while improving the service quality for EV users. The effectiveness of the developed algorithms is tested by using the MOSEK solver in the General Algebraic Modeling System (GAMS) software.

2.3.1. The contributions of the first method

In the first method, an EV fleet including a number of EVs that have the possibility to connect to different buses of the electrical grid is considered. The mobility of EVs provides a more flexible grid management and enables different sizes of capacities to be provided at the bus node according to the demand.

The main aim of the study is to maximize the economic benefits of using an EV fleet while providing the necessary support to the grid. To this end, a strategy based on demand response implementation is proposed where the optimal usage of the energy stored in the EV battery is investigated in order to shave the peak load in the system. At the same time, a loss reduction is accomplished by supplying energy to the closest branch to the consumer.

The contribution of this study is multifaceted:

- The use of the EVs as energy storage units within the scope of VfG is evaluated.
- In order to determine the places and times where and when the EVs will be used, an energy management algorithm is proposed to make the most appropriate decisions as a result of certain comparisons, and it is aimed to make the charging and discharging operations of the EVs in a way that provides the highest economic benefit.
- Considering the fact that the real data are used in the designed system, the benefits of EV technology for the network and the problems to be encountered during real applications create an infrastructure for future research.

2.3.2. The contributions of the second method

In the second method, a distribution system with different types of consumers, medium-scale wind and biomass energy power plants, permanent charging stations (PCSs) and a MCS that is capable of providing bidirectional energy flow is considered. In the system, the MCS is a self-powered EV and has charging sockets on it. It is considered that the MCS can behave as an energy storage system for supporting the EV load demand during the peak energy period. While the MCS can be charged at several different points of the considered distribution system, it can only serve for discharging at a limited number of points. In the determination of these points, the routing constraints such as MCSs' travel time between buses are taken into account. The contributions of this study are threefold:

- The developed energy management algorithm examines the role of MCSs in facilitating the operation of the grid and reducing the number of EVs waiting for charging.
- Both energy storage and charging features of MCSs are evaluated within the scope of Vehicle-to-Vehicle (V2V).
- The obtained results provide an insight into the real applications of MCSs and V2V technology.

3. MATERIALS AND METHODS

3.1. A Framework for Dispatching of an Electric Vehicle Fleet using Vehicle-to-Grid Technology

3.1.1. System description and mathematical model

In the proposed model, a distribution system with commercial consumers that have different load characteristics is considered. Charging stations that have six charging sockets are located at Low-Voltage (LV) side of the distribution system to serve bidirectional energy flow at each bus node. Transformers at each LV bus node provide energy as the main energy supplier as shown in Figure 3.1 (Abdullah Kürşat Aktar et al. 2023). Besides, the EV fleet belonging to a Distribution System Operator (DSO) is parked at a parking area for travelling to bus nodes when it is needed. It is assumed that the parking area is at a location where it will be possible to reach all the bus nodes in a reasonable time. Each EV connected to the bus nodes behaves like a stationary ESS. When selecting the bus node to be connected, the optimization algorithm considers the load demand of the bus nodes and the amount of energy required to travel to the relevant nodes. The designed system aims to determine the optimum size and operation of EVs as an energy storage system. The optimization problem and related mathematical expressions are given by Equations (3.1)- (3.28).

As mentioned above, the main objective of the proposed optimization problem based on mixed integer linear programming is to minimize the Energy Drawn (ED) from the grid via transformer during the peak load period and the energy consumption of EVs to travel bus node described between t_1 and t_2 by (3.1). Active and reactive energy flow equations are expressed by (3.2) and (3.3). Transformers are the supplier side and commercial facilities and homes are the consumer side of system. The EVs can behave as supplier or consumer using the bidirectional operation modes via charging stations shown by Equations (3.4) and (3.5). AC power flow Equations (3.6)-(3.11) taken from (Baradar and Hesamzadeh 2015) represent the system with second order conic programming.

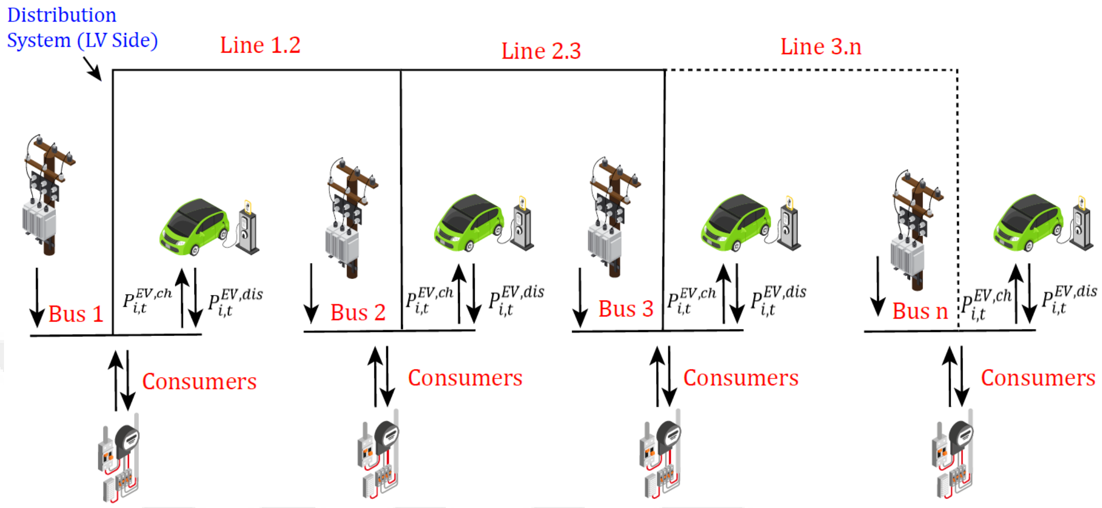


Figure 3.1. Block diagram of the distribution system considered.

The rated power limitations of EV charging and discharging are shown by (3.12) and (3.13), respectively. The change in the SOE of the EVs when they are connected to the bus node and when they are traveling is calculated by (3.14) and (3.15), respectively. Constraint (3.16) determines the EV battery limitations and initial value of EV battery is defined by Equation (3.17).

$$Minimize\ ED = \sum_{t1}^{t2}\sum_{i} P_{i,t}^{S} + \sum_{EV}\sum_{i} EC_{i}^{EV} \tag{3.1}$$

subject to:

$$P_{i,t}^{G} - P_{i,t}^{L} = \sum_{l\in B_{l}^{ij}} \left(M_{i,l}^{F}\cdot P_{l,t}^{r} + M_{i,l}^{L}\cdot P_{l,t}^{\text{loss}}\right)\ \forall i,t \tag{3.2}$$

$$Q_{i,t}^{G} - Q_{i,t}^{L} = \sum_{l\in B_{l}^{ij}} \left(M_{i,l}^{F}\cdot Q_{l,t}^{r} + M_{i,l}^{L}\cdot Q_{l,t}^{\text{loss}} - B_{l}\cdot M_{l,i}^{W}\cdot W_{i,t}\right)\ \forall i,t \tag{3.3}$$

$$P_{i,t}^{G} = P_{i,t}^{EV,dis} + P_{i,t}^{S}\ \forall i,t \tag{3.4}$$

$$P_{i,t}^{L} = P_{i,t}^{L,total} + P_{i,t}^{EV,\mathrm{ch}} \; \forall i,t \tag{3.5}$$

$$W_{i,t} = V_{i,t}^{2} \; \forall i,t \tag{3.6}$$

$$P_{l,t}^{\mathrm{loss}} = 2 \cdot R_{l} \cdot \hat{P}_{l,t}^{\mathrm{loss}} \; \forall l,t \tag{3.7}$$

$$X_{l} \cdot P_{l,t}^{\mathrm{loss}} - R_{l} \cdot Q_{l,t}^{\mathrm{loss}} = 0 \; \forall l,t \tag{3.8}$$

$$\sum_{i} \left(M_{l,i}^{W} \cdot W_{i,t} \right) - 2 \cdot \left(R_{l} \cdot P_{l,t}^{r} + X_{l} \cdot Q_{l,t}^{r} \right) = R_{l} \cdot P_{l,t}^{\mathrm{loss}} + X_{l} \cdot Q_{l,t}^{\mathrm{loss}} \;\; \forall l,t \tag{3.9}$$

$$2 \cdot \hat{P}_{l,t}^{loss} \cdot W_{r,t} \geq {P_{l,t}^{r}}^{2} + {Q_{l,t}^{r}}^{2} \; \forall l,t \tag{3.10}$$

$$V_{min}^{2} \leq W_{i,t} \leq V_{max}^{2} \; \forall i,t \tag{3.11}$$

$$0 \leq P_{i,t}^{EV,\mathrm{ch}} \leq R_{i}^{EV,\mathrm{ch}} \cdot u_{i,t}^{ch} \; \forall i,t \tag{3.12}$$

$$0 \leq P_{i,t}^{EV,dis} \leq R_{i}^{EV,dis} \cdot (1 - u_{i,t}^{ch}) \; \forall i,t \tag{3.13}$$

$$\mathrm{SOE}_{\mathrm{i,j,m,t}}^{\mathrm{EV}} = \mathrm{SOE}_{\mathrm{i,j,m,(t-1)}}^{\mathrm{EV}} + \left(\mathrm{CE}^{\mathrm{EV}} \cdot \mathrm{P}_{\mathrm{i,t}}^{\mathrm{EV,ch}} - \frac{\mathrm{P}_{\mathrm{i,t}}^{\mathrm{EV,dis}}}{\mathrm{DE}^{\mathrm{EV}}} \right) \cdot \Delta\mathrm{T} \; \forall \mathrm{t} \;\; \text{if i = j} \tag{3.14}$$

$$\mathrm{SOE}_{\mathrm{i,j,m,t}}^{\mathrm{EV}} = \mathrm{SOE}_{\mathrm{i,j,m,(t-1)}}^{\mathrm{EV}} - \mathrm{EC}^{\mathrm{EV}} \cdot \Delta\mathrm{L}_{\mathrm{j,m}} \; \forall \mathrm{t} \;\; \text{if i} \neq \text{j} \tag{3.15}$$

$$SOE_{i,j,m}^{EV,min} \leq SOE_{i,j,m,t}^{EV} \leq SOE_{i,j,m}^{EV,max} \;\; \forall i,j,m,t \tag{3.16}$$

$$SOE_{i,j,m,1}^{EV} = SOE_{i,j,m}^{EV,ini} \;\; \forall i,j,m \tag{3.17}$$

Mathematical model equations to calculate the energy consumption of EVs are described by (3.18) – (3.22) (Şengör et al. 2020). Total traction force $F_{v,tt}^{t}$ consists of four main forces, which are acceleration force, $F_{v,tt}^{ac}$, aerodynamic drag force, $F_{v,tt}^{a}$, rolling friction force, F_{tt}^{r}, and gravity force, F_{tt}^{g}. Mechanical and electrical power needed to move the EVs are expressed by (3.23) and (3.24), respectively. Total energy consumption of EV during the driving period can be calculated by (3.25).

$$F_{v,tt}^{t} = F_{v,tt}^{ac} + F_{v,tt}^{a} + F_{tt}^{r} + F_{tt}^{g} \ \ \forall v, tt \tag{3.18}$$

$$F_{v,tt}^{a} = \frac{1}{2}.\rho.A.C_d.(V_{v,tt}^{EV} - V_{v,tt}^{W})^2 \ \ \forall v, tt \tag{3.19}$$

$$F_{tt}^{r} = M^{EV}.g.C_{rr}.\cos(\theta) \ \forall tt \tag{3.20}$$

$$F_{tt}^{g} = M^{EV}.g.\sin(\theta) \ \forall tt \tag{3.21}$$

$$F_{v,tt}^{ac} = f_m.M^{EV}.\alpha \ \forall v, tt \tag{3.22}$$

$$P_{v,tt}^{vm} = F_{v,tt}^{t}.V_{v,tt}^{EV} \ \forall tt \tag{3.23}$$

$$P_{v,tt}^{ve} = \frac{P_{v,tt}^{vm}}{\eta_d} \ \forall tt \tag{3.24}$$

$$EC^{EV} = \sum_{tt} \frac{\left(P_{v,tt}^{ve}.\Delta T\right)}{1000} \tag{3.25}$$

Equation (3.26) ensures that an EV can be connected to only one bus in time interval t. Since each bus has a certain number of connection sockets, the number of EVs that can be connected is limited by Equation (3.27). The displacement of the EV in each time interval creates an inefficient situation in terms of both energy consumption and travel time. To have a more efficient operation, the departure of an EV from the bus is prevented by (3.28). Consequently, the objective function (3.1) is minimized by considering the constraints (3.2) - (3.28).

$$\sum_{i} m_{i,t}^{EV} = 1 \ \forall t, EV \tag{3.26}$$

$$0 \leq \sum_{EV} m_{i,t}^{EV} \leq CS \ \forall i, t \tag{3.27}$$

$$m_{i,t}^{EV} - m_{i,(t-1)}^{EV} = 0 \ \forall i, t, EV \ if \ t > 1 \tag{3.28}$$

The equations of the electrical grid and EV models in the optimization algorithm are given by (3.1) – (3.28). The sequential representation of the proposed optimization algorithm consisting of mainly seven steps is presented in Figure 3.2.

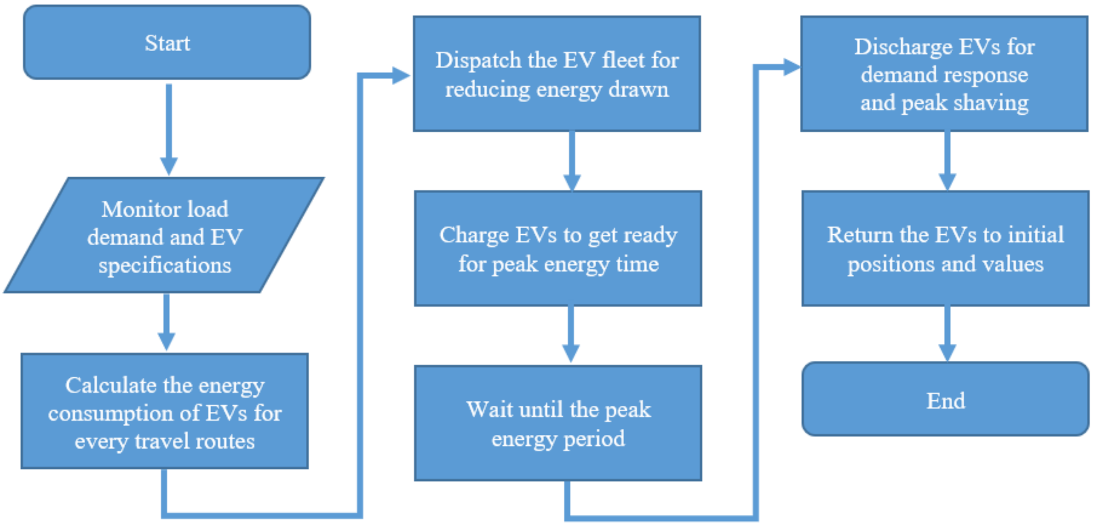


Figure 3.2. Sequential representation of the proposed optimization algorithm.

3.2. Optimal Charging and Discharging Operation of Mobile Charging Stations

3.2.1. System description and mathematical model

In this study, a distribution system with 15 buses with different load characteristics is considered. Two PCSs connected to the buses of the distribution system and one MCS that can be charged from different nodes in the system are placed. All the PCSs and MCSs are considered as the assets of the distribution system operator and are used to charge the EVs while also providing economic benefits and improving the power system operation quality. The MCS settles in the PCS area at the required time intervals and performs V2V operations with its charging sockets without connecting to the grid. The load demand is met by the transformer in the system and the energy generation of the wind farm and biomass power plant contributes to the system. Distribution system diagram with the power plants and MCS charge/discharge buses are shown in Figure 3.3. The designed system aims to make the optimum use of the MCS and the charging station aspects of EVs that are used for V2V operations

(Abdullah Kursat Aktar, Tascikaraoglu, and Catalao 2022). The objective function, constraints of the system and other expressions are given by Equations (3.29)-(3.59).

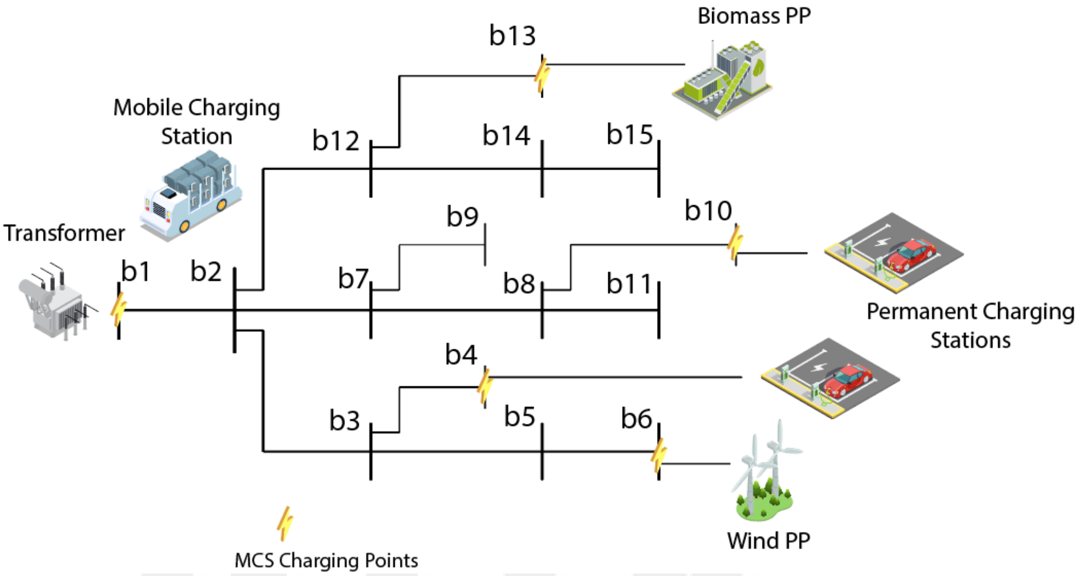


Figure 3.3. Block diagram of the system considered.

The proposed approach aims to maximize the operational and economic benefits of MCSs by using them as mobile energy storage and charging systems. The main purpose of the proposed constrained optimization algorithm is to minimize the difference between the total hourly power demand of EVs and the power supplied by PCS and MCS, as shown in Equation (3.29). Thus, the number of missed vehicles is determined by dividing the minimized amount of power by the rated power of a socket. Equations (3.30) and (3.31) show active and reactive energy flow relations. As stated in Equations (3.32) and (3.33), the transformer, wind farm and biomass power plant constitute the supplier part in the system, while commercial, domestic and EV charging load form the consumer part. AC power flow equations taken from (Baradar and Hesamzadeh 2015) are given in Equations (3.34)-(3.39). These equations presented in a second-order cone formulation can be used in a linear optimization algorithm by choosing the appropriate solver. MCS charging and discharging power constraints are shown by (3.40) and (3.41), respectively. Equation (3.42) prevents simultaneous charging and discharging in time interval t when the MCS is connected to bus i. The PCS has unidirectional energy flow and Equation (3.43) specifies the power flow constraint for EV charging. Calculation of the MCS's battery state-of-the-energy

(SOE) according to the operation mode of charge, discharge or travel is done by Equation (3.44). Battery capacity constraints and initial value are defined by Equations (3.45) and (3.46), respectively.

$$Minimize\ MV = \sum_{t}\sum_{i}((P_{i,t}^{CPD} - P_{i,t}^{MCS,dis} - P_{i,t}^{PCS,PD}) \cdot \Delta\mathrm{T}) \tag{3.29}$$

subject to:

$$P_{i,t}^{G} - P_{i,t}^{L} = \sum_{l\in B_{l}^{ij}} \left(M_{i,l}^{F} \cdot P_{l,t}^{r} + M_{i,l}^{L} \cdot P_{l,t}^{\mathrm{loss}}\right)\ \forall i,t \tag{3.30}$$

$$Q_{i,t}^{G} - Q_{i,t}^{L} = \sum_{l\in B_{l}^{ij}} \left(M_{i,l}^{F} \cdot Q_{l,t}^{r} + M_{i,l}^{L} \cdot Q_{l,t}^{\mathrm{loss}} - B_{l} \cdot M_{l,i}^{W} \cdot W_{i,t}\right)\ \forall i,t \tag{3.31}$$

$$P_{i,t}^{G} = P_{i,t}^{S} + P_{i,t}^{W} + P_{i,t}^{BM}\ \forall i,t \tag{3.32}$$

$$P_{i,t}^{L} = P_{i,t}^{L,total} + P_{i,t}^{MCS,\mathrm{ch}} + P_{i,t}^{PCS,PD}\ \forall i,t \tag{3.33}$$

$$W_{i,t} = V_{i,t}^{2}\ \forall i,t \tag{3.34}$$

$$P_{l,t}^{\mathrm{loss}} = 2 \cdot R_{l} \cdot \hat{P}_{l,t}^{\mathrm{loss}}\ \forall l,t \tag{3.35}$$

$$X_{l} \cdot P_{l,t}^{\mathrm{loss}} - R_{l} \cdot Q_{l,t}^{\mathrm{loss}} = 0\ \forall l,t \tag{3.36}$$

$$\sum_{i}\left(M_{l,i}^{W} \cdot W_{i,t}\right) - 2 \cdot \left(R_{l} \cdot P_{l,t}^{r} + X_{l} \cdot Q_{l,t}^{r}\right) = R_{l} \cdot P_{l,t}^{\mathrm{loss}} + X_{l} \cdot Q_{l,t}^{\mathrm{loss}}\ \ \forall l,t \tag{3.37}$$

$$2 \cdot \hat{P}_{l,t}^{loss} \cdot W_{r,t} \geq {P_{l,t}^{r}}^{2} + {Q_{l,t}^{r}}^{2}\ \forall l,t \tag{3.38}$$

$$V_{min}^{2} \leq W_{i,t} \leq V_{max}^{2}\ \forall i,t \tag{3.39}$$

$$0 \leq P_{i,t}^{MCS,\mathrm{ch}} \leq R_{i}^{MCS,\mathrm{ch}} \cdot u_{i,t}^{ch}\ \forall i,t \tag{3.40}$$

$$0 \leq P_{i,t}^{MCS,dis} \leq R_{i}^{MCS,dis} \cdot u_{i,t}^{dch}\ \forall i,t \tag{3.41}$$

$$u_{i,t}^{ch} + u_{i,t}^{dch} = m1_{i,t} \tag{3.42}$$

$$0 \leq P_{i,t}^{PCS,PD} \leq R_{i}^{PCS,PD} \ \forall i, t \tag{3.43}$$

$$\mathrm{SOE}_{\mathrm{t}}^{\mathrm{MCS}} = \mathrm{SOE}_{(\mathrm{t}-1)}^{\mathrm{MCS}} + \sum_{i} \left(\mathrm{CE}^{\mathrm{MCS}} \cdot \mathrm{P}_{\mathrm{i,t}}^{\mathrm{MCS,ch}} - \frac{\mathrm{P}_{\mathrm{i,t}}^{\mathrm{MCS,dis}}}{\mathrm{DE}^{\mathrm{MCS}}} \right) \cdot \Delta\mathrm{T} - (\mathrm{EC}^{\mathrm{MCS}} \cdot m2_{t}) \ \forall \mathrm{t} \tag{3.44}$$

$$SOE^{MCS,min} \leq SOE_{t}^{MCS} \leq SOE^{MCS,max} \ \ \forall t \tag{3.45}$$

$$SOE_{t}^{MCS} = SOE^{MCS,ini} \ \ if \ t = 1 \tag{3.46}$$

$$\sum_{i} m1_{i,t} \leq 1 \ \forall t \tag{3.47}$$

$$m2_{t} = 1 - \sum_{i} m1_{i,t} \ \ \forall t \tag{3.48}$$

$$\sum_{t-T_{i,j}+1}^{t} m4_{i,t} \leq 1 - m3_{j,t} \ \forall t, i, j \tag{3.49}$$

$$m3_{j,t} - m4_{i,t} = m1_{i,t} - m1_{i,(t-1)} \ \forall i, t \tag{3.50}$$

$$m3_{j,t} + m4_{i,t} \leq 1 \ \forall i, t \tag{3.51}$$

Connection and routing constraints of MCS are given by Equations (3.47)–(3.51). Equation (3.47) ensures that the MCS can only be connected to one bus node in a time interval. If the MCS is not connected to any bus in time interval t, its traveling condition is expressed by Equation (3.48). However, the MCS traveling from the bus i to the bus j is prevented from connecting to the bus j before the required travel time has elapsed by Equation (3.49). The change in the arrival and departure status and preventing the MCS from arriving at a bus node and leaving at the same time are expressed in (3.50) and (3.51), respectively. The energy consumption of the MCS is calculated according to Equations (3.52)-(3.59) that are taken from (Garcia-Val, Rodrigole 2013). Four main forces, which are the acceleration force, $F_{v,tt}^{ac}$, aerodynamic drag force, $F_{v,tt}^{a}$, rolling friction force, F_{tt}^{r}, and gravity force, F_{tt}^{g} constitute the total traction force $F_{v,tt}^{t}$. Equations (3.57) and (3.58) are used to calculate the mechanical and electrical power needed, respectively. Total energy consumption of MCS to travel between two bus nodes is calculated by Equation (3.59).

$$F_{v,tt}^{t} = F_{v,tt}^{ac} + F_{v,tt}^{a} + F_{tt}^{r} + F_{tt}^{g} \;\; \forall v, tt \tag{3.52}$$

$$F_{v,tt}^{a} = \frac{1}{2}.\rho.A.C_d.(V_{v,tt}^{MCS} - V_{v,tt}^{W})^2 \;\; \forall v, tt \tag{3.53}$$

$$F_{tt}^{r} = M^{MCS}.g.C_{rr}.\cos(\theta) \; \forall tt \tag{3.54}$$

$$F_{tt}^{g} = M^{MCS}.g.\sin(\theta) \; \forall tt \tag{3.55}$$

$$F_{v,tt}^{ac} = f_m.M^{MCS}.\alpha \; \forall v, tt \tag{3.56}$$

$$P_{v,tt}^{vm} = F_{v,tt}^{t}.V_{v,tt}^{MCS} \; \forall tt \tag{3.57}$$

$$P_{v,tt}^{ve} = \frac{P_{v,tt}^{vm}}{\eta_d} \; \forall tt \tag{3.58}$$

$$EC^{MCS} = \sum_{tt} \left(P_{v,tt}^{ve}.\Delta T\right) \tag{3.59}$$

4. ASSESSMENT OF THE FINDINGS

4.1. A Framework for Dispatching of an Electric Vehicle Fleet using Vehicle-to-Grid Technology

4.1.1. Input data

The data used during the study are as follows. Line parameters of 6 LV buses are given in Table 4.1. Resistance and reactance values between bus nodes in the table are shown in per unit (pu) values. The base values used are 1 MVA for apparent power, 20 kV for voltage and 400 Ω for impedance.

Table 4.1. Line parameters of the distribution system considered.

Line	From	To	R [pu]	X [pu]
L1	2	1	0.00071	0.00036
L2	3	2	0.00017	0.00009
L3	4	3	0.00153	0.00051
L4	4	5	0.00035	0.00012
L5	5	6	0.00133	0.00044

As a mobile energy source, each EV can move from the parking lot to different connection points. Thus, EV’s energy consumption during travel period between parking area and any bus node has to be taken into account to determine the SOE of EV battery. In general, it is possible to find EVs with a wide variety of battery capacities and specific features. In this study, two types of EVs are considered; however, the results of the optimization algorithm for many EVs can be examined with simple changes to the parameters. EV type-1 is considered as any commercial EV and EV type-2 is considered as an EV similar to Tesla Cybertruck Tri Motor, but with a larger battery. The parameters for calculating the energy consumption of EV type-1 and EV type-2 are given in Table 4.2 (Garcia-Val, Rodrigole 2013). The electrical energy consumption of the EV is calculated by Equations (3.18) - (3.25) using environmental parameters such as wind speed, air density, and the EV-related parameters such as mass and front area.

Table 4.2. EV parameters used in the calculation of the relevant energy consumption.

Parameter	EV Type-1	EV Type-2
Mass	1360 kg	3000 kg
Mass factor	1.05	1.05
Coefficient of rolling resistance	0.02	0.0126
Air density	1.225 kg/m^3	1.225 kg/m^3
Vehicle frontal area	2 m^2	3.4 m^2
Aerodynamic drag coefficient	0.5	0.47
Wind speed	0 m/s	0 m/s
Road slope angle	0 °	0 °
Gravity of Earth	9.8 m/s^2	9.8 m/s^2
Efficiency of EV	0.9	0.9

When an EV is connected to any bus node, it operates as a stationary energy storage system. The energy charge and discharge exchanges occur according to the limitations in Table 4.3 (Taşcıkaraoğlu 2018; Anonym 2022). Charge - discharge efficiency, and the initial and minimum SOE values of EVs are same for both EV type-1 and EV type-2. EV type-1 has a battery capacity of 100 kWh with 25 kW charging - discharging rate, while EV type-2 has a capacity of 200 kWh with 75 kW charging - discharging rate. Units in the electrical grid model are expressed in pu, while the power units in the EV model are expressed in kW. It should be noted that the related parameters and variables in the power grid model are multiplied by the base power due to the use of pu values.

In this study, the load demand of the consumer for a typical spring day between 09:00 am and 09:00 pm is selected. The data for demand power curves are obtained from a regional distribution company in order to ensure the similarity to the real cases. According to the load profile given in Figure 4.1. The power demanded by each bus during the test period., the charging, discharging and no operation time intervals are selected. EVs are placed in the most suitable locations determined by the algorithm at 09:00 am. After the arrival of EVs to the bus nodes, the EV charging mode is active between 09:00 am and 11:30 am, which is the low energy consumption period, to be ready for the peak shaving operation.

Table 4.3. EV & ESS parameters for energy exchange

Parameter	EV Type-1	EV Type-2	ESS
CE^{EV}	0.95	0.95	0.95
DE^{EV}	0.95	0.95	0.95
$R^{EV,\mathrm{ch}}$	25 kW	75 kW	75 kW
$R^{EV,dis}$	25 kW	75 kW	75 kW
$SOE^{EV,ini}$	60 kWh	60 kWh	250 kWh
$SOE^{EV,min}$	25 kWh	25 kWh	50 kWh
$SOE^{EV,max}$	100 kWh	200 kWh	400 kWh

There is no operation between 11:40 am and 2:30 pm so as to use the energy stored in the EV battery efficiently at the peak energy period. At the same time, for avoiding the early battery degradation, the attention is paid to both the discharge period and the minimum SOE of the battery. Therefore, the discharge period is chosen between 2:40pm and 6:40pm, which is also the peak energy period. After the discharge period, it is assumed that the EVs can be recharged or returned to the parking area with the minimum SOE value until the test period ends. Comprehensive evaluations are made on the optimization algorithm by using different types and numbers of EVs in order to increase the economic and operational benefits. Besides, using an ESS can offer remarkable economic benefits by charging when electricity prices are low and discharging when electricity is expensive. The use of EVs as mobile ESS enables more effective use of the grid thanks to the load shifting operation. The main aim of evaluating the different quantities of EVs in different cases is to reveal the economic and operational benefits on the grid by having opportunity to use different storage capacities.

4.1.2. Simulation and results

In order to determine the benefits of the proposed model, five different cases are considered:

Case 1: 15 type-1 EVs are available in the parking lot.

Case 2: 30 type-1 EVs are available in the parking lot.

Case 3: 15 type-2 EVs are available in the parking lot.

Case 4: 30 type-2 EVs are available in the parking lot.

Case 5: 15 type-2 EVs are available in the parking lot. RES and ESS are included.

A time granularity of 10 min (i.e., 0.166 h) is used in all five cases. General Algebraic Modeling System (GAMS) version 25.1.3 is used to test the constrained optimization algorithm and MOSEK solver is used to solve the problem. The average solution time is 0.3 seconds on a 2.21 GHz, quad-core i7-8750H processor PC with 16GB of RAM. The stopping criteria and the iteration limit are chosen 1.0e-6 and 1000000, which are the MOSEK solver's default values, respectively. The algorithm produces the optimal results without reaching the termination limits, which indicates that reliable results are obtained in terms of the accuracy.

In Case 1 and Case 2, the same type of EVs with a maximum capacity of 100 kWh is used for VfG operation. The only difference between these two cases is the number of EVs used. In Case 3 and Case 4, it is assumed that the EV has a capacity of 200 kWh. In these five cases, the benefits of EVs that have different specifications and numbers on the grid supporting operations are investigated. In all cases, it is aimed to optimally reduce the energy drawn from the transformer in the peak energy time interval by connecting the EVs to different buses where the load values of each bus are shown in Figure 4.1.

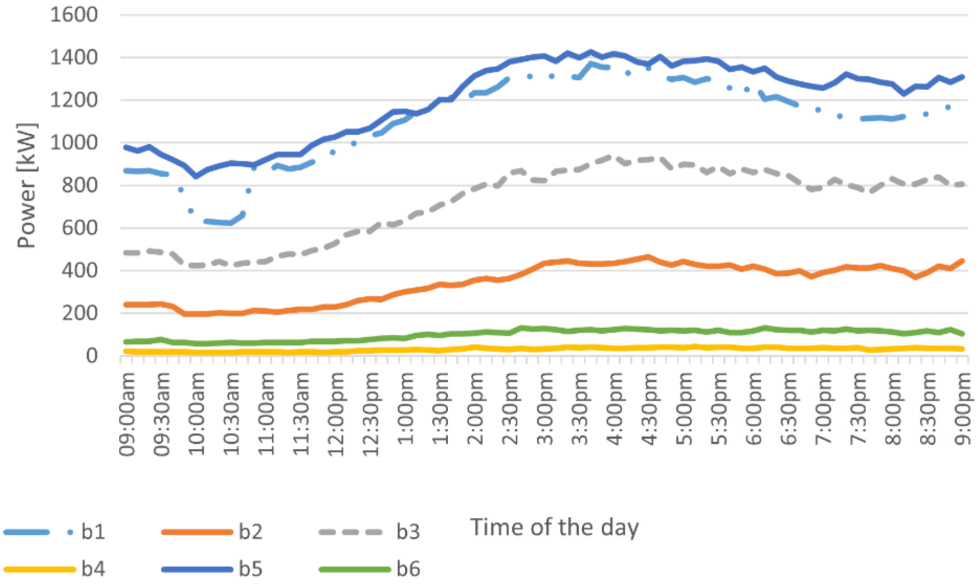


Figure 4.1. The power demanded by each bus during the test period.

As shown in Figure 4.2, Case 1 and Case 2 are effective in stabilizing the energy drawn from the grid during the test period. Between 09:00 am and 11:30 am, it is observed that the load curve moves upwards due to the charging operations of the EVs. Since the number of EVs in Case 2 is more than Case 1, it causes more power demand for charging.

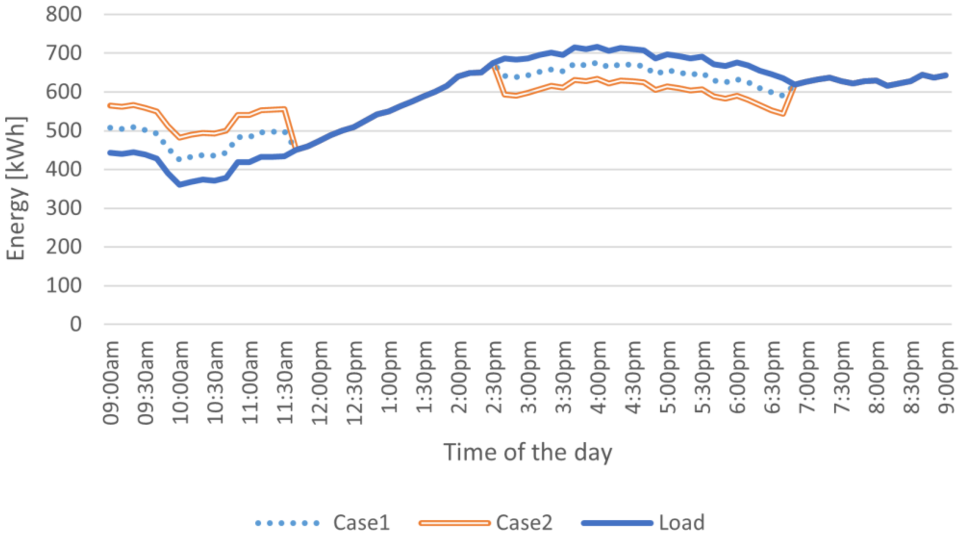


Figure 4.2. The energy supplied by the grid during the test period for the Case 1 and Case 2.

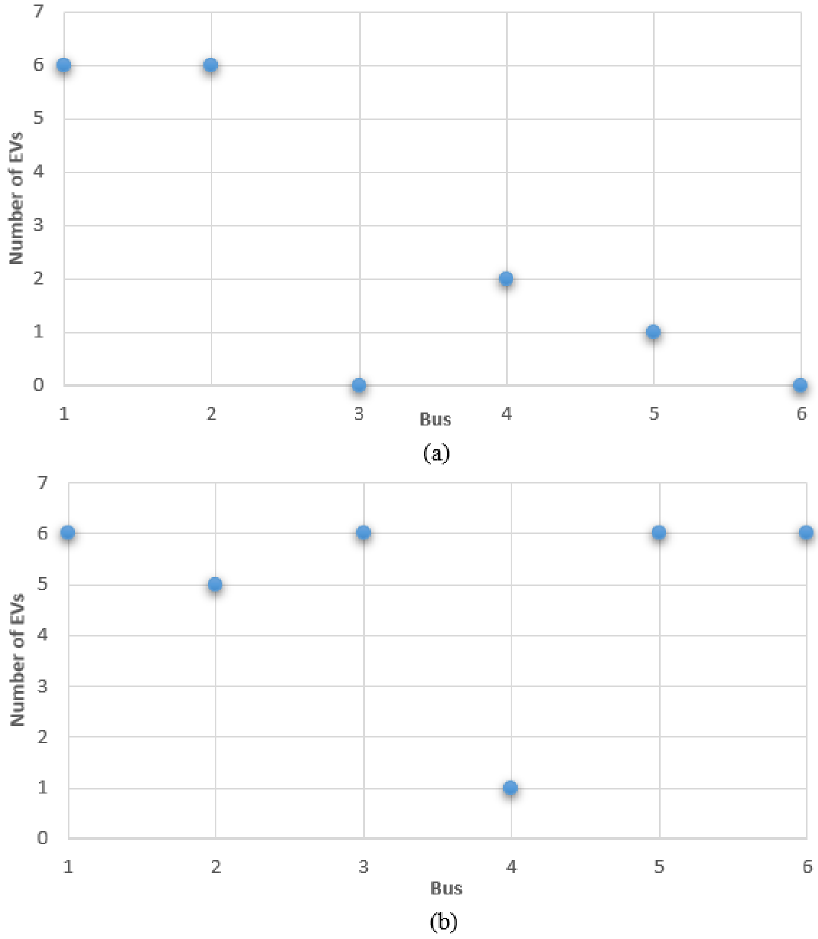
In both cases, the charged energy is used to supply the electrical grid at bus nodes that are determined by the optimization algorithm between 2:40 pm and 6:40 pm. Especially in Case 2, the difference between the minimum and maximum values of load curve is noticeably reduced, which enables the grid to be more efficient and to have a higher capacity utilization rate. In determining the connection points of the EVs, the power demand of the bus and the energy that the EV will consume while reaching the bus are taken into account. Using the values given in Table 4.2 and Equations (3.18) - (3.25), the amount of the energy required for the EVs to travel to different bus nodes is calculated as shown in Table 4.4.

Table 4.4. Energy consumption of the EVs to travel towards the buses.

	EV Type-1 (kWh)	EV Type-2 (kWh)
Bus 1	7.082	10.959
Bus 2	6.668	10.335
Bus 3	15.204	23.991
Bus 4	3.230	4.923
Bus 5	10.685	16.567
Bus 6	17.060	26.709

The objective function of the constrained optimization algorithm determines the number of the EVs connected to the buses in order to minimize the energy drawn from the grid during the peak energy period by taking the values in Table 4.4 into account. The values determined for Case 1 and Case 2 are shown in Figure 4.3 (a) and (b), respectively. In Case 1, 15 type-1 EVs are dispatched to Bus 1, Bus 2, Bus 4 and Bus 5 and the quantities of the EVs are 6, 6, 2 and 1, respectively. As each bus has six sockets for these cases, a maximum of six EVs can be connected. In determining the number of EVs going to the bus nodes, the optimization algorithm takes into account the energy demand of each bus node and the amount of energy to be spent to reach these nodes. For Case 1, the maximum number of EVs are connected to Bus 1 and Bus 2. Likewise, for Case 2, the maximum number of EVs are connected to Bus 1, Bus 3, Bus 5 and Bus 6.

After the travel period, EV’s battery is charged to be efficient at the peak period. The power demand of consumers is variable throughout the day. The low demand period is the best time to charge EVs. For Case 1 and Case 2, the values of the only four EVs randomly selected are shown in Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7 for the sake of the brevity.



(a)

(b)

Figure 4.3. The number of EVs connected to the buses for (a) Case 1 (b) Case 2.

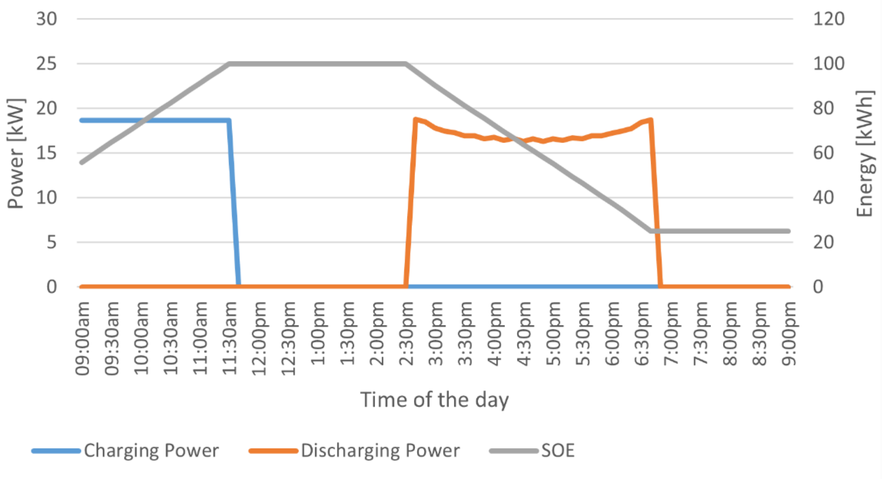


Figure 4.4. Battery outputs of EV 5 that is connected to Bus 1 during the test period for Case 1.

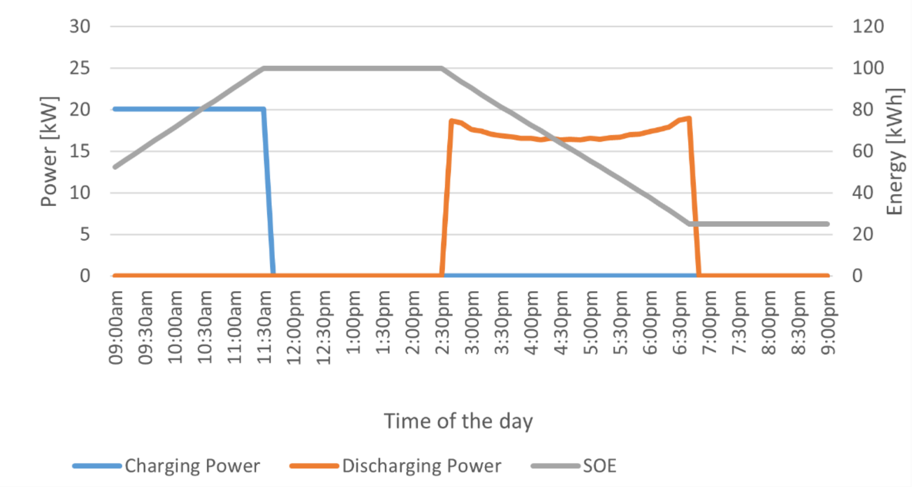


Figure 4.5. Battery outputs of EV 14 that is connected to Bus 5 during the test period for Case 1.

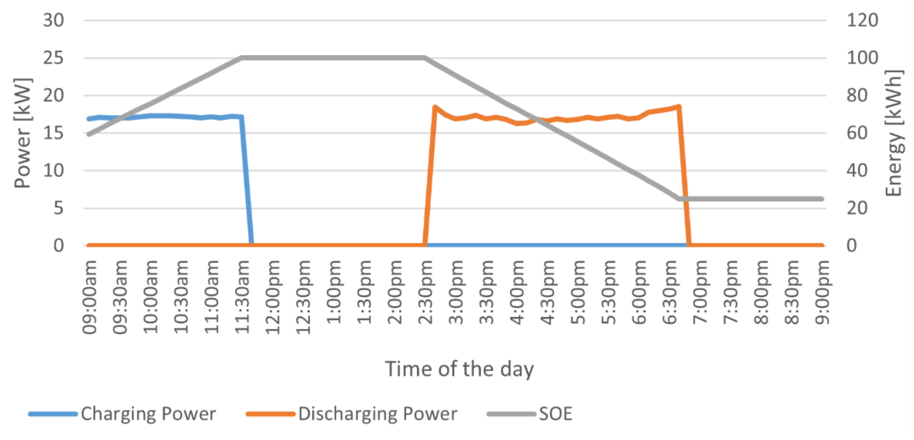


Figure 4.6. Battery outputs of EV 19 that is connected to Bus 4 during the test period for Case 2.

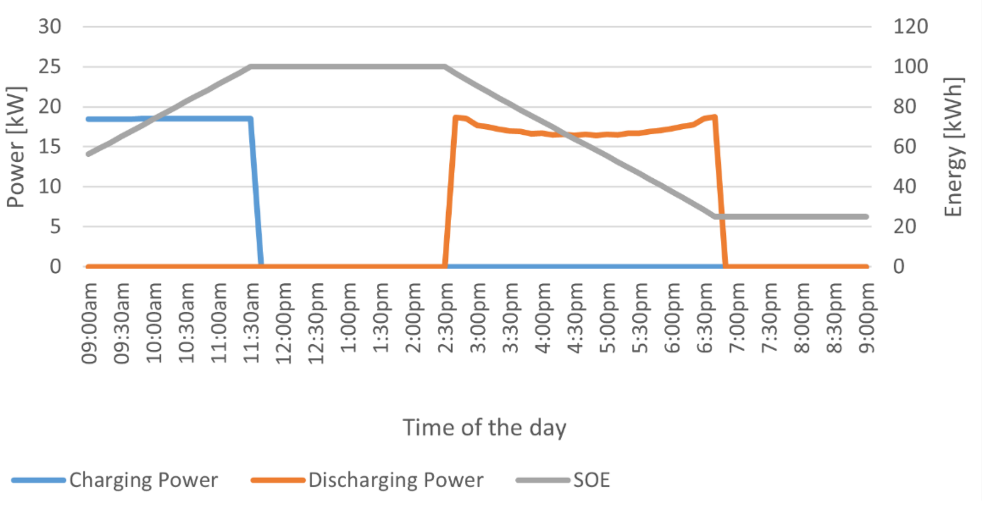


Figure 4.7. Battery outputs of EV 15 that is connected to Bus 2 during the test period for Case 2.

Compared to Case 1 and Case 2, the EV type with larger capacity is used for operations in Cases 3 and 4. While the power demand of the consumers remains the same, the change in the specifications of the EV causes great changes in the amount of energy drawn from the grid. The energy supplied by the grid during the test period for Case 3 and Case 4 is shown in Figure 4.8. It is obviously observed that quantity of EV is important for economic and reliable system management. In Case 3, it can be said that the optimal operation is possible with the decided quantity of EVs. However, in Case 4, the peak energy period of the curve is changed due to the high energy demand of EVs.

The power demanded, the power the EV can provide, and the amount of energy required to travel to any bus have a significant effect on the number of EVs to be connected to the different buses. For Case 3 and Case 4, the distribution of the EV fleet to the buses is shown in Figure 4.9 (a) and (b), respectively.

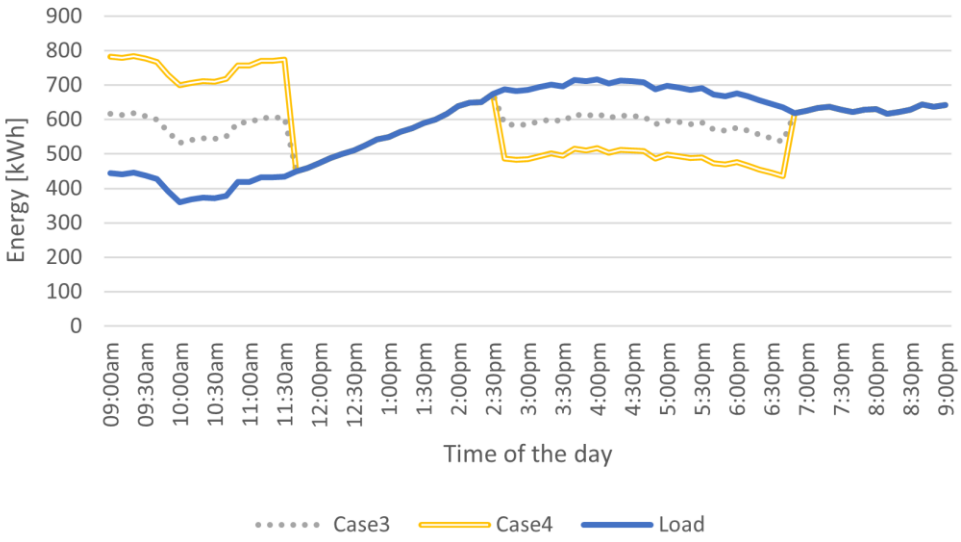


Figure 4.8. The energy supplied by the grid during the test period for the Case 3 and Case 4.

For Case 3 and Case 4, the battery characteristics of randomly selected EVs are shown in Figure 4.10, Figure 4.11, Figure 4.12, and Figure 4.13. Compared to the first two cases, it is seen that more energy is stored due to the large capacity of the battery. In order to charge and discharge the larger capacities in the same time interval, the charging stations with high instantaneous power are used.

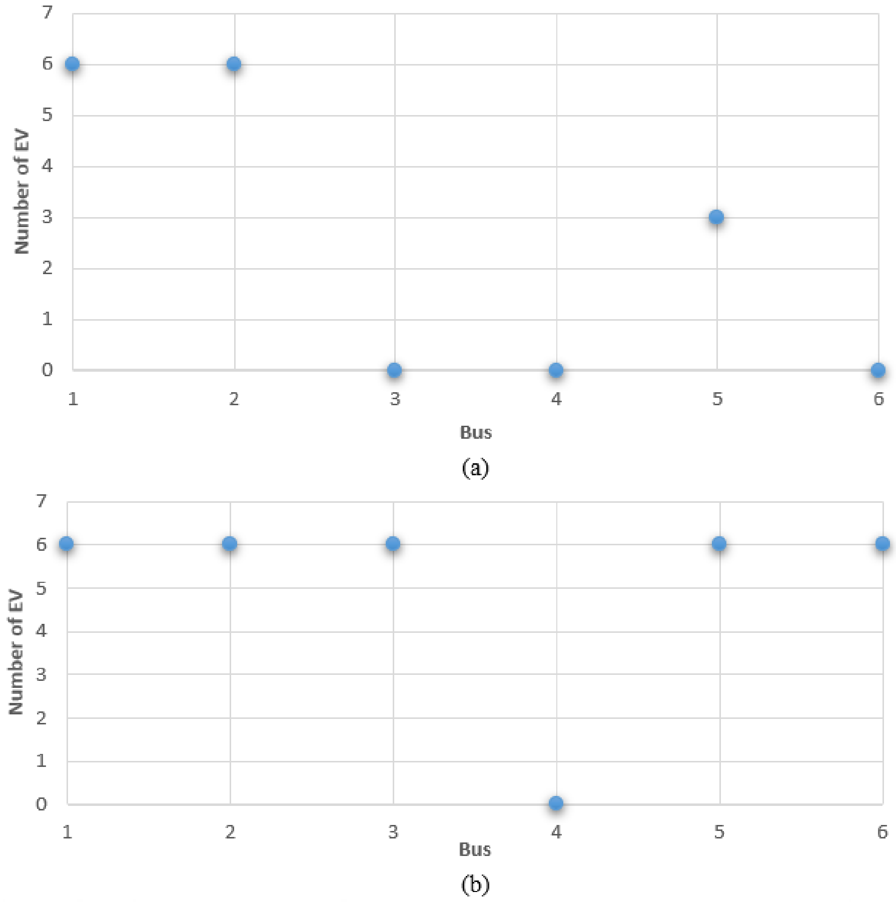


Figure 4.9. The number of EVs connected to the buses for (a) Case 3 (b) Case 4.

For Case 1 and Case 2, the instantaneous charging and discharging powers are around 20kW while for Case 3 and Case 4, these values are around 60kW and 40kW, respectively. Lastly, it can be seen that the increase in the number of EVs reduces the load on the grid. In particular, the number and battery capacity of EVs evaluated in Case 3 achieve greater improvement in the load curve than in the other cases. Besides, when the Peak-to-Average Power Ratio (PAPR) values of all cases are compared, it is seen that Case 3 outperforms the other cases. The calculated PAPR values are 1.1578, 1.1593, 1.1469, 1.3295 and 1.2274 for Case 1, Case 2, Case 3, Case 4 and Load Curve, respectively. The fact that the EV fleet in Case 4 might demand more energy from the grid causes the peak time to change in the load curve. At the same time, due to the higher peak value in Case 4, the largest PAPR value calculated in Case 4. EVs reduce the difference between the minimum and maximum points of the power curve by performing valley filling and peak shaving with charging and discharging operations in different time periods. The flattening of the load curve indicates the possibility of an increase in the capacity utilization rate. This provides a more efficient system in terms of investment costs and benefits. The energy that the EV supplies to the grid is shown in Table 4.5 for all cases.

The results obtained show that the EV fleet is used flexibly since it belongs to the distribution company, i.e., it can be used at any time period and in any place with a required capacity, differently from shared ESSs. Therefore, the EV fleet can be managed according to the short-time and seasonal load changes in the form of fleet expansion or contraction. In addition, considering that the capacity and location of the shared ESS are fixed, it is obvious that the proposed system brings an advantage in terms of costs.

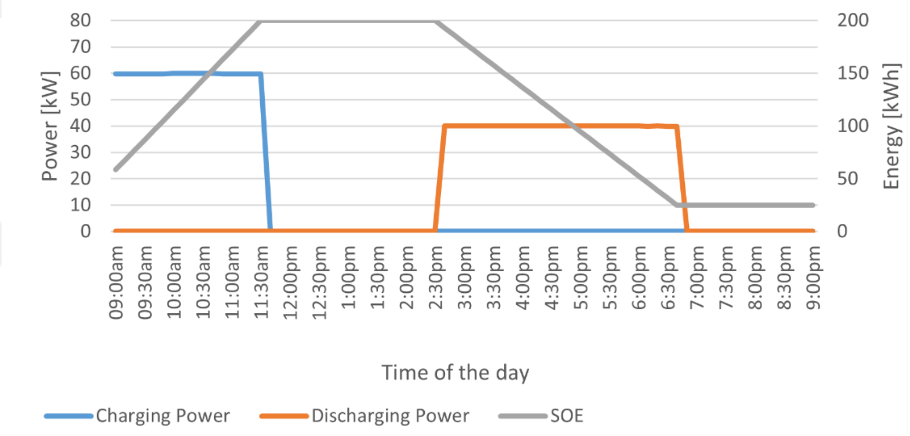


Figure 4.10. Battery outputs of EV 8 that is connected to Bus 1 during the test period for Case 3.

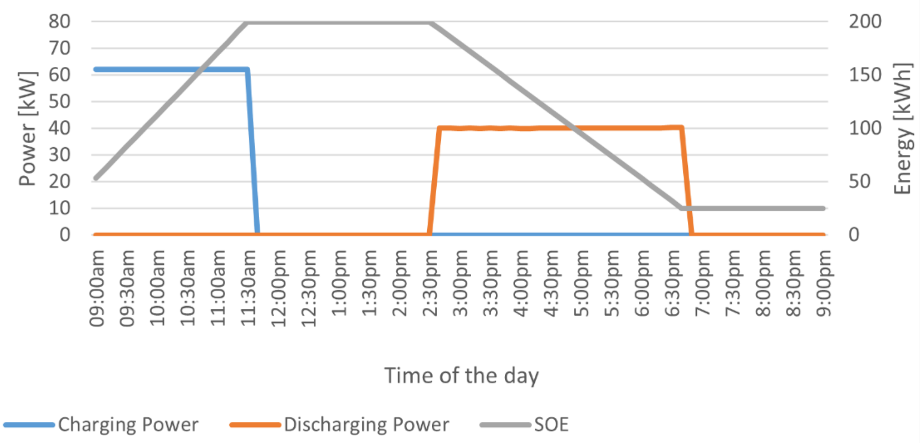


Figure 4.11. Battery outputs of EV 6 that is connected to Bus 5 during the test period for Case 3.

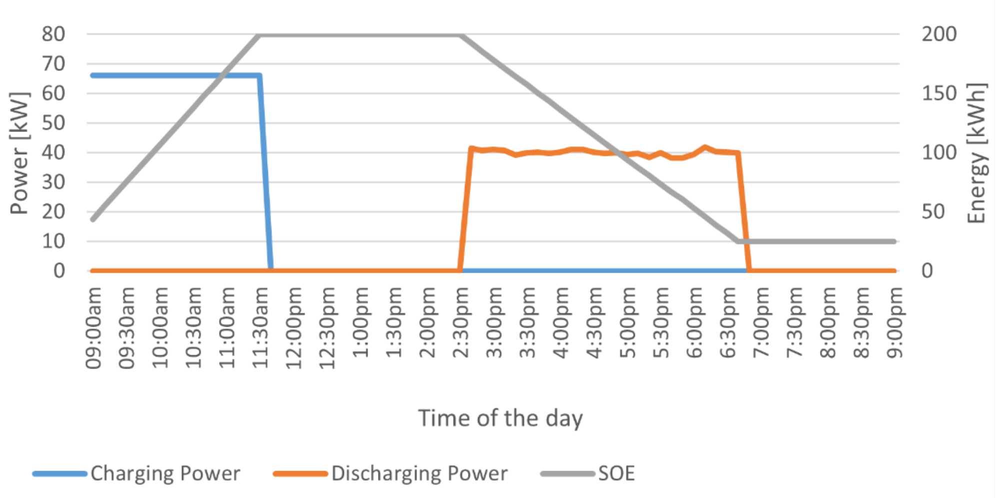


Figure 4.12. Battery outputs of EV 17 that is connected to Bus 6 during the test period for Case 4.

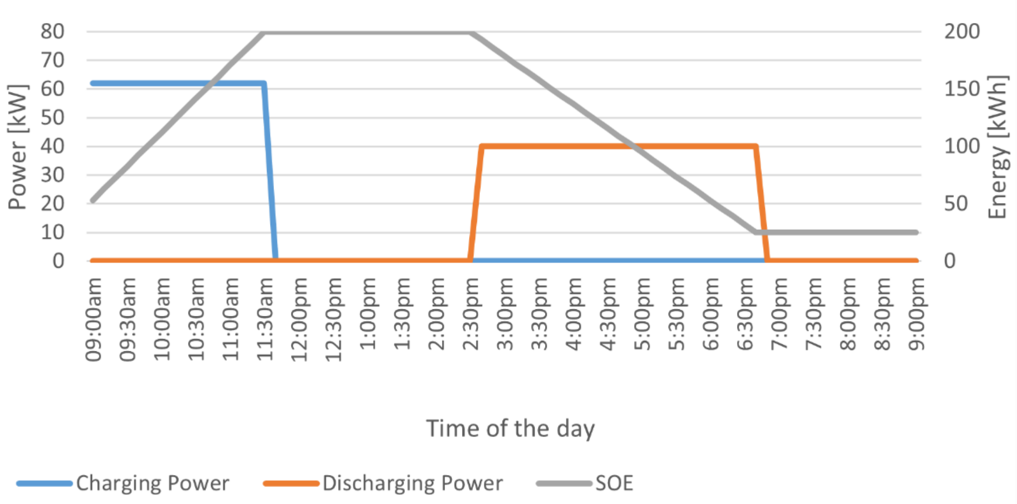


Figure 4.13. Battery outputs of EV 12 that is connected to Bus 5 during the test period for Case 4.

Table 4.5. Energy consumption values

	Energy drawn from grid during peak energy period (kWh)	Energy supplied by EV during peak energy period (kWh)
Case 1	34851.837	739.427
Case 2	33783.087	1624.133
Case 3	33426.837	2406.945
Case 4	30933.166	5000.360
Case 5	30620.773	2340.467

As another important issue, it should be noted that the battery aging and operating costs of the EVs should be taken into account in determining the charge and discharge periods of the EV fleet. Thus, the EV fleet is used only for the time intervals where needed instead of more frequently usage that might also provide some benefits. Moreover, the unnecessary operation of the EVs is prevented since the energy required to travel to a bus and the power demand of the bus are taken into account before any EV is connected to the related bus. Besides, the line losses are reduced as the load demand is supplied from the closest bus thanks to the VfG operations.

In Case 5, in addition to an EV fleet with 15 type-2 EVs, RES and an ESS are added to the network. It is assumed a renewable energy power plant and an ESS are connected to each bus node. The generated power values of the power plants considered are shown in Figure 4.14.

Besides, each bus node is equipped with an ESS with a capacity of 400 kWh in Case 5. In order to evaluate the effects of the ESSs on the system, the constraints (4.1)-(4.5) are added to the optimization algorithm where (4.1) and (4.2) represent the charge and discharge power constraints, respectively and the SOE of the ESS at each bus node is calculated by Equation (4.3). Also, the constraints and initial values of SOE are expressed by Equations (4.4) and (4.5). The energy exchange parameters of the considered ESSs are given in Table 3.

$$0 \leq P_{i,t}^{ESS,\mathrm{ch}} \leq R_{i}^{ESS,\mathrm{ch}}\ \forall i,t \tag{4.1}$$

$$0 \leq P_{i,t}^{ESS,dis} \leq R_{i}^{ESS,dis}\ \forall i,t \tag{4.2}$$

$$\mathrm{SOE}_{\mathrm{i,t}}^{\mathrm{ESS}} = \mathrm{SOE}_{\mathrm{i,(t-1)}}^{\mathrm{ESS}} + \left(\mathrm{CE}^{\mathrm{ESS}} \cdot \mathrm{P}_{\mathrm{i,t}}^{\mathrm{ESS,ch}} - \frac{\mathrm{P}_{\mathrm{i,t}}^{\mathrm{ESS,dis}}}{\mathrm{DE}^{\mathrm{ESS}}}\right) \cdot \Delta\mathrm{T}\ \forall\mathrm{t} \tag{4.3}$$

$$SOE_{i}^{ESS,min} \leq SOE_{i,t}^{ESS} \leq SOE_{i}^{ESS,max}\ \ \forall i,t \tag{4.4}$$

$$SOE_{i,1}^{ESS} = SOE_{i}^{ESS,ini}\ \ \forall i \tag{4.5}$$

The energy drawn from the grid in Case 5 is shown in Figure 4.15. Compared to Case 3, which was the best case among the previous cases, there is no significant change in the charging period. However, it is seen in Case 5 that the energy drawn from the grid is less than Case 3, which implies a more effective peak shaving operation. Besides, in this case, the PAPR value is calculated as 1.1727.

The power curves of the charging and discharging operations of the ESSs are shown in Figure 4.16 and Figure 4.17, respectively. Also, the change in the SOEs of ESSs during the test period is shown in Figure 4.18. Except for Bus 4, all the buses use their highest capacity to obtain the maximum operational benefits from the ESSs. In Bus 4, it is seen that less amount of energy is charged and discharged due to the relatively lower load demand.

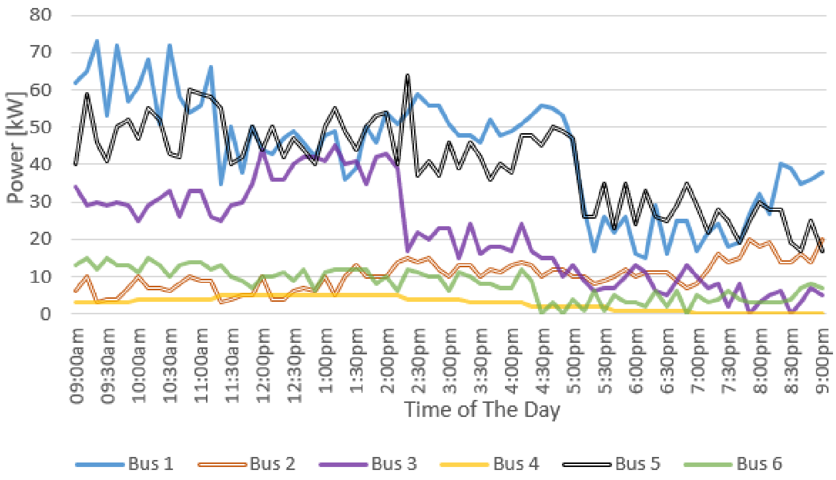


Figure 4.14. The power generation of power plants during the test period.

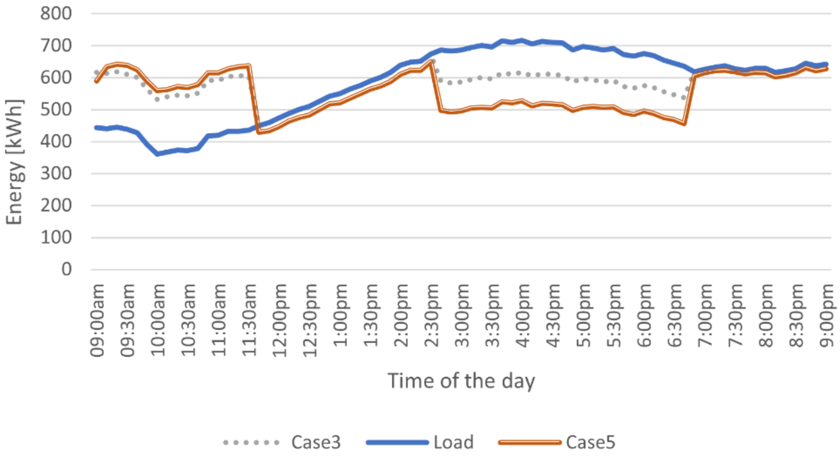


Figure 4.15. The energy supplied by the grid during the test period for the Case 3 and Case 5.

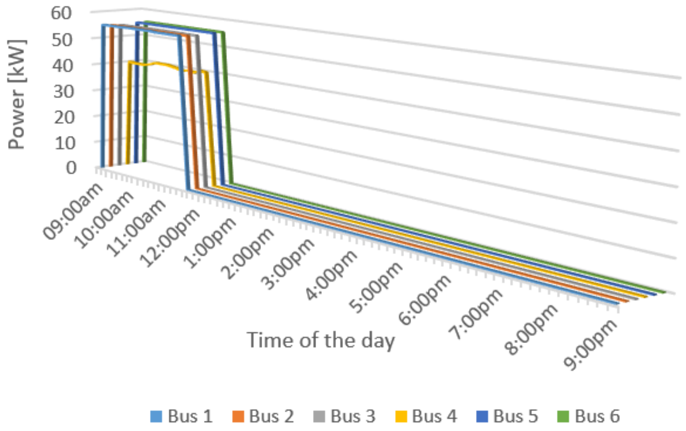


Figure 4.16. The charging power of ESSs during the test period for Case 5.

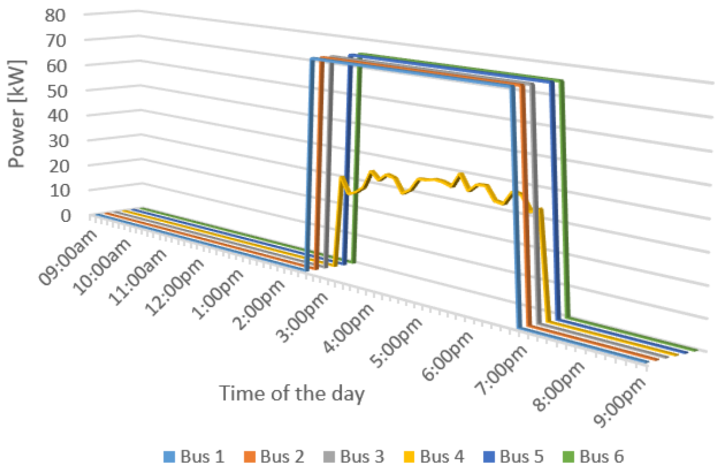


Figure 4.17. The discharging power of ESSs during the test period for Case 5.

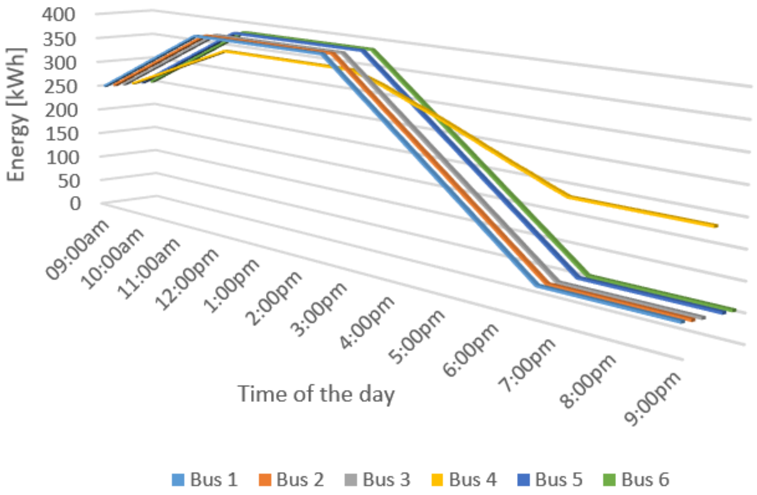


Figure 4.18. The change in SOEs of ESSs during the test period in Case 5.

4.2. Optimal Charging and Discharging Operation of Mobile Charging Stations

4.2.1. Input data

The data of the 15-bus distribution system are shown in Table 4.6 (Erenoğlu and Erdinç 2021). Resistance and reactance values are expressed as per unit. In addition, a base voltage of 12.66 kV, a base apparent power of 100 kVA and a base impedance of 1602 Ω are used.

During the displacement of any EV, an energy consumption occurs depending on the parameters related to the EV and environment. MCS moves between bus nodes in different locations to provide the most optimum service. The values used to calculate the energy consumption during the travel of the MCS are shown in Table 4.7.

Table 4.6. Line parameters of the distribution system

Line	From	To	R[pu]	X[pu]	Line	From	To	R[pu]	X[pu]
L1	1	2	0	0	L8	7	9	0.11	0.11
L2	2	3	0.075	0.1	L9	8	10	0.11	0.11
L3	3	4	0.08	0.11	L10	8	11	0.08	0.11
L4	3	5	0.09	0.18	L11	2	12	0.11	0.11
L5	5	6	0.04	0.04	L12	12	13	0.09	0.12
L6	2	7	0.11	0.11	L13	12	14	0.08	0.11
L7	7	8	0.08	0.11	L14	14	15	0.04	0.04

Table 4.7. MCS and environmental parameters to calculate energy consumption.

Parameter	Value	Parameter	Value
Coefficient of rolling resistance	0.02	Aerodynamic drag coefficient	0.5
Mass	5000 kg	Wind speed	0 m/s
Mass factor	1.05	Road slope angle	0 °
Air density	1.225 kg/m^3	Gravity of Earth	9.8 m/s^2
Vehicle frontal area	4 m^2	Efficiency of MCS	0.9

A single type of EV is utilized in the study; however, the consumption values of different EVs and various environmental conditions can be included with minor changes. Moreover, the change in the SOE of the MCS appears while charging from grid and discharging to serve EVs. Parameters regulating charging and discharging operations are given in **Hata! Yer işareti başvurusu geçersiz.**. The load demand of the consumers, the generated power values of the wind farm and biomass power plant are considered for a period of one day in the study, as shown in Figure 4.19.

Table 4.8. MCS parameters for energy exchange

Parameter	MCS	PCS	Parameter	MCS	PCS
CE^{MCS}	0.95	-	$SOE^{MCS,ini}$	200	-
DE^{MCS}	0.95	-	$SOE^{MCS,min}$	200	-
$R^{MCS/PCS,ch}$	20 kW/socket	20 kW/socket	$SOE^{MCS,max}$	2500	-
$R^{MCS/PCS,dis}$	20 kW/socket	20 kW/socket			

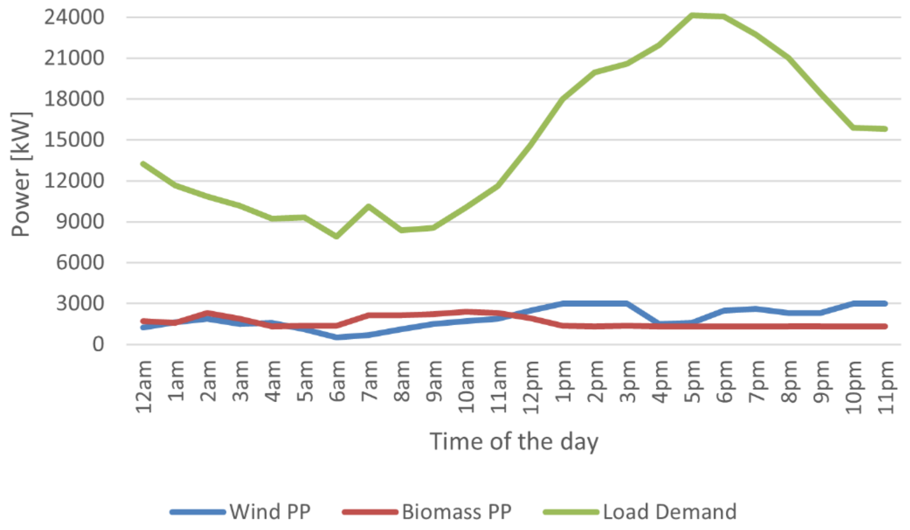


Figure 4.19. The power demanded and energy generation of power plants during the test period.

According to the designed system, while MCS can be charged at five different bus nodes, it provides discharge service at only 2 nodes that are PCS areas. Available points for charging and discharging are indicated in Figure 3.3. Another important issue that the optimization algorithm considers while making a decision is the socket number and priority order of the MCS and PCS. In the study, while MCS has 18 sockets, each PCS has 10 sockets.

By taking into account the number of EVs arriving at the charging points, the optimization algorithm determines the point where MCS will provide the most appropriate service and gives priority to the sockets of the MCS. If there are EVs waiting after the MCS switches to full capacity operation, the sockets of the PCS are activated.

The EV queue graph used in making the service point decision of the MCS is shown in Figure 4.20, and the graph showing the time periods required for the MCS to travel between bus nodes is shown in Table 4.9.

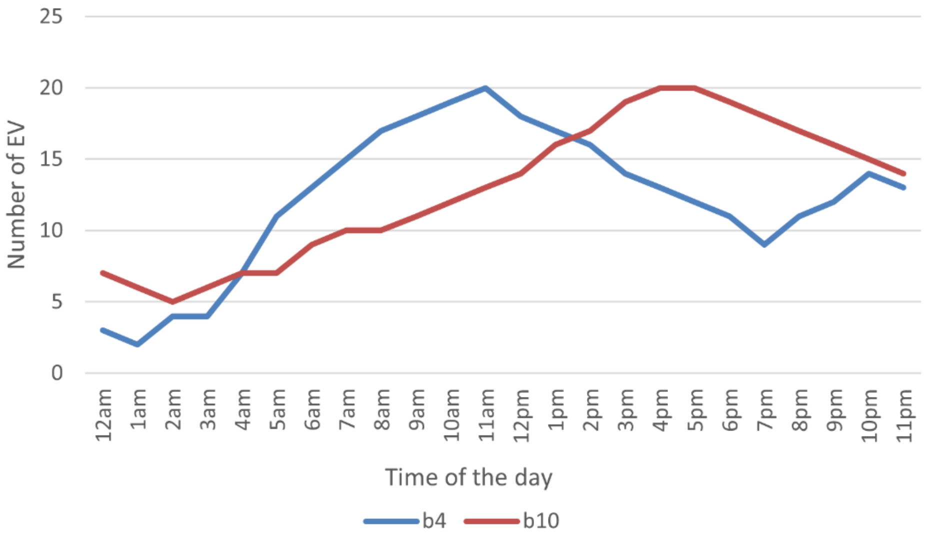


Figure 4.20. The number of EVs waiting for charge at Bus 4 and Bus 10.

Table 4.9. Required travel time between bus nodes

Road	From [Bus]	To [Bus]	Period [t]	Road	From [Bus]	To [Bus]	Period [t]
R1	B1	B4	2	R6	B4	B10	3
R2	B1	B6	1	R7	B4	B13	2
R3	B1	B10	1	R8	B6	B10	2
R4	B1	B13	1	R9	B6	B13	2
R5	B4	B6	3	R10	B10	B13	2

4.2.2. Simulation and results

In order to reveal the benefits of the proposed approach, three different cases are evaluated:

Case 1: MCS is movable and energy tariff is fixed pricing.

Case 2: MCS is fixed at Bus 10 and energy tariff is fixed pricing.

Case 3: MCS is movable and energy tariff is dynamic pricing.

A time granularity of one hour is used in all three cases.

In Case 1, the MCS operates in optimum conditions according to the demand in the charging areas in a system where energy prices are fixed. In addition, instead of an increase in the socket number of PCSs which are busy for a period of the day, the benefits of using MCS are investigated. Moreover, it could be useful as a quick and simple solution where grid infrastructure is not suitable to extend.

In Case 2, it is assumed that the MCS is connected to Bus 10 and never disconnected during the test period. In the two cases mentioned above, the optimization algorithm aims to minimize the number of EVs that cannot be served as there are no empty sockets.

In Case 3, the status where the MCS is movable and prices are varying on an hourly basis is evaluated. For this purpose, with a change made in the objective function, both the number of EVs that cannot be served and energy costs are minimized.

As shown in Figure 4.21, the MCS battery completes the test period with its initial SOE by performing the charge and discharge operations at different time intervals. Bus nodes where MCS performs these operations are indicated in Figure 4.22.

After determining the use of the limited charging sockets of MCS, the number of EVs that could not be serviced in the relevant buses is shown in Figure 4.23. On the other hand, the comparison of the number of active sockets in PCS and MCS, the number of EVs that coming to charge and the number of EVs that could not be charged are given in Figure 4.24. In addition, PCSs can charge 62% of EVs in the queue within their capabilities, while 18% of the EVs in demand cannot be serviced.

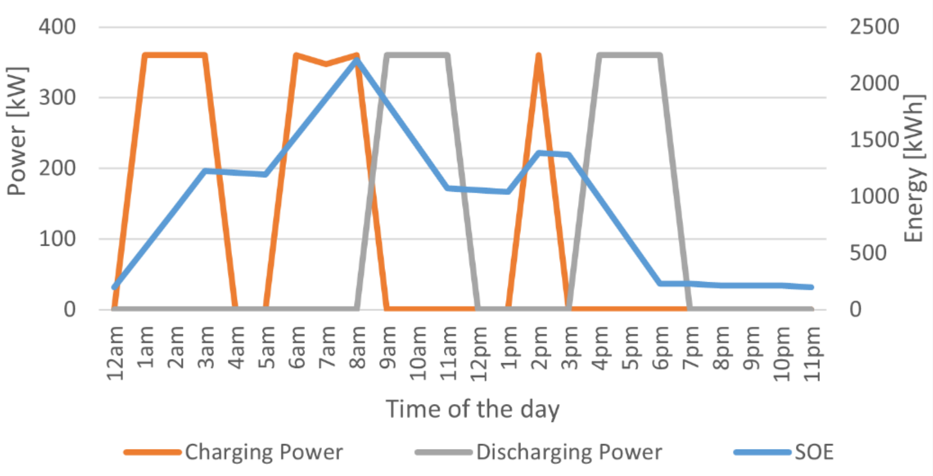


Figure 4.21. Battery outputs of MCS for Case 1.

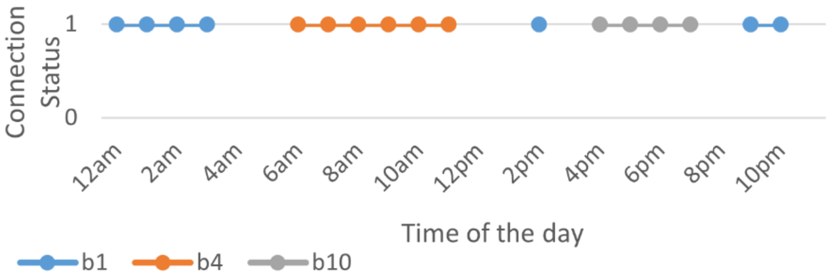


Figure 4.22. MCS connection status during the test period for Case 1.

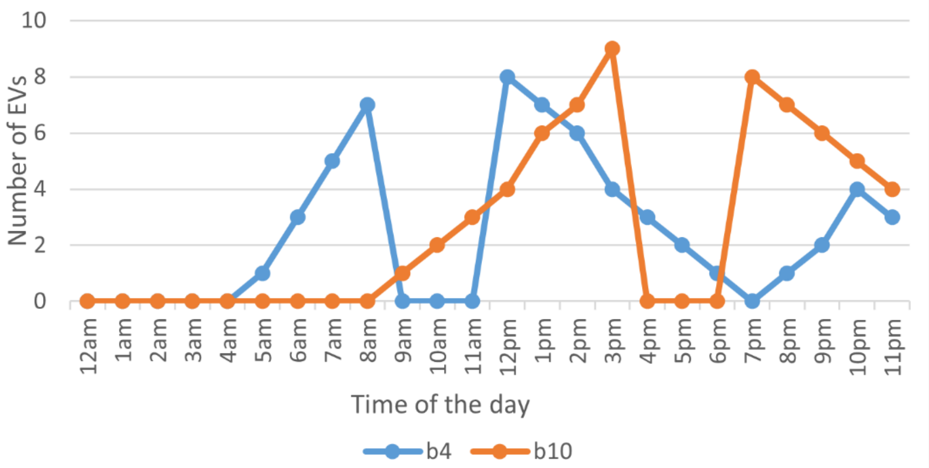


Figure 4.23. Number of EVs missed due to lack of sockets for Case 1.

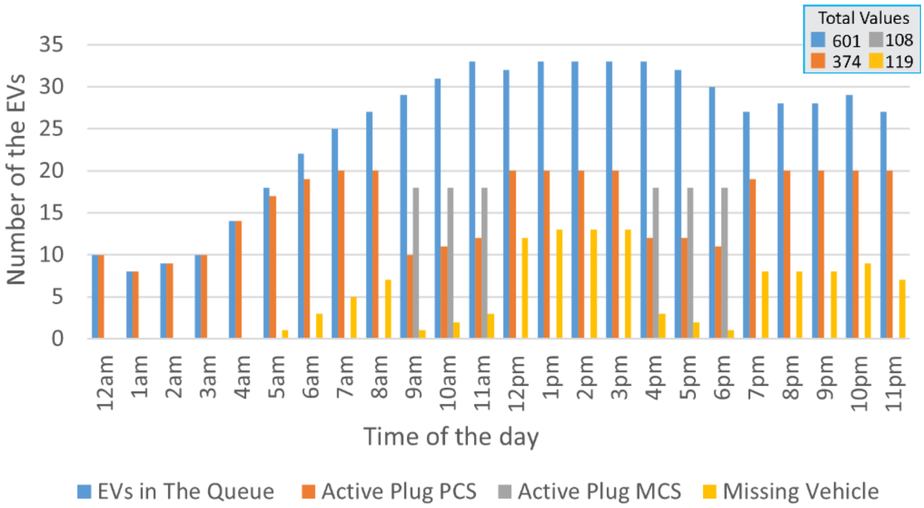


Figure 4.24. Comparison of the PCS, MCS, EV queue and missing EV for Case 1.

Expansions in the PCS can be made in order to reduce the charge demand congestion that occurs especially at certain times of the day. Based on this fact, in Case 2, the MCS is fixed to Bus 10 as shown in Figure 4.26. In this operating mode, where it acts as an energy storage system, the characteristic curves of the battery could be seen in Figure 4.25. In this case, it is seen from Figure 4.27 that it carries out the charging and discharging operations in the connected bus nodes in a way that reduces the missing EVs. As can be seen from the outputs in Figure 4.28, the fixed MCS operation is less efficient compared to the mobile operation (shown in Figure 4.24). During fixed operation, 16% of the all EVs are served by MCS and 62% by PCSs.

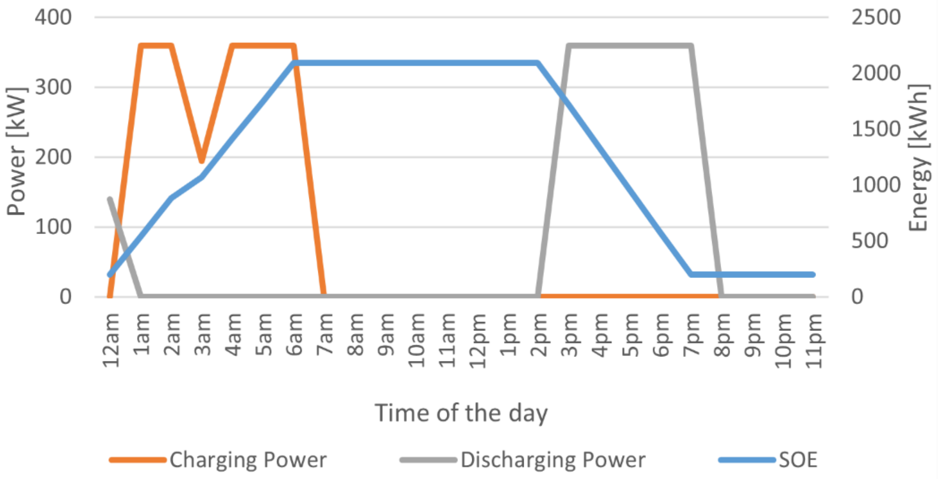


Figure 4.25. Battery outputs of MCS for Case 2.

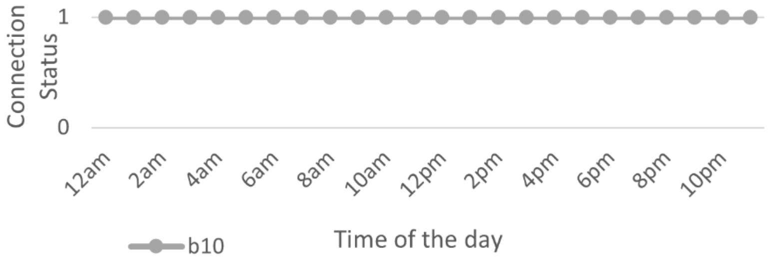


Figure 4.26. MCS connection status during the test period for Case 2.

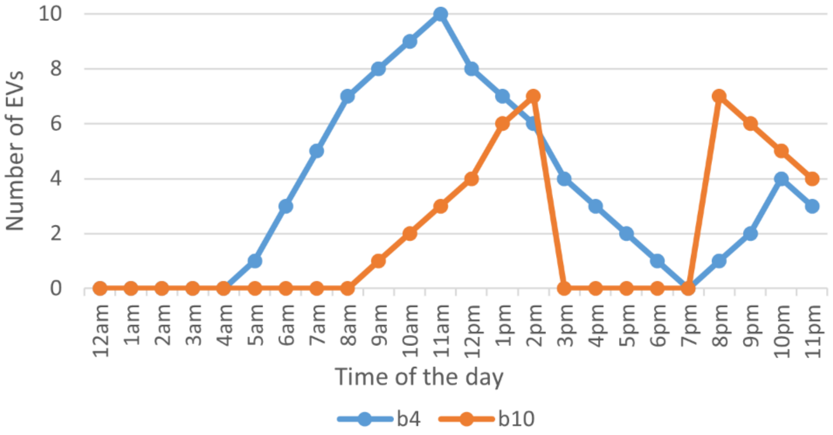


Figure 4.27. Number of EVs missed due to lack of sockets for Case 2.

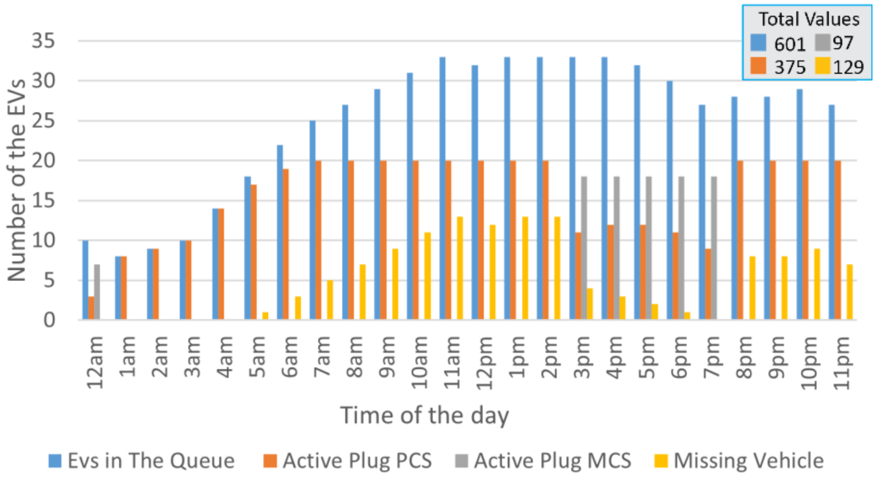


Figure 4.28. Comparison of the PCS, MCS, EV queue and missing EV for Case 2.

In Case 3, differently from the previous cases, energy prices have dynamic characteristic on an hourly basis. To this end, a change is made in the objective function as seen in (4.6).

$$Minimize\ MV = \sum_t \sum_i ((P_{i,t}^{CPD} - P_{i,t}^{MCS,dis} - P_{i,t}^{PCS,PD}) \cdot \Delta T \cdot Price_t) + \sum_t \sum_i ((P_{i,t}^{MCS,ch} - P_{i,t}^{MCS,dis}) \cdot \Delta T \cdot Price_t) \tag{4.6}$$

The increase in energy prices with load demand, shown in Figure 4.29, highlights the value of MCS's mobile battery feature. Thanks to this feature, economic benefits are provided by charging when electricity prices are lower and discharging when electricity is more expensive. At the same time, the objective function aims to minimize the number of missed EVs. Thus, a multi objective situation arises in terms of both electrical grid and charging operation. It is seen from the MCS battery characteristic shown in Figure 4.30 that the charging operation takes place in the cheaper price period, and discharge occurs when both prices and number of EVs coming to charge are high.

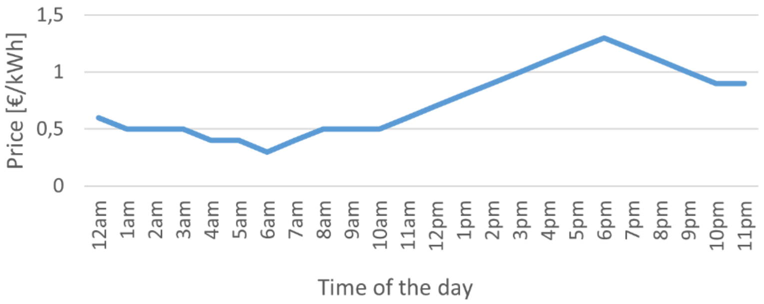


Figure 4.29. Dynamic electricity price for Case 3.

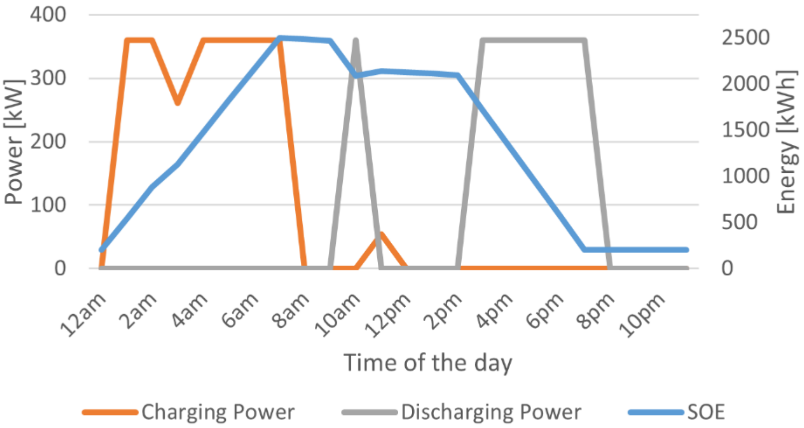


Figure 4.30. Battery outputs of MCS for Case 3.

Besides, Figure 4.31 shows that MCS is in operation at Bus 1, Bus 4 and Bus 10 during the test period. The discharge operation takes place between 3:00 pm and 7:00 pm, which is the peak period of the price and charging orders as seen in Figure 4.32. Statistical outputs of MCS and PCS are given in Figure 4.33. Besides, considering the energy prices in Case 3, a majority of the service, 62%, is conducted at the PCSs, while 20% is conducted by the MCS.

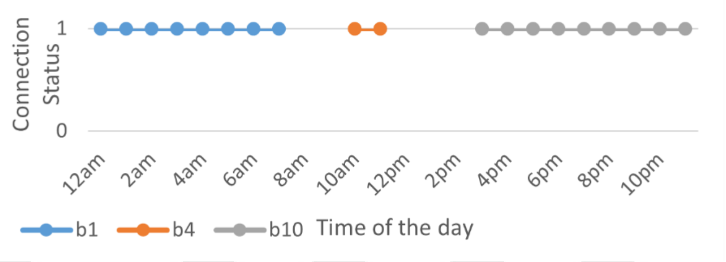


Figure 4.31. MCS connection status during the test period for Case 3.

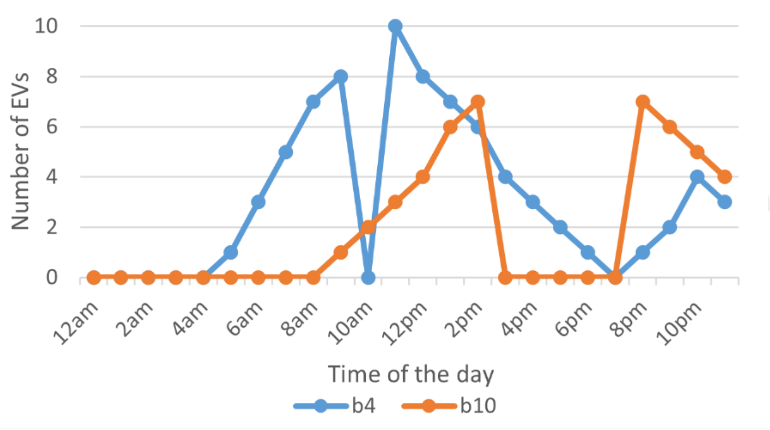


Figure 4.32. Number of EVs missed due to lack of sockets for Case 3.

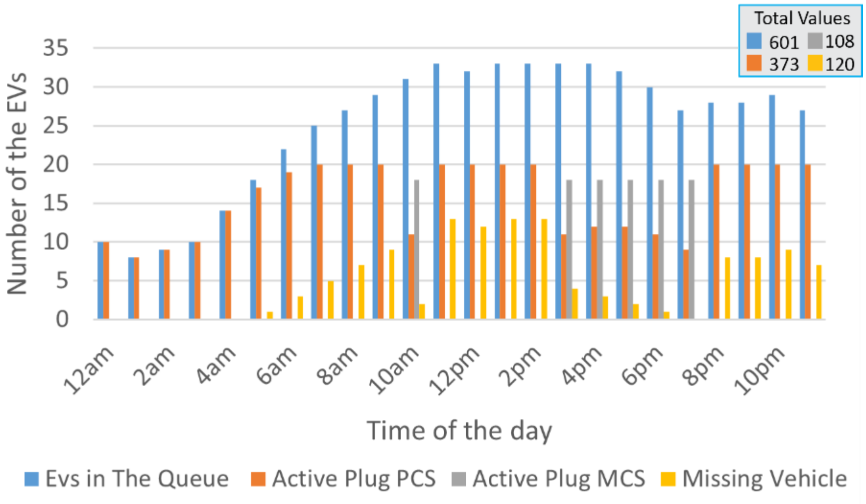


Figure 4.33. Comparison of the PCS, MCS, EV queue and missing EV for Case 3.

Lastly, regarding the number of EVs that could not be serviced for all cases, in Case 2, since the MCS is fixed to Bus 10, it only serves the relevant bus. Therefore, 129 EVs are not charged for Case 2 when evaluated for the entire test period.

Similarly, when Case 1 and Case 3 are evaluated, it is calculated that 119 and 120 EVs are not served, respectively. In Case 1, where the prices do not change and the MCS is movable, it is seen that the least number of EVs are missed. Likewise, as the MCS is fixed on Bus 10, which is busy in a very short time of the day, it turns out that Case 2 is the most missed EV case.

5. CONCLUSIONS

5.1. General Conclusions

In this thesis, a detailed evaluation of V2G technology is conducted by considering various types of operations in the different systems designed. There are technical, economic, regulatory and social barriers to the development of the V2G technology. In the near future, the developments in the battery structures, charging infrastructures, power network design, data security and communication network technology will facilitate the expansion of V2G operations. From an economic point of view, the decrease in EV purchase and maintenance prices, the charging station installation costs and communication costs will support the spread of the V2G technology. Synchronously with all these technological developments, it is necessary for the legislators to prepare the necessary market laws, and in the social sense, the users who have confidence problems in V2G operations and who have anxiety about running out of battery should be included in the system with incentives (Noel et al. 2019; Crisostomi et al. 2017).

In the first method, the proposed constrained optimization algorithm aims to use EVs as mobile energy storage systems at appropriate times in order to offer a more flexible, safe and efficient grid management. Besides, using EVs in VfG mode prevents the distribution system operator from facing any restrictions on the use of EVs. Due to the constraints imposed by the EV owners in the V2G mode, the required amount of energy and quantity of EV may not be in use during the peak energy period of the electrical grid, which can be stated as the main drawback of the V2G mode. The results prove that the use of EVs in VfG mode in the peak energy period is beneficial in alleviating the overload on the grid.

Besides, in the real applications, distribution system operators already use mobile transformers and mobile batteries in the situations such as planned maintenances, temporary capacity increases, system failures and natural disasters. Motivated by this fact, it can be foreseen that the VfG technology including mobile batteries with different capacities would be used by the distribution system operators to provide further operational benefits to the system operations. Furthermore, the widespread use of EVs and increase in the charging and service points would make the VfG technology one of the most applicable and effective options in near future in the system operations during especially the peak load demand periods.

The constrained optimization algorithm minimizes the objective function by taking into account the energy demand of each bus node and the amount of energy required to travel between them. The EV fleet is dispatched to the bus nodes determined by the algorithm, not exceeding the maximum number of sockets. The best results are observed in Case 3 were 15 type-2 EVs each with 200-kWh batteries are included. Thanks to the valley filling and peak shaving operation of the EVs, the PAPR value for the load curve decreased by 6.56% in Case 3. While there is a double difference between the minimum and maximum points in the load curve, it is seen that the difference almost disappears, and the curve becomes horizontal. Since the EVs in Case 4 have the highest storage capacity, it provides the best discharging power performance that is 5000 kWh during the peak energy period. The large amount of energy drawn from the grid to charge the EVs shifts the load curve upwards and causes the peak time to change. Thus, the number and characteristics of EVs should be determined by considering the energy consumption between the parking area and the bus node, and the load characteristics of the system.

In the second method, the constrained optimization algorithm is aiming at using an MCS as a mobile energy storage system and charging station at appropriate buses to supply to the highest number of EVs while providing effective grid management. The results demonstrated that using MCS was beneficial in reducing the number of EVs waiting for charging at different buses at different time intervals. In addition, fixing the MCS to a single point did not provide a significant advantage in terms of operation. However, it might be useful where the grid infrastructure is inadequate. In networks where electricity prices are dynamic, when the right energy storage capacity is chosen, it may be possible to increase both economic and operational benefits in the peak energy period.

5.2. Future Studies

The applicability of V2G technology in real applications is in its very early stages. Several studies have been conducted using different network components to determine the benefits of the V2G technology. During this thesis study, research has been conducted on two sub-topics that are EV fleet for VfG operations and MCS.

Existing studies can be expanded and evaluated from different perspectives and new results can be found. As a future direction, additional results can be obtained using the grid with different load profiles and the fleet of EVs with various battery capacities by also improving the designed algorithm. In addition, the most suitable operating conditions can be determined by taking the purchase, operation, maintenance and repair costs of the EVs and MCS into account. Besides, the role of renewable energy sources in the system can be increased by considering different numbers of MCS.

Apart from the conducted studies, V2G technology can be evaluated with sub-topics such as battery swapping stations and different kind of inductive or wireless charging operations. In addition, more frequent charging-discharging cycles of EV batteries due to V2G operations highlight the issue of battery degradation. High charging and discharging rate of the battery during V2G operations causes stress on the battery and can accelerate battery degradation.

Moreover, the economic impact of the incentive programs that can be implemented to convince EV owners to sell energy to the grid can be examined. Financial incentives can eliminate barriers to expensive V2G equipment, while time-of-use tariffs can enable EV users to benefit economically by charging under variable electricity prices at different time periods of the day. In particular, if the EV user receives economic benefits from purchasing energy from a charging station that owns or has an agreement with an RES, a significant impact on RES integration can be achieved.

Lastly, education programs for the widespread adoption of V2G technology can raise awareness of the benefits of V2G technology for all system stakeholders and make it easier for EV owners to understand the importance of their participation. The willingness of EV owners to participate in V2G operations can play a vital role in the rapid adoption and success of V2G operations. Particularly, if the concerns of EV owners are addressed and their willingness to participate in V2G operations is positively influenced by legislators, incentives and infrastructure improvements, there will be greater benefits for both the grid and EV users. Therefore, it may be worth considering the topic of EV users' willingness to V2G participate in future studies.

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Aktar, Abdullah Kursat, Akin Tascikaraoglu, and Joao P. S. Catalao. 2022. “Optimal Charging and Discharging Operation of Mobile Charging Stations,” SEST 2022 - 5th International Conference on Smart Energy Systems and Technologies. 1–6. https://doi.org/10.1109/sest53650.2022.9898463.

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