Evaluation of the Impacts of Plug-in Hybrid Electric Vehicles on Electricity Load Curve for İstanbul

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Industrial and Systems Engineering.

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Abstract

The greenhouse gas emissions, depletion of fossil fuels and high petroleum prices are major concerns of the world in the recent years. Plug-in Hybrid Electric Vehicles (PHEVs) are emerging as an alternative solution in the transportation sector due to their economic and environmental advantages. PHEVs have a grid connection capability to charge their batteries. Therefore, it is crucial to investigate the impacts of PHEVs on the electricity grid when the PHEVs penetrate into the system.

In this study, the effects of PHEVs on electricity network is evaluated for İstanbul. For this purpose, the related data is obtained and the Monte Carlo simulation is applied to generate new daily load curve while considering the charging characteristics, driving characteristics and penetration level of PHEVs. Two different scenarios are defined with regard the time of charging: uncontrolled charging and off-peak charging. For each scenario, various cases are created by considering different percentages of battery sizes, different distribution of charger types, and risk perception of the vehicle owners. The new daily load curve is generated for 10% and 50% penetration levels of PHEVs. The changes in the daily load curve due to the additional demand from PHEV charging is analyzed for each scenario. According to the results, in particular with high penetration level, the electricity consumption increases significantly and new peak loads are created on the daily load profile.

Keywords: Plug-in hybrid electric vehicles, Monte Carlo simulation, load curve

Şarj Edilebilen Elektrikli Araçların İstanbul Yük Eğrisi Üzerindeki Etkilerinin Değerlendirilmesi

Seda EDİZ

Öz

Artan sera gazı emisyonu, fosil yakıtların tükenmesi ve yüksek petrol fiyatları son yıllarda dünyanın başlıca sorunlarından biri haline gelmiştir. Şarj edilebilen elektrikli araçlar (ŞEEA), ekonomik ve çevresel avantajlarından dolayı ulaşım sektöründe alternatif bir çözüm olarak ortaya çıkmaktadır. ŞEEA'ların bataryalarını şarj edebilmek için şebekeye bağlanma özelliği vardır. Bu nedenle, ŞEEA'lar sisteme dahil olduğunda elektrik şebekesi üzerinde oluşturacakları etkileri araştırmak gerekir.

Bu çalışmada, ŞEEA'ların İstanbul elektrik şebekesi üzerindeki etkileri değerlendirilmiştir. Bu amaçla, gerekli veriler elde edilmiş ve ŞEEA'ların şarj özellikleri, sürüş özellikleri ve yayılım seviyeleri dikkate alınarak yeni oluşan yük eğrisini elde etmek için Monte Carlo simülasyonu uygulanmıştır. Şarj etme zamanına göre iki farklı senaryo tanımlanmıştır: denetimsiz şarj ve yoğun olmayan saatlerde şarj. Her bir senaryo için, batarya boyutlarının farklı yüzdelikleri, şarj tiplerinin farklı dağılımları ve araç sahiplerinin risk algısı düşünülerek farklı durumlar oluşturulmuştur. Yeni yük eğrisi ŞEEA'ların ulaşım sektöründeki oranının %10 ve %50 olduğu durumlar için elde edilmiştir. ŞEEA'lardan kaynaklanan ek talebin, yeni yük eğrisi üzerinde oluşturduğu değişiklikler her bir senaryo için analiz edilmiştir. Sonuçlara göre, özellikle yüksek yayılım seviyesinde elektrik tüketimi belirgin bir şekilde artmış ve günlük yük eğrisinde yeni pik yükler ortaya çıkmıştır.

Anahtar Sözcükler: Şarj edilebilen elektrikli araç, Monte Carlo simülasyonu, yük eğrisi

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Chapter 1

Introduction

The petroleum consumption, greenhouse gas emissions, and climate change are major concerns of the world in recent years. The transportation sector is one of the main reasons for these problems as the conventional vehicles consume fossil fuels and emit pollutants. The electric vehicles are considered as an alternative solution for addressing environmental concerns since they consume electricity as an energy source. Therefore, the number of electric vehicles is increasing rapidly all over the world due to their environmental and economic advantages.

Plug-in Hybrid Electric Vehicles (PHEVs) are a type of the electric vehicles that have a grid connection capability to recharge their batteries. Despite the advantages of PHEVs, they raise concerns about the negative impacts on the electricity network. As number of PHEVs increases, additional electricity generation would be required for charging of PHEVs. Therefore, in order to investigate the additional electricity demand, the impacts of PHEVs on the load curve should be examined explicitly.

PHEV charging load profile is affected by many factors such as charging characteristics, driving behaviors, and penetration level of PHEVs. The charging characteristics include charging power level, battery size, and state of charge (SOC), which is a remaining energy in the battery. These factors affect the daily load curve since they determine the amount of electricity drawn per hour from the power grid. The driving characteristics depend on the vehicle owners' behavior and this factor includes the distribution of arrival times and distribution of daily driving distances. This impact factor plays an important role to determine time and location of charging and the amount of required energy based on daily traveled distance. The penetration level of PHEVs affects the additional electricity from the PHEV charging. These impact factors are incorporated into the model and their effects on the electricity load curve are investigated in this study.

On the top of these factors, conception of the risk is another important factor because it determines how often the batteries will be charged. Risk-averse people might charge their batteries every day regardless of the remaining electricity. On the other hand, risk-neutral or risk-seeking people might wait until the battery depletes. We also incorporate this behavior changes into our study and examine the effects of personal preferences.

In this study, Monte Carlo simulation is applied to simulate new daily load profile while considering impact factors mentioned above. Since PHEVs are a new technology, there are uncertainties regarding vehicle owners' behaviors such as timing of plug-in, charging location, and so on. Therefore, Monte Carlo simulation approach is an efficient method as it uses set of probability distributions associated with PHEV uncertainties. Different scenarios are defined with respect to impact factors considered and hourly electricity consumption is generated for each scenario and results are discussed under different penetration levels. In this thesis, İstanbul is considered as a case study and related data associated with impact factors are obtained for İstanbul.

In this thesis, two main scenarios with regard to charging time are considered: uncontrolled charging and off-peak charging. In uncontrolled charging scenario, there is no information provided to the customers or any incentive to shift their time of plug-in. On the other hand, in off-peak charging the charging period is restricted between 11 pm to 7 am in order to avoid higher additional load to the peak hours. For each scenario, we created four cases by considering the different percentages of the battery sizes, different distribution of charger types at homes, and different charging decision thresholds in order to see the differences in the new load profile due to the changes in these factors. According to the results, in most cases the uncontrolled charging strategy was the worst-case scenario since the electricity consumption increased significantly and new peak loads were created on the daily electricity load curve. As expected, the off-peak charging strategy was optimal charging since it shifted the PHEV charging to the low-load hours and reduced the peak loads.

1.1 Motivation

In recent years, carbon dioxide (CO_2) emissions from fuel combustion have been increasing significantly. The average CO_2 emission concentrations will be 44.1 Gt CO_2 by 2035, which is the 46% higher than the value in 2015. According to International Energy Agency (IEA) report, CO_2 emissions from transportation sector was 23% [2]. Air pollution problem caused by CO_2 emissions must be taken into consideration, especially in the metropolitan cities with a large number of vehicles.

Petroleum is the most common energy source for the vehicles with the internal combustion engine (ICE). Petroleum requirement increases day by day in the world. Dependency on foreign countries will increase in the near future as a requirement of petroleum increases. Turkey is one of the countries with the limited petroleum sources and it imports the crude oil from other countries. As petroleum import is a significant portion of total import in Turkey, the economy will be affected in the future.

Environmental concerns, petroleum dependency on foreign countries, and rising oil prices have fostered alternative energy source in the transportation sector. Electric vehicles (EVs) are accepted as a potential solution for these problems. They reduce environmental damage, as they do not emit CO_2 while driving. Additionally, EVs use electricity as an energy source and this feature of EVs reduces the requirement of petroleum. In addition, due to electric motor run quieter than internal combustion engine motors, noise pollution caused by EVs is much lower when compared to conventional vehicles.

EVs become widespread over the world due to all of the advantages that mentioned above. Most developed countries have started the policies in order to support the introduction of EVs. Turkey is one of the countries that support the EVs because of their economic and environmental advantages.

It is clear that the number of electric vehicles in the transportation sector will be increasing in Turkey. They consume the electricity as an energy source and so the additional electricity generation will be required for the electric vehicles. It is important to produce electricity from clean sources to avoid gas emissions. Therefore, the additional electricity from electric vehicles charging should be taken into account in order to investigate the negative impacts of electric vehicle on the power system. In this study, We would like to help the policy makers in managing the potential risks and determining the additional generation on the distribution grid.

Understanding the load curve changes is important in order to help the policy makers to shape the future of the electricity network. One of the purposes of the study is to provide a path to policy makers to develop a better plan to meet the additional electricity demand. By taking the findings of this study into consideration, they can see in which scenarios the electricity load curve changes respectively. Accordingly, they can provide incentives to vehicle owners for appropriate plans.

1.2 Contribution

With the integration of electric vehicles into the transportation sector in Turkey, the economic and environmental impacts, as well as the energy impacts, should be analyzed comprehensively. As electricity is drawn from the distribution network to recharge the battery, it is required to focus on impacts of PHEVs on the power grid. Some studies conducted to investigate the impacts of electric vehicles in Turkey, but there is no comprehensive study that evaluates the impacts of electric vehicles on electricity network in İstanbul, as a most crowded city in Turkey. In this study, new daily load curve for İstanbul, which is generated after adding the PHEV charging demand, is analyzed explicitly.

In the literature, the daily load profile is investigated with considering the impact factors such as driving behaviors, charging characteristics, and penetration level of electric vehicles, but the conception of risk is not considered in the studies. The personal preference is one of the important factors that affect the load curve. This is one the first studies that incorporate the risk perception of the vehicle owners into the study.

In this study, we created various cases by determining the different percentages of battery sizes, different distribution of charger types at homes, and different charging decision thresholds. Although there are some studies that consider the effects of battery sizes and charging power level, different distribution of these factors are not considered. To the best of our knowledge, this is the first study that consider all of these factors with different distributions at the same time.

1.3 Thesis Outline

In the first chapter of Chapter 2, types of electric vehicles with their advantages, available electric vehicles in the world, country incentives for the introduction of electric vehicles, and the electric vehicle technology in Turkey are presented. Section 2.2 includes the brief definition the impact factors of PHEV charging, which are charging characteristics, driving characteristics, and penetration level. A literature review is provided in Section 2.3.

Chapter 3 begins by presenting the related data for İstanbul, which is used to generate new daily load profile. In the second section, the Monte Carlo simulation method is defined and simulation algorithm flow that used in this study is explained comprehensively. Then the simulation results under two charging scenarios are given for 10% and 50% penetration levels. The last section presents the conclusion of the study and future work.

Chapter 2

Background and Literature Survey

This chapter includes three sections. The first section provides general information about the electric vehicles (EVs). In the second section, the impact factors, which are taken into account in order to investigate the daily charging demand when Plug-in Hybrid Electric Vehicles (PHEVs) are integrated into the electric grid, are explained in more detail. Finally, the literature survey on impacts of PHEVs on the electricity grid and a detailed summary of the studies is given in the last section.

2.1 Electric Vehicles

Electric vehicles (EVs) have one or more electric motor instead of internal combustion engine for propulsion. In terms of energy conversion, there are four types of electric vehicles: Hybrid Electric Vehicle (HEV), Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicle (FCEV), and Plug-in Hybrid Electric Vehicle (PHEV).

HEVs have an internal combustion engine (ICE) and battery to propel the vehicle. Once the battery is depleted, a conventional engine takes over. Since hybrid electric vehicles use both gasoline and battery, their range is not limited. On the other hand, HEVs are not able to charge their batteries from the power grid externally.

BEVs only use the battery as an energy source. Different from the hybrid electric vehicles, battery electric vehicles do not have any internal combustion engine and so their range is limited. Moreover, the battery of BEVs can be charged from the electricity grid.

FCEVs have fuel cells instead of a battery in order to power their electric motor. FCEVs generate electrical energy through chemical reaction by using oxygen from the air and hydrogen. FCEVs produce only water and heat, thus the tailpipe emissions are not created.

PHEVs combine the advantages of HEVs and BEVs. They use both electric motor and internal combustion engine as a power source for propulsion. The PHEVs have a similar structure with HEVs but they can also recharge their batteries from the power outlet. Since PHEVs have much larger batteries than conventional HEVs, they are able to drive 20 to 60 miles solely on electric mode without recharge their batteries [3].

PHEVs operate in two modes: charge-depleting (CD) and charge-sustaining (CS) mode. In the charge-depleting mode, the vehicle uses the electricity in the battery as an energy source and then the vehicle consumes gasoline under charge sustaining mode if the minimum state of charge is reached [4].

2.1.1 Advantages of Electric Vehicles

EV technology has potential advantages in different areas such as an economy, energy, environmental, and politics. Emissions from the conventional vehicles, which are due to combustion of fossil fuels, are a significant portion of the total emissions. Since EVs do not produce gas emissions while driving in all-electric mode, they have a potential to reduce greenhouse gas emissions, which has a impact on global warming. However, EVs produce zero emission if the electricity is generated from clean resources. Therefore, the emission caused by both electricity generation and tailpipe should be taken into account in order to investigate emission impacts of EVs. In addition, due to electric motor run quieter than internal combustion engine motors, noise pollution caused by EVs is much lower when compared to conventional vehicles.

Petroleum is the most fundamental energy source in the transportation sector. Due to the rapid increase in the requirement of petroleum in the world, EVs are a solution to reduce consumption of fossil fuels. Using electricity as an energy source provides to reduce fuel cost in the transportation. In addition, a reduction in petroleum usage offers to reduce dependency on imported oil. High efficiency and low maintenance cost are also the advantages of EVs.

The total number of EVs in the automobile industry has increased due to several advantages of EVs. On the other hand, EVs have some challenges such as high initial cost, inadequate infrastructure, and lack of charging stations. Therefore, the automobile manufacturers and governments play an active role to incentive the vehicle owners for the introduction of EVs.

2.1.2 History of Electric Vehicles

Electric vehicles are not a new invention in the transportation sector. In fact, first experimental electric vehicles have appeared on the roads in the USA, UK, and the Netherland in the 1830s. Development of batteries improved the electric vehicle technology during the same era. In 1859, Belgian Gaston Planté invented the first lead-acid battery cell, which is still used in as a battery in most electric vehicles and in all internal combustion engine (ICE) vehicles. In 1901, Thomas Edison developed the more efficient nickel-iron battery, which stores 40% more energy per weight than the lead battery but the production cost of the nickel-iron battery was very high [5].

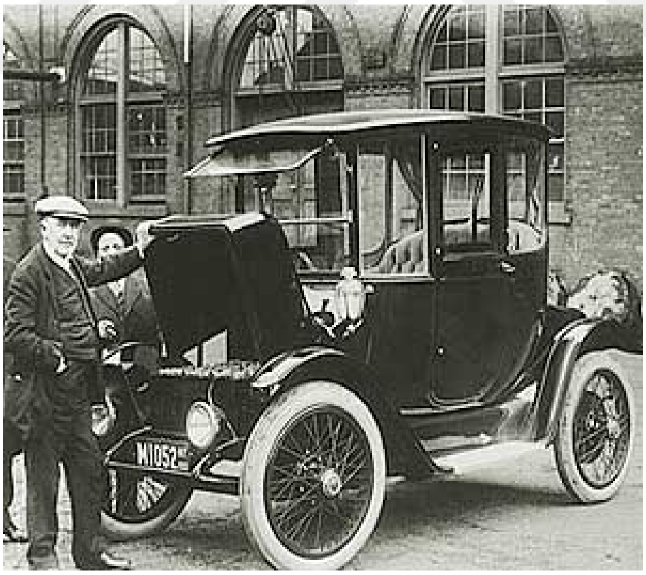

Figure 2.1: First electric cars [6]

In the golden age from 1880 to 1900, important technological developments, which still form the basis for electric vehicle technology, were achieved. Electric vehicles gained popularity in the golden age. Many hybrid and battery electric vehicles were produced by different car manufacturers and individuals in the early 1900s. Ferdinand Porsche developed the first hybrid electric vehicle in this period [7]. However, ICE vehicles dominated in the car industry until 1990s due to the high production of electric cars, reduction of oil prices, and weight of an electric vehicle.

In recent years, electric vehicles become popular again and they are supported by politicians due to air pollution caused by conventional vehicles and increasing oil prices.

2.1.3 Electric Vehicle Market Over the World

After electric vehicles gained their popularities again, many popular car manufacturers like Toyota, Ford, Honda, Tesla, and Nissan produced their EV models. Toyota Prius is the first HEV produced in 1997. Chevrolet Volt and Nissan Leaf introduced their PHEVs and they dominated the market in 2011. Tesla, BMW, and Honda are also among the most widely used electric vehicles in the world.

In Table 2.1, some available electric vehicles over the world are shown, data was obtained from company's websites [8–14].

Table 2.1: Some available electric vehicles over the world

Model	**Battery Capacity**	**Battery Type**	**Range**
Nissan Leaf (EV)	30 kWh	Lithium-ion	107 miles
Chevrolet Volt (PHEV)	18 kWh	Lithium-ion	53 miles with electric 420 miles in total
Tesla Model S (EV)	100 kWh	Lithium-ion	315 miles
BMW i3 (EV)	33 kWh	Lithium-ion	114 miles
BMW i8 (PHEV)	7 kWh	Lithium-ion	25 miles with electric 330 miles in total
Mitsubishi iMiev	16 kWh	Lithium-ion	62 miles
Kia Optima (PHEV)	10 kWh	Lithium-ion polymer	29 miles with electric 660 miles in total

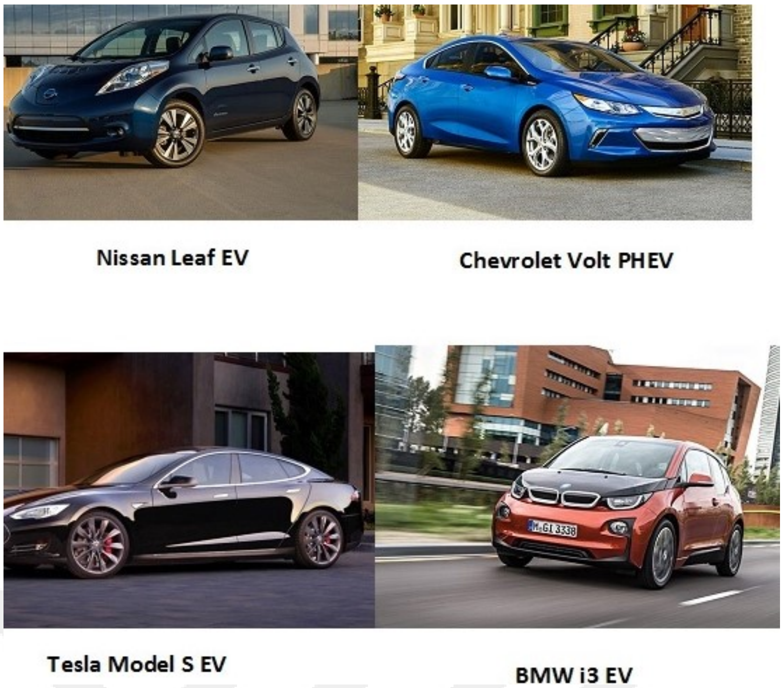

FIGURE 2.2: Some important electric vehicles produced by popular car manufacturers [15]

The penetration of electric vehicles is rapidly increasing in the world. According to the International Energy Agency (IEA) report, the number of electric vehicles was 1 million in 2015 and 2 million in 2016 [1]. Even though that doubled, the number of electric vehicles is only 0.2% of the total vehicles.

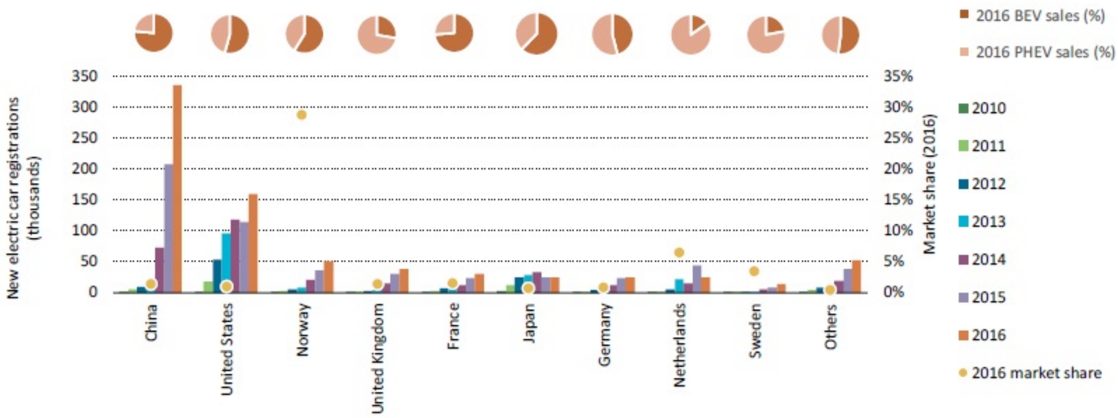

FIGURE 2.3: Electric vehicle sales and market share in selected countries [1]

In Figure 2.3, electric vehicle sales and market share in different countries were depicted. In the IEA report, market share is defined as the penetration of electric vehicles in the total of all light-duty vehicles. Norway has the highest market share (with a 29%) in the world according to 2016 records. Netherlands follows this rate with 6.4% market share. In 2016, electric vehicle sales in China were more than 40% of electric vehicles sold in the world and China overtook the United States which has the largest electric vehicles market in 2015. China ranked the largest electric vehicle market in the world in 2016 with 336 thousand new electric vehicles [1]. It is clear that the penetration of EVs will increase rapidly in the upcoming years and achieve a significant value. According to government targets, the number of electric vehicles is expected to have a range from 9 million to 20 million by 2020.

Most developed countries support the introduction of EVs due to their environmental and economic advantages. In Table 2.2, incentives such as rebates, exemptions, and tax breaks in different countries were provided.

Table 2.2: Current EV support policies in some countries [1]

Country	Incentives
China	Exemption for excise tax based on engine price 20% reduction in 2016 subsidies Free charging and free parking
Denmark	Exemption for registration tax Purchase tax rebate based on battery capacity
France	Bonus scheme for PHEVs based on CO_2/km when returning a diesel vehicle Exemption for electricity and hydrogen tax
Germany	EUR 4000 in purchase rebates for BEVs and EUR 3000 for PHEVs Ten-year tax exemption Tax rebate for company vehicles Special plates for EVs Free charging and free parking
Japan	Purchase support based on battery capacity and range (JPY 850 000) Access to restricted traffic
Netherlands	Registration tax exemption for BEVs, EUR 6 CO_2/km for PHEVs in 2016 50% discount on ownership tax for PHEVs and exemption for BEVs
Sweden	SEK 20000 purchase reduction for BEVs and SEK 40000 for PHEVs Five-year annual tax exemption for EVs Tax rebate for company vehicles
United Kingdom	Purchase support based on zero-emission range Excise duty exemption for BEVs and reduction for PHEVs, tax rebate for company cars GBP 600 million for supporting low emission vehicles adoption
United States	Corporate Average Fuel Economy (CAFE) standard for EVs Mandates of zero-emission vehicle production in nine states Purchase tax rebate and exemption for registration tax

2.1.4 Electric Vehicle Market in Turkey

Mitsubishi i MiEV, which is the first electric car to be offered for sale, was introduced to Turkey within the scope of the Japanese year in 2010. At the end of 2011, Renault Fluence Z.E model was introduced to Turkish electric vehicle market but the company stopped the sale of this model due to insufficient demand in 2014. However, Renault was offered the new electric vehicle models, Twizy and Zoe for sale. Besides, the other popular car brands such as Tesla, BMW, Opel, and Toyota introduced their electric vehicles to Turkey.

According to the Turkish automotive market reports published by Turkish Automotive Distributers' Association, 44 electric vehicles have been sold in 2016 while 120 electric vehicles have been sold in 2015 [16]. Compared to developed countries, electric vehicle sales are very low in Turkey. Therefore, the Turkish government has started the policies in order to increase the penetration of EVs in the transportation sector. Additionally, some universities and institutions have focused on researches for developing EV technologies.

In 2011, Turkish government applied the discounts on excise duties applied in car sales by the decision of Council of Ministers. According to tax regulation, the electric cars were classified based on their power of the electric motor and an excise duty was applied with a minimum of 3% and a maximum of 15% [17].

The Scientific and Technological Research Council of Turkey (TUBITAK) invests the projects about EVs in order to improve research and development (R&D) support for electric vehicles. TUBITAK developed the 'Electrical Vehicle Development Platform' in 2012 and the council is continuing studies on electric vehicles [18].

2.1.5 Charging Stations in Turkey

Constructing the charging infrastructure is an important issue for the plug-in hybrid electric vehicles. In Turkey, both government and private companies construct the charging points in order to improve the charging infrastructure. BD automotive and Eşarj are the most important companies that construct the charging stations in Turkey. BD automotive has total 41 charging points and 39 of them are located in İstanbul [19]. In Figure 2.4, charging station points in Istanbul constructed by BD automotive are shown.

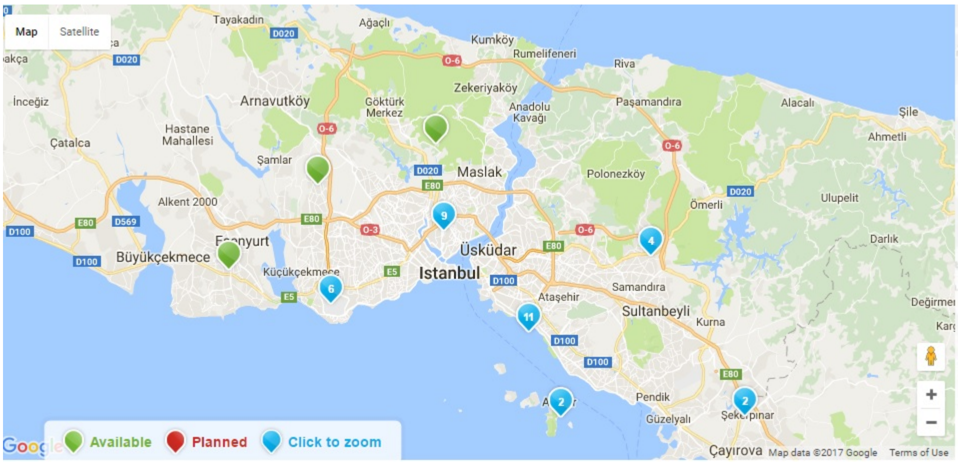

FIGURE 2.4: BD Automotive charging station points in İstanbul [19]

Another private company Eşarj has 101 charging stations with 162 vehicle capacities in Turkey [20]. Most of these charging points are located in shopping malls. Besides, there are charging stations in universities, hotels, and parking areas.

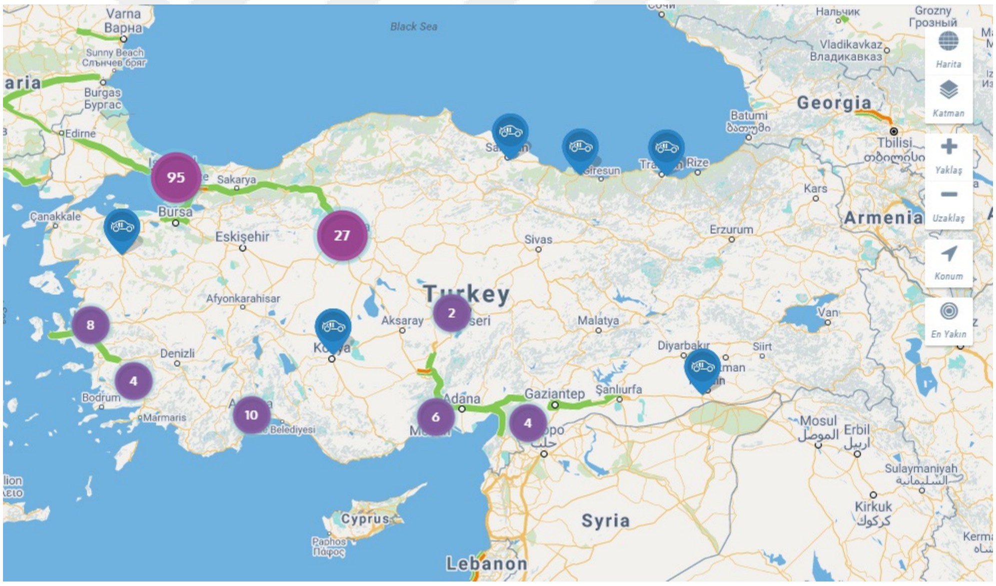

FIGURE 2.5: Eşarj charging station points in Turkey [20]

İstanbul Metropolitan Municipality (IBB) supports the spread of electric vehicle charging stations to improve the infrastructure. There are available charging stations constructed by the municipality in different districts of İstanbul such as Avcılar, Çamlıca, Florya, Şişli and so on [21]. Even though the existing charging points are sufficient now, the number of charging stations should be increased when the EVs become widespread in the up coming years in Turkey.

2.2 Impact Factors

PHEVs are a type of electric vehicles that have a grid connection capability. As the number of PHEVs increases, negative impacts on distribution network could occur. In order to mitigate the negative impacts of PHEVs, understanding of additional demand and new peaks on the load curve is necessary.

PHEVs charging patterns should be analyzed to generate new daily load curve. The load increase when the PHEVs are charged from the grid is affected by many factors, such as charging characteristics, driving characteristics, and penetration levels of PHEVs. When and where the charging will occur, how much electricity is drawn from the power grid and how many electric vehicles will be charged have significant impacts on PHEVs charging patterns. These impact factors must be taken into consideration in order to generate the new daily charging demand. In the following section, these aspects are explained in more detail and some definitions are provided.

2.2.1 Charging Characteristics

The charging characteristics of the PHEVs can be considered as the loading characteristics. These characteristics relate to power system structure or the features of PHEVs such as battery type. Since there are different types of batteries and the vehicle owners would charge their PHEVs with different power levels, the charging characteristics which includes PHEV charging power levels, battery size, and state of charge (SOC), which is a remaining energy in the battery, play an important role in determining the load increase on the electricity grid for unit time and the amount of time required for charging. Therefore, it is necessary to comprehensively examine the charging characteristics.

2.2.1.1 Charging Power Level

The charging power level has high importance to determine the power demand for PHEVs and this factor also affects the required time duration to recharge the battery pack.

The various charging power levels are specified according to voltage and current ratings and the charging power levels determine the amount of load added to the electric grid.

The SAE J1772 (Society of Automotive Engineers) determines two power levels for AC (alternating current) and three power levels for DC (direct current) to be used in the studies to investigate the effects on the power grid, as shown in Table 2.3.

TABLE 2.3: PHEV charging power level

Type	Voltage	Power Current	Power Level
AC Level 1	120V	15A	1.4 kW
AC Level 1	120V	20A	2 kW
AC Level 2	240V	30A	6 kW
DC Level 1	200-450V	80A	36 kW
DC Level 2	200-450V	200A	90 kW
DC Level 3	200-600V	400A	240 kW

There are two types of battery chargers, which are on-board and off-board chargers according to the location on the PHEV. An on-board charger is a charger located on the vehicle while an off-board charger is placed outside the vehicle. The vehicle with on-board charger plug into the AC (alternating current) supply network and the battery pack is charged slowly with this method [22]. In alternating current (AC), the power flow is a bidirectional. In the bidirectional charging system, the PHEVs can be charged from the grid and the battery energy loaded back to the grid. On the other hand, the direct current (DC) is the unidirectional power flow and the flow of charging has an only one direction. The off-board charger is connected the DC (direct current) supply network and the vehicle is charged as fast as possible. Therefore, the on-board charger is applicable for residential areas while the off-board charger is used in public stations.

International Electrotechnical Commission (IEC) and SAE J1772 (Society of Automotive Engineers) determine the charging modes for the studies on the impact of PHEVs on the grid. These modes are summarized below.

AC Level 1 Charging: This mode of charging is rated at 120V with an either 15A or 20A current ratings and the load added would be about 1.4 kW and 2 kW, respectively. The time required for charging is prolonged since the Level 1 method creates a small amount of load per unit time. The battery pack can be charged in 8 to 20 hours with using AC Level 1 mode depending on the battery capacity and state of charge (SOC) [23]. The applicable locations for this charging mode are residential buildings. Additionally, the existing infrastructure is adequate and no special equipment is necessary for the Level 1 method.

AC Level 2 Charging: It uses a 240V outlet with 30A current rating. The amount of load added to the grid would be 6 kW by using the Level 2 charging method. The amount of time required to fully recharge the battery is low for this charging mode compared to the Level 1 charging method. Level 2 method requires 3 to 8 hours depending on the state of charge (SOC) and the battery capacity of the vehicle [23]. This mode of charging is suitable for residential and commercial areas. Compared to the Level 1 charging, Level 2 charging is preferable since it does not take long hours. However, the additional infrastructure with special equipment is necessary for this charging method.

DC Charging: This type of charging operates with between 200V and 600V. The DC charging has a maximum current level of 400A. The load added to the grid is up to 240 kW depending on the voltage and power current. This mode of charging is designed for public charging stations with high voltage. The charging time can be less than 30 minutes depending on the battery capacity and the state of charge (SOC) in the DC charging. The DC charging has a potential to increase the peak demand since the amount of load added to the grid per unit time is very high.

The PHEVs charging levels vary depending on the power system standards for the different countries [24]. In Belgium, the power standard is rated at 240V and 4.6 kW [25]. According to North America, the charging power levels are defined as the SAE J1772 (Society of Automotive Engineers) [24]. Based on Australian Standard, the charging power levels operate at 240V with an either 5 or 10 amperes current ratings and the load are 1.2 kW and 2.4 kW, respectively [26]. In Turkey, there are four charging levels based on voltage and current, which are 3.7 kW (230V, 16A), 7.4 kW (230V, 32A), 11 kW (380V, 16A), 22 kW (380V, 32A) [27].

2.2.1.2 Battery Size

The companies manufacture the PHEVs with a different battery sizes in the market. Since the vehicle owners would have different types of PHEVs from the various companies, the distribution of different sizes of batteries should be taken into account to see the potential impacts of PHEVs to the grid.

The size of the battery plays an important role on the amount of time required for recharging and the frequence of charging. Therefore, it is very crucial to consider the battery capacity to investigate the load increase on the electricity grid.

There are different types of PHEVs based on the capacity of the battery. Plug-in Hybrid Electric Vehicles are specified by 'PHEVx' notation, where x denotes the miles, which the vehicle drives in all-electric range (AER) [28]. In other words, 'PHEVx' can drive 'x' miles on electricity mode without a recharge. From this definition, PHEV20 travels 20 miles (32km) and PHEV60 travels 60 miles (96 km) using the battery alone before the secondary energy source, such as an internal combustion engine is used. The PHEVs with different miles of AERs are considered in the literature.

Electric Power Research Institute's (EPRI's) Hybrid Electric Working Group has conducted many studies on PHEVs issues. Since automobile manufacturers produce PHEVs with various battery size, it is not possible to consider all of the different battery sizes in the studies. Therefore, some calculations used by EPRI has been taken as reference in the literature. Detailed information about these calculations can be found below.

EPRI has categorized the energy consumption per mile for different types of PHEVs in 2001, as shown in Table 2.4 [29].

Table 2.4: Electrical energy consumption for different vehicle types

Vehicle Type	**Energy Consumption [kWh/mile]**
Compact Sedan	0.26
Mid-size Sedan	0.30
Mid-size SUV	0.38
Full-size SUV	0.46

As mentioned above, AER is the expected miles driven with solely electrical energy. The battery capacity for the PHEVs with different AER is calculated as,

$$BC = AER \times EC \tag{2.1}$$

where BC is the battery capacity and EC is the energy consumption per mile.

Referring to Equation 2.1, the battery capacity for PHEVs with AER of 20, 30, and 40 miles is shown in Table 2.5.

TABLE 2.5: Battery capacity for different PHEVs (kWh)

Vehicle Type	PHEV20	PHEV30	PHEV40
Compact Sedan	5.2	7.8	10.4
Mid-size Sedan	6	9	12
Mid-size SUV	7.6	11.4	15.2
Full-size SUV	9.2	13.8	18.4

As noted earlier, battery capacity and charging power level affect the length of charging time and frequence of charging. In Table 2.6, the power requirements and the amount of time needed for four types of PHEV20 have been calculated with using the battery capacities given in Table 2.5. The voltage rating was considered 120 V with the current level of 15 A. When considered the charging power levels, these ratings correspond to AC Level 1 charging mode and the load added to the grid would be 1.4 kWh as shown in Table 2.3. The charging efficiency was assumed to be 90% in order to evaluate the total demand. By dividing the total demand by 1.4 kW, the time needed for fully charging the PHEV was calculated. In [3], the charging schedule for PHEV20 is provided for the efficiency of 85%.

TABLE 2.6: Power requirements for different types of PHEV20 at 120V/15A

	Hour								
Type of PHEVs	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	
	Power Requirements (kW)								**Total Demand (kWh)**
Compact sedan	1.4	1.4	1.4	1.4	0.2	0	0	0	5.8
Mid-size sedan	1.4	1.4	1.4	1.4	1.1	0	0	0	6.7
Mid-size SUV	1.4	1.4	1.4	1.4	1.4	1.4	0	0	8.4
Full-size SUV	1.4	1.4	1.4	1.4	1.4	1.4	1.4	0.4	10.2

As shown in Table 2.6, higher battery capacity increases the power demand and also the time required for charging. According to the levels of voltage and current ratings, time needed to recharge the battery would increase or decrease. Additionally, the battery capacity is an important factor in determining how many times the PHEVs will be charged.

As seen in Figure 2.6, the charging profile is obtained for each type of PHEV20 with respect to different voltage and current ratings.

It can be easily figured out that, a higher level of voltage and current increase the amount of electricity drawn from the grid per unit time and this could increase the overall peak. Additionally, the charging is completed with the partial charge in the final hours.

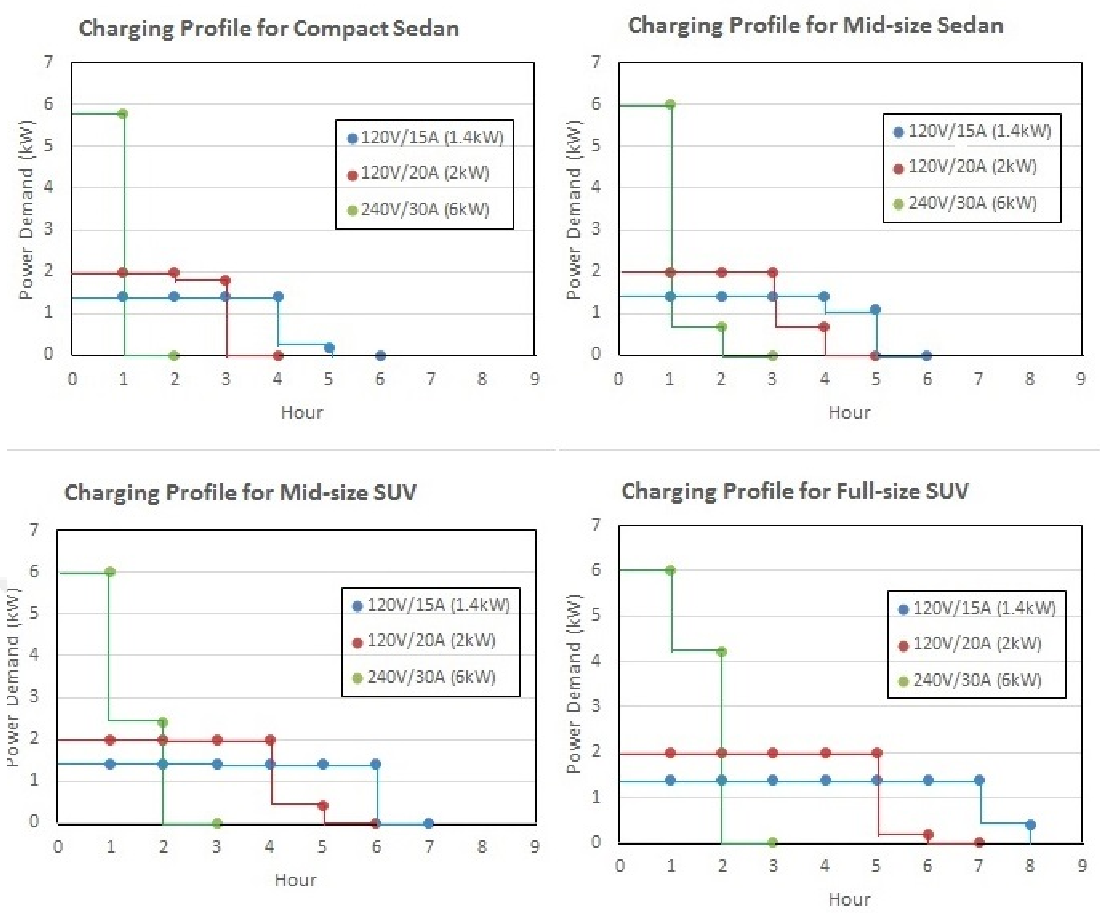

FIGURE 2.6: Hourly demand at various charging power levels for different types of PHEVs

2.2.1.3 State of Charge

State of charge (SOC) indicates the percentage of remaining energy in the vehicle battery when the PHEVs arrive the place where the charging will occur.

SOC is calculated based on the daily driven mileage and the AER of the PHEV. SOC of PHEV is expressed as:

$$SOC = \begin{cases} 100.(1 - \dfrac{d}{AER}), & d \leq AER \\ 0 & d > AER \end{cases} \tag{2.2}$$

where AER is the all-electric range of PHEV and d is the total distance traveled. When d reaches the AER, SOC will be zero and the secondary fuel will be used.

SOC of PHEV determines the amount of required energy to recharge the battery. Therefore, it is important to know the remaining energy of the battery after the last trip in order to calculate the electrical energy drawn from the grid.

The required energy to fully charge the battery is calculated as:

$$RE = (1 - SOC).BC \tag{2.3}$$

where RE is the required energy and BC is the battery capacity of the vehicle.

As an example, consider the mid-size sedan with PHEV30. So, this type of PHEV can drive 30 miles in AER. According to Table 2.5, the battery capacity of the mid-size sedan with PHEV30 is 9 kWh. Assuming that the number of daily miles driven by this vehicle is 15 miles, SOC is calculated as 100.(1- 15/30)=50 by using Equation 2.2. Thus, this vehicle would have SOC of 50% after the last trip. The required energy to fully charge the battery would be (1- 50/100).9=4.5 kWh by using Equation 2.3.

Many vehicle owners will not begin to charge their vehicles with the SOC of 0% when they arrive the charging places. Also, the PHEVs can be disconnected before the battery reaches the full charge. These cases are important, but some studies did not consider these scenarios, they assumed the PHEVs will be charged from no charge to full charge.

2.2.2 Driving Characteristics

The driving characteristics depend on the vehicle owners' behavior. It is important to know this impact factor to provide information about the when and where the PHEVs will be charged. The driving characteristics are analyzed under two titles, which are the distribution of the arrival times and distribution of daily driving distances. The average daily miles driven are also explained under the title of distribution of daily driving distances.

The driving characteristics must be examined in order to determine where the vehicle owners will charge their vehicles, how often the vehicles will be charged, the amount of load added to the grid and the time at which the PHEVs will introduce the additional load at the daily load curve.

In the literature, residential areas, workplaces, shopping malls, and the public charging stations are considered as charging places and the analyses are performed considering these locations.

The following section covers more information about the driving characteristics.

2.2.2.1 Distribution of Arrival Times

The distribution of arrival times in different places such as home, workplace, or a shopping mall is crucial in order to know the starting of charging time and the charging location.

The PHEV charging time cannot be estimated exactly, but the potential hours at which the vehicle owners would charge their PHEVs can be determined by using the distribution of arrival times. Therefore, the distribution of arrival times plays an important role to investigate the changes in load curve. Additionally, the place of destination provides information about where the charging will occur.

The distribution of arrival times is directly related to driving behaviors. Thus, the driving characteristics differ based on weekends and weekdays. At weekdays, most of the people return their homes after the working hours. On the other side, at weekends, they prefer to spend time at shopping malls or stay their homes. Also, there is a difference between the distribution of arrival times in summer and winter seasons.

2.2.2.2 Distribution of Daily Driving Distances

The daily driving mileage is related to the vehicle usage of the owners and the distance between the place of departure and destination in the vehicle owners' daily drive. The number of miles driven by PHEV determines the SOC based on the battery capacity. The distribution of daily driving distances plays an important role to examine the amount of electrical energy drawn from the power grid. Also depending on the battery capacity, the number of miles traveled has an importance to determine frequence of charging. Thus, the battery size, SOC of PHEV, and daily miles driven are interrelated and they affect the amount of electricity required to recharge the vehicle.

Since the driving patterns are different at weekends and weekdays, the average daily miles driven is also different based the weekends and weekdays. Therefore, this factor should be considered to investigate the new daily load curve.

2.2.3 Penetration levels

The penetration level of PHEVs is one of the important factors in order to investigate the amount of load added to the grid. Increasing the penetration level of PHEVs will affect the power system and will increase the total electricity required on the grid. High penetration level may create new peak loads on the load curve and also the additional electricity capacity may be required for the high level. Thus, the different penetration levels of PHEVs must be examined in order to generate the new daily load curve.

In many countries, the projections about the penetration levels of PHEVs were published and the impacts of the PHEVs on the power grid are analyzed referring to these projections in many studies. Some studies made assumptions about the penetration levels of PHEVs since these types of vehicles are new in the transportation sector.

In Turkey, the studies made some assumptions for the number of PHEVs in the future. For example, in [30], prediction of the number of light-duty vehicles for İstanbul from 2011 to 2020 was calculated first and then the number of electric vehicles was obtained for the penetration level cases of 2%, 5%, and 10%.

2.2.4 Personel Preferences

In addition to all the impact factors mentioned above, it is also necessary to consider the human factor to examine the effect of PHEVs on the power system. Impact factors of PHEVs could change based on personal preferences.

PHEV owners who have the same daily driving distances could prefer different battery sizes and this decision may have a different effect on the electricity network. Furthermore, vehicle owners could arrive the home at the same time but they may start the charging in different hour. Also, they could prefer the different charging location for charging and so the charging power level, which is one of the impact factors, may change. Even though, PHEV owners have same driving patterns, same battery capacity or same arrival times, their personal preferences will have different impacts on the power system. Therefore, this factor should be taken into consideration in order to analyze the impacts of PHEVs on the distribution grid.

On the top of these changes in personal preferences, conception of the risk is another important factor. The vehicle owners could have same daily driving distances and same remaining energy in their battery at the end of the day but they have different decisions for charging the vehicles. Risk-averse people might charge their batteries every day regardless of the remaining electricity on the battery. On the other hand, risk-neutral or risk-seeking people might wait until the battery depletes. Therefore, conception of the risk plays an important role on the electricity load curve.

2.3 Related Work

In the literature, there is a extensive resource about impacts of PHEVs. After a detailed literature review, related works conducted energy impacts of PHEVs on distribution network are summarized in this section. While several studies apply the simulation method, some studies develop new methods to analyze electricity consumption of PHEVs. Many authors have focused on scenario analysis in which different assumptions and impacts factors are considered. Few studies about the economic and emission impacts of electric vehicles are also reviewed in this section.

Chen *et al.* [31] applied the Monte Carlo simulation in order to analyze the daily charging demand of EV in Taiwan. The characteristics of both vehicle and driving were taken into account to generate the daily load curve. The penetration levels were assumed to be 7.5%, 16%, 24.5% and 33% for the total 600,000 private vehicles and four different places, which are home, charging station, workplace, and shopping mall were considered as charging locations. The Monte Carlo method was used with 50,000 iteration and the new daily load curves were provided.

Jung *et al.* [32] also used the Monte Carlo method with 1,000 iterations to obtain daily load profile of PHEV. In this study, it is assumed that the vehicle owners charge their batteries from no charge to fully charge once a day when they return home from work. This scenario was considered as a worst-case scenario. The penetration rates were considered as 36% and 52%, which the PHEVs could reach by 2020 and 2030 respectively.

Weiller [33] studied the impacts of PHEVs on electricity demand for various scenarios. The simulation algorithm in Matlab was proposed to get daily load profile. Three different scenarios were determined according to different charging places, which are home, workplace, and shopping mall. Three charging power rates were considered and the PHEV load profiles were produced for each scenario with the different power levels. The sensitivity analysis was also developed according to the vehicle age, vehicle type, weekend-weekday and urban-rural regions.

Zhang *et al.* [34] developed the simulation model in Matlab to examine the electricity consumption of electric vehicles. For this purpose, both vehicle and charging parameters were used in the simulation model and the new load curves were illustrated with considering different charging scenarios. In this study, battery capacities varied from 1 kWh to 10 kWh and the charging power levels were considered as 1.44 kW, 2.88 kW, 4.32 kW, 5.76 kW, and 7.2 kW. Three scenarios were defined based on charging time; immediate charging, delayed charging, and average charging. In the immediate charging, vehicle owners charge their batteries as soon as trip ends. The charging start time is delayed in the delayed charging scenario and the charging is finished at the starting of the next trip. In the average charging scenario, vehicle owners recharge their batteries with the minimum power rate. According to parameters and charging scenarios, the electricity consumption was calculated. The PHEV load profiles were obtained and the peak hours were analyzed for each scenario.

Parks *et al.* [35] used the simulation method in order to estimate the energy consumption of PHEVs. The additional load curve was calculated and this curve was added to the native load profile. In this study, a midsize PHEV20 was chosen as an electric vehicle and it was assumed that the electric vehicle was recharged once a day. Four different charging scenarios were determined. The impacts of the electric vehicles on the grid were analyzed by considering the new daily load curves produced for each scenario. The uncontrolled charging case was considered as a worst-case scenario. In this case, the PHEVs can be charged only at home with the power level of 1.4 kW. It is assumed that the vehicle owners recharge the batteries to fully charge. There is no restriction or incentive about the charging time in this scenario. In the delayed charging case, vehicle owners recharge their batteries at home only with the rate of 1.4 kW. Unlike the first scenario, the start time of charging is delayed to 10 p.m. This helped to optimize the energy consumption. The charging occurs at home only in the overnight hours with the rate of 3.2 kW in the off-peak charging case. The charging starts after 11 p.m. and ends until 7 a.m. In the continuous charging case, vehicles are charged at home and public stations with the charging rate of 1.4 kW.

The study of Darabi [36] is about analyzing PHEV charging load profiles under three charging policies. For this purpose, the transportation data was obtained from the National Household Travel Survey, which includes detailed data about transportation in the United States. The driving characteristics are derived from this data source. The vehicle characteristics and the charging levels were also considered as impact factors and the load curves were provided regarding these factors. The new load profiles were obtained for 40,000 vehicles and PHEV20, PHEV30, and PHEV40 vehicle types were taken into account for each load curves.

The author of [37] investigated the impacts of PHEVs on a residential distribution network. Chevy Volt was selected as an electric vehicle and the battery characteristics of this vehicle were used in this study. Two different charging strategies, which are normal charging with the low power level and quick charging with the high power level, were taken into account in order to evaluate the load profiles. Two scenarios were also developed. In the first scenario, the charging starts at 6 pm while the vehicles are charged at off-peak hours in the second scenario. The daily load curves were obtained under these scenarios with considering the different penetration levels.

The effects of PHEVs in different regions were examined in [38]. The author analyzed how the load curve affected when the charging power level and the charging time changed. The potential PHEV market share was evaluated for each region and the additional electricity demand was estimated with considering the different PHEV penetration levels. Results showed that some regions may need additional capacity to meet the new demand with evening charging of PHEV.

Clement *et al.* [25] discussed the charging impacts of PHEVs on the Belgium distribution network. The load profiles, as well as the power losses and voltage deviations, were obtained under three different uncontrolled charging scenarios. For these scenarios, charging periods are between 9 pm - 6 am, 6 pm - 9 pm, and 10 am - 4 pm respectively. The penetration levels of 0%, 10%, 20%, and 30% were taken into account and the results were shown with these four penetration levels. In this study, both deterministic and stochastic analysis were applied and the results from these analyses were compared.

The effects of the PHEVs on the distribution system in Stockholm were analyzed in [39]. Three distinct areas with different load profiles in Stockholm were selected. For each area, the additional electricity consumption was estimated for different penetration levels under two charging scenarios: unregulated and regulated charging. In the unregulated charging, there is no restriction for charging time or incentives about the electricity prices while the vehicle owners have an information about the electricity price in the regulated charging. In order to generate daily load curves, PSS/E (Power System Simulation Engineering) software was applied in this study. It was concluded that the development is needed for the pure residential area if the large penetration level of PHEVs is introduced.

Kintner-Meyer *et al.* [29] investigated the grid impacts on the power system as well as the emission impacts on the plant when the PHEVs will be introduced to the U.S. transportation sector. The upper limit of the PHEV penetration level supported by existing infrastructure was determined in this study.

An analysis of economic assessment of PHEV was taken into account in [40]. In order to analyze economic benefits, the life cycle cost (LCC) analysis of PHEVs was performed and compared it with the life cycle cost analysis for the conventional vehicles.

Yu [41] studied the impacts of PHEVs on generation expansion. In this paper, national energy modeling system (NEMS) software was used to predict the impacts of PHEVs on generation expansion. Four different charging strategies at high penetration level were considered, which are uniform charging, home-based charging, off-peak charging, and vehicle-to-grid (V2G) charging. It was concluded that all charging strategies require new sources of power generation plants while the V2G charging method needs a smallest electric capacity expansion and smallest infrastructure payment.

Roe *et al.* [42] researched the system level impacts of PHEVs using analytic PHEV model and vehicle simulation model. Two simulation scenarios were examined: a base case with no PHEVs and case with 10% and 20% PHEVs. The additional power demand was calculated and analytic model results and simulation model results were compared. The emission impacts were also investigated for each scenario in this study.

Yağcıtekin *et al.* [30] investigated the energy, environmental, and economic impacts of electric vehicles in İstanbul, Turkey. The prediction of electricity consumption was presented for 2%, 5%, and 10% penetration level cases. Results showed that energy consumption of electric vehicles in İstanbul will not be negligible. In this study, total energy consumption of electric vehicles was discussed, the daily load curve for İstanbul was not performed. Reductions in carbon dioxide (CO_2) emissions for different charging levels and economic benefits were also examined in this study.

Another study conducted to analyze the impacts of PHEVs in Ohio power system under two charging scenarios: controlled and uncontrolled charging [43]. In controlled charging, the system operator has a control about the time of charging, while there is no restriction about the charging decision in uncontrolled charging. A unit commitment model was developed in order to determine hourly electricity generation in the power system. Results showed that in uncontrolled charging case, PHEVs increase the peak loads on the grid but the generation of electricity is cleaner. With controlled charging case, the coal-fired penetration is high thus, the rate of emissions is worse.

A very comprehensive study from Argonne National Laboratory used the well-to-wheels analysis to examine the energy use, oil consumption, and greenhouse gas emissions of PHEVs for different regions in the US [44].

Axsen and Kurani [45] investigated the potential impacts of PHEVs on the power grid in California. In order to collect data about the consumer behaviors, an online survey was designed. Information about the timing of charging, driving distances, and parking location is derived from the survey and energy impacts were examined under four different scenarios.

Soares *et al.* [46] applied Monte Carlo method to analyze electric vehicle impacts on Portuguese distribution network. The power demand and energy losses were calculated for two EV integration scenarios: 25% and 50%.

Gerkensmeyer *et al.* [47] discussed three questions: how the existing capacity will be affected after the integration of PHEVs, what is the optimal hour in the day for charging, and where the PHEVs would be charged. Six scenarios according to charging location, charging power level, and charging time were defined and daily load profiles were generated under these scenarios with various penetration levels.

Jansen *et al.* [48] developed a resource and emissions model to analyze PHEVs impacts on the US western grid. Two scenarios were considered in this study. In the best guess scenario, vehicle owners charge their batteries when they arrive at homes whereas, charging hours are shifted to off-peak hours in the valley filling scenario. Research showed that intensities of greenhouse gas (GHG) and CO emissions would increase with the addition of the 40% PHEV penetration.

Kelly *et al.* [49] examined the electricity consumption of PHEVs by using National Household Travel Survey data. Eight scenarios were created in order to see the effects of impacts factors such as charging location, charging level, battery size, and so on. Utility factor for different demographics groups was also investigated to plan to add infrastructure by taking into consideration the vehicle owners' needs.

Green *et al.* [50] reviewed the previous studies about the impacts of PHEVs on the distribution grid. The impact factors were explained comprehensively and charging scenarios in other studies were summarized in this paper.

In order to evaluate the integration of electric vehicles in weak grids, Colmenar-Santos *et al.* [51] analyzed the electricity demand of Tenerife Island as an isolated network. The real data collected for Tenerife was used to examine the impact of electric vehicles for a special type of EV by using simulation.

Tehrani and Wang [52] proposed a probabilistic estimation to predict PHEVs charging load demand. The studies [53–56] focused on optimization of PHEVs charging strategies to minimize the impact on the power grid.

In [57–66] energy impacts of PHEVs on the distribution system for different countries were investigated and electricity consumption was analyzed with considering various charging scenarios and several assumptions.

Chapter 3

Application of Monte Carlo Simulation On Electricity Network

In this thesis, İstanbul is considered as a case study and the related data for a weekday is obtained from İstanbul Metropolitan Municipality (İBB), Turkish Electricity Transmission Company (TEİAŞ), and Turkish Statistical Institute (TÜİK) resources.

The first section gives information about the collected data for İstanbul and these data is explained in more detail. In the second section, new daily load curve for İstanbul is generated under different scenarios with using the Monte Carlo simulation method and the scenario results are analyzed at the end of the chapter.

3.1 Related Data

As described in the previous chapter, load added to the electricity grid is affected by many factors. In the coming subsections, the related data associated with the impact factors is explained comprehensively.

Distribution of Arrival Times

As mentioned in Chapter 2, the distribution of arrival times is very important to detect when the vehicle owners would recharge their PHEVs. Knowing the plug-in time provides information to determine the additional load for each hour on the electricity network.

Besides arrival times, the places where the vehicle owners end their last trips should be taken into account in order to know the charging locations. During the day, PHEV owners go to their workplaces and return their homes and they can also go to shopping malls, restaurants etc. between trips. Therefore, they may recharge their vehicles in anywhere. It is expected that vehicle owners would like to charge their vehicles at home since they spend significant time at this place during the day, especially at night.

In this thesis, homes, workplaces, shopping malls, and public stations are considered as charging locations and the related data is collected for these places.

The distribution of arrival times at home, work, and shopping mall are obtained from İstanbul Metropolitan Municipality (İBB), but due to lack of real data about the distribution of arrival times in public stations, we assume that the PHEV owners charge their vehicles at the public station which is close to their home.

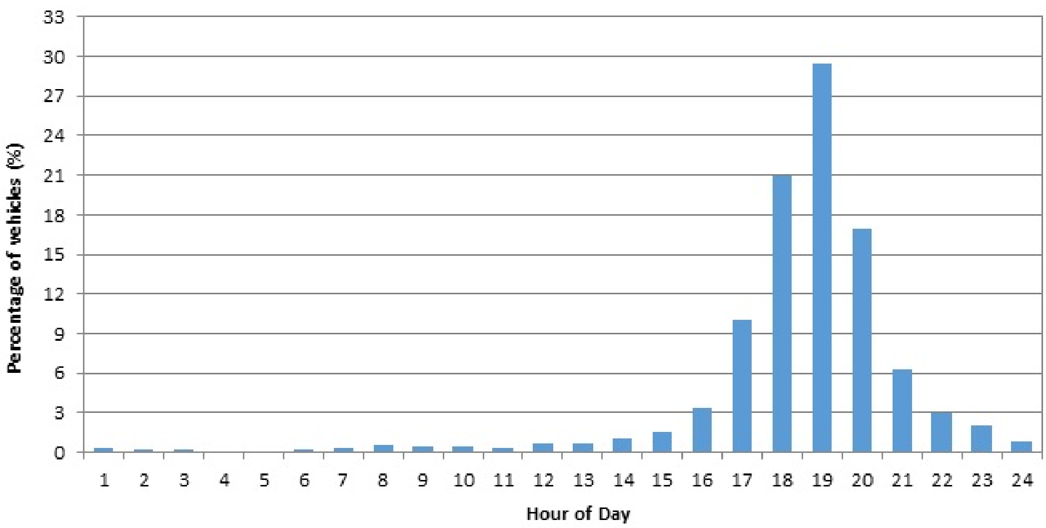

Figure 3.1: Distribution of arrival times at home from work

Figure 3.1 shows the percentage of vehicles arrival times at home from work. The daily load curve is created while considering the charging start time based on this distribution. It is clear that peak arrival time is between 17:00 and 21:00 and about 30% vehicles arrive at home at 19:00. This data is from typical weekday and the daily load curve is generated only considering the weekdays.

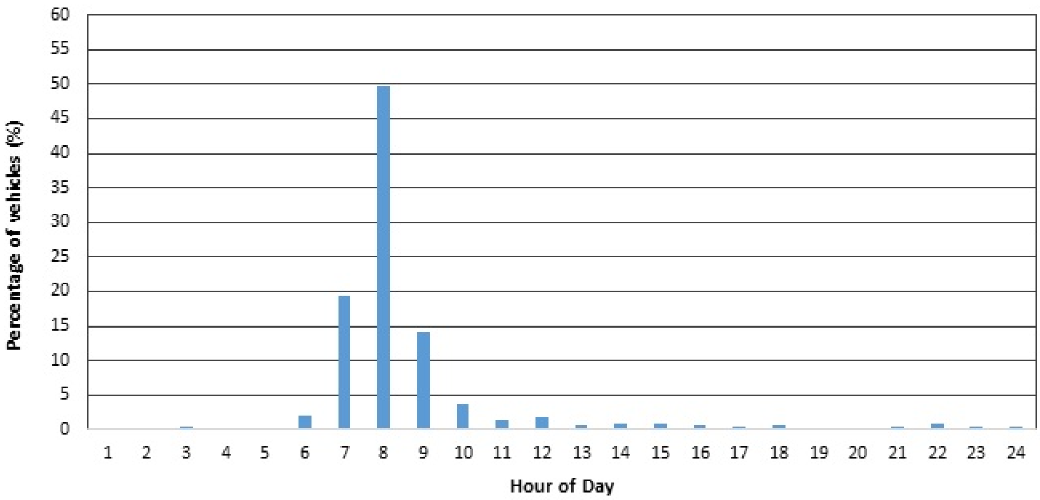

Figure 3.2: Distribution of arrival times at work from home

The distribution of arrival times to work is shown in Figure 3.2. As it can be seen from this figure, many people arrive their workplaces in the morning between 7:00 to 9:00 and about 50% of vehicle owners arrive at the workplace at 8:00. This data is used for the case which the vehicle owners recharge their batteries in the workplaces.

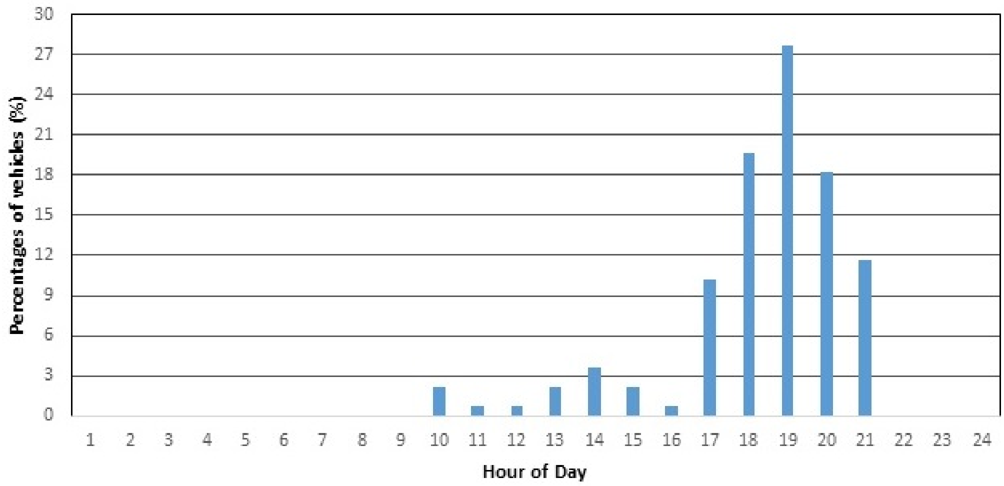

Figure 3.3: Distribution of arrival times at shopping malls

Figure 3.3 depicts the percentage of vehicles arrival times at shopping malls from various places. Since shopping malls open at 10:00 and close at 22:00, the vehicle arrival times distribute between these hours. It is clear that the peak arrival time for shopping malls is 19:00 at which the vehicle owners leave their works.

The vehicle owners, who prefer to charge their batteries in the charging places different from homes and workplaces, may recharge their vehicles in the shopping malls. Therefore, this data is important for this case.

Distribution of Daily Driving Distances

Daily driving distances depend on the vehicle owners' driving behaviors and as noted earlier, this factor affects the amount of load added to the power grid. Based on the battery capacity and SOC, the daily miles driven determines the amount of electricity required to recharge the PHEVs. Therefore, the data about this factor is very crucial in order to generate the daily load curve.

Since we consider İstanbul as a case study, we contacted with İstanbul Metropolitan Municipality (İBB) to obtain the real data about the distribution of daily driving distances for İstanbul. However, we have only reached the data about the distribution of trip duration and the average daily distances driven in İstanbul, which is about 16 km [67]. Due to lack of real data about the distribution of daily driving distances, we made some assumptions and we derived the distribution of daily driving distances by using trip duration data.

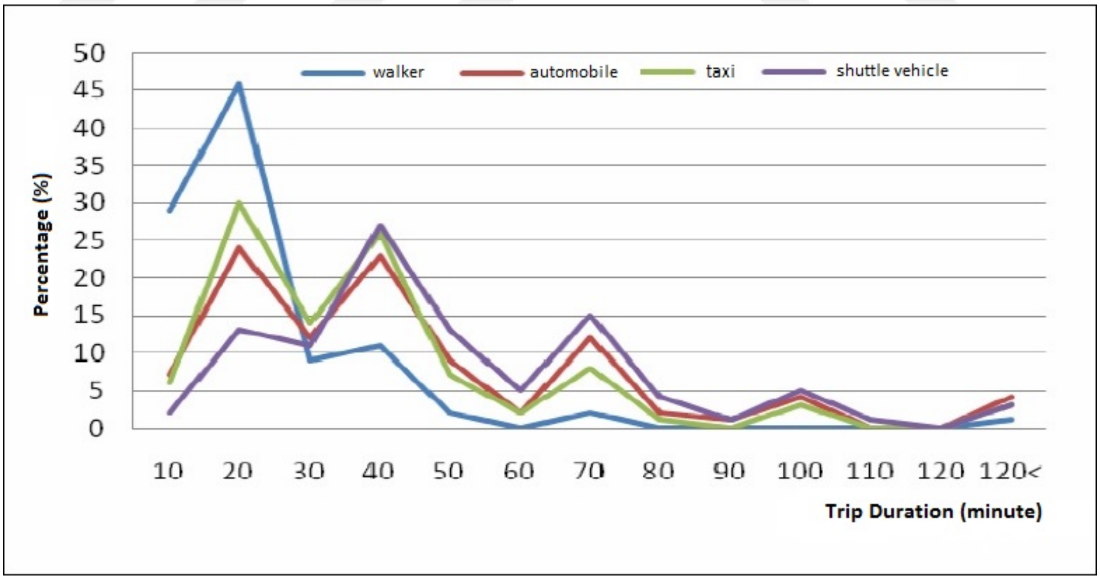

Figure 3.4: Distribution of trip duration with respect to type of transportation [67]

Figure 3.4 illustrates the distribution of trip duration for different types of transportation such as an automobile, walker and so on. İstanbul Metropolitan Municipality (İBB) made a household survey with 90000 households and they gathered information about 360000 trip attributes. Figure 3.4 is generated by using this household survey results.

Since the private car is considered as a PHEV in this study, the distribution for automobile, which is marked with a red line, is only examined. As seen in Figure 3.4, about 30% of private cars travel 20 minutes per day or less and about 77% of private cars travel 60 minutes or less daily.

In addition to this data, it is assumed that people drive 60 kilometers per hour. According to this assumption and distribution of trip duration data, distribution of daily driving distances are derived (Figure 3.5).

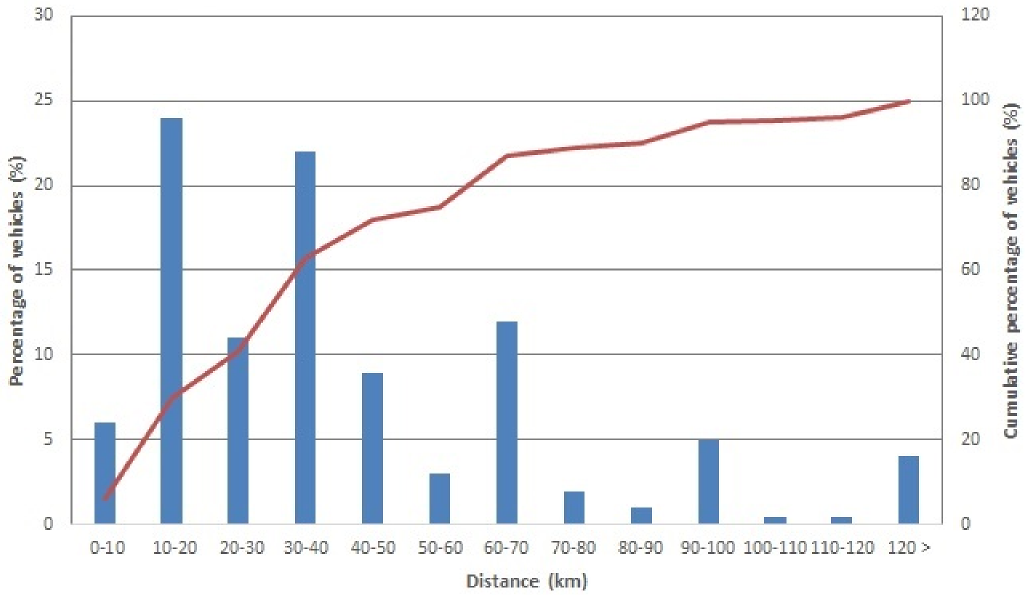

FIGURE 3.5: Distribution of Daily Driving Distances

Figure 3.5 represents the distribution of daily mileage driven and cumulative distribution curve. As seen in Figure 3.5, about 30% of vehicles travel 20 km or less and about 63% of vehicles travel 40 km or less per day. The peak distance is in the range of 10-20 km.

Daily Load Curve

As noted earlier, PHEVs will increase the electricity load demand when they are integrated into the power grid. Therefore, new daily load curve will occur. Knowing the pattern of daily load curve is crucial in order to compare with new daily load curve. For this purpose, daily load curve data for İstanbul is obtained from Turkish Electricity Transmission Company (TEİAŞ). However, desired data exists only for Turkey. Due to lack of specific data for İstanbul, we made some calculation to obtain daily load curve for İstanbul.

According to Turkish Statistical Institute (TÜİK), the electricity consumption in İstanbul is equal to about one-sixth of the total electricity consumption in Turkey [68]. Based on this information, the electricity consumption per hour for Turkey is divided by 6.08, which is the exact proportion and the daily load curve for İstanbul is derived by using acquired values (Figure 3.6).

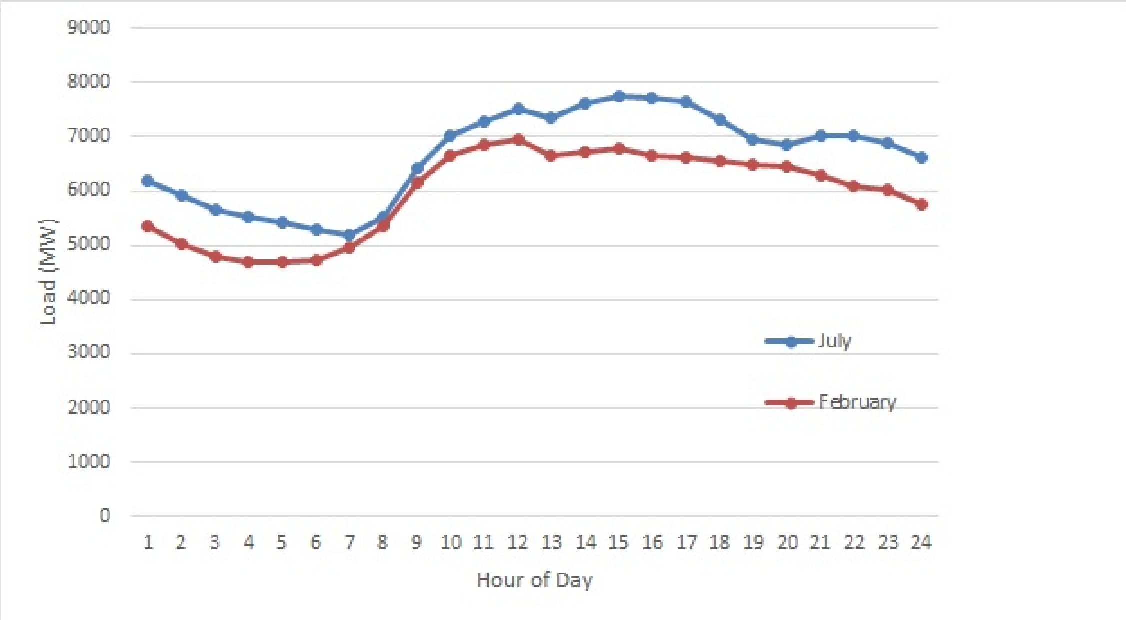

FIGURE 3.6: Daily load curve for summer and winter season

Turkish Electricity Transmission Company (TEİAŞ) has daily load curves for both summer and winter seasons [69]. In this study, it is only examined the weekdays while generating the new daily load curve and above daily load curves are from the weekdays which have high electricity consumption for winter and summer. Since the amount of electricity drawn from the grid per hour is different for summer and winter seasons, the changes in the new load profile could be differ based on the seasons. We use the summer and winter load profiles in order to see the differences on the new daily load curve due to the seasonal changes in electricity consumption. The new daily load curves are generated after adding the charging demand to winter and summer base load profiles and results are discussed. The other data, which is used to obtain new daily load curve, is same for winter and summer seasons.

Number of Vehicles for Penetration Levels

As mentioned in Chapter 2, the penetration level of PHEVs is important to investigate the total energy required on the distribution system. Since the PHEVs are new in the Turkish transportation sector, some assumptions are made about the penetration levels of PHEVs. In this study, penetrations levels are considered as 10% and 50% and the results are achieved based on these assumptions.

The data about the number of vehicles is obtained from Turkish Statistical Institute (TÜİK). Since only the private cars in İstanbul are considered as PHEVs in this thesis, the related data is obtained for automobiles. According to the Turkish Statistical Institute (TÜİK), the number of private cars is 2696245 in İstanbul by the end of April 2017 [70]. The number of PHEVs is calculated for each scenario based on the assumed penetration levels with using the data about the number of private vehicles in İstanbul.

Battery Size

The battery size affects the amount of time required to recharge the PHEVs. Therefore, battery size is an important factor in order to generate the new daily load curve.

According to brand and model of PHEV, the battery capacity ranges in the market. However, the available brands in Turkey like Renault, Tesla, Nissan, and BMW do not provide the wide range of battery sizes since the PHEV technology is new in Turkey transportation sector.

In this study, we consider the different types of battery while simulating the daily load curve. Since the available PHEVs generally have a range of battery capacity, from 5 kWh to 25 kWh in Turkey, the battery capacities, which are 5 kWh, 10 kWh, 15 kWh, 20 kWh and 25 kWh are taken into account in this thesis.

3.2 Methodology to Generate Daily Load Curve

In order to generate new daily load curve under different scenarios, Monte Carlo simulation method is applied in this study. Monte Carlo simulation is a technique that uses set of probability distributions to define random variables. This method involves repetition and the random variables are selected for each repetition from the probability function to represent stochastic nature of the PHEV charging. Monte Carlo simulation is an efficient approach due to the PHEVs uncertainties and this method helps predict the potential impacts of PHEVs on the power grid.

To perform the simulation, four probabilistic inputs must be taken into account: SOC (state of charge), time of plug-in, charger type and the penetration level.

State of Charge

As mentioned previously, state of charge (SOC) is a percentage of remaining energy in the vehicle based on daily driven mileage and the battery size. Since the vehicle owners could start the travel with different amount of energy in their batteries, SOC is an unknown variable and it should be selected randomly for each vehicle.

It is assumed that vehicles drive 5 km with 1 kWh energy and the vehicle owners recharge their batteries at most once a day. If the remaining energy in the battery is enough for next traveling, they could start the day with remaining battery or they could decide to recharge their vehicles. Using these assumptions, all the possible SOC is calculated based on different battery sizes and the travel distances and then SOC is randomly generated based on these values in each iteration.

Time of Plug-in

Since PHEV technology is new in Turkey, the information how the vehicle owners will utilize the PHEVs is not available. One of the uncertainties in vehicle owners' behaviors is a time of charging. As mentioned in Chapter 2, time of plug-in is related to the driving habits such as vehicle owners' arrival times. In order to take into account the uncertainty of plug-in time, the probability distribution of arrival times to various places such as home, workplace, shopping mall, and the public station is used (Figure 3.1, Figure 3.2, Figure 3.3).

Plug-in time is randomly generated for each vehicle with using the probability distribution of arrival times to charging locations by applying Monte Carlo simulation. This unknown variable is crucial to obtain new daily load curve and determine the additional load for each hour in the load shape.

Charger Type

Four charger types, 3.7 kW (230V, 32A), 7.4 kW (230V, 32A), 11 kW (380V, 16A), 22 kW (380V, 32A) are available in Turkey. Since the charging location is uncertainty in PHEV aspects and the vehicle owners would prefer the different charger type even they recharge their batteries in same charging places, charger type should be chosen randomly with different probabilities for each vehicle in Monte Carlo simulation.

22 kW charging units are available in the public stations and shopping malls to reduce the length of charging duration. If the home is selected as a charging location, four charger units are available. Although 3.7 kW charging unit is preferable for homes, four charger types are randomly selected with different probabilities in this study in order to represent the impacts of charging power level factor.

Penetration Level

Due to the uncertainty of the PHEV penetration levels in İstanbul, two penetration rates are considered in this study: 10% and 50%. Since only the private cars are taken into account in this thesis, the data about the number of private cars in İstanbul is used for this input. The number of PHEVs is decided based on these penetration cases for different charging scenarios. This variable is important to represent the amount of electricity drawn from the power grid for per hour.

3.2.1 Monte Carlo Simulation

In this section, general steps in Monte Carlo simulation algorithm is described in more detail. This simulation approach is an efficient to evaluate the impacts of PHEVs on distribution network due to the uncertainties of PHEV usage. Monte Carlo simulation is run for 100 iterations and each iteration will show a possible snapshot of the system. In this study, MATLAB software is used to simulate daily load curves.

First of all, the initial characterization of PHEVs and the variables related to the vehicle owners' behaviors are defined in the simulation. The algorithm begins by determining the number of PHEVs for a given penetration level. And then, the daily driven kilometer for each vehicle is allocated by using the probability distribution of daily driving distances as presented in Figure 3.5.

The second step is to select the battery size for each vehicle. In this study, five battery sizes are considered: 5 kWh, 10 kWh, 15 kWh, 20 kWh, 25 kWh. Due to the assumption that the vehicles are recharged at most once a day, it is assumed that the vehicle owners will not prefer the battery type that would not be sufficient for their daily driving distances. For example, if the vehicle owner drives 60 km per day this owner can not have battery size less than 15 kWh energy since it is assumed that vehicles drive 5 km with 1 kWh energy. For each vehicle a set of possible battery sizes are defined and then the battery size is randomly chosen from this set in order to represent the impacts on a selection of different battery types. For the selection of the battery size, two approaches are considered. In the first approach, we randomly assign a battery size from the set. In the second approach, we assume that vehicle will have either 20 kWh or 25 kWh in order to see how the higher battery capacity will affect the additional load curve. In this approach, it is also assumed the vehicle owners will not prefer the battery type that would not be sufficient for their daily driving distances. For example, the vehicle owner could only prefer 25 kWh battery size if the vehicle drives 120 km per day.

As mentioned previously, the state of charge (SOC) is a percentage of remaining electricity in the battery and it depends on the battery size and daily driven distances. For example, consider a case where the vehicle has 20 kWh battery size and the daily driven distance is 20 km. Due to the assumption that the vehicle travels 5 km with 1 kWh of energy, this vehicle consumes 4 kWh of energy per day. For this case there are 5 possibilities for SOC just before charging. These are 80%, 60%, 40%, 20%, and 0%. The vehicle could start the day with full capacity, since it will consume 4 kWh energy during the day just before the charging there will be 16 kWh of energy in the battery. It will mean that this vehicle has 80% of SOC. Similarly, the vehicle could start the day with 12 kWh of energy (this means that the last charging was 3 days ago) and in this case the vehicle will have 40% of SOC just before the charging. Since we are generating the snapshot of the system, any SOC is equally possible for a simulated date. Therefore, we define a possible SOC sets for each vehicle by considering the battery size and daily driving distance and then we randomly select a SOC from the set for the considered vehicle.

After selection of SOC, charging decision is performed in the fourth step. According to SOC and energy requirement for next trip, charging decision is randomly generated. If the remaining energy in the battery is not adequate for next trip, vehicle owner charges the battery. Otherwise, charging decision is randomly generated. If the randomly generated number is smaller than the predefined threshold, vehicle owner charges the battery. The random number is updated for each iteration. In order to see the impacts of personal preferences on the daily load curve, conception of the risk factor is taken into account. Risk-averse people might charge their batteries every day regardless of the remaining electricity on the battery. On the other hand, risk-neutral people might wait until the battery depletes. To examine the differences in the load curve due to the changes in personal preferences, two different threshold is defined: 0.5 and 0.8. In the cases, where the vehicle owners are risk-neutral, the threshold is defined as 0.5. On the other hand, 0.8 threshold is defined for the cases, where the vehicle owners are assumed as risk-averse.

The next step is a selection of the charging location since there are different charger types for different charging locations. Charging types affects electricity drawn from the system per unit time. Therefore, they should be incorporated into the study. In this analysis, for the shopping malls and public stations we consider 22 kW charger types. For the homes and workplaces, we consider 3.7 kW, 7.4 kW, 11 kW, and 22 kW charger types and we assume that these charger units are equally distributed for homes and workplaces.

The data about the preferences of charging location is not available for İstanbul. Therefore, distribution of location preferences is gathered from the survey results that the undergraduate students made in İstanbul Şehir University. According to the survey results, the location selection are independent from the daily driving distances. Therefore, the distribution of location preferences for all participants are used without categorizing the people according to their daily driven kilometer. The probability distribution of the charging places, which are home, workplace, shopping mall, and public station, are presented in Table 3.1. The charging location is randomly selected based on this distribution. Due to the assumption of the charging occurs at most once a day, vehicles are not allowed to recharge in different places within a day.

Table 3.1: Probability Distribution of Charging Places Preferences

Charging Location	Home	Workplace	Shopping Mall	Public Station
Probability	0.4	0.2	0.1	0.3

Determination of the time needed to recharge the battery for each vehicle is performed in the next step of the simulation. According to remaining energy in the battery and the charging power level, which is assigned based on the selected charging location in the previous step, charge duration is calculated. The general assumption of this study is that the vehicles are not interrupted until to fully charge. Time needed for charging is estimated with considering this assumption.

To determine the starting time of the charge, the probability distribution of arrival times to the selected charging location is used as presented in Section 3.1. Charging time is randomly determined between the arrival and departure times if the charging occurs at homes or workplaces. For shopping malls and public stations it is assumed that the vehicle owners start charging their batteries as soon as they arrive to charging locations. Since we just know arrival times to the homes and workplaces, we had to calculate the departure times. We assume that people spend 9 hours at their works. We calculate how many hours they spend on roads. To calculate the departure times from the homes, we subtract the total of the time spent in the workplace and time spent on the roads from the arrival time to the home. For the workplace, since we know the arrival times we just add 9 hours to the arrival time to calculate the departure time. For the stations, the arrival times are assumed one hour before the arrival time to the home. For the shopping malls, we have the distribution of arrival times. For instance, if the vehicle owners arrives to home at 6 pm and leaves at 8 am and the charging duration is 4 hours to fully charge the battery, the charging must be finished until 4 am. Therefore, the time of plug-in is randomly selected from 6 pm to 4 am. Then the charge ending time is computed for each vehicle based on the charge starting time and the charge duration.

In the next step, electricity drawn from the power grid are calculated per hour. Finally, daily load curve is obtained by finding the average of 100 iterations. Load curves of the day with the minimum and maximum electricity consumption are also calculated in order to represent the worst case and best case in the total consumption. In addition, maximum and minimum loads for each hour are computed before finding the average of the results.

The flow of the Monte Carlo algorithm that developed in this study is presented in Figure 3.7.

3.3 Scenario Definition

In order to evaluate new daily load curve by applying Monte Carlo simulation technique, two main charging scenarios are developed. Hour by hour electricity demand is performed under different charging scenarios for two penetration levels. This section

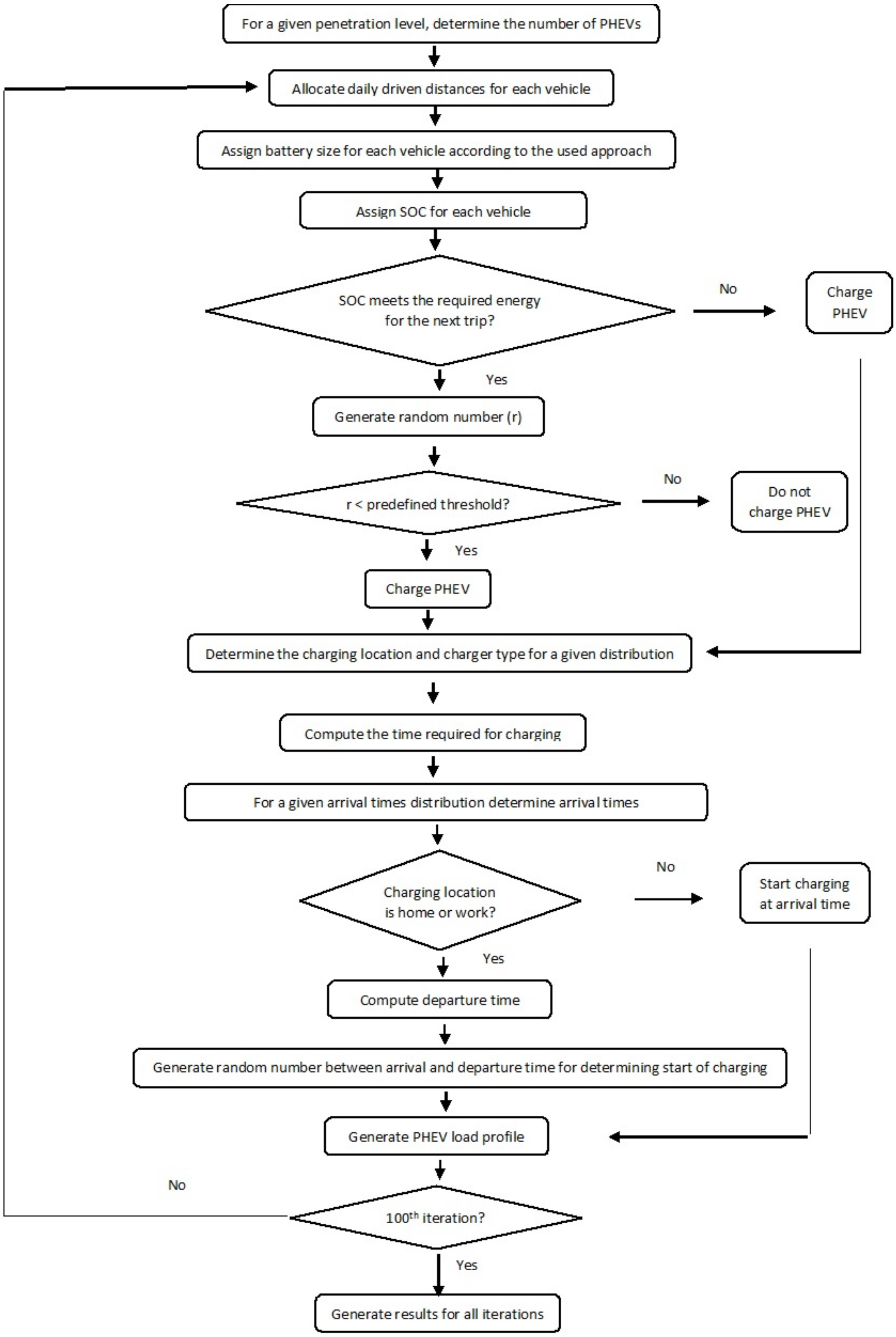

Figure 3.7: Monte Carlo Algorithm Flow

provides information about the defined charging scenarios: uncontrolled and off-peak charging.

3.3.1 Uncontrolled Charging

The uncontrolled charging scenario provides continuous charging during the day. In this scenario, PHEVs are charged whenever they are plugged in until their batteries reach full capacity. Vehicle owners are not restricted on charging periods or there is no incentive such as time-of-use rates for shifting the time of plug-in. In this scenario, charging occurs exclusively at home and charging occurs everywhere cases are considered. Additionally, with considering other parameters such as charging power levels,battery sizes, and charging decision threshold various cases are created under uncontrolled charging scenario and results are analyzed for different penetration levels

3.3.2 Off-Peak Charging

The off-peak charging scenario is defined in order to shift the PHEV loads to off-peak hours. In this scenario, all off-peak charging occurs at home during the hours when the electricity demand is minimum. The vehicle owners are allowed to initiate the charging at 11 pm and complete by 7 am at home. This charging strategy proposes to optimize utilization of the grid with restriction on charging period. The off-peak charging scenario attempts to provide the low cost charging, improve the system performance, and reduce the peak loads.

Under this charging strategy, two cases are considered: off-peak charging only at home and off-peak charging everywhere. In off-peak charging everywhere scenario, if the vehicle owners decide to recharge their batteries at homes, they are allowed to charge between 11 pm to 7 am. If they prefer the other locations as a charging places, they are allowed to charge their vehicles without a time restriction.

Monte Carlo simulation is developed for two charging scenarios in order to investigate PHEV electricity requirement among 24 hours of a day and simulation results are analyzed under two penetration levels.

3.4 Simulation Results

Monte Carlo simulation is performed to obtain new daily load curve under two charging strategies and results are generated. 100 iterations are run and the average daily load shape as well as the maximum and minimum loads per hour are generated. The specific days with the maximum and minimum electricity consumption are also obtained. In this section, the results of the simulations are presented and analyzed under two penetration levels: 10% and 50%.

In order to observe the differences on the new daily load profiles due to the changes in battery sizes, charging power levels, and charging decision threshold, four cases are created, as seen in Table 3.2

TABLE 3.2: Different cases based on battery sizes, charging power levels, and charging decision threshold

	Battery Size	**Charger Type at home**	**Charging Decision Threshold**
Case 1	5 kWh, 10 kWh, 15 kWh, 20 kWh, 25 kWh	3.7 kW, 7.4 kW	0.5
Case 2	5 kWh, 10 kWh, 15 kWh, 20 kWh, 25 kWh	3.7 kW, 7.4 kW, 11 kW, 22 kW	0.5
Case 3	5 kWh, 10 kWh, 15 kWh, 20 kWh, 25 kWh	3.7 kW, 7.4 kW	0.8
Case 4	20 kWh, 25 kWh	3.7 kW, 7.4 kW	0.5

3.4.1 Results of 10% PHEV Penetration Level

The daily load curve is generated under two main charging strategies for 10% penetration level of PHEVs in this section. The various cases are created under different charging scenarios in order to observe the differences in magnitude of charging demand due to changes in vehicle characteristics and vehicle owners' charging behaviors. In the subsections, simulation results are presented for 10% PHEV penetration levels.

3.4.1.1 Results for Uncontrolled Charging At Home Only

As mentioned previously, uncontrolled charging scenario is examined under two charging location cases: charging at home only and charging everywhere. In this scenario, homes are considered as a charging location and charging is allowed without a time restriction. Four different cases are created with regard to battery size, charging power level, and charging decision threshold. The Monte Carlo simulations are run for different cases and the new daily load curves are generated.

Case 1: In this study, it is assumed that the vehicle owners will not prefer the battery type that would not be sufficient for their daily travelled distances as mentioned in Section 2. Under this assumption, the battery size distribution is considered as uniform in this case. For home charging, four charger types are available in Turkey: 3.7 kW, 7.4 kW, 11 kW, 22 kW. Since low charger types are most commonly used in the houses, it is assumed that half of the vehicle owners prefer the charging unit with 3.7 kW and half of them prefer the charging unit with 7.4 kW. The charging decision threshold is considered as 0.5. In other words, all vehicle owners are risk-neutral. If the randomly generated number is smaller than 0.5, then vehicle owner will decide to charge. The simulation results for Case 1 are presented below.

Figure 3.8 depicts the average additional load arising from the PHEVs for 10% penetration level. The vehicle owners are allowed to charge their batteries at any time after arriving home. As can be seen in the figure, most charging occurs in the evening hours and the early morning since the people spend significant time at homes in this period. The maximum additional load appears at 12 am and its value about 275 MW. Charging demand is always greater than zero since charging occurs during all day.

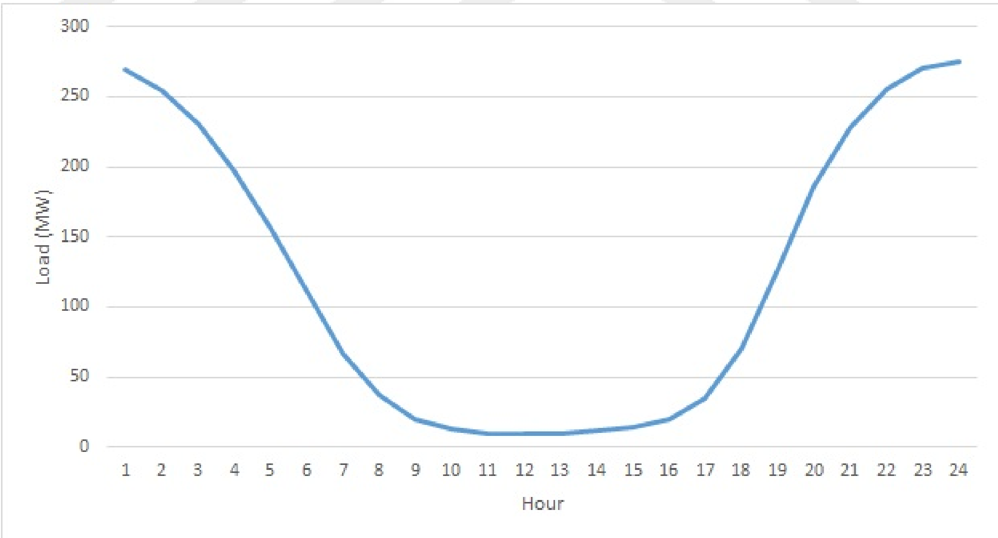

Figure 3.8: Additional load in uncontrolled charging at home only - Case 1 - 10% penetration

Knowing the maximum load added for each hour is important to detect overall peak loads that would be created. Figure 3.9 illustrates the maximum, minimum, and average load for each hour. For instance, among 100 iterations maximum load is 263 MW and minimum load is 249 MW at 10 pm while the average load is 255 MW. This means that, the load would be between 249 MW to 263 MW at 10 pm and the maximum load could be crated at any day.

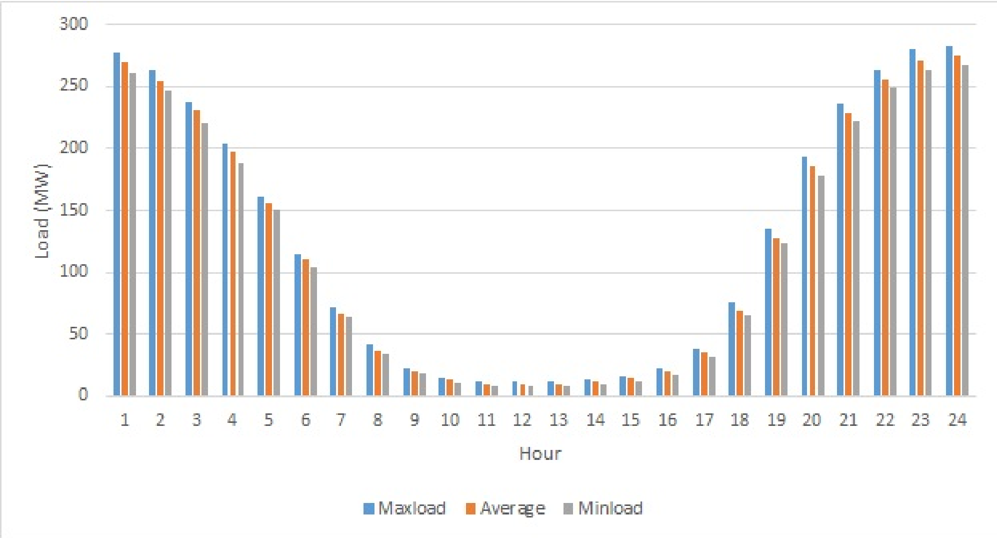

FIGURE 3.9: Maximum, average, and minimum load per hour in uncontrolled charging at home only - Case 1 - 10% penetration

Figure 3.10 represents a specific day with the maximum and minimum electricity demand from the PHEVs charging. According to the simulation results, maximum total energy consumption is about 2900 MW and minimum total consumption is about 2850 MW. Total amount of electricity drawn from the power grid is negligible due to the low penetration level in this case.

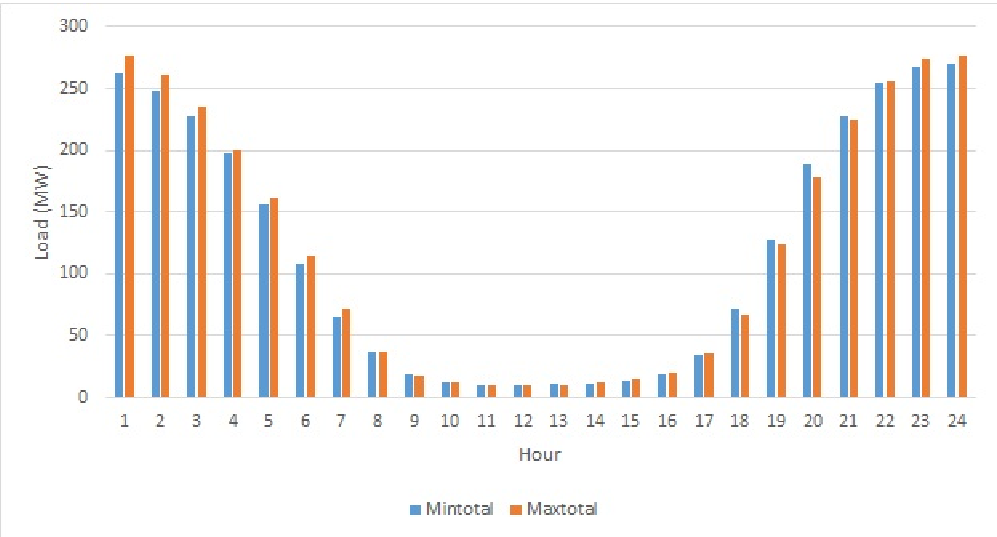

FIGURE 3.10: Maximum and minimum total electricity consumption in uncontrolled charging at home only - Case 1 - 10% penetration

Figure 3.11 and Figure 3.12 show the new daily load curves for winter and summer season respectively. The blue lines represent the original load profiles without PHEVs while red lines represent the new load shapes after adding the average PHEV loads to the base load profiles. The maximum demand occurs at 12 pm in winter base load profile and at 3 pm in summer base load profile. As seen in figures, the hour when the peak demand occurs does not change after integration of PHEVs. Due to the low penetration level, the additional electricity consumption is not increased significantly.

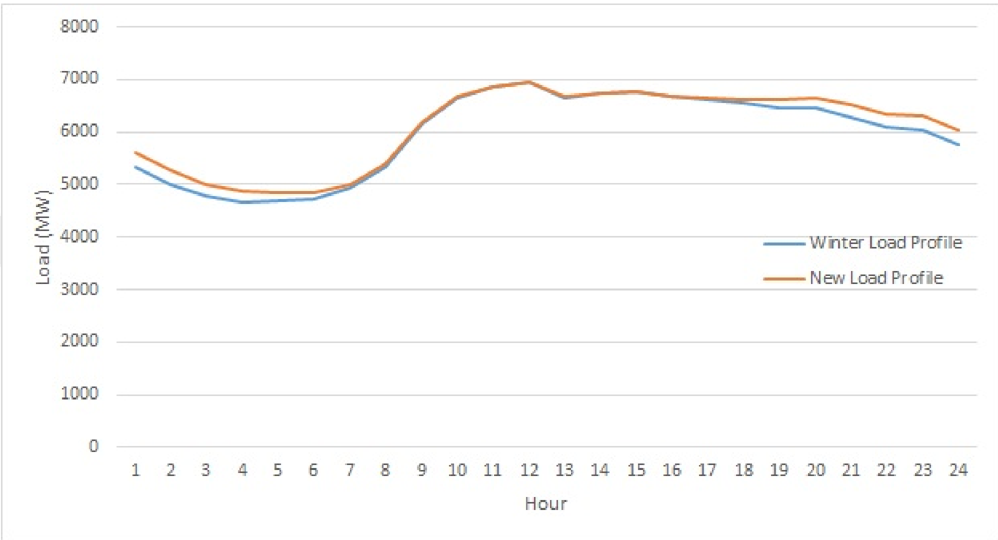

FIGURE 3.11: New daily load curve for winter in uncontrolled charging at home only - Case 1 - 10% penetration

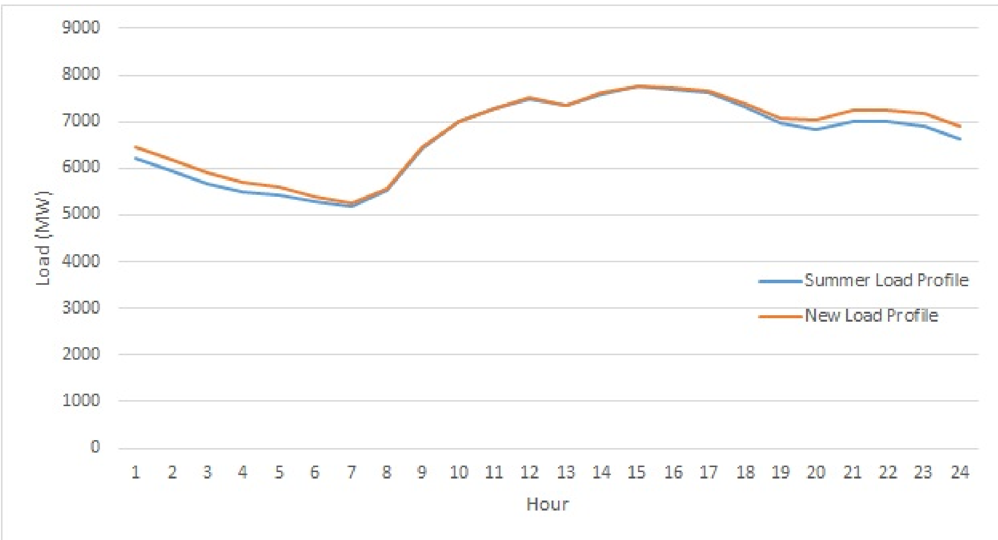

FIGURE 3.12: New daily load curve for summer in uncontrolled charging at home only - Case 1 - 10% penetration

Case 2: In order to see the differences in PHEV load profile due to changes in distribution of charging power levels, it is assumed that the vehicle owners would prefer four charging units with the power of 3.7 kW, 7.4 kW, 11 kW, and 22 kW, under the uniform distribution. The battery size distribution is also uniform in this case. The charging decision threshold is defined as 0.5 and results are generated.

Figure 3.13 and Figure 3.14 represent the new load profiles among 24 hours of a day for winter and summer respectively. As can be seen in figures, the shapes of the daily load curves are almost same as the load profiles in Case 1. The additional load is maximum at 12 am, same hour as Case 1 and its value is about 255 MW. The new peak loads are not created compared to base load profile.

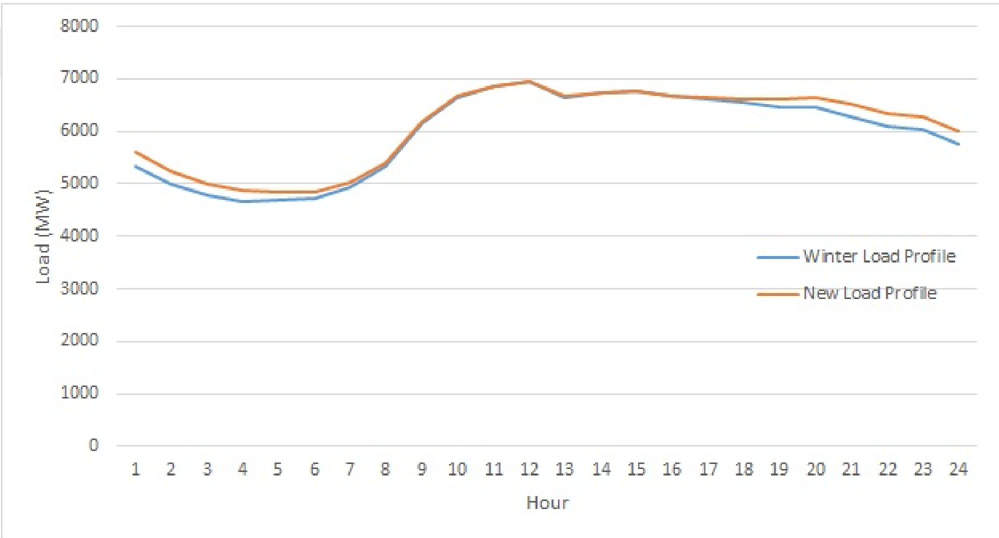

FIGURE 3.13: New daily load curve for winter in uncontrolled charging at home only - Case 2 - 10% penetration

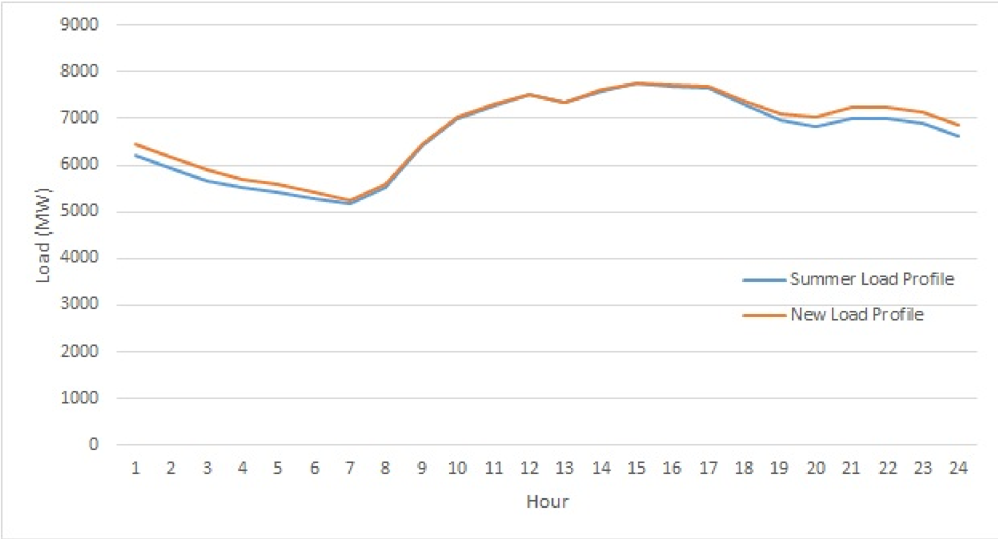

Figure 3.14: New daily load curve for summer in uncontrolled charging at home only - Case 2 - 10% penetration

Case 3: The decision of charging is one of the important parameters in the simulation. As mentioned in Section 3.2, vehicle owners recharge their batteries if the remaining energy is not adequate for the next trip. Otherwise, they may recharge the batteries or not. In Case 3, it is considered that all vehicle owners are risk-averse. For this, the charging decision threshold is defined as 0.8. If the random number is smaller than 0.8, then the vehicle will be charged. The other factors (battery size and charger type) are same as Case 1.

The new daily load profiles after integration of PHEVs are plotted for both winter and summer seasons, as seen in Figure 3.15 and Figure 3.16. The load profile pattern is almost same as Case 1 with an only straight increase in the amount of the charging demand in each hour. Since more people decide to charge their vehicles, the power demand for charging increases. The amount of total electricity drawn from the system could increase up to 8.16% compared to Case 1.

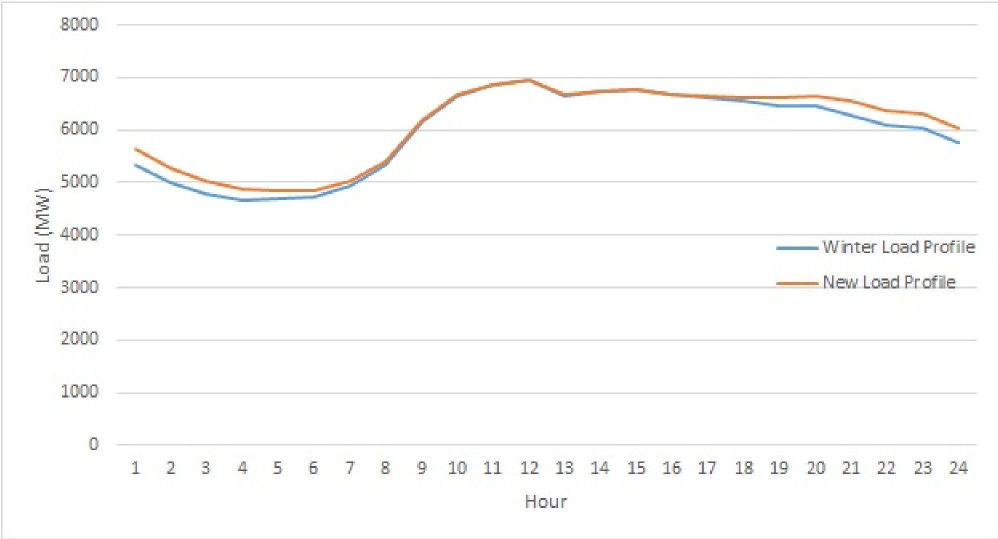

FIGURE 3.15: New daily load curve for winter in uncontrolled charging at home only - Case 3 - 10% penetration

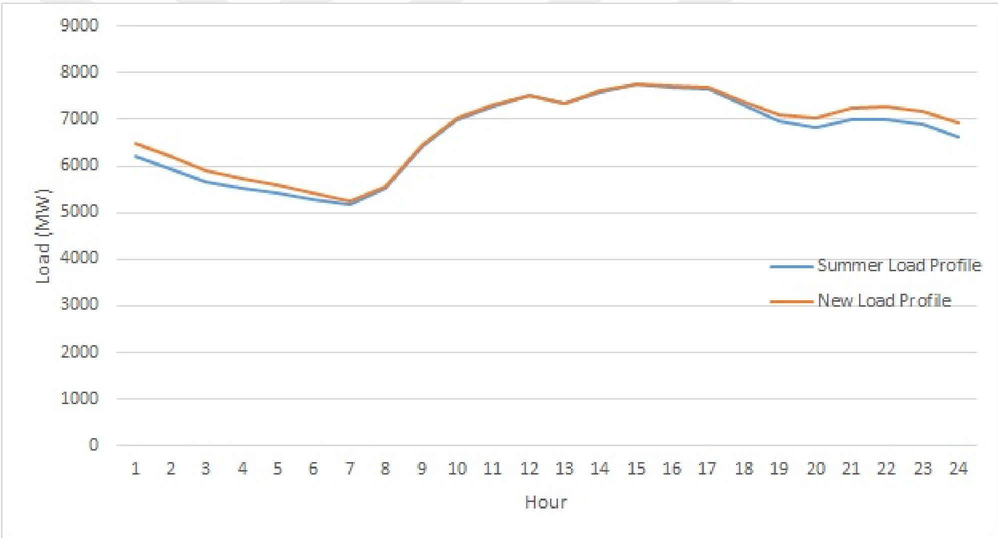

FIGURE 3.16: New daily load curve for summer in uncontrolled charging at home only - Case 3 - 10% penetration

Case 4: In order to investigate the impact of larger battery capacity on the daily electricity consumption, the battery sizes are considered as 20 kWh and 25 kWh. The charger types of 3.7 kW and 7.4 kW are assumed with the probability of 0.5, same as in Case 1. The Monte Carlo simulation is run for 0.5 charging decision threshold and results are obtained.

Figure 3.17 and Figure 3.18 represent the new load profiles for winter and summer seasons after penetration of PHEVs. The shapes of new load profiles are very similar to Case

1, with an increase in magnitude. Since the vehicles are recharged until to reach full capacity, larger batteries show the increase on the electricity load curve. The average daily required electricity for Case 1 and Case 4 is shown together in Figure 3.19. The hour when the peak demand occurs does not change compared to Case 1, but there is a difference in magnitude of PHEV charging demand for each hour. Total electricity drawn from the system could increase up to 12% and this is because the extra electricity is stored in the batteries.

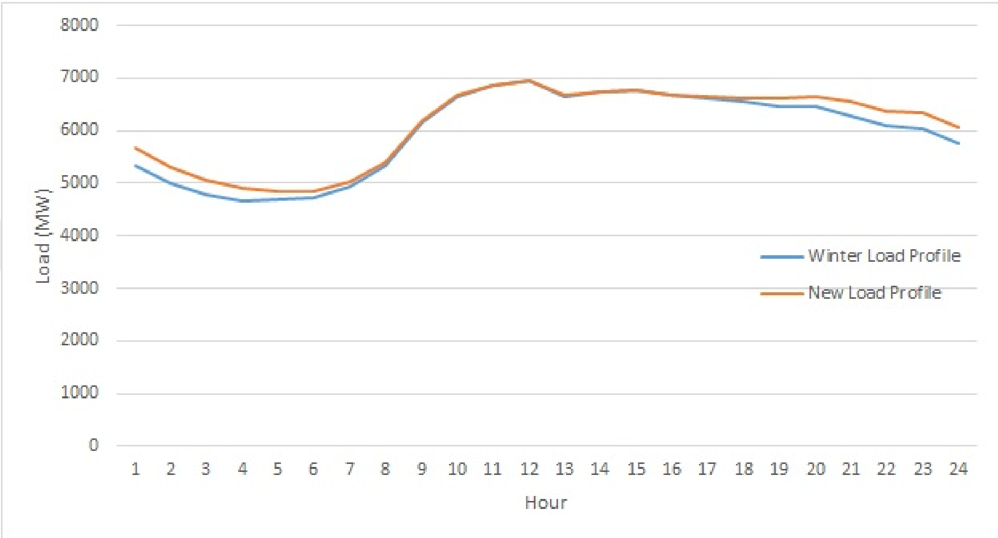

FIGURE 3.17: New daily load curve for winter in uncontrolled charging at home only - Case 4 - 10% penetration

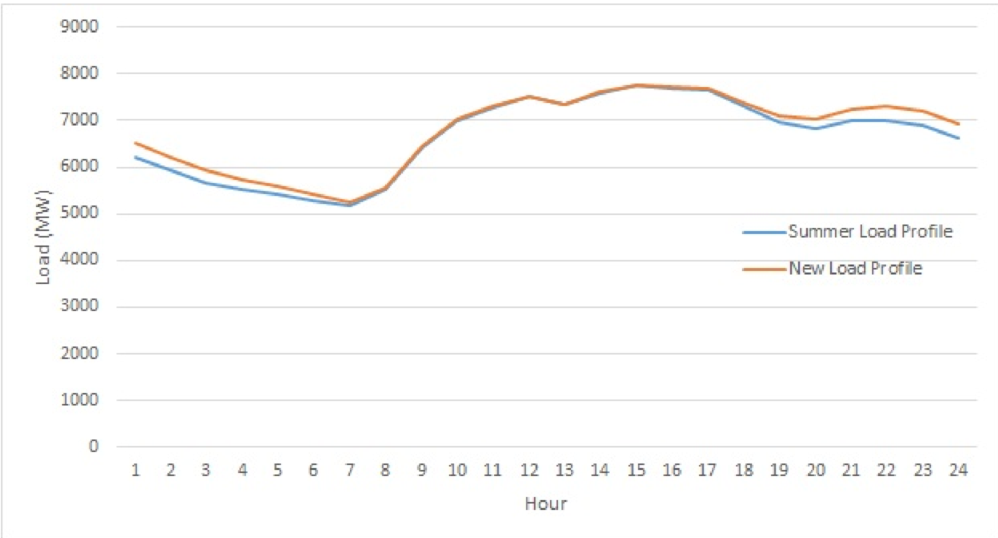

FIGURE 3.18: New daily load curve for summer in uncontrolled charging at home only - Case 4 - 10% penetration

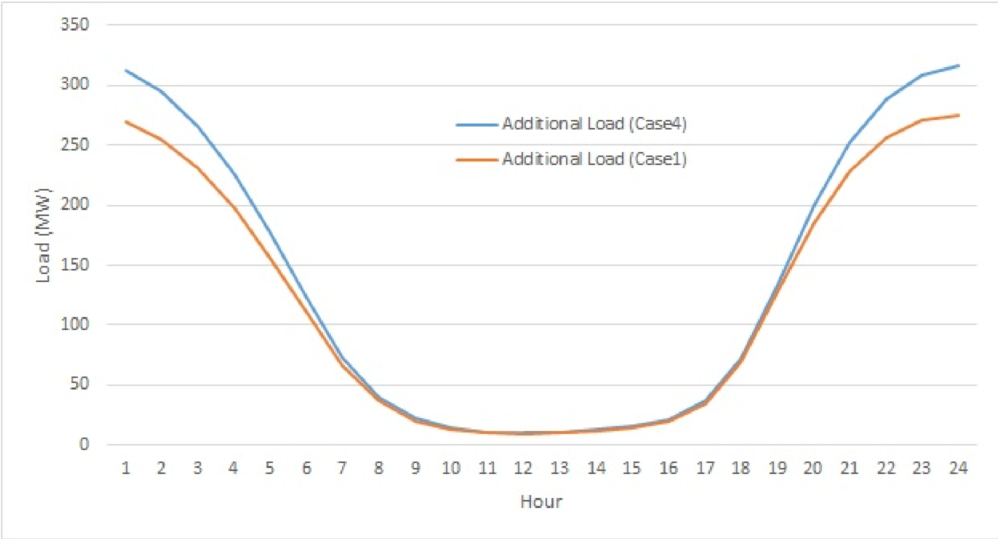

FIGURE 3.19: Additional load in uncontrolled charging at home only according to Case 1 and Case 4 - 10% penetration

3.4.1.2 Results for Uncontrolled Charging Everywhere

The uncontrolled charging everywhere scenario is defined as charging occurs during the day wherever they plug-in. The charging locations are considered as homes, workplaces, shopping malls, public stations and it is assumed that the vehicle owners are not allowed to charge their batteries in different places within a day. The probability distribution of charging places preferences is 0.4, 0.2, 0.1, 0.3 respectively, as given in Table 3.1. It is assumed that four charger types are uniformly distributed in workplaces while charging units with 22 kW are only available in shopping malls and public stations.

The simulation results of the four cases are discussed in this section in order to observe the differences due to the changes in the battery size, charging power level, and charging decision threshold.

Case 1: As mentioned previously, it is assumed that battery distribution is uniform and two charger types are used with same probabilities in this case. The simulation results are obtained for 0.5 charging decision threshold and results are discussed below.

Figure 3.20 illustrates the additional daily load curve according to Case 1. The charging profile ramps up rapidly from 3 pm to 6 pm which corresponds to time of arrival of homes, shopping, and public stations. As mentioned in Section 1, it is assumed that the vehicle owners charge their vehicles at the public stations which is close to their homes and it is also assumed that sufficient number of public stations exists and the drivers reach the available public stations whenever they need to charge. As expected, the rising of the charging demand occurs in the evening hours since significant portion of vehicles arrive to public stations and shopping malls in this period. The amount of electricity drawn from the grid is larger due to the charging power level of 22 kW at the shopping malls and public stations. The peak demand is at 6 pm and it is about 343 MW in the average electricity consumption of PHEVs. The load grows rapidly after 3 pm and drops suddenly after the peak hour. This means that the peak hours have potential to shift from evening hours to late night hours.

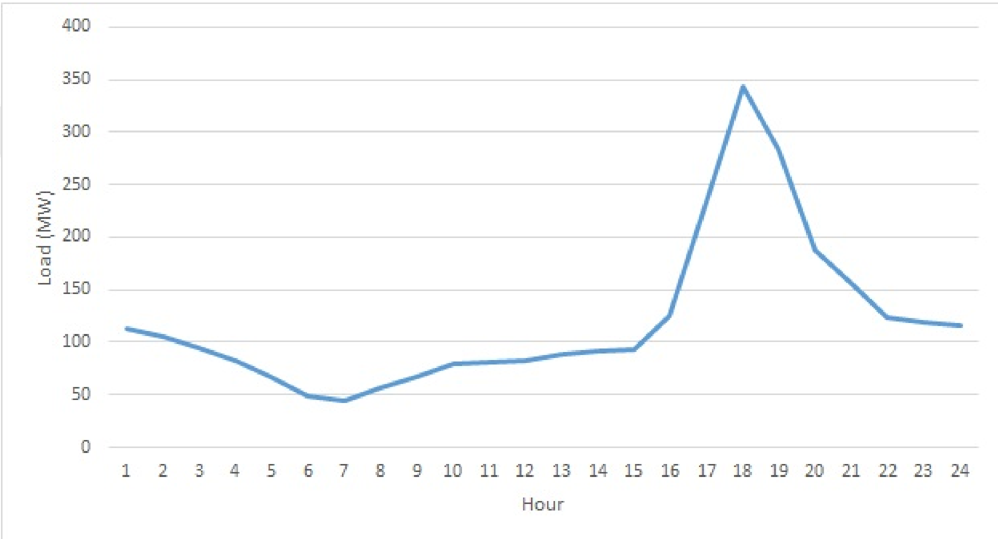

FIGURE 3.20: Additional load in uncontrolled charging everywhere - Case 1 - 10% penetration

Figure 3.21 shows the maximum and minimum loads added to the grid per hour. The maximum required energy is about 359 MW at 6 pm while the minimum charging demand is about 331 MW. It means that at the hour, where the peak charging demand occurs, the electricity drawn from the grid is in the range of 331 MW to 359 MW.

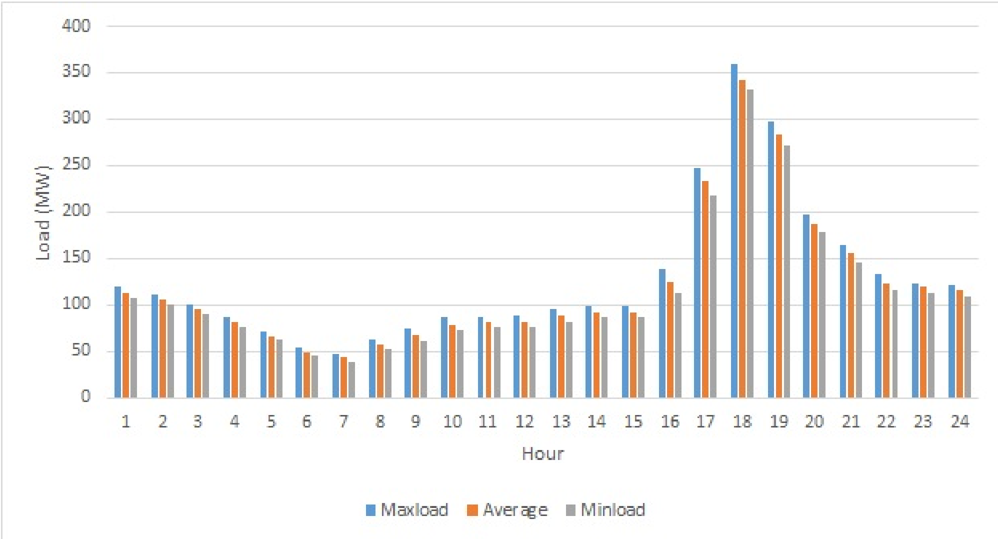

FIGURE 3.21: Maximum, average, and minimum load per hour in uncontrolled charging everywhere - Case 1 - 10% penetration

The specific Monte Carlo iterations, where the total electricity demand are maximum and minimum, are represented in Figure 3.22. As can be seen, the maximum and minimum amount of energy requirement is very close to each other which are 2911 MW and 2859 MW respectively.

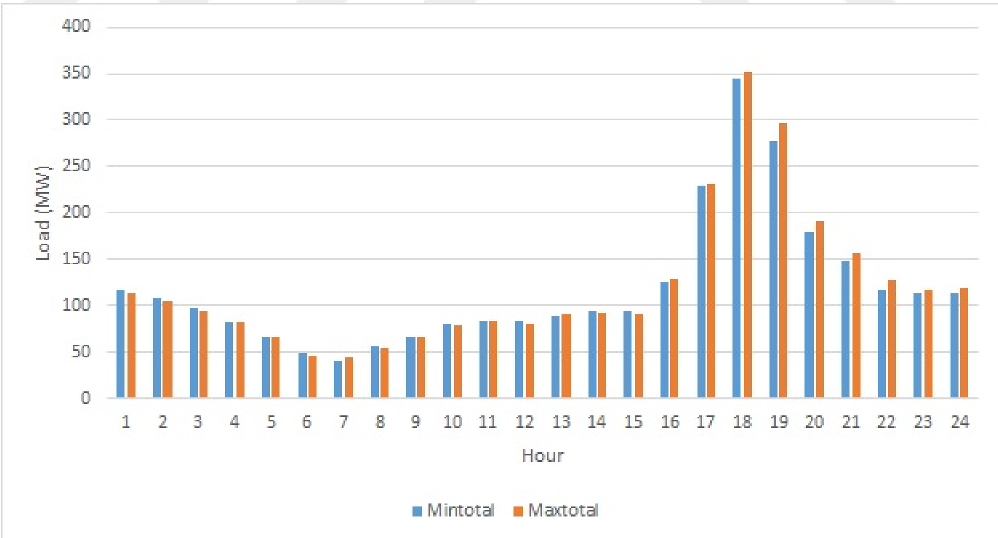

FIGURE 3.22: Maximum and minimum total electricity consumption in uncontrolled charging everywhere - Case 1 - 10% penetration

Figure 3.23 and Figure 3.24 depict the new daily load profiles resulting from the integration of PHEVs for winter and summer seasons respectively. The peak load occurs at 12 pm for winter season, same as the original load profile. However, the peak load is shifted from 3 pm to 5 pm in summer season even with the low penetration level of PHEV. This case would lead to about 1.7% increase in the peak load. In order to manage the negative impacts on the power grid, the peak load arising at the different hour should be taken into consideration in this case.

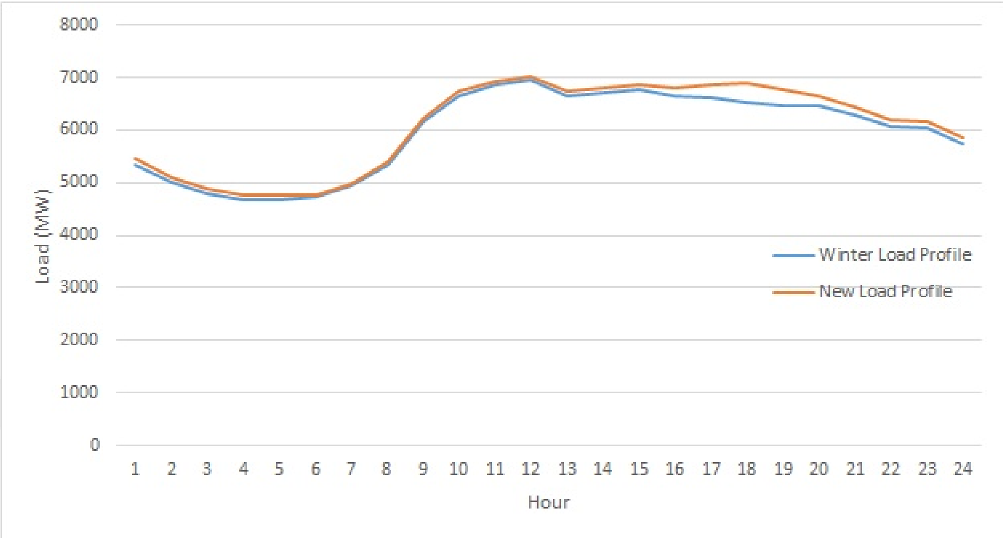

FIGURE 3.23: New daily load curve for winter in uncontrolled charging everywhere - Case 1 - 10% penetration

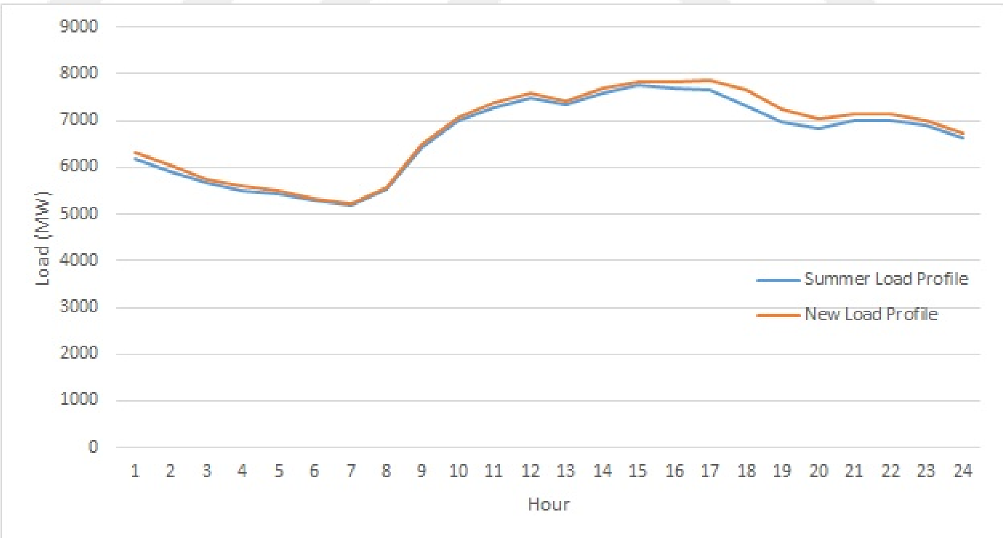

FIGURE 3.24: New daily load curve for summer in uncontrolled charging everywhere - Case 1 - 10% penetration

Case 2: The assumptions about the charging decision threshold and the battery distribution are similar to Case 1. Unlike Case 1, the charging power levels are considered as 3.7 kWh, 7.4 kWh, 11 kWh, and 22 kWh with the same probabilities. The results of

Case 1 and Case 2 are compared with each other in order to examine the effects of higher charging power level.

Figure 3.25 and Figure 3.26 show the seasonal daily load curves, which are generated by adding the average PHEV charging loads to the base load profile. The new load profiles have a similar pattern with Case 1. The maximum PHEV load added to the grid is created at 6 pm and its value about 347 MW. For the summertime, the peak load is shifted from 3 pm to 5 pm, same hour as Case 1.

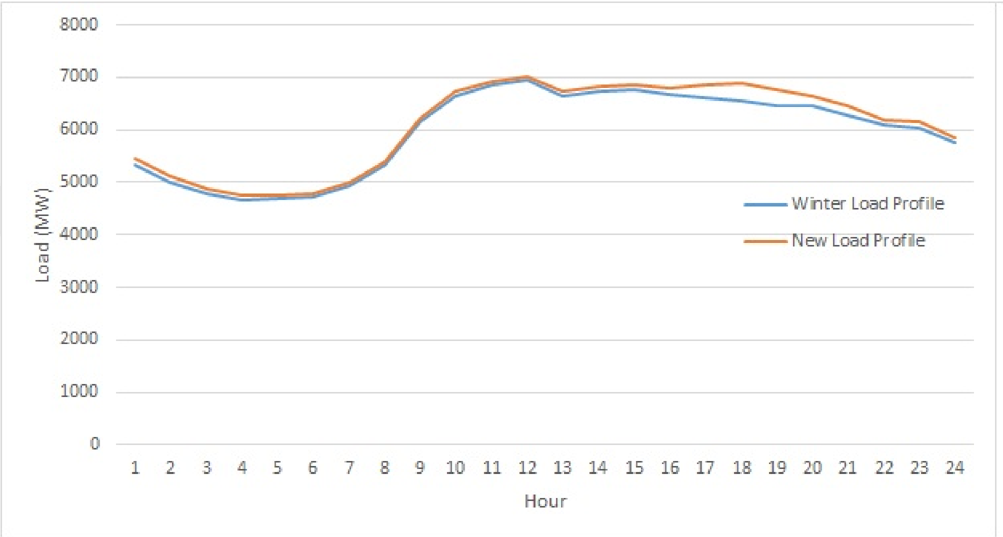

FIGURE 3.25: New daily load curve for winter in uncontrolled charging everywhere - Case 2 - 10% penetration

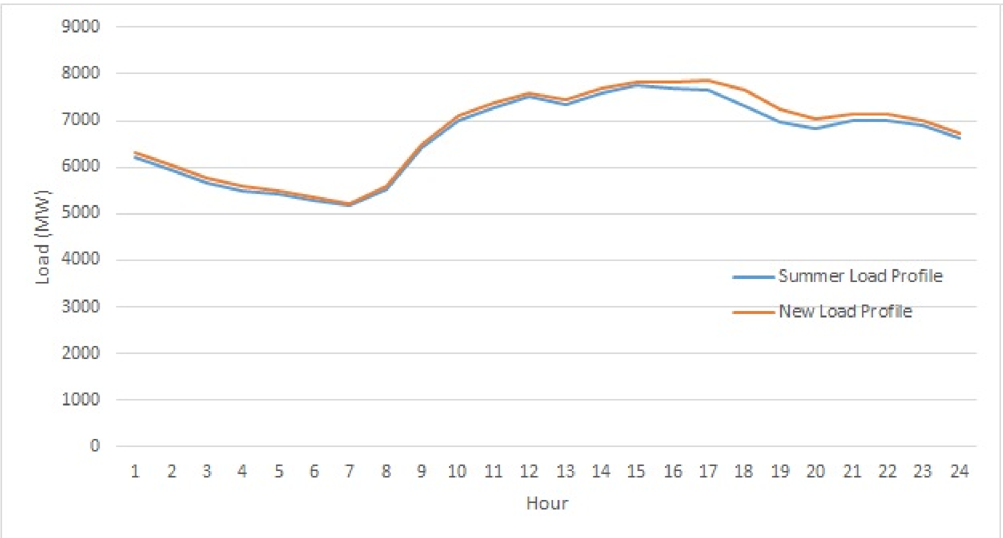

FIGURE 3.26: New daily load curve for summer in uncontrolled charging everywhere - Case 2 - 10% penetration

Case 3: In this case, the battery size distribution and the charging power level assumptions are same as Case 1. In order to see the effects of personal preferences on the PHEV charging profile, the charging decision threshold is defined as 0.8. Figure 3.27 depicts the average additional load profiles for Case 1 and Case 3. Compared to Case 1, total amount of daily electricity drawn from the grid could increase up to 8% in this case. Higher charging decision threshold increases the consumed electricity since more charging occurs during the day.

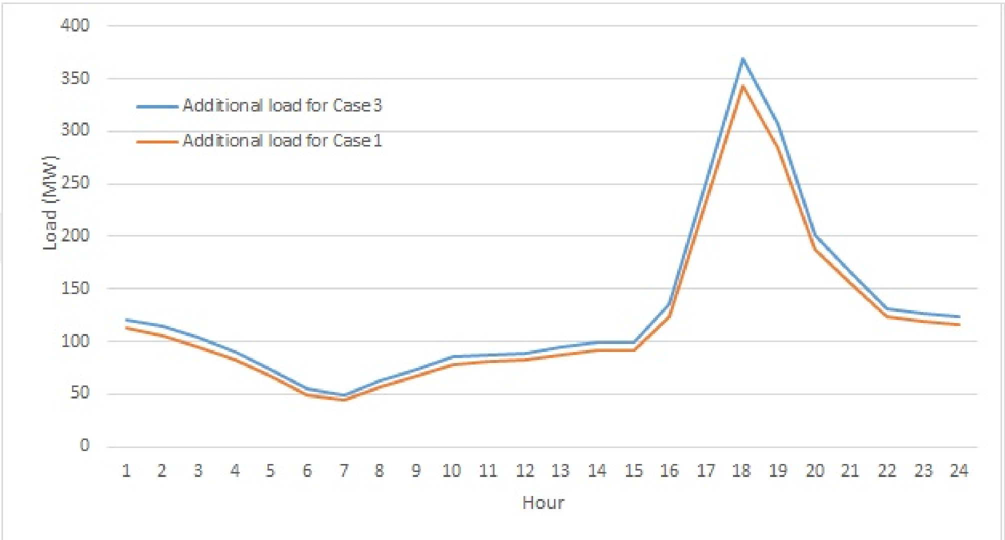

FIGURE 3.27: Additional load in uncontrolled charging everywhere according to Case 1 and Case 3 - 10% penetration

Figure 3.28 and Figure 3.29 illustrate the winter and summer load curves, which are created after adding the PHEV charging demand hour by hour. The new daily load curve has similar characteristics in terms of pattern. There is a slight increase in electricity consumption per hour while the peak demand appears at the same time, compared to Case 1.

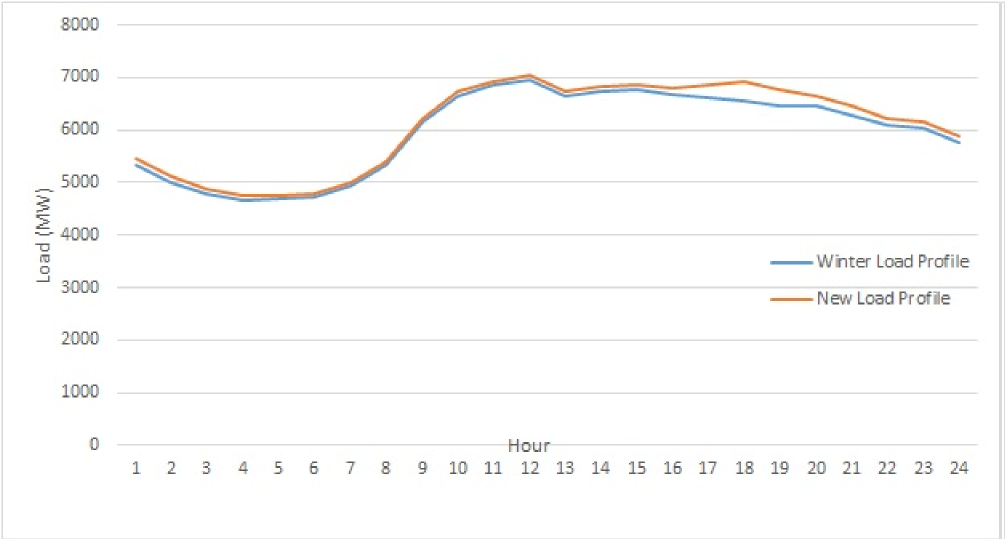

FIGURE 3.28: New daily load curve for winter in uncontrolled charging everywhere - Case 3 - 10% penetration

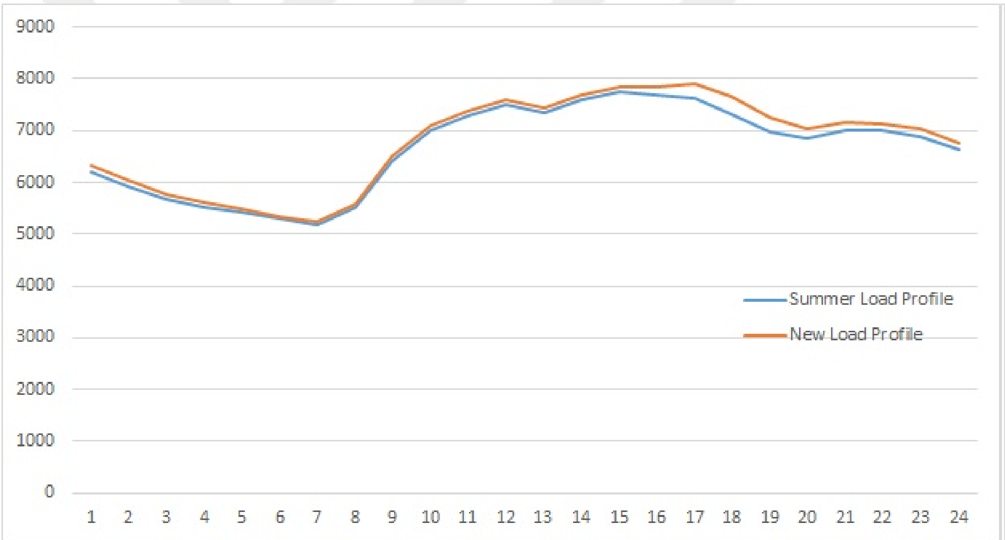

FIGURE 3.29: New daily load curve for summer in uncontrolled charging everywhere - Case 3 - 10% penetration

Case 4: The battery size is an important factor to determine the amount of time required for recharging and the frequence of charging. Higher battery size takes long hours for charging the vehicle and this factor has a potential to change daily load curve. To focus on the differences in the instantaneous electricity consumption profile due to changes in the battery size, it is assumed that half of the people prefer battery size of 20 kWh and half of them prefer battery size of 25 kWh. The other assumptions are same as Case 1. The simulation results are given below.

According to the results, the higher battery size causes the increase in electricity consumption per hour. Figure 3.30 and Figure 3.31 show that the new daily profile shapes for both winter and summer seasons have a similar pattern with a slight increase, compared to that of Case 1. As in Case 1, the peak hour is shifted from 3 pm to 5 pm in the summertime profile and the peak load increases by 2%.

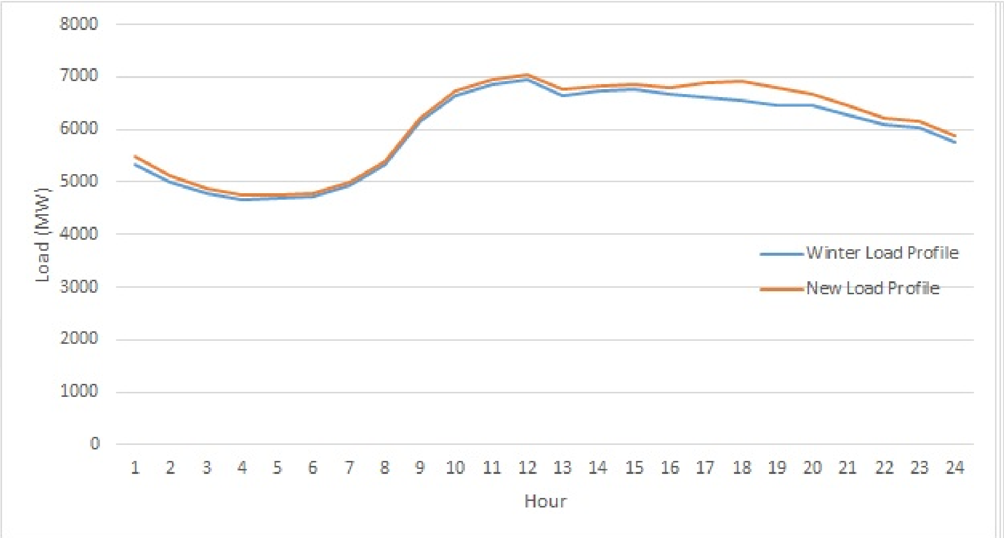

Figure 3.30: New daily load curve for winter in uncontrolled charging everywhere - Case 4 - 10% penetration

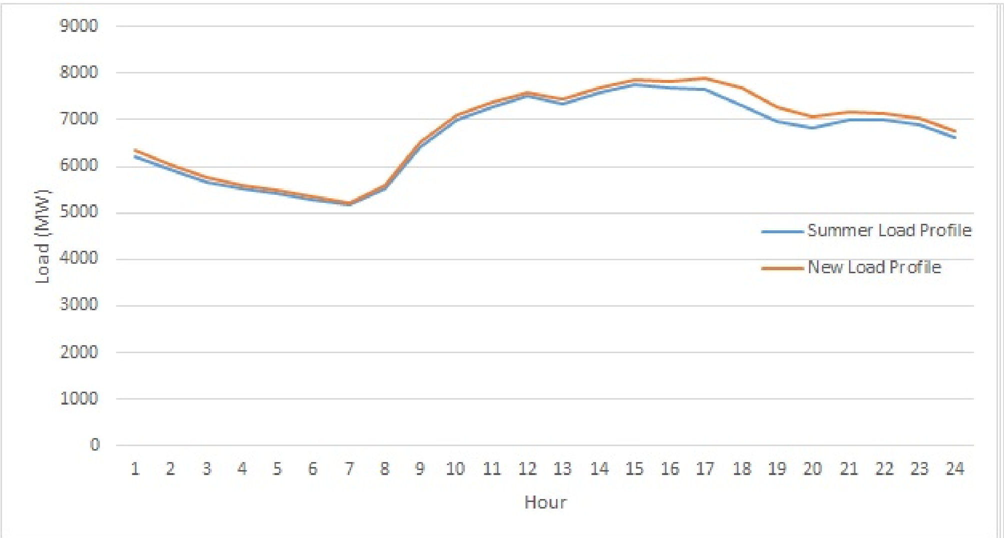

Figure 3.31: New daily load curve for summer in uncontrolled charging everywhere - Case 4 - 10% penetration

3.4.1.3 Results for Off-Peak Charging At Home Only

The PHEV charging occurs between 11 pm to 7 am to shift the peak demand to the overnight hours in this scenario. Since charging period is restricted by 8 hours, the electricity demand will be zero during the working hours. In this case, the vehicle owners' houses are considered as a charging place. Monte Carlo simulation is run for four different cases that mentioned above and results are analyzed.

Case 1: As mentioned previously, low charging power levels and uniform distribution of five battery sizes are considered in this case. The result are obtained for 0.5 charging decision threshold, thus it is assumed that all people are risk-neutral.

Figure 3.32 shows the additional PHEV charging load which ramps rapidly from 11 pm to 2 am due to the restriction on the charging time. The maximum peak demand appears at 2 am which is about 500 MW. The off-peak charging strategy relieves the PHEV impacts on the power grid since the additional peak load is shifted to the overnight hours where the electricity consumption from the other sectors is low.

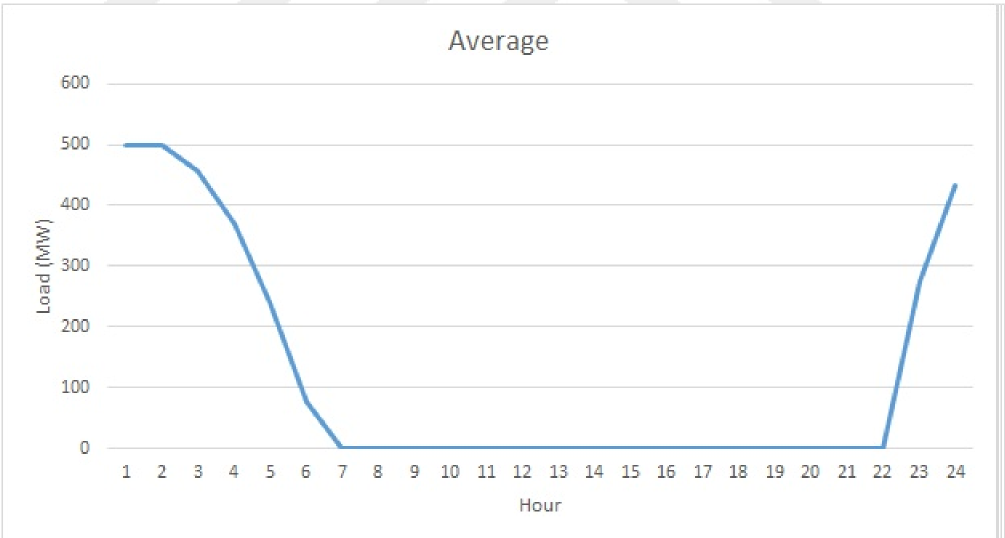

FIGURE 3.32: Additional load in off-peak charging at home only - Case 1 - 10% penetration

Figure 3.33 depicts the maximum, minimum and average load added to the system, which could be created at any day. As seen in the figure, maximum demand could be about 509 MW, minimum demand could be about 492 MW while the average load added to the grid is 500 MW at 2 pm, where the PHEV charging demand is maximum. This helps to see the range of additional load for each hour, which is between 492 MW to 509 MW. This result is important for planning power grid after the integration of PHEVs.

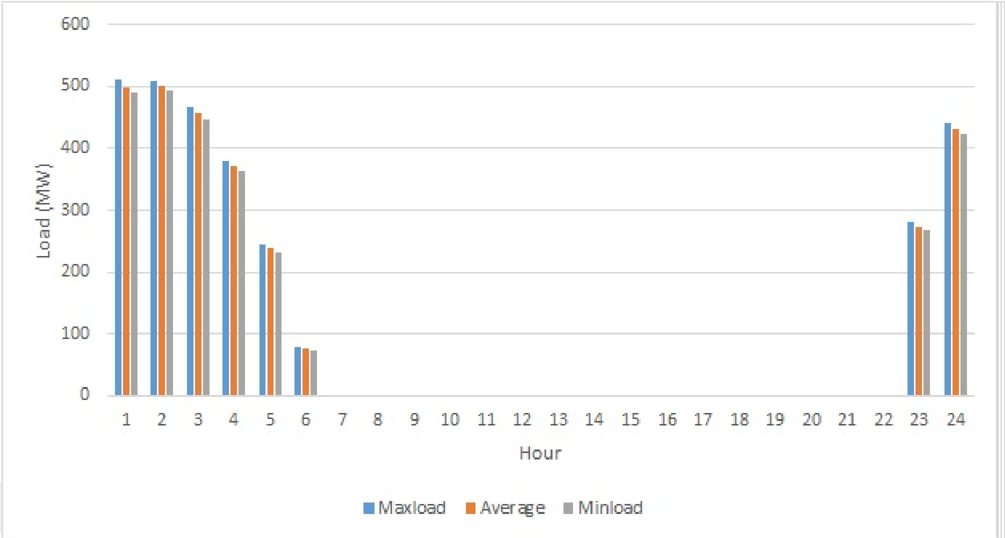

FIGURE 3.33: Maximum, average and minimum load per hour in off-peak charging at home only - Case 1 - 10% penetration

Figure 3.34 indicates that the maximum and minimum total electricity consumption would be 2870 MW and 2824 MW respectively. Although the electricity load drawn from the grid is important for each hour, observing the maximum and minimum total energy consumption is crucial to see potential daily electricity requirement in total.

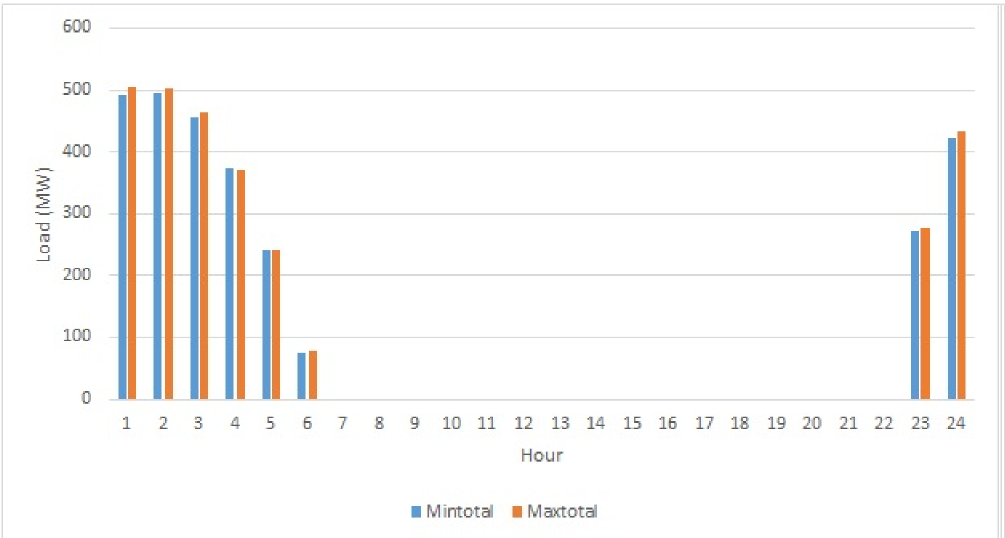

FIGURE 3.34: Maximum and minimum total electricity consumption in off-peak charging at home only - Case 1 - 10% penetration

The new daily load curves for two seasons are generated with considering the assumptions of Case 1 and the results are given in Figure 3.35 and Figure 3.36. As expected, there is no undesired peak load in the new daily load curve for both summer and winter, due to the overnight charging.

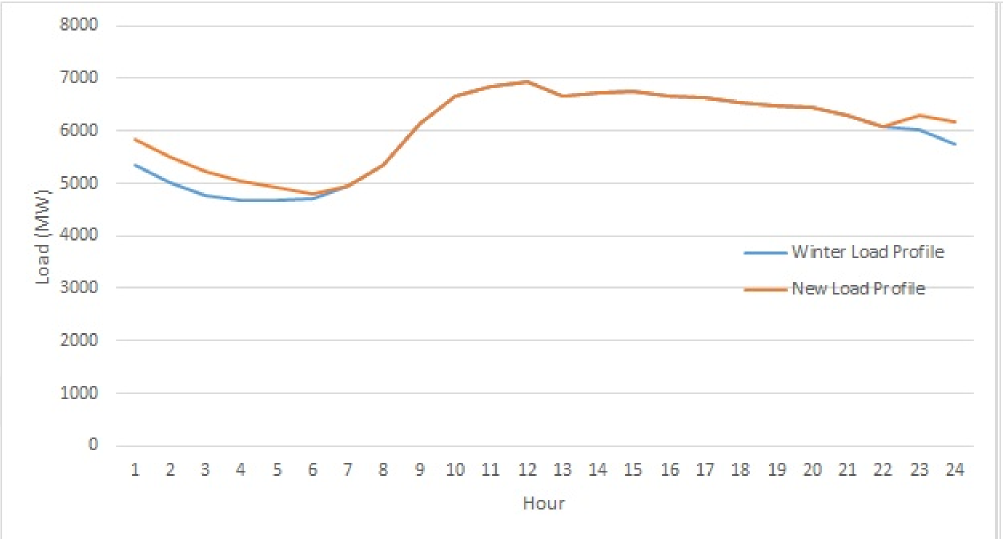

FIGURE 3.35: New daily load curve for winter in off-peak charging at home only - Case 1 - 10% penetration

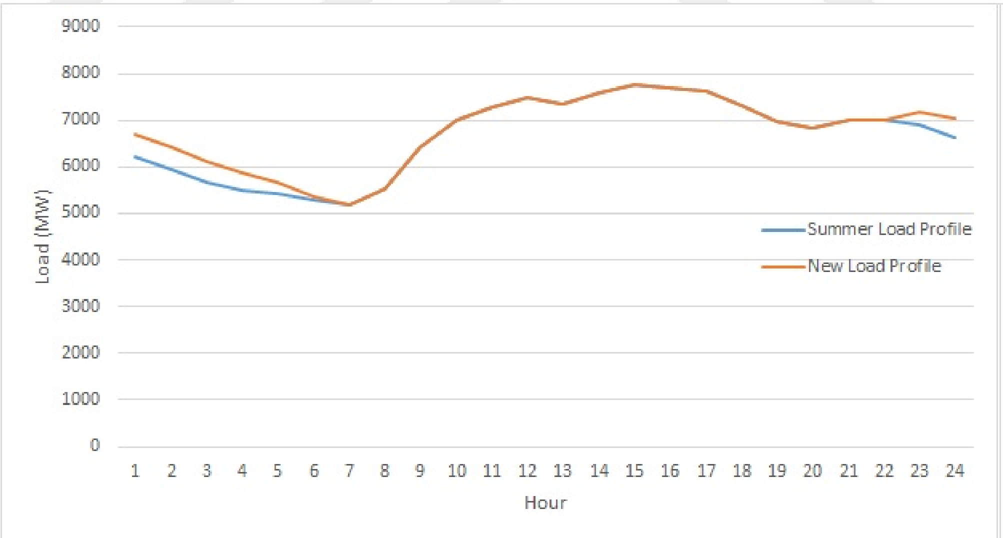

FIGURE 3.36: New daily load curve for summer in off-peak charging at home only - Case 1 - 10% penetration

Case 2: The vehicle owners might prefer the high charging power levels for fast charging. In this case, it is assumed that higher charging levels (11 kW and 22 kW) are added to the home charging and four charger types are uniformly distributed. The other parameters are same as Case 1.

Figure 3.37 and Figure 3.38 illustrate the winter and summer new daily load profile respectively. The hour, where the peak load is created, does not change for both seasons, same as Case 1.

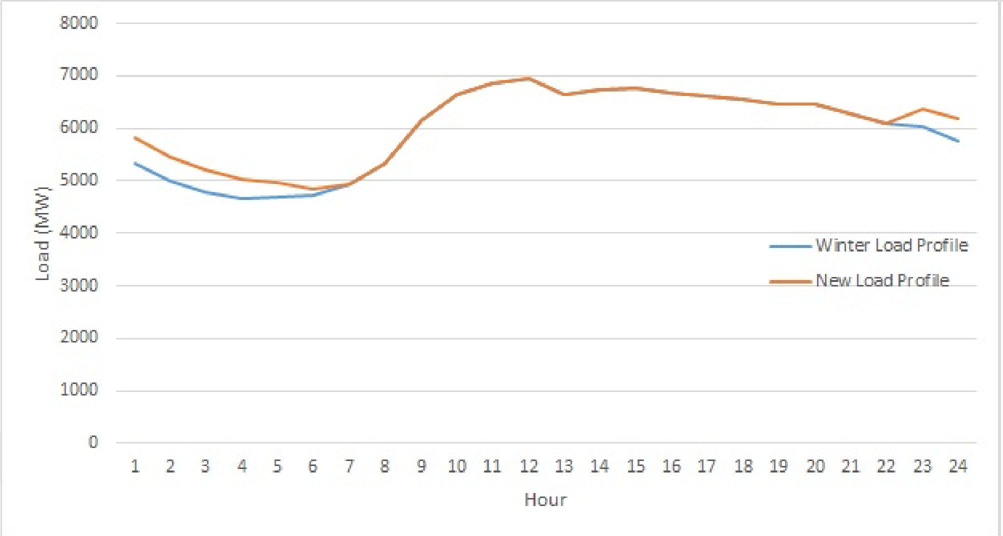

FIGURE 3.37: New daily load curve for winter in off-peak charging at home only - Case 2 - 10% penetration

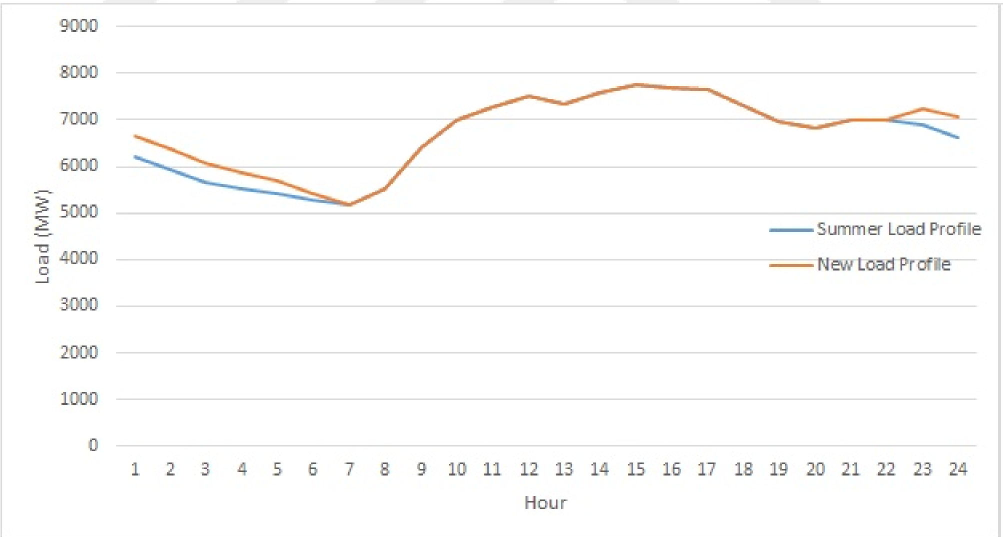

FIGURE 3.38: New daily load curve for summer in off-peak charging at home only - Case 2 - 10% penetration

Case 3: In this case, the charging decision threshold is considered 0.8 while the other parameters are same as Case 1. The peak demand appears at same hour as Case 1 (2 am) but the total electricity drawn from the grid could increase up to 8.2%. The increase in magnitude is expected due to more charging occurs during the day. Besides, the charging pattern is similar to Case 1. The new daily load profiles for winter and summer are plotted, as seen in Figure 3.39 and Figure 3.40.

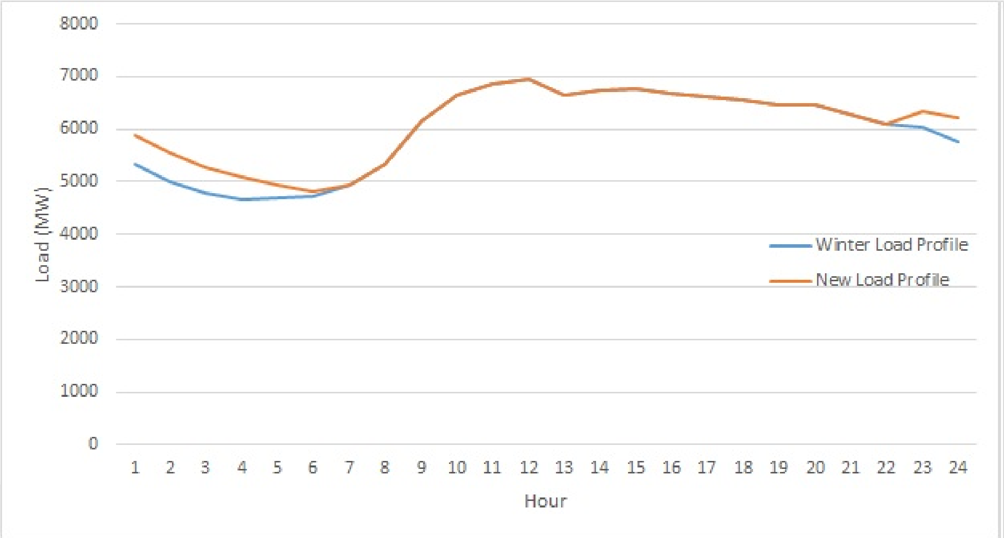

FIGURE 3.39: New daily load curve for winter in off-peak charging at home only - Case 3 - 10% penetration

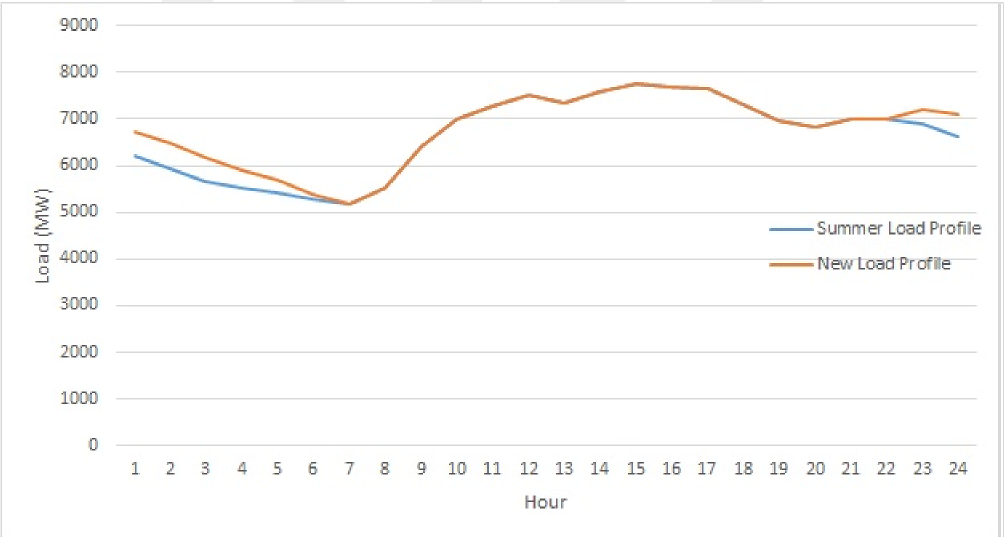

FIGURE 3.40: New daily load curve for summer in off-peak charging at home only - Case 3 - 10% penetration

Case 4: The size of battery increases the total electricity consumption for PHEV charging. In addition, the time required for charging is prolonged with the same charging power level. In this case, two higher battery sizes are considered: 20 kWh and 25 kWh. The Monte Carlo simulation is run for 0.5 charging decision threshold and two charger types assumptions. According to the results, higher battery size increases the total electricity consumption. The new daily electricity load curve is obtained after adding the

PHEV charging demand, as seen in Figure 3.41 and Figure 3.42. The load profiles have similar shapes to that of Case 1. Additionally, Case 4 does not create new peak load on the power system.

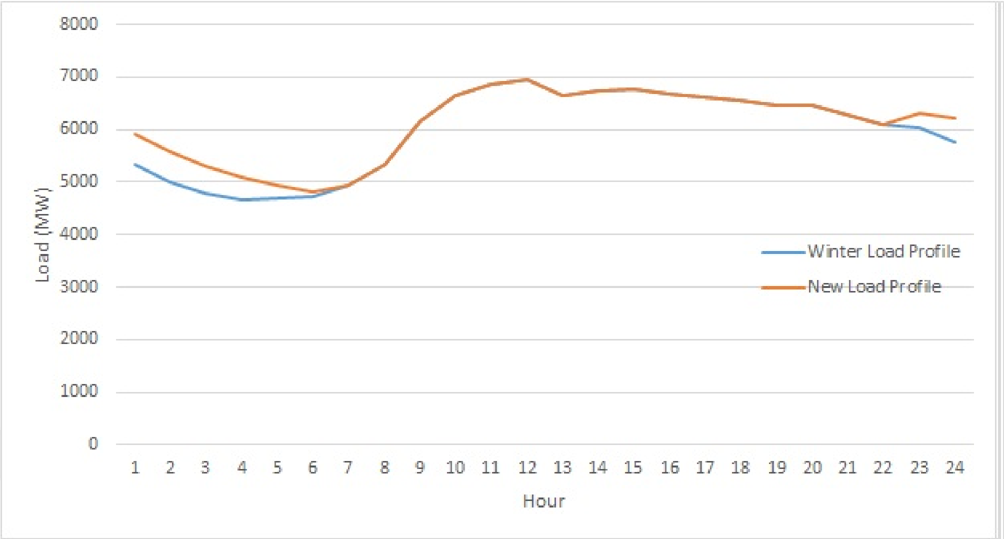

FIGURE 3.41: New daily load curve for winter in off-peak charging at home only - Case 4 - 10% penetration

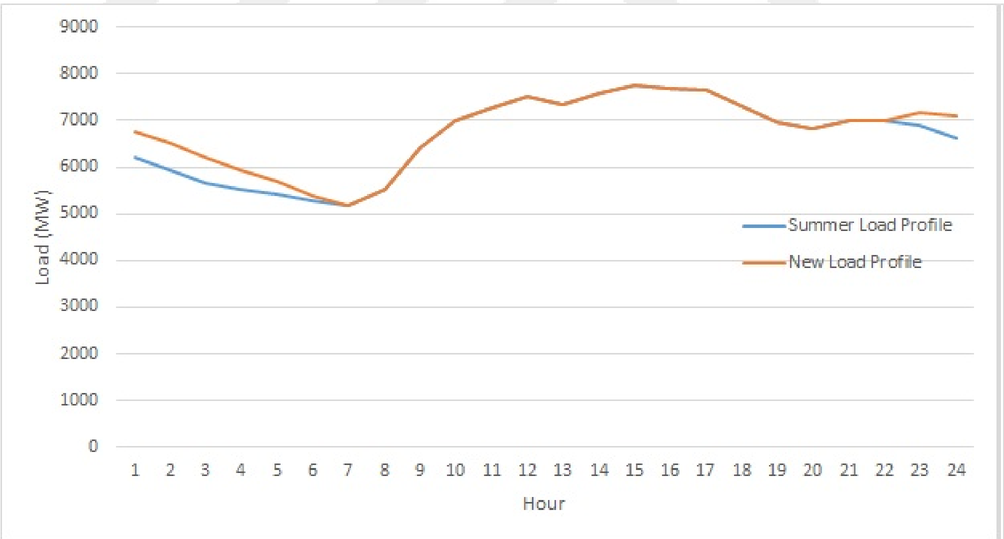

FIGURE 3.42: New daily load curve for summer in off-peak charging at home only - Case 4 - 10% penetration

3.4.1.4 Results for Off-Peak Charging Everywhere

In the literature, only the home is considered as a charging location in off-peak charging. The other scenario can be defined with adding the different charging locations for off-peak charging. In the off-peak charging everywhere scenario, if the vehicle owners decide to recharge their batteries at homes, then they are allowed to charge between 11 pm to 7 am, same period as off-peak charging. On the other hand, if they prefer the other locations as a charging places, which are workplaces, shopping malls, and public stations, they are allowed to charge their vehicles without a time restriction.

Case 1: : In this case, battery distribution is uniform and two charger types are used with same probabilities. The results are obtained for 0.5 charging decision threshold.

Figure 3.43 illustrates the additional load curve for off-peak charging everywhere scenario under 10% penetration level. The peak demand is at 6 pm and it is about 315 MW. When compared to uncontrolled charging everywhere scenario, the amount of load is lower at peak hour due to the shifting home charging to the off-peak hours. The charging profile ramps up from 3 pm to 6 pm because of the charging at shopping malls and public stations with 22 kW charging power level and it ramps up from 10 pm to 2 am because of the charging at home in the off-peak hours.

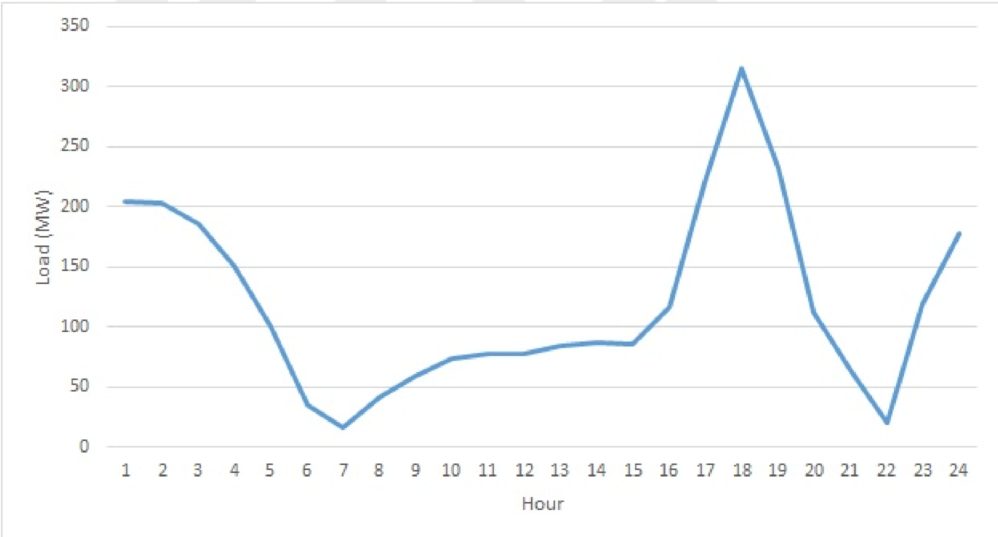

FIGURE 3.43: Additional load in off-peak everywhere - Case 1 - 10% penetration

Figure 3.44 and Figure 3.45 depict the new daily load profiles for winter and summer seasons respectively. The peak hour does not change in the winter load profile while the peak hour is shifted from 3 pm to 5 pm in the summer load profile, same as uncontrolled charging everywhere scenario.

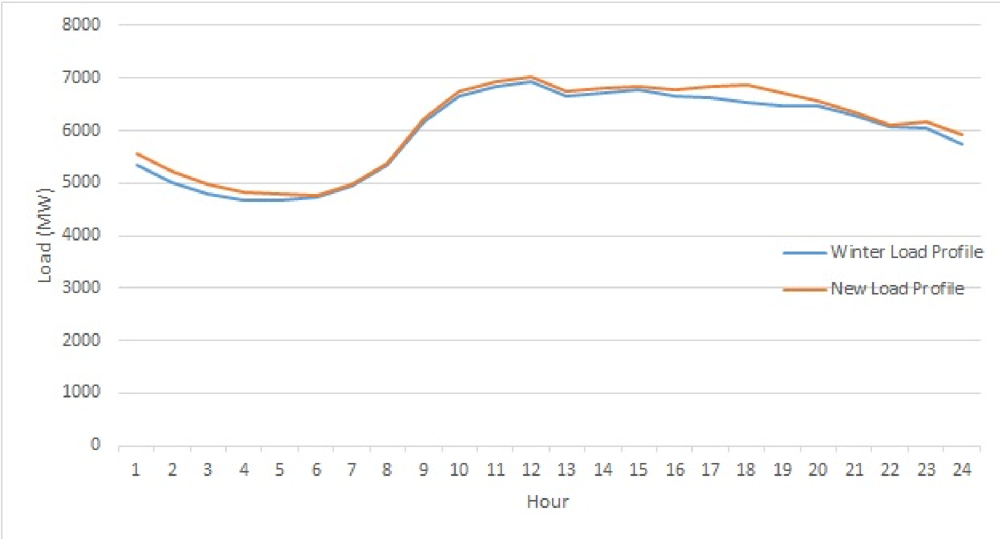

FIGURE 3.44: New daily load curve for winter in off-peak charging everywhere- Case 1 - 10% penetration

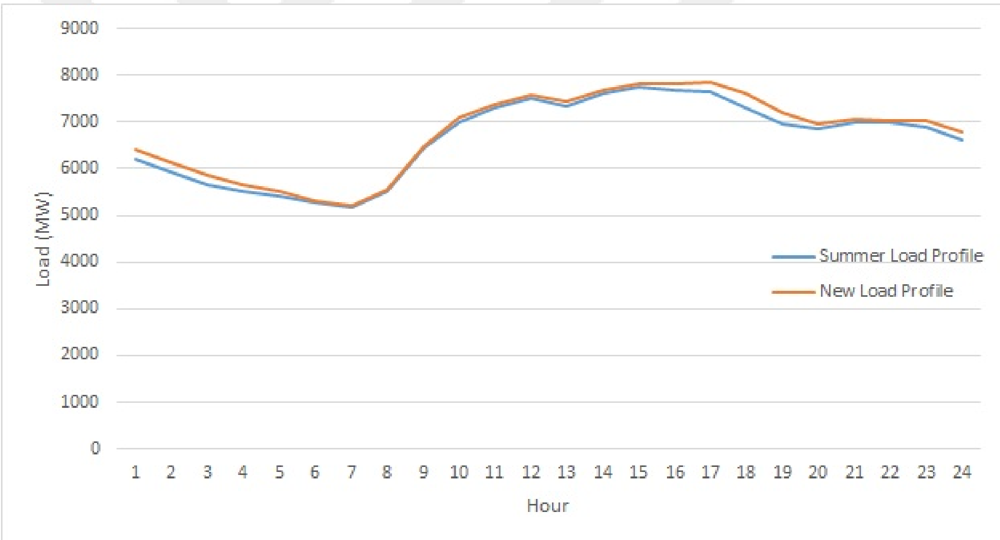

FIGURE 3.45: New daily load curve for summer in off-peak charging everywhere- Case 1 - 10% penetration

Case 2: As explained previously, charging decision threshold and battery sizes assumptions are similar to Case 1. Unlike Case 1, four charger types are considered with same probabilities in this case.

Figure 3.46 and Figure 3.47 show the seasonal daily load curves, which have similar patterns with Case 1. For summer load profile, the peak load is shifted from 3 pm to 5 pm in this case.

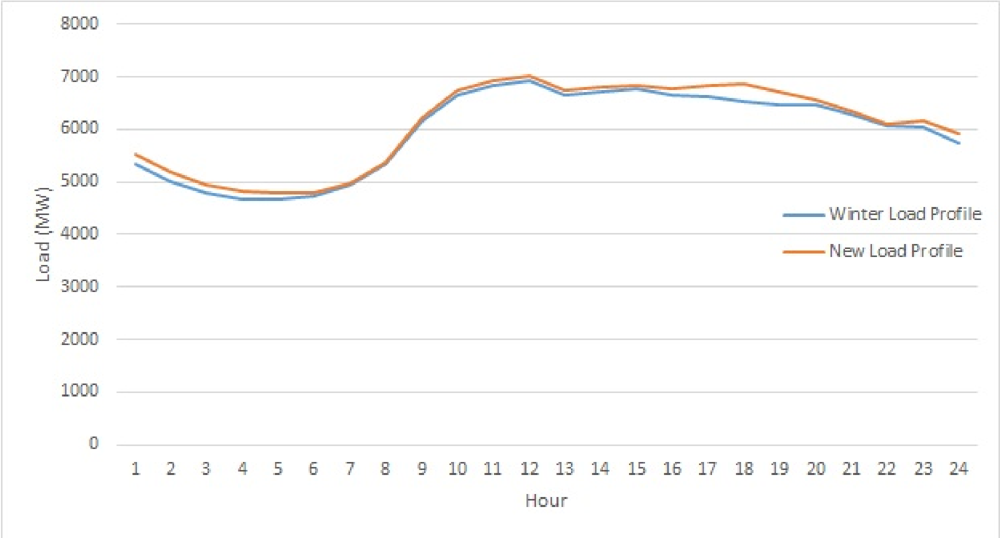

FIGURE 3.46: New daily load curve for winter in off-peak charging everywhere - Case 2 - 10% penetration

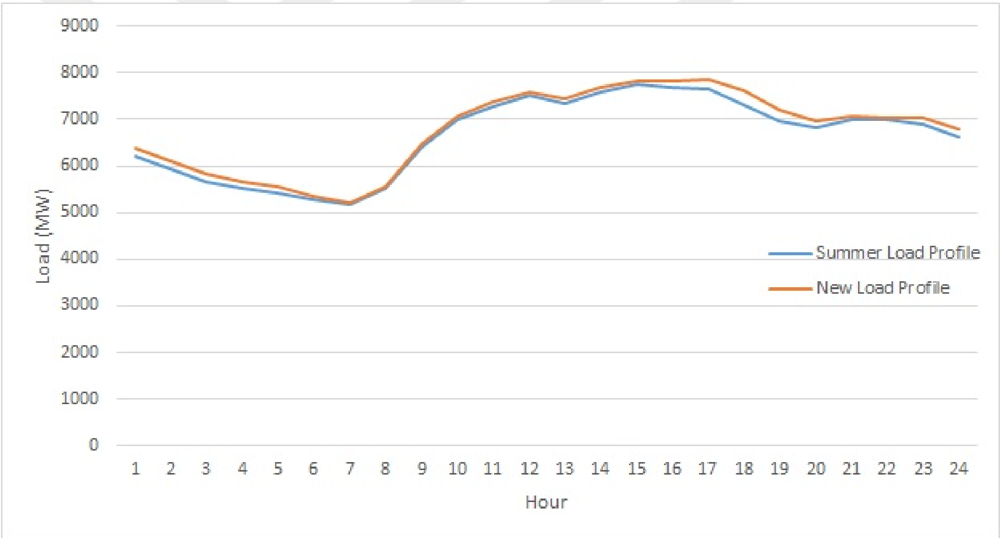

FIGURE 3.47: New daily load curve for summer in off-peak charging everywhere - Case 2 - 10% penetration

Case 3: To see the effects of personal preferences, the charging decision threshold is defined as 0.8 in this case. Figure 3.48 and Figure 3.49 represent new daily load profiles, which are generating by adding the average PHEV charging loads to the base load profiles. The peak load is created at same hour, compared to Case 1 and Case 2. There is a slight increase in electricity consumption since more charging occurs during the day.

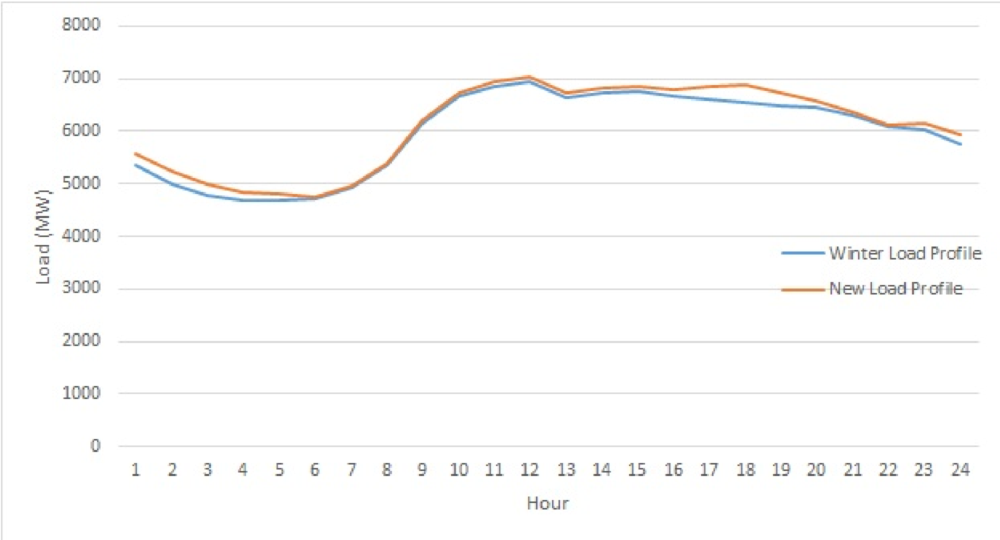

FIGURE 3.48: New daily load curve for winter in off-peak charging everywhere - Case 3 - 10% penetration

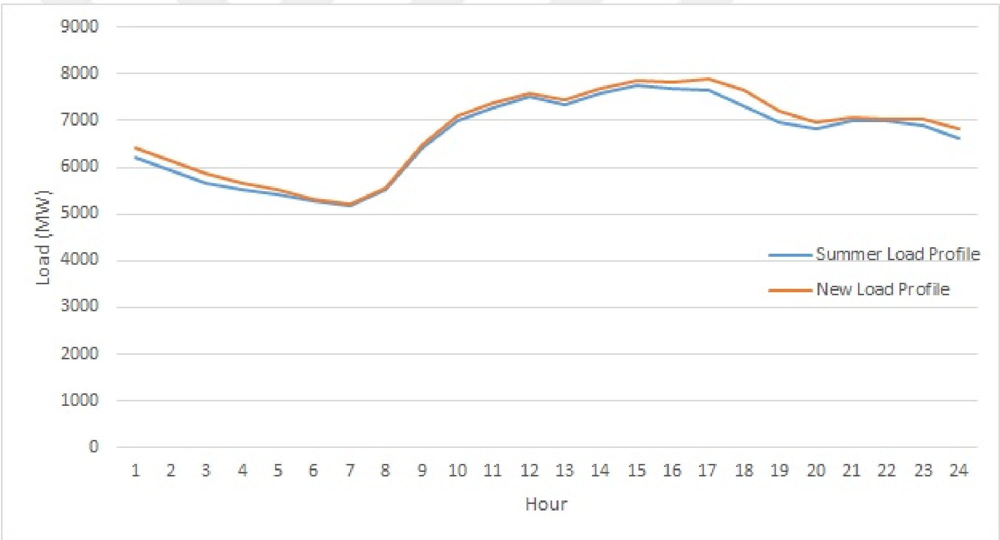

FIGURE 3.49: New daily load curve for summer in off-peak charging everywhere - Case 3 - 10% penetration

Case 4: In this case, it is assumed that the vehicle owners' prefer 20 kWh and 25 kWh battery sizes in order to see the effects of high battery size on the electricity consumption. Figure 3.50 and Figure 3.51 depict the new daily load profiles for winter and summer seasons respectively. The peak hour does not change in the winter load profile while the peak load is shifted from 3 pm to 5 pm in the summer load profile. When compared to Case 1, the peak load increases by 1.8% in the summertime profile.

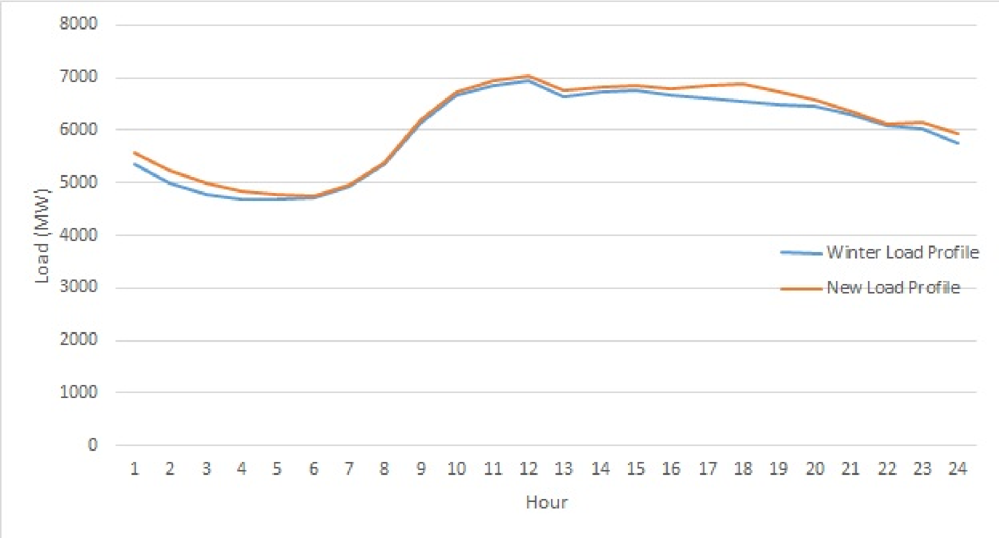

FIGURE 3.50: New daily load curve for winter in off-peak charging everywhere - Case 4 - 10% penetration

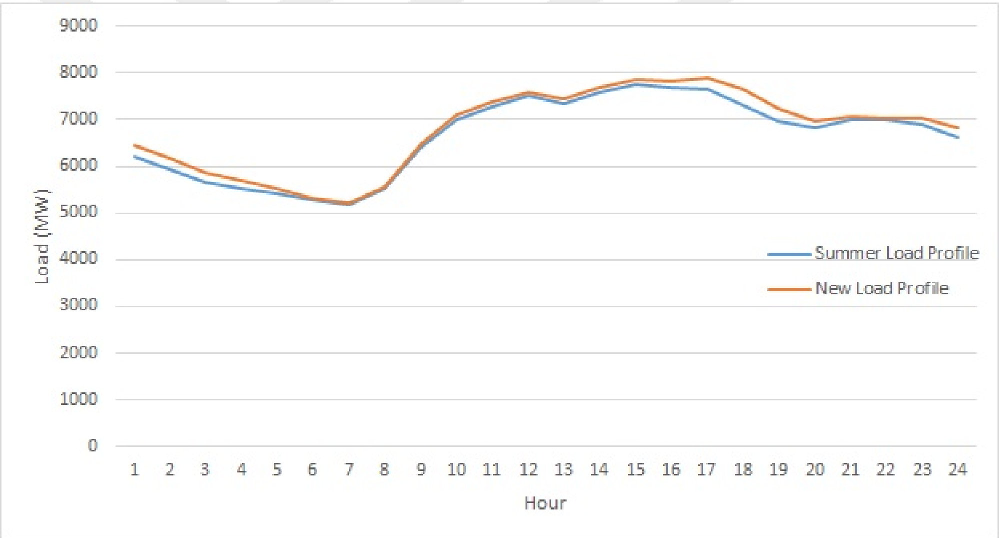

FIGURE 3.51: New daily load curve for summer in off-peak charging everywhere - Case 4 - 10% penetration

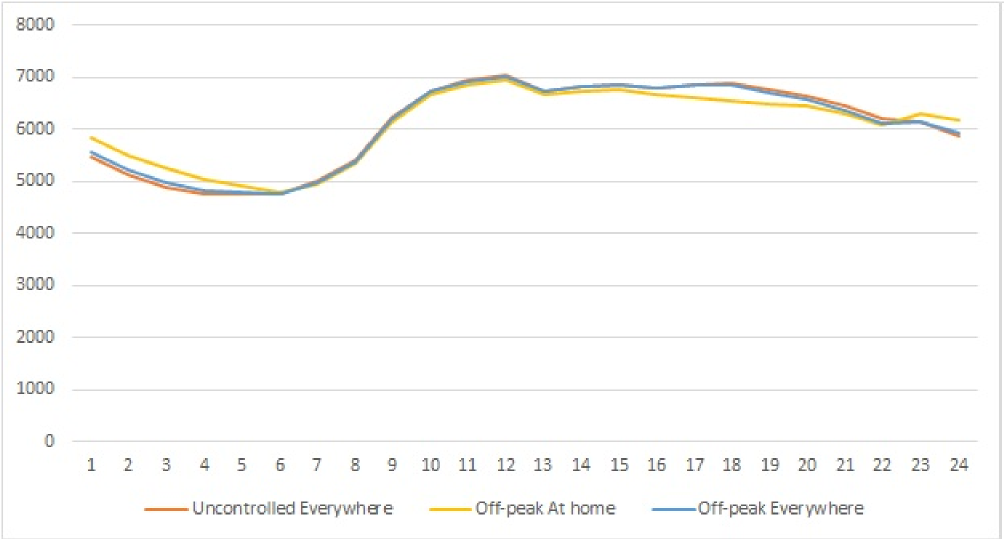

FIGURE 3.52: New daily load curve for winter in uncontrolled charging everywhere, off-peak charging only at home and off-peak charging everywhere - Case 1 - 10% penetration

Figure 3.52 shows the new daily load profiles for three charging scenarios: uncontrolled charging everywhere, off-peak charging at home, and off-peak charging everywhere. The new curves are obtained with adding the PHEV charging demand to the winter base load profile. In off-peak charging everywhere scenario, the peak load is created at 12 pm, same hour as the other scenarios. Besides, there is a decrease in the magnitude of demand at the peak hour, compared to uncontrolled charging. Therefore, off-peak charging everywhere scenario can be considered as more optimal charging strategy due to the decrease in peak demand. Since other charging places are added in this scenario, the amount of additional demand in the late night hours decreases when compared to off-peak charging only home scenario.

3.4.2 Results of 50% PHEV Penetration Level

High penetration level of PHEVs causes undesirable effects on the electricity network due to the increase in the number of vehicles. When 50% of conventional vehicles are converted to electric vehicles, total amount of daily energy will increase and also the shape of load profile will change significantly. Understanding the additional electricity consumption can help the utilities to better plan for electrical demand with high penetration level of PHEVs. The Monte Carlo simulation is run under uncontrolled charging and off-peak charging scenario and results are generated for 50% penetration rate of PHEVs.

3.4.2.1 Results for Uncontrolled Charging At Home Only

As explained previously, the uncontrolled charging exclusively at home scenario provides the continuous charging during the day. The vehicle owners can recharge their batteries at any hour after their arrival times. The simulation results are obtained for four different cases that created with respect to charging power level, battery size, and personal preferences about charging decision.

Case 1: In this case, the most commonly used charging types, which are 3.7 kW and 7.4 kW, are considered. Five battery sizes (5 kWh, 10 kWh, 15 kWh, 20 kWh, 25 kWh) are uniformly distributed and results are generated for 0.5 charging decision threshold.

Figure 3.53 depicts the daily required energy per hour after 50% penetration of the PHEVs. As is seen in the figure, the peak demand occur at 12 am and its value is about 1384 MW. Since the people spend significant time at their homes after 6 pm , majority of charging occurs in the evening and early morning hours.

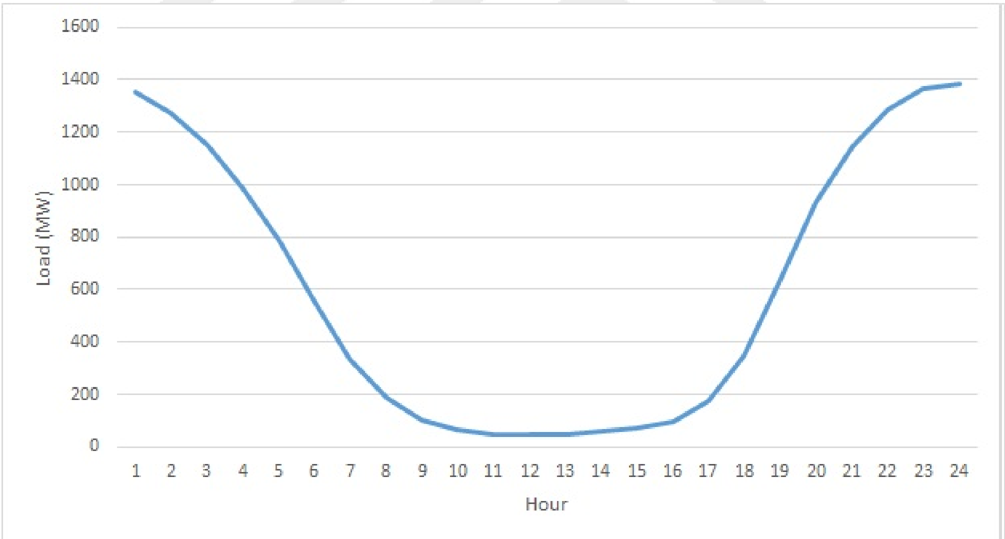

FIGURE 3.53: [Additional load in uncontrolled charging at home only - Case 1 - 50% penetration

The maximum, minimum, and average load added to the power grid per hour is presented in Figure 3.54. According to the curve, the maximum required energy would be about 1400 MW and minimum required energy would be about 1370 MW at 12 am, while the average load is 1384 MW at the peak hour. It means that, the amount of electricity from the grid ranges between 1370 MW to 1400 MW. This information can be used by electrical utilities to plan when the additional capacity will be required to meet the needs of vehicle owners.

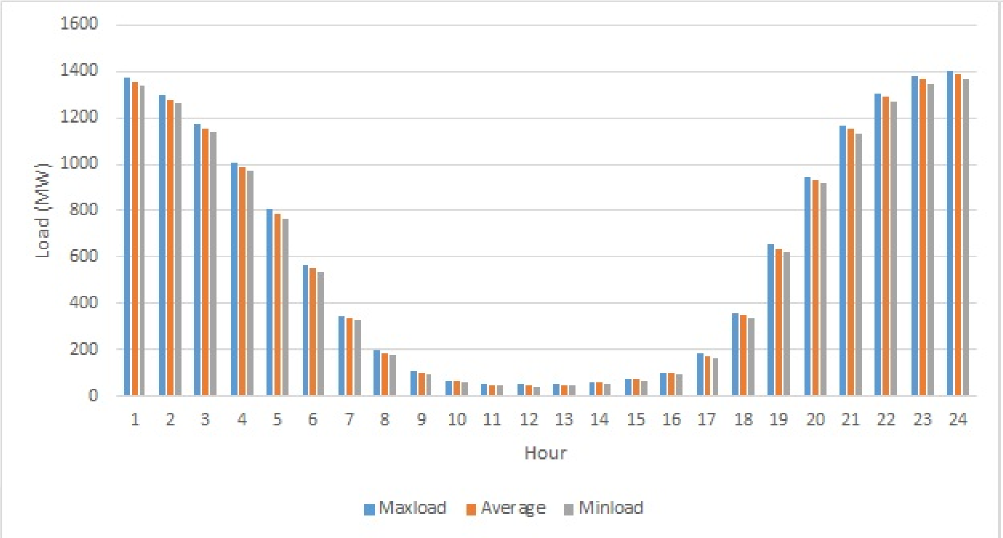

FIGURE 3.54: Maximum, average and minimum load per hour in uncontrolled charging at home only - Case 1 - 50% penetration

Figure 3.55 illustrates the specific Monte Carlo iteration where the total amount of required energy is maximum and minimum. According to the results, the maximum energy consumption is about 14491 MW while the minimum electricity consumption is about 14400 MW. The average total consumption from PHEV charging is about 14445 MW, which is one-tenth of the daily consumption witout PHEVs.

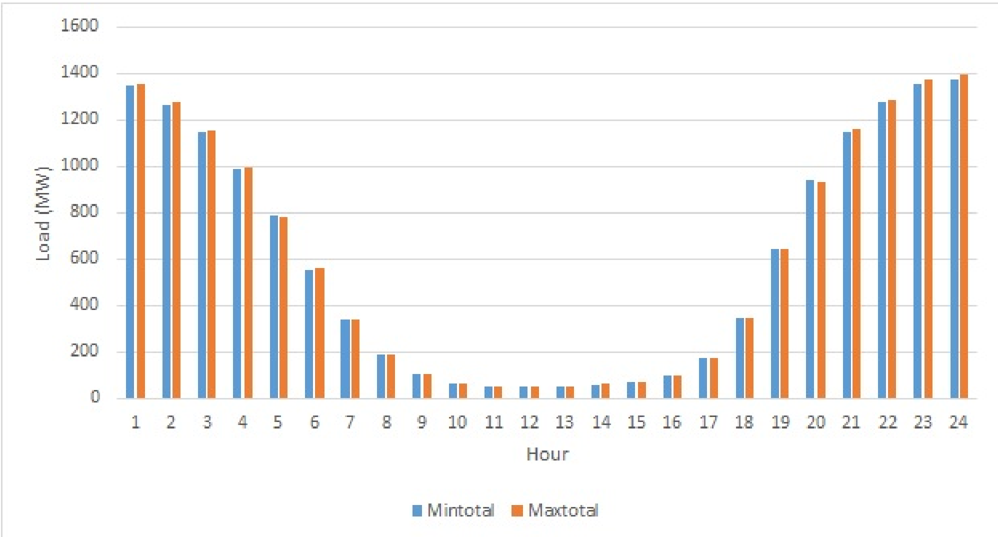

FIGURE 3.55: Maximum and minimum total electricity consumption in uncontrolled charging at home only - Case 1 - 50% penetration

As expected, high penetration level of PHEVs affects the daily load profile due to the increase in the total consumption and the new peak loads created. Figure 3.56 and Figure 3.57 shows the new daily load curves after 50% penetration level of PHEVs for winter and summer seasons respectively. The peak hour is shifted for both winter and summer. In the new daily load curve, the peak load is created at 9 pm for wintertime and is created at 10 pm for summertime. 50% level of PHEV penetration leads to a 7% increase in the peak load for both summer and winter seasons.

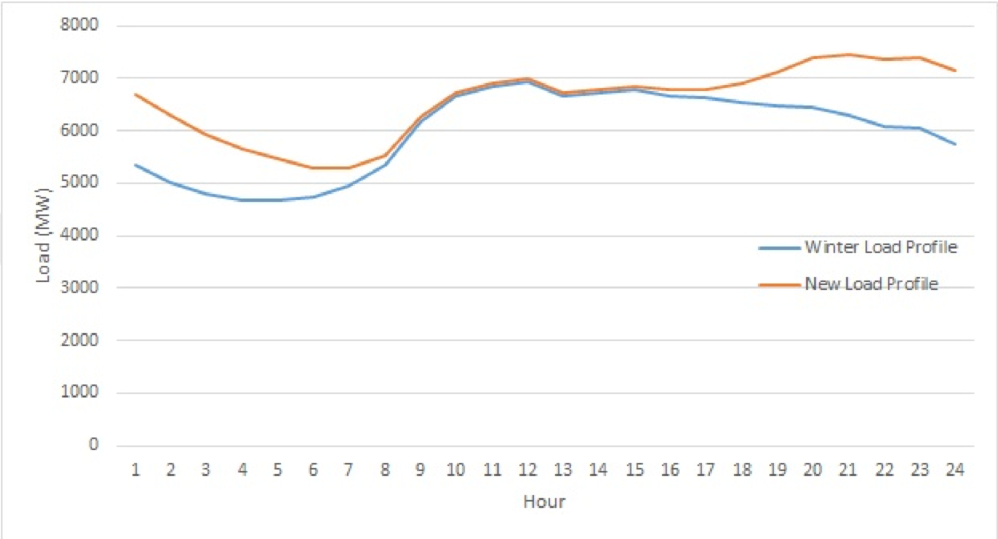

FIGURE 3.56: New daily load curve for winter in uncontrolled charging at home only - Case 1 - 50% penetration

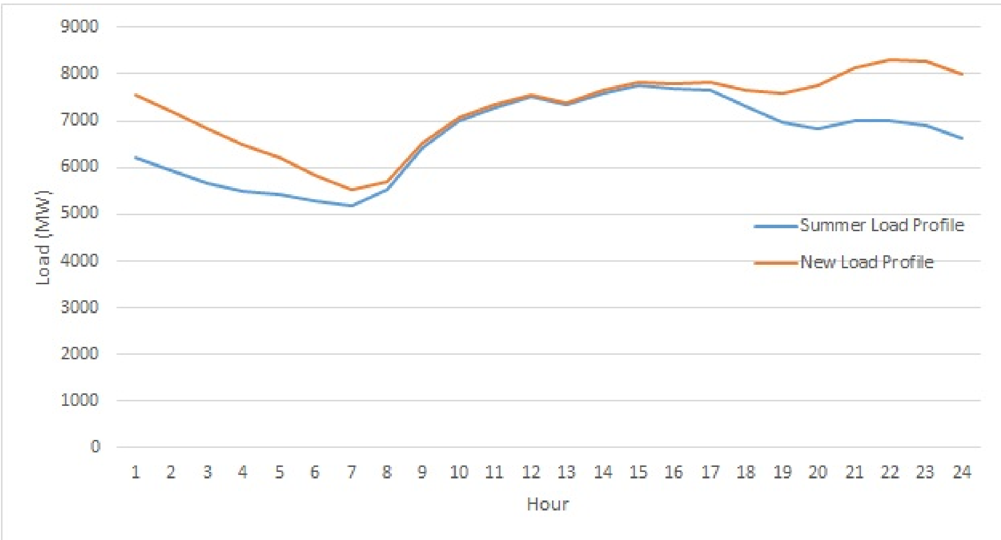

FIGURE 3.57: New daily load curve for summer in uncontrolled charging at home only - Case 1 - 50% penetration

Case 2: In this case, four charger types are examined with other parameters remaining the same as Case 1 and results are given below.

Figure 3.58 and Figure 3.59 display the changes on the daily load curves after the integration of PHEV. The new daily load profiles have a similar shapes to load profiles in Case 1. For wintertime, the peak hour is shifted from 12 pm to 9 pm while it is shifted from 3 pm to 10 pm in the summertime load profile.

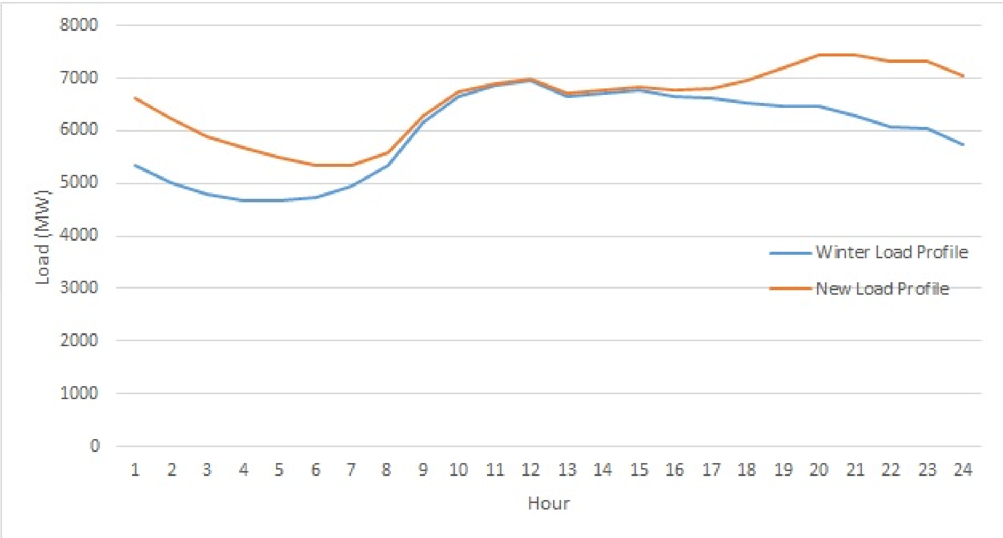

FIGURE 3.58: New daily load curve for winter in uncontrolled charging at home only - Case 2 - 50% penetration

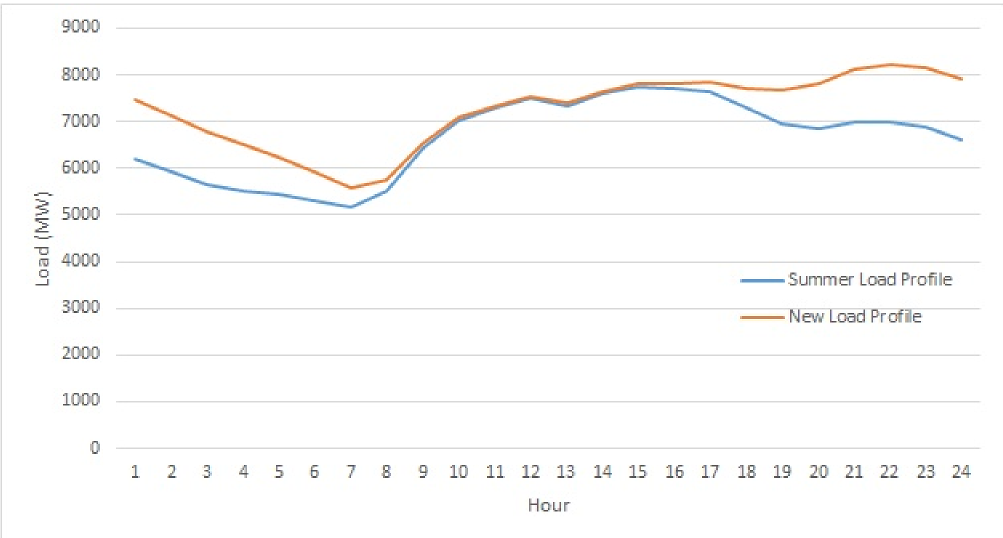

FIGURE 3.59: New daily load curve for summer in uncontrolled charging at home only - Case 2 - 50% penetration

Case 3: The human factor is one of the important factors that affect the PHEV charging demand. Risk-averse people tend to recharge their batteries even the remaining energy in their batteries is adequate for next trip. In this case, all vehicle owners are considered as risk-averse people and the charging decision threshold is defined 0.8. All other parameters are same as Case 1 in order to see the differences due to the changes in personal preferences.

Figure 3.60 and Figure 3.61 represent the new daily load profiles for two seasons. As can be seen from figures, the load curves have similar characteristics to the load profiles in Case 1. Compared to the first case, higher decision threshold increases the total electricity demand. The peak load is created at the hour same as Case 1, for both summer and winter seasons. In addition, the peak load increases by 8% in this case.

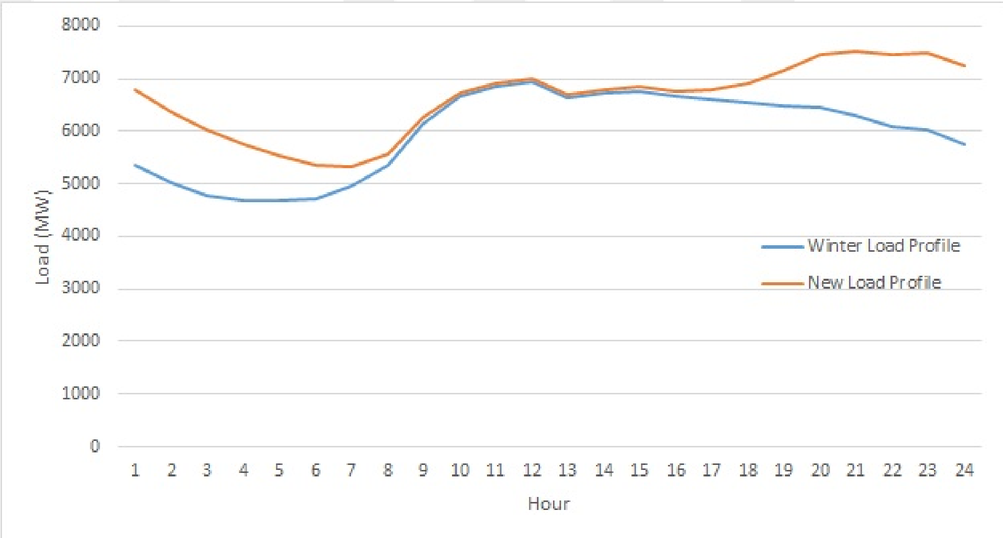

FIGURE 3.60: New daily load curve for winter in uncontrolled charging at home only - Case 3 - 50% penetration

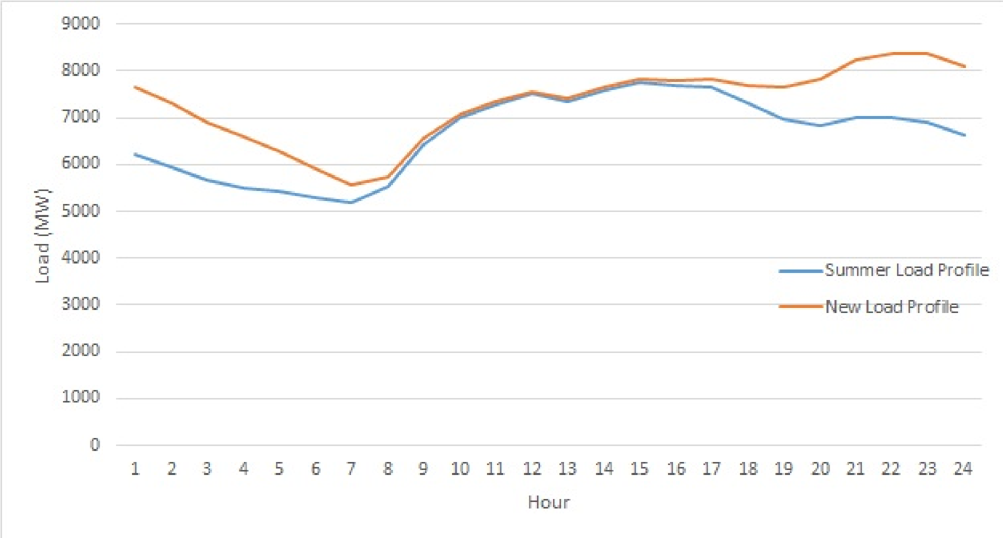

FIGURE 3.61: New daily load curve for summer in uncontrolled charging at home only - Case 3 - 50% penetration

Case 4: As mentioned previously, in this case, the effects of higher battery types are investigated with all other parameters remaining same as Case 1. The higher battery size increases the additional electricity demand. The new peak load appears at 11 pm in the winter load profile for this case, while the peak is created at 9 pm for Case 1. The maximum electricity demand from PHEV charging is created at 12 am, same as Case 1. The peak load is 9% higher than the base load peak for both summer and winter.

The new daily load curves are depicted in Figure 3.62 and Figure 3.63.

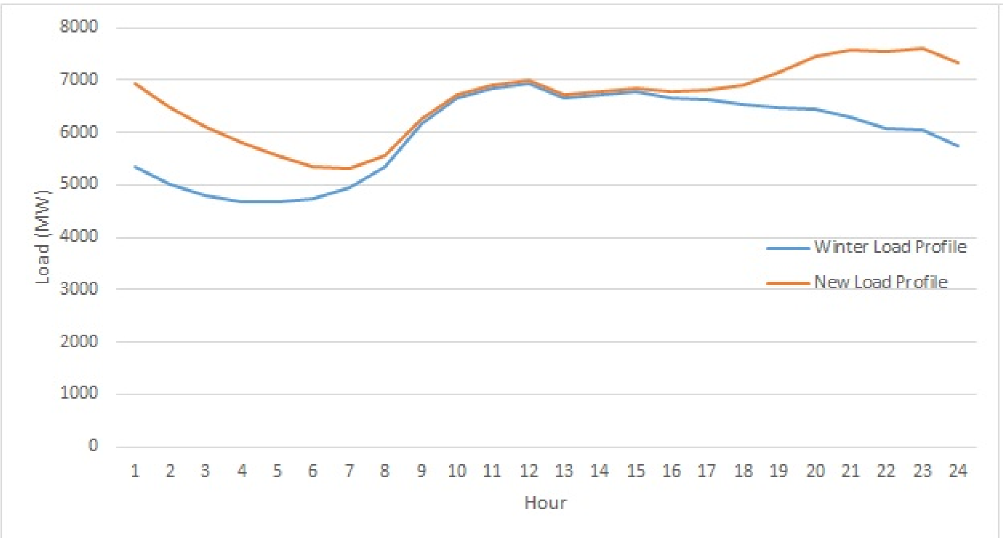

FIGURE 3.62: New daily load curve for winter in uncontrolled charging at home only - Case 4 - 50% penetration

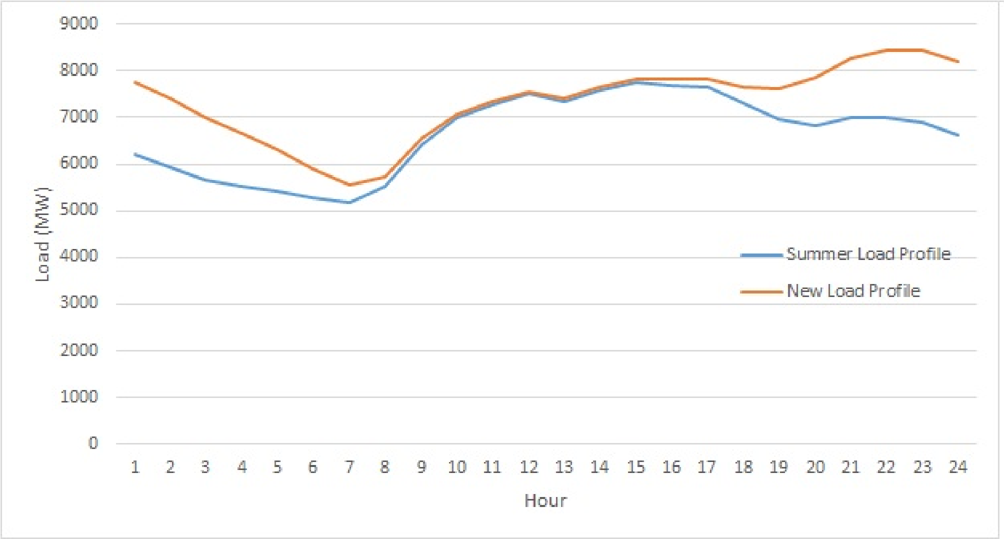

FIGURE 3.63: New daily load curve for summer in uncontrolled charging at home only - Case 4 - 50% penetration

3.4.2.2 Results for Uncontrolled Charging Everywhere

In uncontrolled charging everywhere scenario, the charging continuous during the day without any restriction on time of plug-in and the vehicle owners are allowed to recharge their batteries at four different charging places. Without a restriction on charging time and charging location, the daily load profile will change significantly especially for 50% penetration rate of PHEVs.

The simulation is applied for four different cases with respect to charging power level, battery size, and charging decision threshold and results are discussed.

Case 1: The Monte Carlo simulation is run for two charging power levels, five battery types, and 0.5 charging decision threshold and results are presented below. The shape of the load profile is similar to 10% penetration level with the increase in magnitude of electricity demand.

Figure 3.64 illustrates the additional load profile which ramps up rapidly after 3 pm. The peak load appears at 6 pm, same as the charging profile with 10% penetration level. The peak load is 1724 MW at 6 pm, which is about one-fourth of the original load at 6 pm. Thus, with 50% penetration level, considerable amount of total electricity is required for PHEV charging. The majority of charging takes place in the evening hours which corresponds to the arrival times to homes, shopping malls, and public stations.

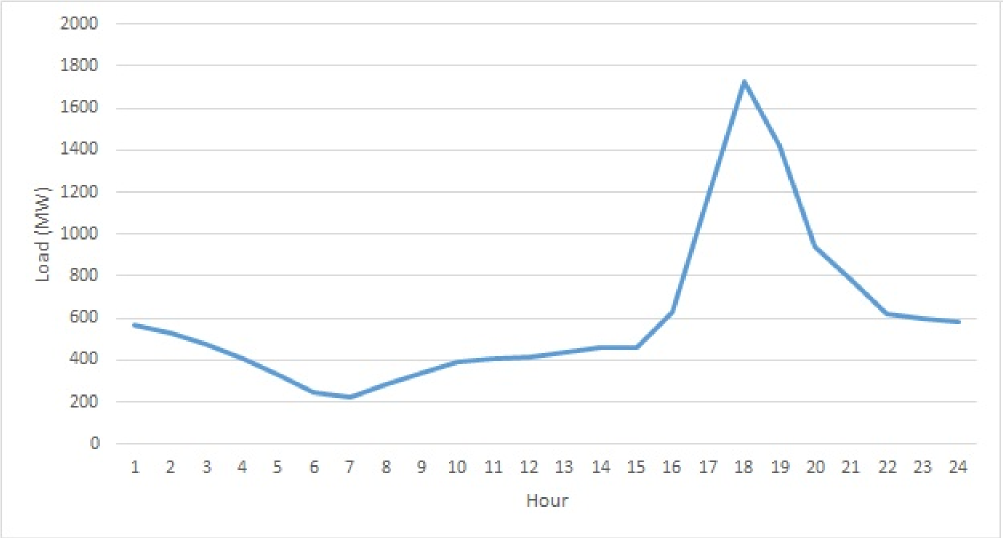

FIGURE 3.64: Additional load in uncontrolled charging everywhere - Case 1 - 50% penetration

In order to see the range of loads per hour, maximum and minimum load added to the power grid for each hour are generated from Monte Carlo simulation. According to the results, the maximum required energy would be about 1753 MW and minimum required energy would be about 1680 MW at peak hour, as seen in Figure 3.65.

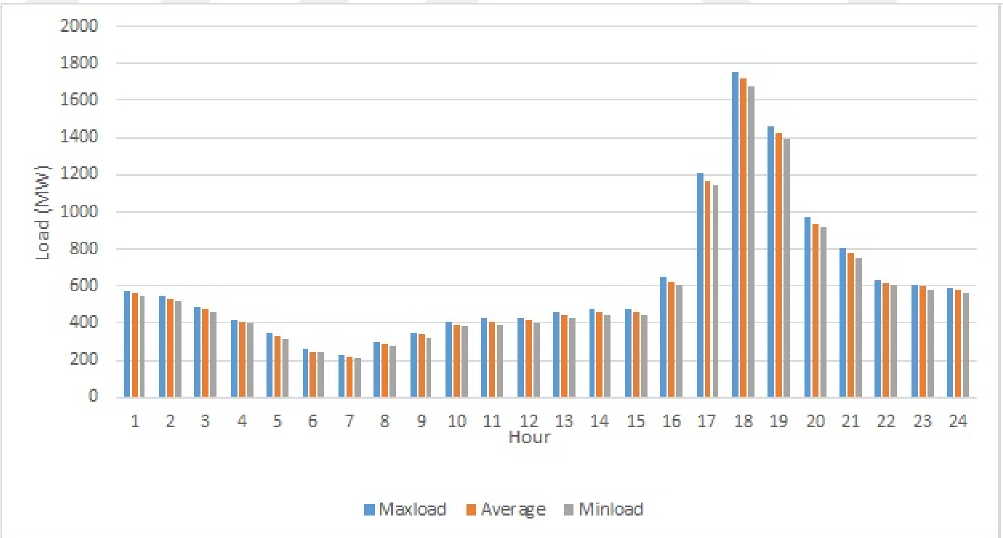

FIGURE 3.65: Maximum, average and minimum load per hour in uncontrolled charging everywhere - Case 1 - 50% penetration

Knowing the total required energy from the charging of PHEVs can help the utilities to plan the total additional generation. Figure 3.66 depicts the daily charging load profile of specific days with minimum and maximum energy consumption. According to the simulation results, the maximum daily energy requirement would be about 14500 MW while the minimum energy consumption would be about 14392 MW.

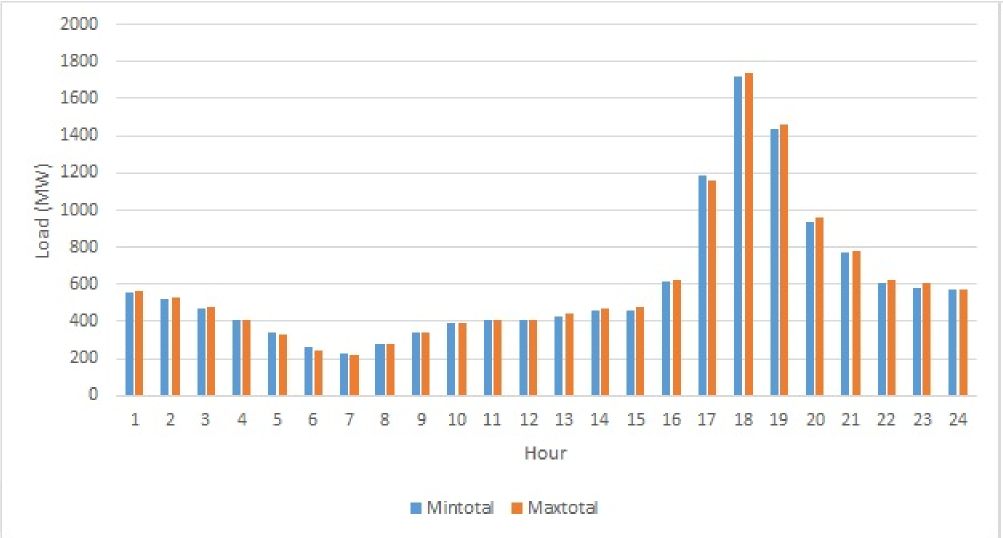

FIGURE 3.66: Maximum and minimum total electricity consumption in uncontrolled charging everywhere - Case 1 - 50% penetration

The daily load profile changes significantly because of high penetration level of PHEVs, as seen in Figure 3.67 and Figure 3.68. The peak load is shifted from 12 pm to 6 pm for winter and is shifted from 3 pm to 6 pm for summer. 50% penetration rate could increase the peak load by 19% in the winter load profile and by 17% in the summer load profile. The results demonstrate that the amount of peak load is considerable since the charging occurs everywhere without time restriction with 50% penetration level.

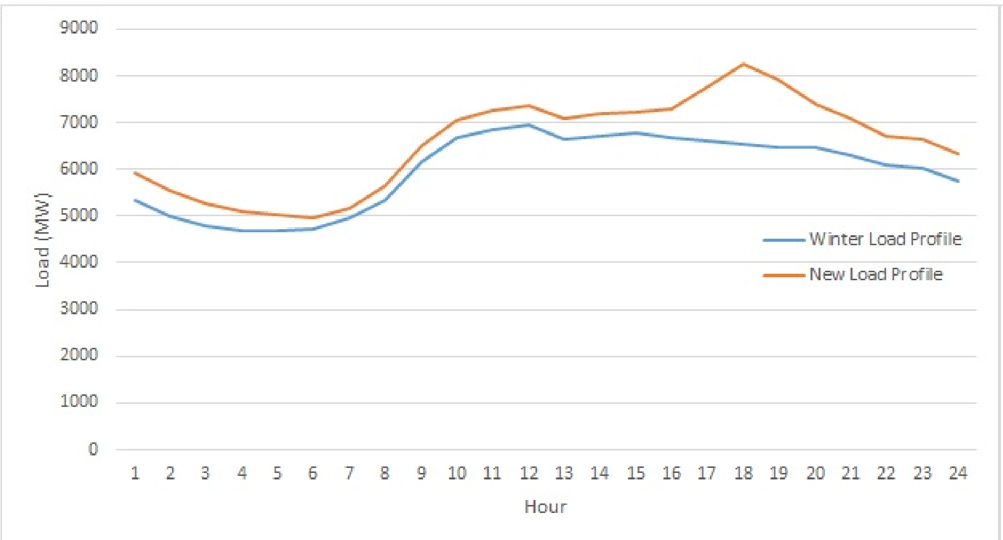

FIGURE 3.67: New daily load curve for winter in uncontrolled charging everywhere - Case 1 - 50% penetration

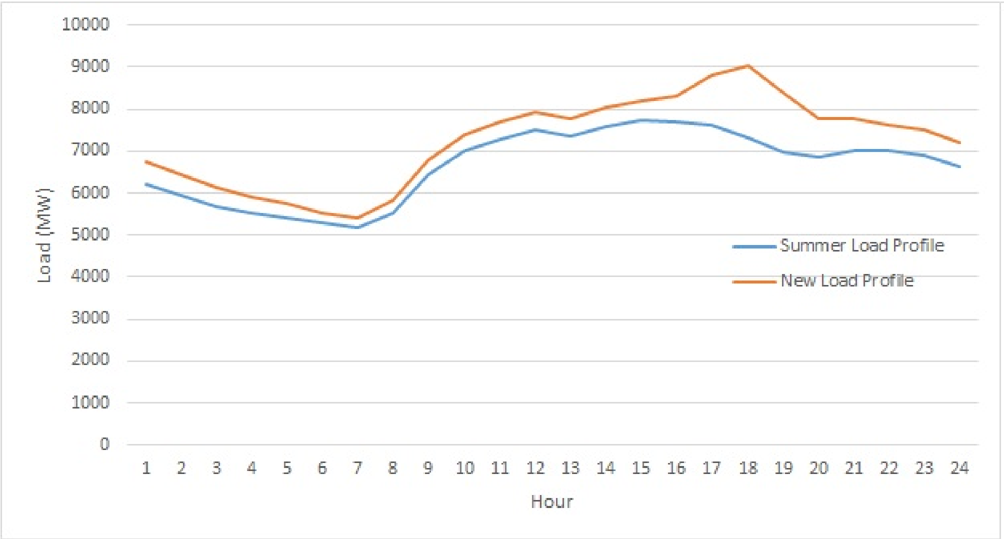

FIGURE 3.68: New daily load curve for summer in uncontrolled charging everywhere - Case 1 - 50% penetration

Case 2: In this case, four charger types are considered: 3.7 kW, 7.4 kW, 11 kW, and 22 kW. The assumptions about the battery size and charging decision threshold are same as previous case.

Figure 3.69 and Figure 3.70 show the new daily load profiles which are obtained after adding the power demand from PHEV charging to the base load curve. The peak load is created at 6 pm for both winter and summer seasons, same as Case 1. The shape of load profile is same as Case 1, but there is a slight increase in the peak hour.

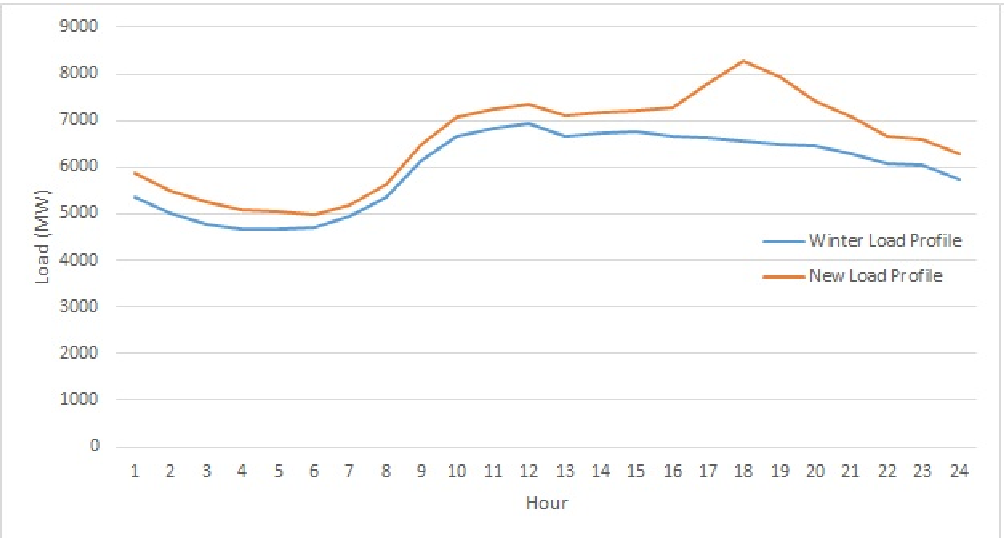

FIGURE 3.69: New daily load curve for winter in uncontrolled charging everywhere - Case 2 - 50% penetration

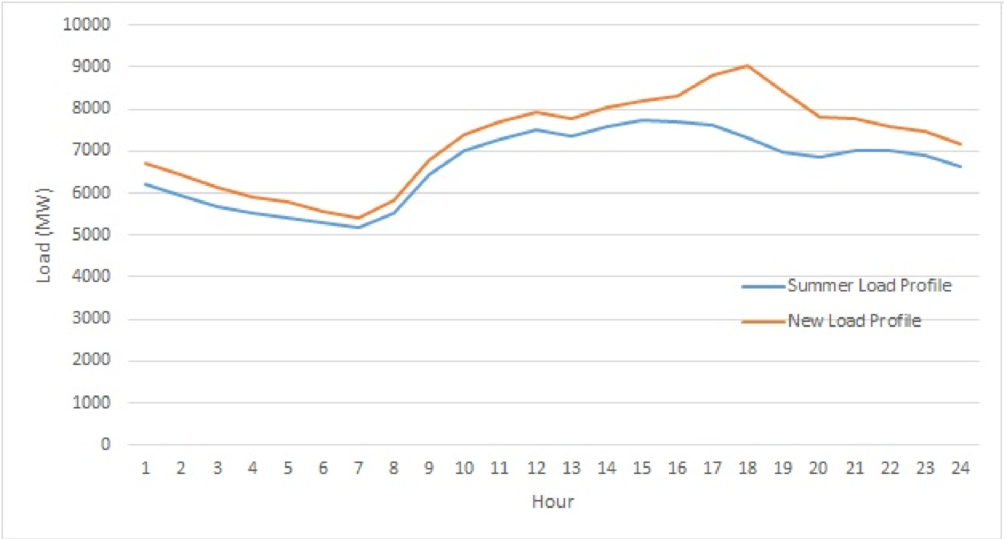

FIGURE 3.70: New daily load curve for summer in uncontrolled charging everywhere - Case 2 - 50% penetration

Case 3: In order to examine the effects of personal preferences, the charging decision threshold is defined as 0.8. This means that, all vehicle owners are assumed to be risk-averse people. Therefore more charging occurs compared to Case 1. The new daily load profiles are plotted, as shown in Figure 3.71 and Figure 3.72. The higher charging decision threshold increases the total additional electricity demand. The peak hour appears at 6 pm, same hour as Case 1. Additionally, this case could increase the peak load by 21% in winter load profile and by 18% in summer load profile.

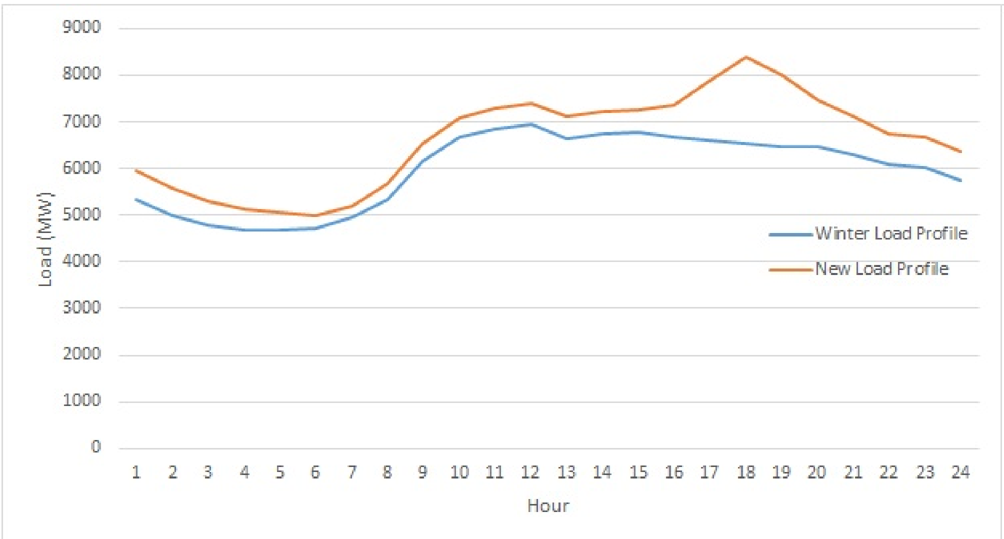

FIGURE 3.71: New daily load curve for winter in uncontrolled charging everywhere - Case 2 - 50% penetration

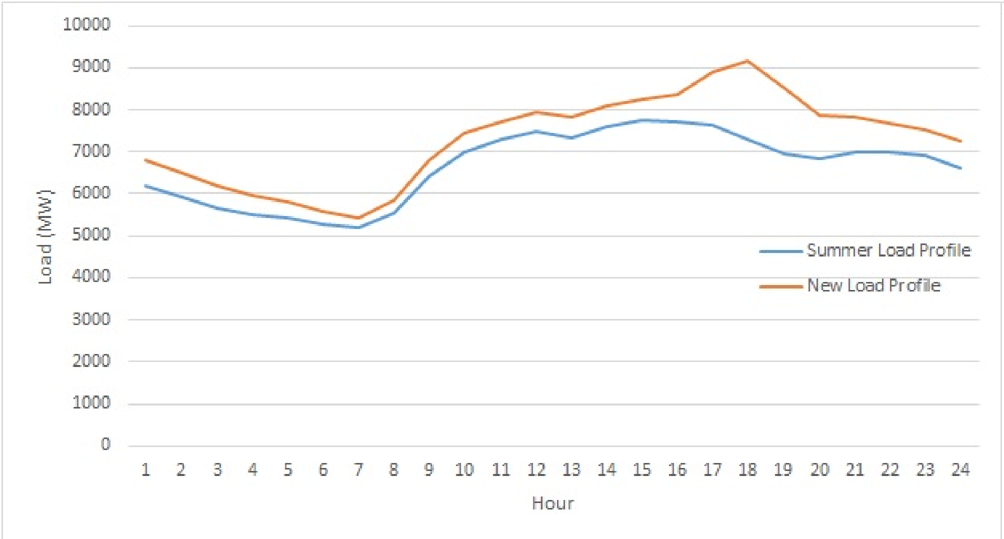

FIGURE 3.72: New daily load curve for summer in uncontrolled charging everywhere - Case 3 - 50% penetration

Case 4: To see the differences due to the changes in battery size, two higher battery types (20 kWh and 25 kWh) are considered in this case. The capacity of battery affects the electricity drawn from the grid per hour as well as the charging duration. The simulation results are generated under the assumptions of two charging power levels and 0.5 charging decision threshold. Figure 3.73 and Figure 3.74 illustrate the new daily load curves after adding the PHEVs charging demand to the original load profile. As seen in the figures, the peak load is created in 6 pm for both summer and winter seasons, same hour as Case 1. In addition, the peak load could increase by 22% in winter and 19% in summer load curve.

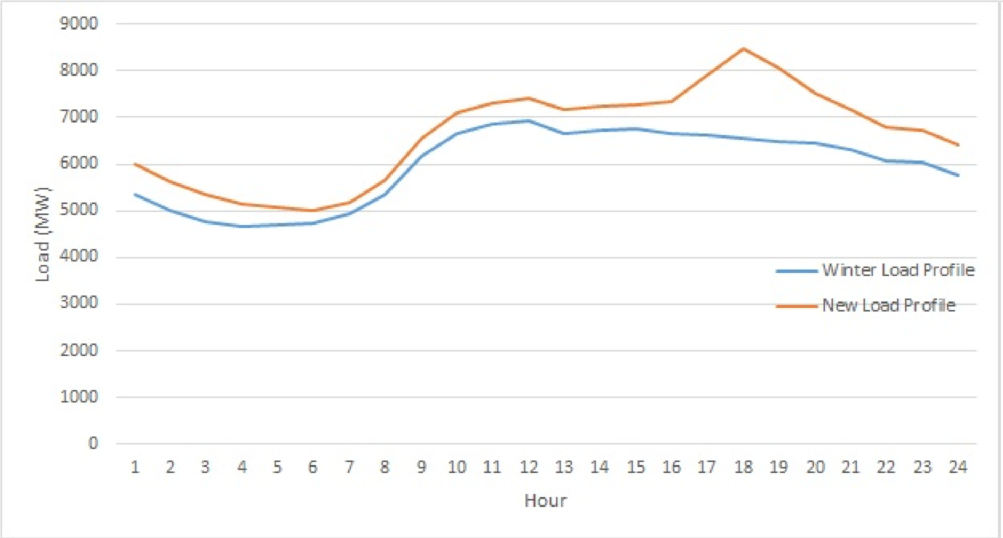

FIGURE 3.73: New daily load curve for winter in uncontrolled charging everywhere - Case 4 - 50% penetration

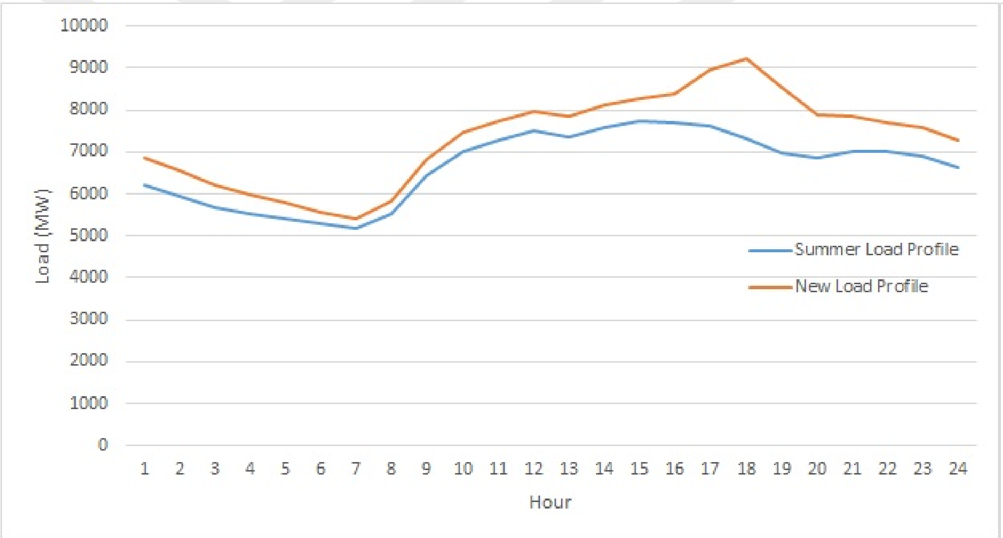

FIGURE 3.74: New daily load curve for summer in uncontrolled charging everywhere - Case 4 - 50% penetration

3.4.2.3 Results for Off-Peak Charging At Home Only

The off-peak charging scenario is defined to shift the PHEV charging demand to the low-load hours. The vehicle owners allowed to recharge their batteries between 11 pm to 7 am. The off-peak charging strategy attempts to relieve the impacts of PHEVs on the electricity grid. Monte Carlo simulation is run with 50% penetration level with considering four cases and results are discussed.

Case 1: The results are obtained for two low charging levels, five battery types with uniform distribution, and 0.5 charging threshold.

Figure 3.75 shows the additional load profile of off-peak charging for 50% penetration level of PHEV. All charging occurs during overnight and early morning hours due to the restriction on charging period. The profile ramps rapidly from 11 pm to 2 am. The peak charging demand is at 2 pm, same as 10% penetration level.

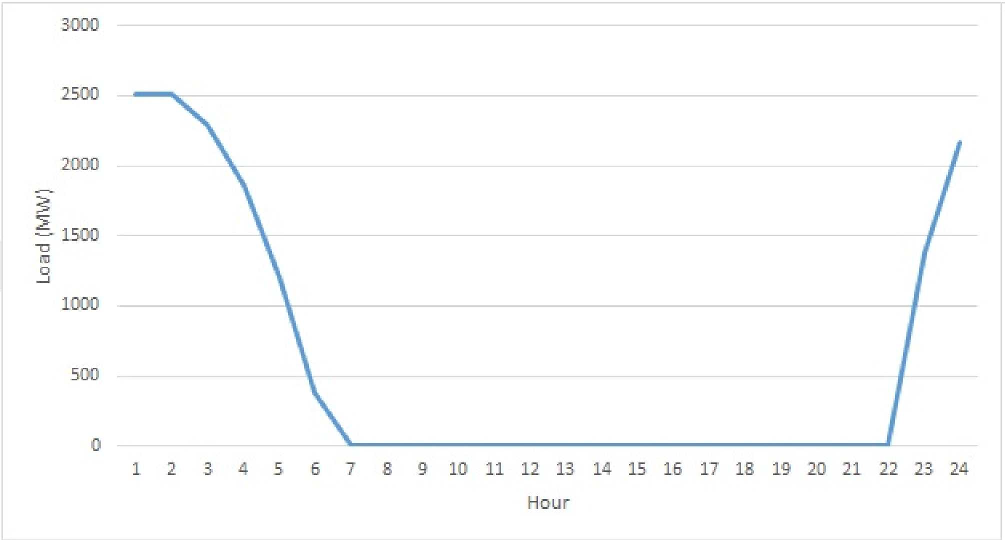

FIGURE 3.75: Additional load in off-peak charging at home only - Case 1 - 50% penetration

The maximum and minimum electricity drawn from the grid for each hour are presented in Figure 3.76. The additional load ranges between 2486 MW to 2527 MW, as seen in the figure. This means that the load added to the grid could be any value in this range. This information is important for utilities to plan the additional infrastructure.

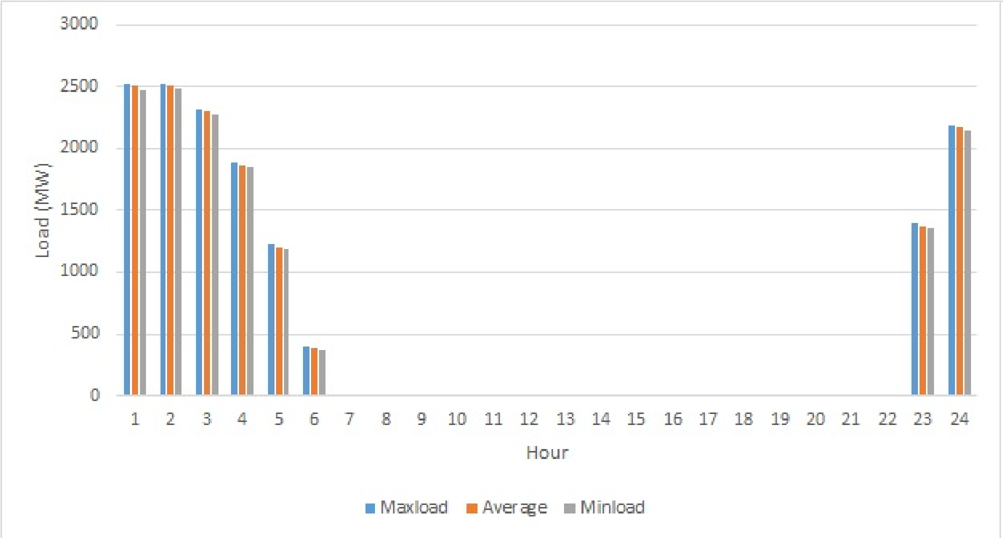

FIGURE 3.76: Maximum, average and minimum load per hour in off-peak charging at home only - Case 1 - 50% penetration

When observed the total daily electricity consumption, the maximum total required energy is 14339 MW while the minimum energy consumption is 14242 MW. (Figure 3.77). Knowing the day which has a maximum electricity consumption helps to estimate maximum additional generation that is needed for PHEV charging.

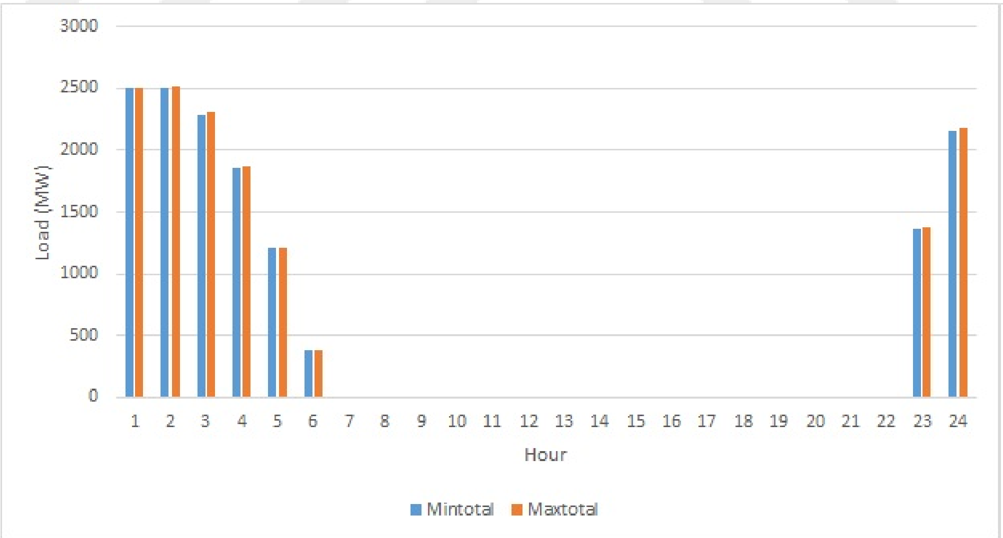

FIGURE 3.77: Maximum and minimum total electricity consumption in off-peak charging at home only - Case 1 - 50% penetration

The new daily load profile after penetration of PHEVs is plotted for summer and winter, as seen in Figure 3.78 and Figure 3.79. Unlike the load profiles with 10% penetration level, the peak hour is shifted to 12 am for both winter and summer seasons. Results demonstrate that the peak load increases by 14% for both summer and winter compared to original load profile. This means that high penetration rate of PHEVs causes the undesirable effects even in the off-peak charging scenario.

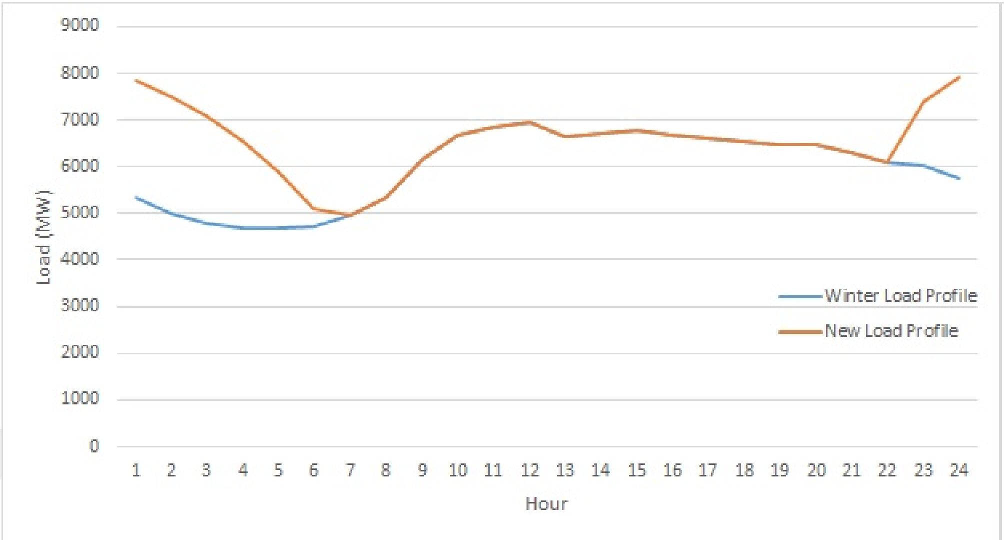

FIGURE 3.78: New daily load curve for winter in off-peak charging at home only - Case 1 - 50% penetration

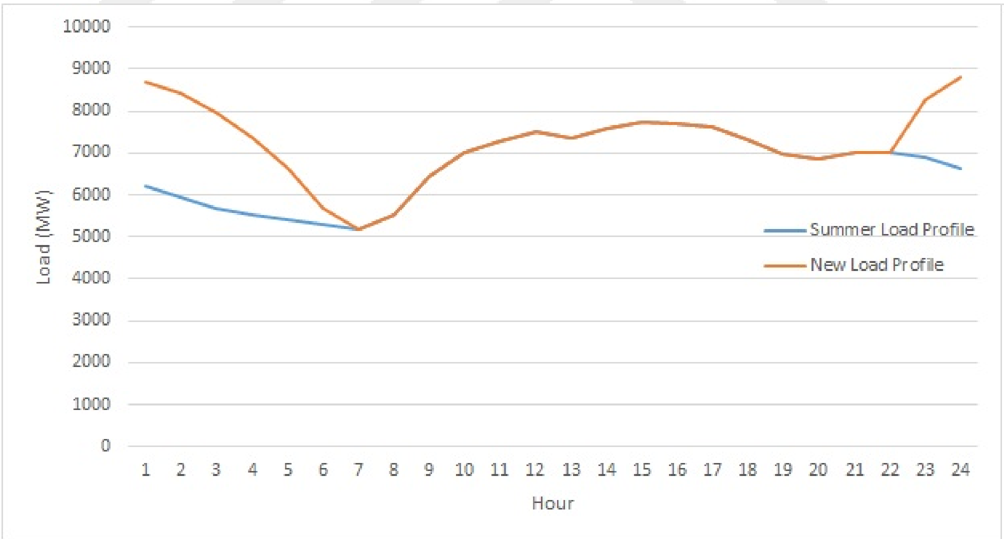

FIGURE 3.79: New daily load curve for summer in off-peak charging at home only - Case 1 - 50% penetration

Case 2: In this case, four charger types (3.7 kW, 7.4 kW, 11 kW, 22 kW) with uniform distribution are considered to examine the differences due to the higher charging power levels. The other parameters remain same as Case 1 and results are generated for off-peak charging scenario.

The new daily electricity load curve is plotted, as shown in Figure 3.80 and Figure 3.81. The charging pattern is same as Case 1, with only small changes in magnitude of demand for each hour. The peak hour shows no changes compared to Case 1 and it appears at 12 am for both summer and winter seasons.

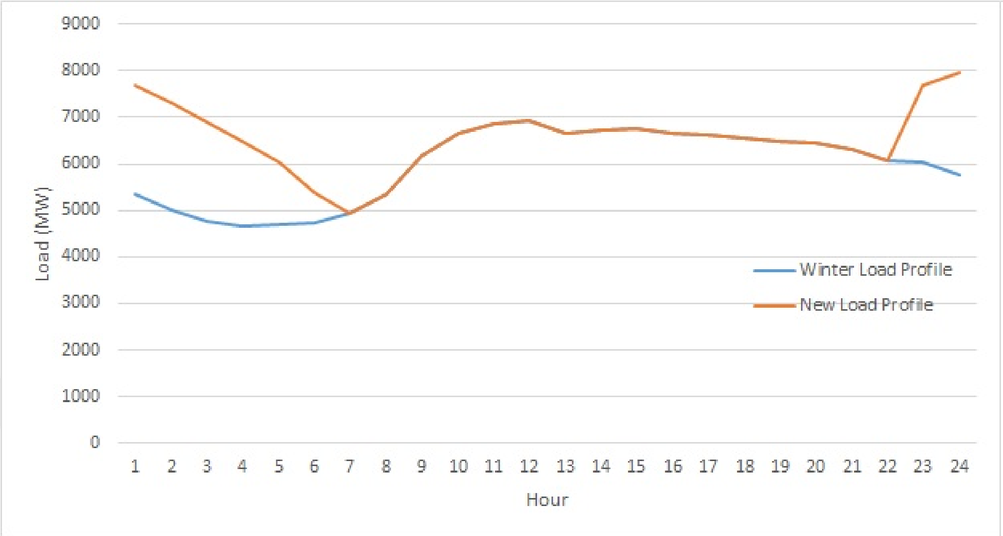

FIGURE 3.80: New daily load curve for winter in off-peak charging at home only - Case 2 - 50% penetration

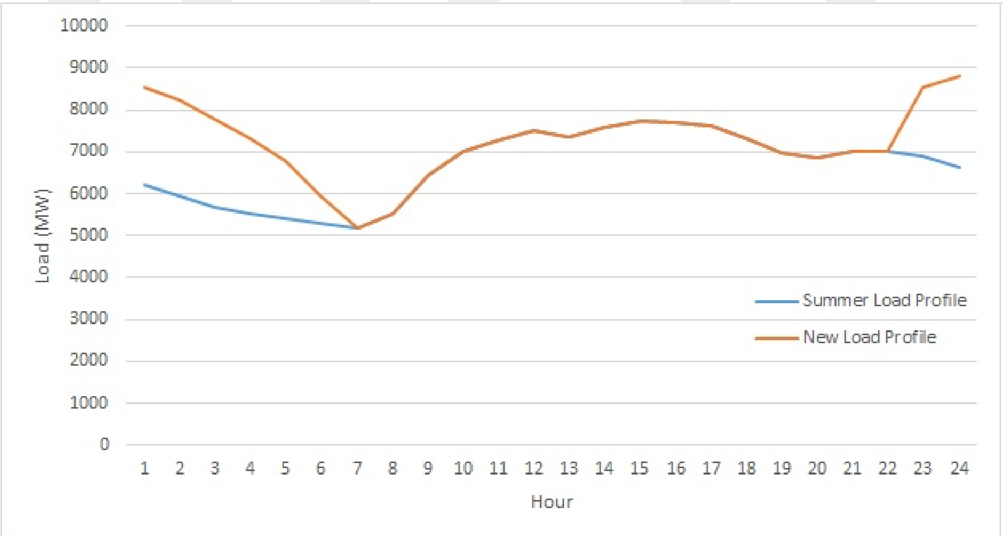

FIGURE 3.81: New daily load curve for summer in off-peak charging at home only - Case 2 - 50% penetration

Case 3: The charging decision threshold is one of the important parameters due to the differences in the personal preferences. In order to examine the effects of vehicle owners' decisions for charging, the charging decision threshold is defined as 0.8. It means that more charging takes place during the day compared to Case 1. In this case, assumptions for the battery size and charger type are same as Case 1.

Figure 3.82 and Figure 3.83 present the new daily load curves which are generated by applying Monte Carlo simulation for Case 3. When compared to Case 1, the peak load is created at the same hour (2 am) for both winter and summer seasons. The load profiles have a similar shapes with increase in magnitude of demand. The new peak load in the winter profile is 17% higher than the base load peak and is 16% higher than the base load profile in the summer profile.

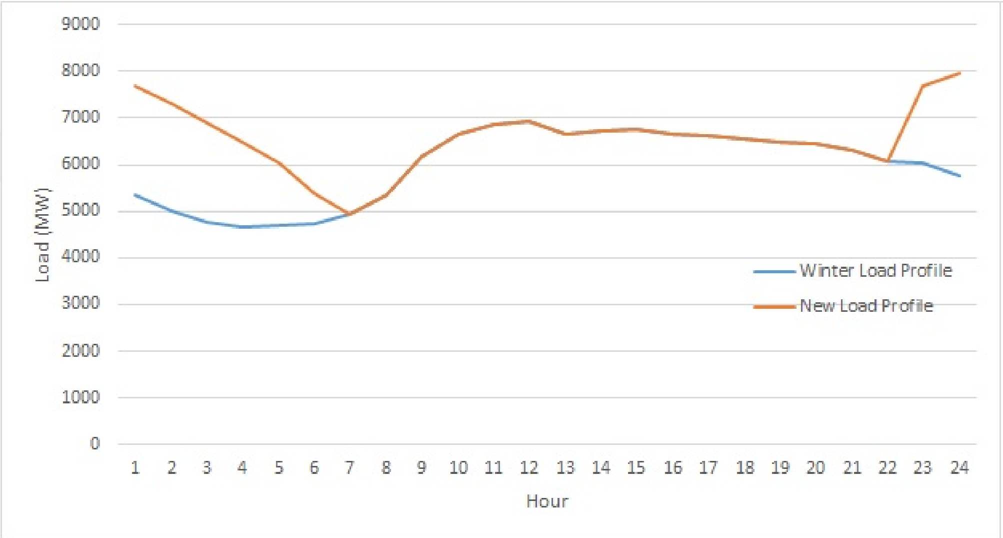

FIGURE 3.82: New daily load curve for winter in off-peak charging at home only - Case 3 - 50% penetration

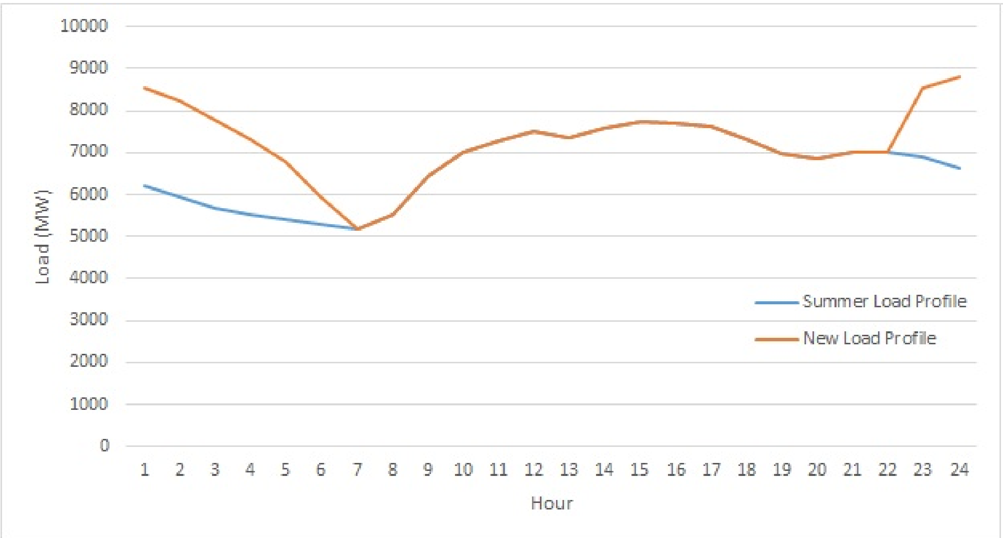

FIGURE 3.83: New daily load curve for summer in off-peak charging at home only - Case 3 - 50% penetration

Case 4: The higher battery size increases the amount of electricity consumption, as discussed for 10% penetration level. The increase will be higher for 50% penetration level of PHEVs. In this case, two batteries with large capacities are considered while other parameters remain same as Case 1.

Figure 3.82 and Figure 3.83 depict the new daily load profiles for winter and summer seasons. There are some changes in load pattern and magnitude of demand compared to load profile in Case 1. Unlike Case 1, the peak hour appears at 1 am in both winter and summer load profiles. This means that higher battery capacity has a potential to create new peak load in the electricity load curve. Additionally, 50% level of PHEV penetration leads to a 18% increase in the winter and 17% increase in the summer.

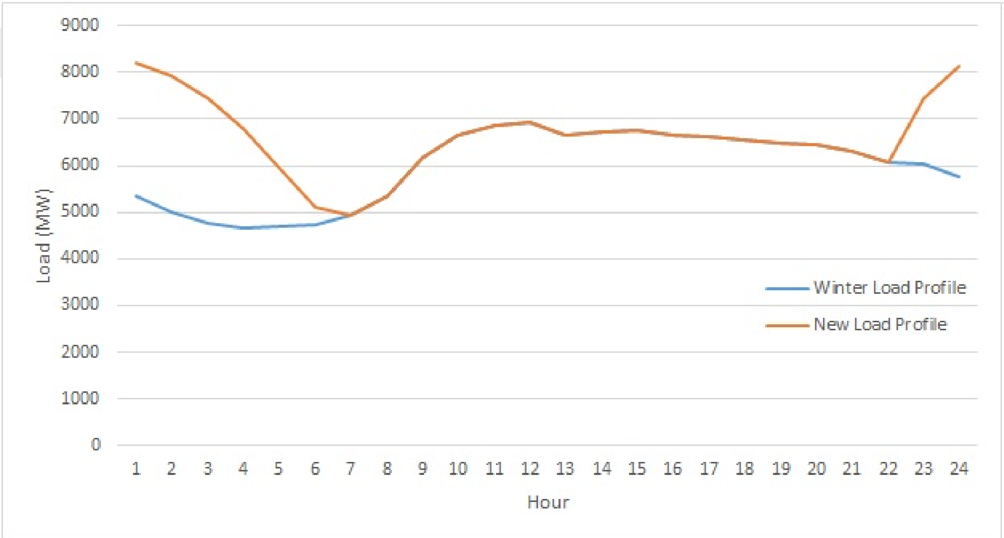

FIGURE 3.84: New daily load curve for winter in off-peak charging at home only - Case 4 - 50% penetration

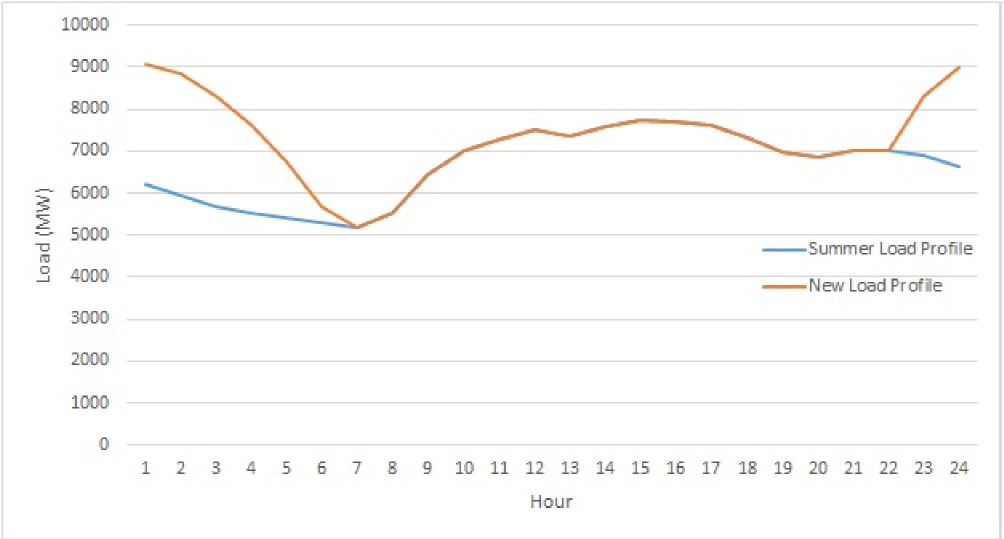

Figure 3.85: New daily load curve for summer in off-peak charging at home only - Case 4 - 50% penetration

3.4.2.4 Results for Off-Peak Charging Everywhere

This scenario assumes that the vehicle owners can charge their batteries at the home in the off-peak hours while they can charge their batteries without a time restriction in the other places.

Case 1: Two charging power levels, five different battery types and 0.5 charging decision threshold are considered in this case and results are given below.

Figure 3.86 shows the additional load curve under off-peak charging everywhere scenario for 50% penetration level. As seen in figure, peak load appears at 6 pm and it is about 1585 MW. When compared to uncontrolled charging everywhere scenario, the amount of peak load is lower since home charging is shifted to off-peak hours in this charging scenario.

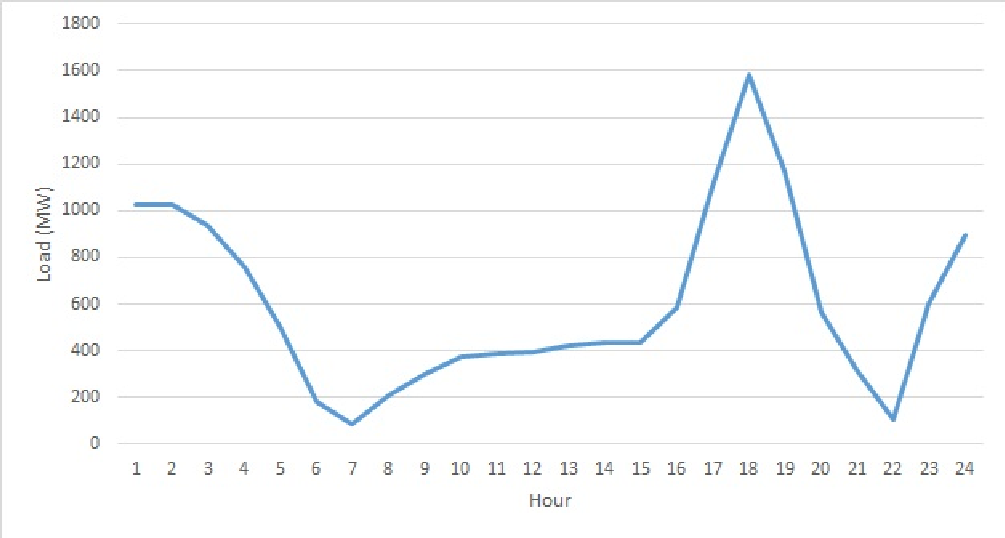

FIGURE 3.86: Additional load in off-peak everywhere - Case 1 - 50% penetration

Figure 3.87 and Figure 3.88 represent new daily load profiles for two seasons. The load curve changes significantly under high penetration level, as seen in figures. The new peak load is created at 6 pm for both winter and summer seasons. 50% penetration level could increase the peak load by 17% in the winter load profile and by 15% in the summer load profile.

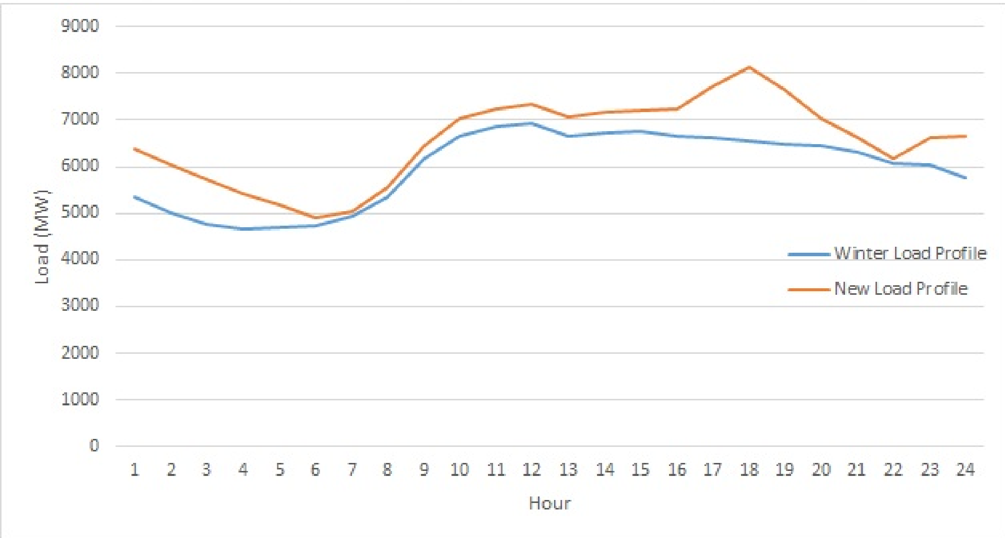

FIGURE 3.87: New daily load curve for winter in off-peak charging everywhere- Case 1 - 50% penetration

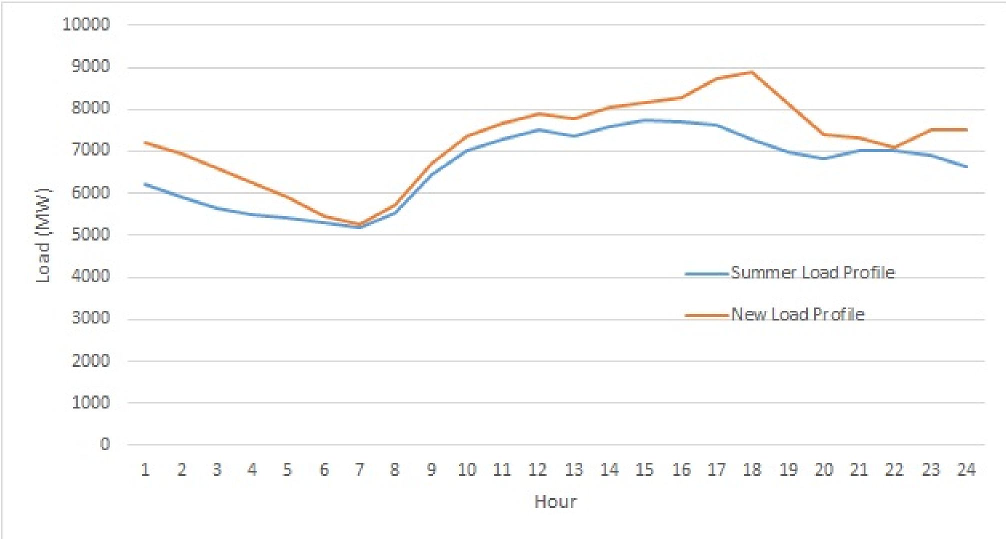

FIGURE 3.88: New daily load curve for summer in off-peak charging everywhere- Case 1 - 50% penetration

Case 2: The assumptions about the battery sizes and charging decision threshold is same as Case 1. In this case, four charging levels are considered: 3.7 kW, 7.4 kW, 11 kW, 22 kW.

The new daily load profiles are presented in Figure 3.89 and Figure 3.90. The peak load is shifted from 12 pm to 6 pm for winter and is shifted from 3 pm to 6 pm for summer, same as Case 1.

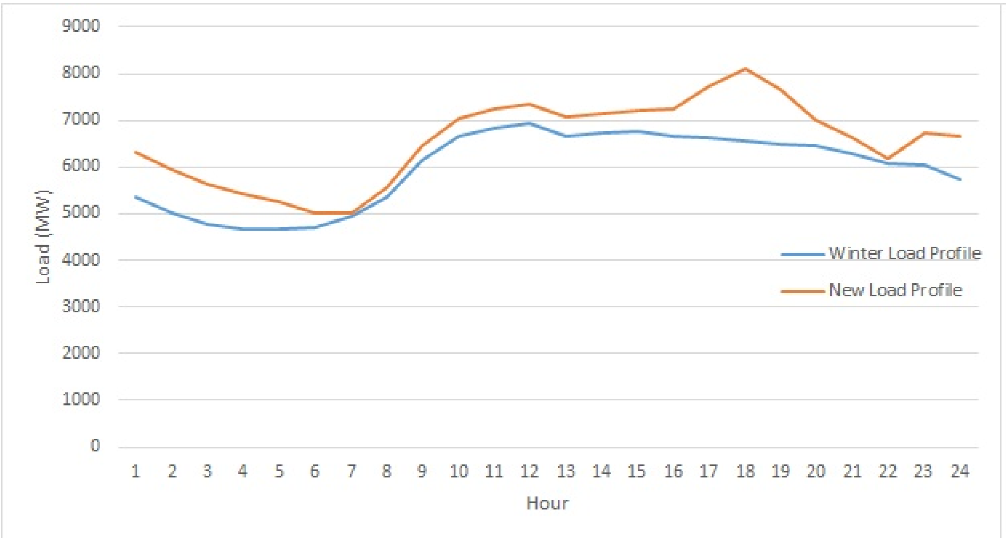

FIGURE 3.89: New daily load curve for winter in off-peak charging everywhere- Case 2 - 50% penetration

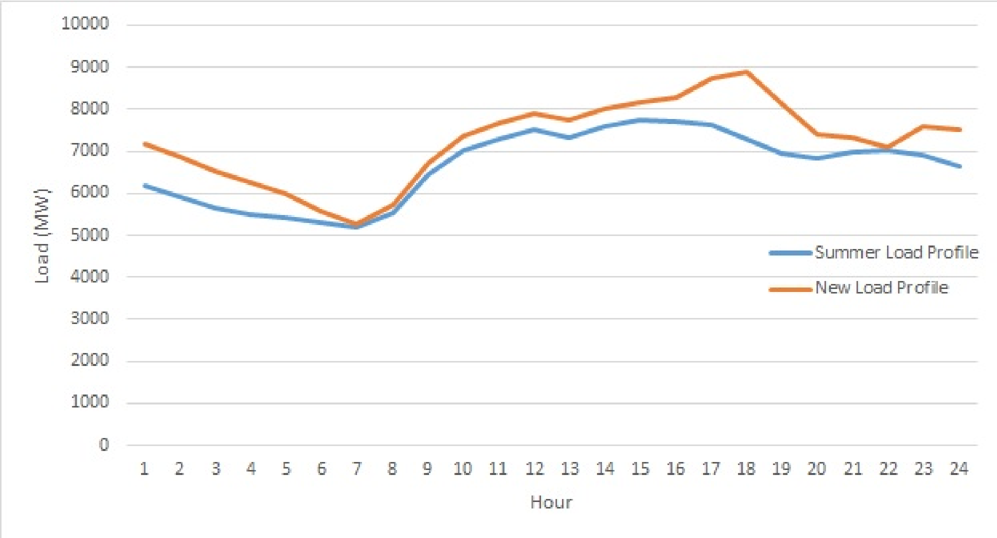

FIGURE 3.90: New daily load curve for summer in off-peak charging everywhere- Case 2 - 50% penetration

Case 3: In this case, all vehicle owners are assumed to be risk-averse people and charging decision threshold is defined as 0.8. The other assumptions are same as Case 1. Figure 3.91 and Figure 3.92 illustrate the new daily load profiles. Since more charging occurs compared to Case 1, total additional electricity demand increases in this case. The peak load appears at 6 pm for both winter and summer profiles.

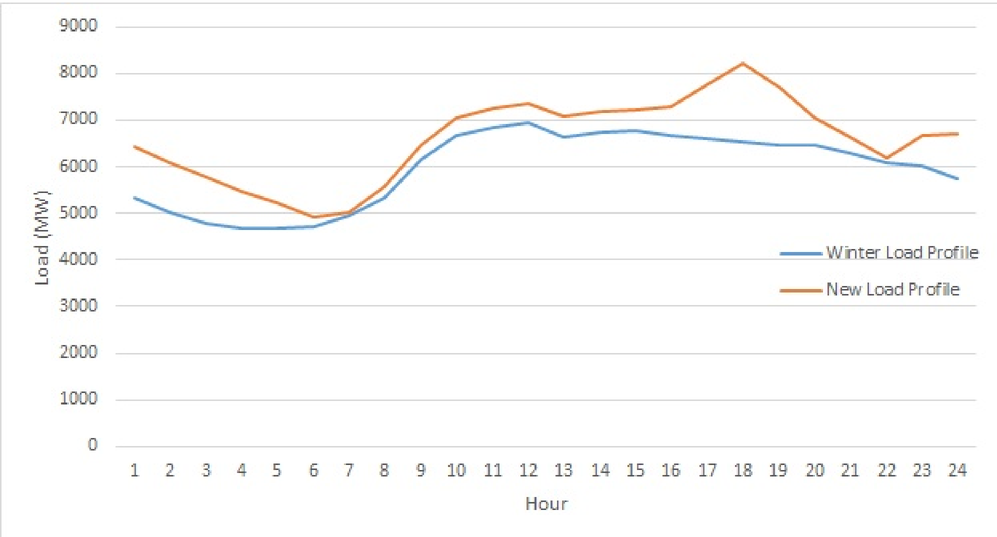

FIGURE 3.91: New daily load curve for winter in off-peak charging everywhere- Case 3 - 50% penetration

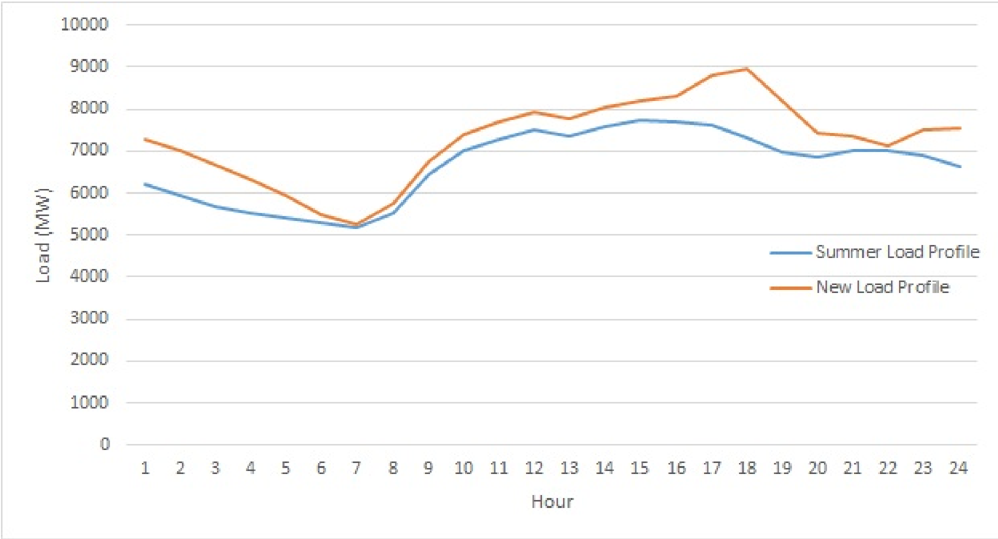

FIGURE 3.92: New daily load curve for summer in off-peak charging everywhere- Case 3 - 50% penetration

Case 4: Two higher battery types are taken into account in order to see the differences due to the changes in battery size. Figure 3.93 and Figure 3.94 show the new daily load profiles after adding the PHEVs charging demand to the base load profile. The peak hour is shifted to 6 pm for both winter and summer seasons, as seen in the figures. Additionally, this case could increase the peak load by 20% in winter and 17% in summer load curve.

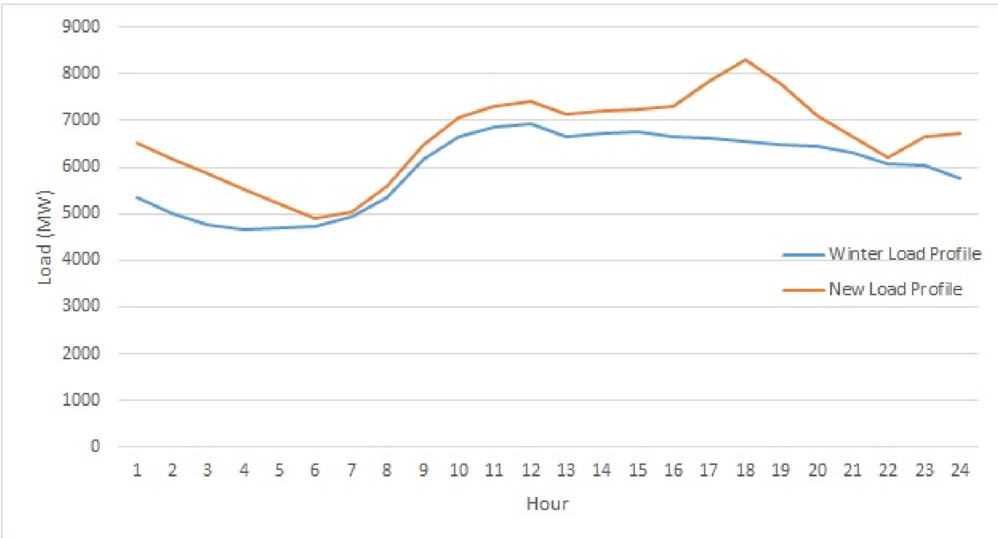

FIGURE 3.93: New daily load curve for winter in off-peak charging everywhere- Case 3 - 50% penetration

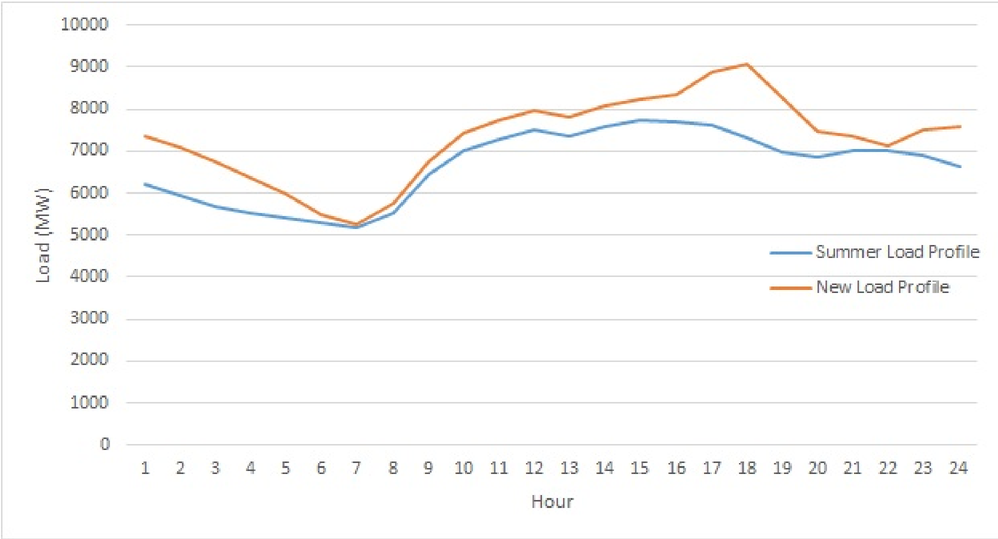

FIGURE 3.94: New daily load curve for summer in off-peak charging everywhere- Case 3 - 50% penetration

Comparison of Different Scenarios

In order to see the differences on the load profiles for the charging scenarios that are explained above, new daily load curves under the different charging scenarios are given together in Figure 3.95. Since the load pattern of 10% penetration level is similar to that of 50% penetration level, the daily load profiles are shown for only high penetration level. The results are obtained while considering the Case 1 assumptions and winter load profile is considered as a base load.

As seen in figure, uncontrolled charging has a spike at 6 pm because there is no restriction on charging time and charging location. The peak load increases significantly in this scenario. Additionally, the amount of electricity drawn from the grid is low in the late night hours compared to other scenarios.

In the uncontrolled at home charging, the peak load is shifted from 12 pm to 9 pm. The increase in the peak load is smaller than the others in this strategy. Majority of charging occurs after 6 pm because most people spend significant time at their homes in the evening hours.

The peak hour is shifted to 12 am in the off-peak charging. The new peak is created for 50% penetration level even the charging time is restricted by off-peak hours.

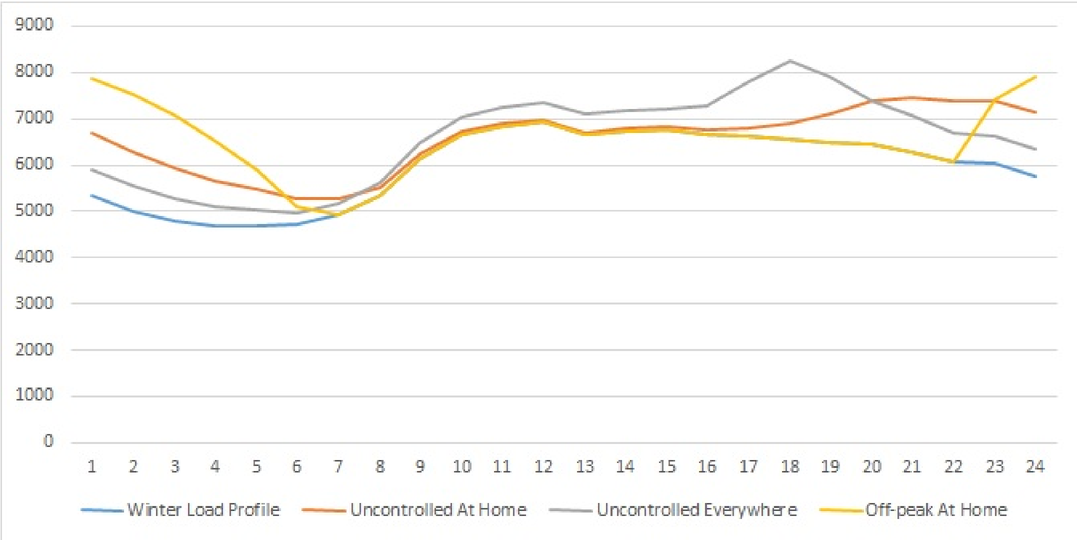

Figure 3.95: Comparison of different charging scenarios - Case 1 - 50% penetration

Chapter 4

Conclusion and Future Work

PHEV penetration into the transportation sector has a potential to create substantial changes on the electricity network. A deep study is required in order to understand the additional electricity load on the system after integration of PHEVs. In this study, the impacts of PHEVs on the power grid are estimated for İstanbul, by analyzing the different charging scenarios. For this purpose, Monte Carlo simulation is developed to generate new daily load profile while considering driving characteristics, charging characteristics, and a penetration rate of PHEVs. Firstly, the distribution of arrival times and distribution of daily driving distances were extracted from available reports and some assumptions were made about the PHEV characteristics.

Two charging scenarios, which are uncontrolled and off-peak charging, are defined and the additional electricity consumption is estimated for each scenario by applying Monte Carlo simulation. To see the differences on the daily load curve, the additional demand from PHEV charging is added to the hourly base load profile and results are discussed.

The scenario results are evaluated for two different penetration levels: 10% and 50%. In this way, the changes on the distribution grid as the number of PHEVs increases are examined. Additionally, four different cases are created in order to observe the differences in the new daily load pattern due to the changes in battery size, charging power level, and risk perception of vehicle owners.

The simulation results of this study can help policy makers to schedule the electricity network for meeting the additional demand after integration of PHEVs. According to the new daily load curves obtained from different scenarios, the decision makers can provide incentives to the vehicle owners about when and where they charge their vehicles.

According to the results, 50% penetration level leads to undesirable effects on the power system. At this penetration level, the new peak loads are created and the total electricity consumption increases significantly in all charging scenarios. These results are important for policy makers to develop a better plan for the future network.

Another issue to be mentioned is that high battery size could increase the total electricity drawn from the power system. Therefore, referring to the results of this study, the policy makers can encourage vehicle owners to buy a battery with an appropriate size, i.e. offering the required energy for daily driven distances and preventing them from using higher capacities. On the other hand, only the grid-to-vehicle technology is considered in this study. The PHEVs could store the energy in the batteries and release the energy to grid in order to supply balance of the power network in the vehicle-to-grid technology. The results of this case may lead and contribute to other studies that investigate the vehicle-to-grid technology.

When the scenario results are compared, uncontrolled charging everywhere scenario can be considered as a worst-case scenario among the cases that are evaluated in this study. In this scenario, undesirable effects occur on the system since there is no restriction on the charging time and the charging place. Besides, the increase in the peak load in this case is higher when compared to the increases in the peak demand for other scenarios. This information can be used by policy makers to make a plan for meeting the additional electricity demand from PHEV charging.

As expected, the off-peak everywhere scenario is better than the uncontrolled everywhere scenario since the vehicle owners, who charge their batteries at homes, are allowed to charge only in off-peak hours. The increase in the peak load is lower in this charging scenario when compared to the peak demand in uncontrolled charging everywhere scenario. This may be helpful for the policy makers in providing incentives to vehicle owners such as time-of-use prices for shifting the charging period to the off-peak hours for home charging.

4.1 Future Work

The data related to impact factors such as daily driving distances, distribution of arrival times is obtained from available reports in this study. Since PHEV technology is new promising technology in Turkey, the information how the people will utilize the PHEVs is not available. Therefore, different approaches are assumed for distribution of battery sizes that the vehicle owners will have, distribution of charging locations where the people will primarily prefer to charge, and distribution of charging units that the people will use in their homes. For future research, the survey can be performed to obtain the data about the potential PHEV users. The distribution of battery sizes and charging location, and the personal preference for charging can be gathered from the survey based on daily driven distances of people.

Risk perception of people is considered as one of the impact factors on the daily load curve in this study. Two different charging decision thresholds are defined for risk-averse and risk-neutral people. If all the vehicle owners are assumed to be risk-averse, then the charging decision threshold is defined as 0.8. For the risk-neutral people, threshold is defined as 0.5. In this case, the charging decision is determined based on the predefined threshold regardless of the battery size and daily driven distance for each person. It is assumed that all people are risk-averse or risk-neutral. For another possible future work, experimental study can be performed in order to define a function for each vehicle owner with regard to daily traveled kilometers and remaining energy in the battery.

In this study, it is assumed that sufficient number of public stations exists and the drivers reach the available public stations whenever they need to charge. In the another possible future work, the location of the public stations and waiting times could be considered. In order to incorporate location of public stations into the study, the data about where the charging stations are located in İstanbul is required.

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