ASSESSMENT OF IMPACTS OF ELECTRIC VEHICLES ON LOW VOLTAGE DISTRIBUTION NETWORKS IN TURKEY

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ABSTRACT

ASSESSMENT OF IMPACTS OF ELECTRIC VEHICLES ON LOW VOLTAGE DISTRIBUTION NETWORKS IN TURKEY

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The number of Electric Vehicles (EVs) has reached a substantial value all over the globe due to economic and environmental factors. The increasing penetration of EVs to the distribution grids urges the requirement to investigate the impacts of EVs on the planning and operation of distribution networks. Despite the fact that there are numerous studies discussing the impacts of EVs on distribution grids, a particular study concerning the Turkish distribution networks does not exist. Therefore, this study focuses on analyzing the impacts of EVs on low voltage distribution networks in Turkey.

Three distribution network models, two of them belonging to actual Turkish distribution network segments and one being generic, including different customer attributes and network structures are constructed and utilized throughout this study. An extensive EV model is developed using probabilistic models and assumptions. Gaussian distribution function for EV plug-in times and Weibull distribution function for daily travel times are adapted in Digsilent PowerFactoy simulation tool.

Monte Carlo based load flow simulations are performed in order to evaluate the response of the distribution networks to various EV and load scenarios considering different multi-tariff mechanisms.

Furthermore, a methodology is developed to obtain and present network results based on transformer and cable overloads, voltage drops, and grid losses. This methodology will help the decision maker determine the necessary investments on the distribution networks and associated time frames. This approach will improve the planning process of distribution companies. Hence, distribution companies will submit more realistic and accurate investment plans to the regulatory agencies.

Keywords: Electric Vehicles, Load Flow, Monte Carlo Simulation, Power Distribution Networks

ÖZ

ELEKTRİKLİ ARAÇLARIN TÜRKİYE ALÇAK GERİLİM DAĞITIM ŞEBEKELERİNE ETKİLERİNİN İNCELENMESİ

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Ekonomik ve çevresel etkenler elektrikli araç sayısını küresel boyutta azımsanmayacak bir seviyeye ulaştırmıştır. Bu durum, elektrikli araçların dağıtım şebekelerinin tasarım ve yönetimi üzerine etkilerinin incelenmesi gerekliliğini zorunlu kılmaktadır. "Elektrikli Araçların Dağıtım Şebekelerine Etkisi" üzerine birçok çalışma gerçekleştirilmesine rağmen, Türkiye dağıtım şebekesine uygulanan herhangi bir çalışma bulunmamaktadır. Bu sebeple bu çalışma, elektrikli araçların Türkiye alçak gerilim dağıtım şebekelerine etkilerinin analizi üzerine yoğunlaşmaktadır.

Bu çalışmada, farklı kullanıcı davranışları ve şebeke yapılarına sahip iki adet Türkiye ve bir adet de genel model olmak üzere üç adet dağıtım şebekesi modellenip incelenmiştir. Olasılıksal modeller ve varsayımlar kullanılarak geniş çaplı bir elektrikli araç modeli geliştirilmiştir. Şarja takılma zamanları için Gauss dağılım fonksiyonu, günlük seyahat mesafeleri için Weibull dağılım fonksiyonu Digsilent PowerFactory benzetim aracına uyarlanmıştır. Dağıtım şebekelerinin farklı tarife, elektrikli araç ve yük senaryolarına verdiği cevabı değerlendirmek üzere Monte Carlo tabanlı yük akış analizi uygulanmıştır.

Bunlara ek olarak, transformatör ve hat yüklenmeleri, gerilim düşümleri ve şebeke kayıplarına dayalı sonuçların elde edilmesi ve sunulması üzerine bir yöntem geliştirilmiştir. Bu yöntem, dağıtım şirketlerinin gerekli yatırımları ve zamanlarını belirlemede yardımcı olacaktır. Bu yaklaşım dağıtım şirketlerinin planlama mekanizmasını geliştirecektir. Böylece, dağıtım şirketleri daha gerçekçi ve doğru yatırım planlarını düzenleme kuruluna ibraz edebilecektir.

Anahtar Kelimeler: Elektrikli Araçlar, Yük Akışı, Monte Carlo Benzetimi, Dağıtım Şebekeleri

To My Beloved Family

And My Friends

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INTRODUCTION

1.1 Motivation

Electrification of transportation vehicles has recently gained momentum and continues to increase due to economic and environmental factors. Many countries have already initiated some governmental programs and policies in order to increase the usage of Electric Vehicles (EVs). In addition, automobile manufacturers have recently produced and released various types of EVs into the car market. As a result of all these developments, the number of EVs has reached a substantial value all over the world in recent years. Hence, it is required to focus on impacts of EVs on the design and operation of power grids. Since EVs are mostly charged at low voltage levels, first and major effects of the EV integration will occur on low voltage (LV) distribution networks. Therefore, the increasing penetration of EVs to the distribution grids urges utilities to investigate the prospective impacts of EVs on the design and operation of distribution networks.

Developments in EV sector and increase in the momentum of EV sales take place not only in developed countries but also in Turkey. The number of EVs on Turkish roads shows an upward trend. Besides, Turkish government has already announced a new incentive program in order to support investments on the production of domestic EVs in the near future. Hence, the effect of EVs on distribution networks should also be analyzed for Turkish distribution networks. Despite the fact that there are various studies in the literature discussing the impacts of EVs on distribution grids, a particular study concerning the distribution networks in Turkey does not exist.

As a developing country, main characteristics of distribution networks in Turkey are the high load growth rate (without any EV penetration) and the need for continuous expansion and investment due to fast urbanization. In a deregulated environment, distribution companies in Turkey are obliged to periodically submit their long-term investment plans to the regulatory agency for approval. Up to now, they have prepared their investment plans based only on the forecasted load growth without any EV effect. Therefore, it is an inevitable requirement to assess impacts of EVs on Turkish LV distribution networks from the perspective of distribution companies.

1.2 Scope and Contribution of the Thesis

The focus of this study is to analyze impacts of EVs on the design and operation of LV residential distribution networks and also to investigate the feasibility of some mitigation mechanisms, such as implementing or revising the multi-tariff systems in order to shape the daily load curve. A methodology is developed to help the distribution planners determine the necessary investments on the distribution networks and associated time frames. This approach will improve the planning process of distribution companies. Hence, distribution companies will submit more realistic and accurate investment plans to the regulatory agencies.

In this study, three different residential LV network models, two of them belonging to actual network segments in Ankara (corresponding to two different socio-economic regions), and one being generic, have been developed with their customer attributes and network connectivity. All scenarios and cases have been applied to all of these sample networks. Implemented scenarios involve different penetration rates of EVs among residential customers, different annual load demand increasing rates and different multi-tariff mechanisms.

An extensive EV model has also been developed using probabilistic models in this study. Gaussian distribution function for EV plug-in times and Weibull distribution function for daily travel times in Ankara (to determine the state-of-charge status of battery at the beginning of charging process) are adapted and implemented in Digsilent PowerFactoy simulation tool. Monte Carlo based load flow simulations are performed in order to evaluate the response of the distribution networks to various EV scenarios. Furthermore, the daily load curve (on a 24 hour base) have also been employed in simulations to investigate the operational acceptability of the network in terms of the following criteria: Transformer and line/cable loading level, voltage drop and grid losses.

1.3 Thesis Outline

The information about the general background of EVs is explained in Chapter 2. Historical background, technical aspects, types of EVs, and market information are stated at the beginning of this chapter, while the literature review on impacts of EVs on distribution networks is presented in the second section of the chapter.

Chapter 3 focuses on the definition of the system model and cases. The methodology and assumptions used while modelling LV distribution networks, residential loads, EVs, and other grid elements are addressed in detail with the determination process of five cases in this chapter.

The methodology of load flow simulations is explained with the presentation of the obtained results in Chapter 4. Details of Monte Carlo based load flow simulations and the reporting methodology are explained in Section 4.1. Moreover, all simulation results for each pilot distribution network are presented regarding the transformer and line overloads, voltage drops, and grid losses in the following section. Finally, the discussion of results is presented in Section 4.3.

Chapter 5 concludes the study by evaluating the obtained results from the perspective of distribution companies.

CHAPTER 2

GENERAL BACKGROUND AND LITERATURE REVIEW

2.1 Electric Vehicles

2.1.1 Overview

An EV, as a general definition, is a vehicle that uses one or more electric motors instead of a conventional combustion engine for propulsion [1]. The technology behind EVs is not a new technology or invention on the contrary to general belief. In fact, an EV has been on the roads since 19th century. Although it was just a model car with an electric motor at the beginning, first practical cars have been developed and appeared on the roads in mid of 1800s. Moreover, at the beginning of 20th century, EVs gained their popularities significantly and it would not be wrong to indicate that it was a golden age for EVs until 1920s. Unfortunately, the need for longer-range vehicles, the reduction of gasoline prices, the invention of electric starter for conventional cars, and the initiation of mass production of internal combustion EVs resulted in declining the interest of EVs until the beginning of 21st century.

Environmental concerns of conventional transportation and increasing oil prices have led to renewed interest in electric cars in recent years [2]. Moreover, recent developments and investments on EV technology and positive views of people on EVs have increased the total number of EVs in the car market. On the other hand, EVs have to face some challenges given in Table 1 in order to widely spread over the world. Despite some possible challenges, potential benefits of EVs pointed in the

Table 1 are a precursor of a new transportation concept in the near future: Electric vehicles.

Table 1. Benefits and Challenges of EVs [3]

Benefits:	**Challenges:**
Efficiency, lower fuel cost, lower emissions	Limited range
Simpler transmission	Large battery weight/size
Fuel choice	Long charge times
Oil/energy independence	High initial cost
Emissions improve with time	Battery life
Fewer moving parts	Grid integration
Emissions at few large locations is easier to control than millions of tailpipes	Consumer acceptance

2.1.2 Types of EVs

General classification of EVs is carried out based on the energy converter type used to propel the vehicles [4]. In terms of the energy conversion type, four types of EVs are available [5]: Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), Extended Range Electric Vehicle (EREV), and Battery Electric Vehicle (BEV). Table 2 shows the summary of types of EVs.

Hybrid Electric Vehicles (HEVs)

HEVs contain both a conventional combustion engine and an electric motor for propulsion. Electric motor takes its power from a small battery and operates at the beginning of acceleration. Then, the combustion engine takes over the car drive. This coordination brings around 25% less fuel consumption compared to conventional cars. Moreover, HEVs have no external charging points, thus the small battery is recharged by the help of the gasoline engine and while breaking action.

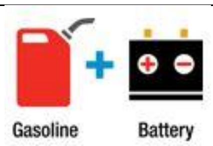
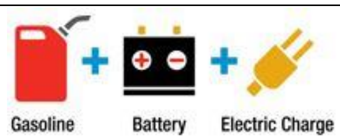
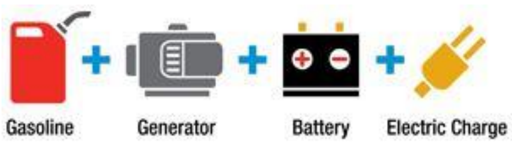
Plug-in Hybrid Electric Vehicles (PHEVs)

PHEVs also use two motors, a standard combustion engine and an electric motor, for propulsion. The driving technology and power conversation structure to the wheel are almost the same with the technology and structure in HEVs. On the other hand, the battery size and external charging capability are different between HEVs and PHEVs. Additionally, PHEVs can be recharged from the grid externally.

Extended Range Electric Vehicles (EREVs)

The power that supplies the wheels is generated only from an electric motor in EREVs. The combustion engine has designed to feed the electric generator, which aims to extend the driving range. It is also possible to charge the battery of an EREV using the power grid externally.

Table 2. A Summary of Different Types of EVs

HEV:	**PHEV:**
	
EREV:	**BEV:**
	

Battery Electric Vehicle (BEVs)

BEVs do not contain any combustion engine. The electric motor that is supplied by the battery propels the wheels in BEVs. Moreover, the battery of a BEV is charged from the power grid using a plug-in electric cable.

2.1.3 Technical Aspects

This study mainly focuses on the assessment of impacts of EVs on distribution networks. Therefore, the technical aspects will be addressed only for plug-in capable EVs that directly affect the power gird. Three main technologies become predominant in plug-in EVs: Driving and motor technology, battery technology and charging technology.

2.1.3.1 Driving and Motor Technology

PHEVs, EREVs, and BEVs have the capability of plug-in charging. The technology behind them have briefly mentioned in the previous section. However, more details about the driving and motor technology of EVs will be given in this section mainly focusing on the technology of BEVs.

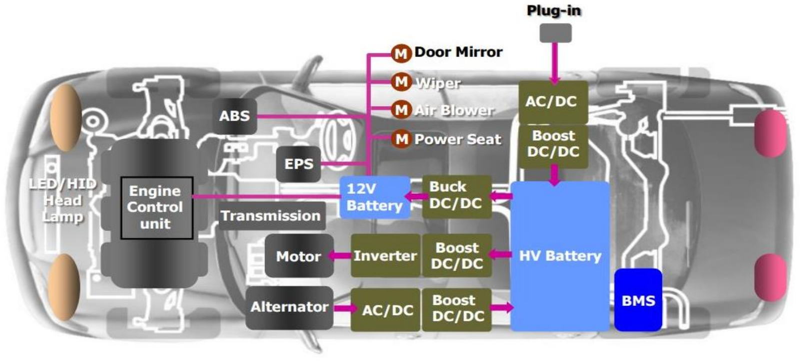


Figure 1. Components of a BEV [6]

Figure 1 illustrates the components and their interactions in a BEV. The main energy source for propulsion is the battery. It provides the required energy to the electric motor. An external plug-in charging using an AC/DC converter recharges the battery. In addition, there is a small battery that supplies energy for internal electronic operations requiring small amount of electric power in a BEV. Furthermore, several AC/DC and DC/DC converters are needed in order to make energy transformation between the battery and other components.

Using an electric motor instead of a fuel engine, BEVs reduces CO2 emissions and contributes to the air pollution positively [7]. Besides the environmental contribution, energy transfer efficiency in a BEV is substantially higher than the efficiency in a conventional car due to the high-energy losses occurring in conventional combustion engines. Figure 2 compares the conventional and electric cars in terms of the internal energy losses. It is presented in Figure 2 that energy losses in a combustion engine are almost 8 times higher than the losses occurred in an electric motor.

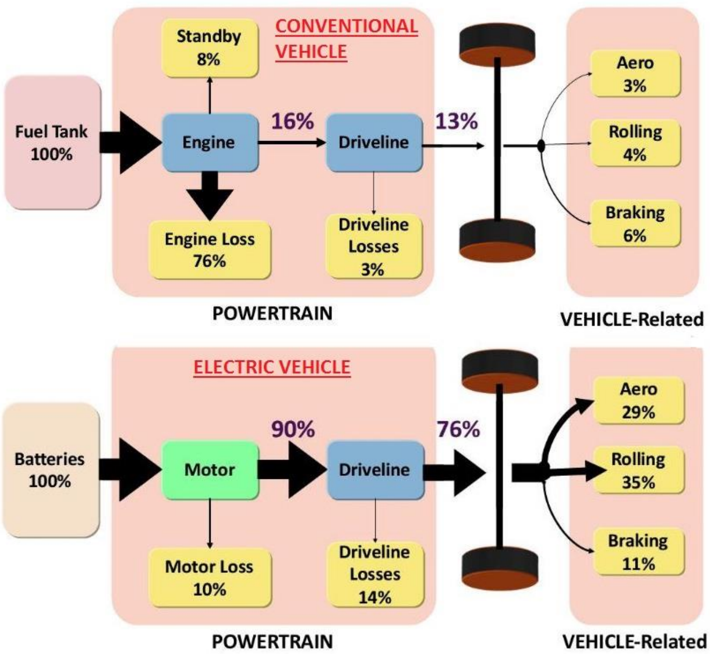


Figure 2. Energy Efficiency for BEVs and Conventional Vehicles [3]

2.1.3.2 Battery Technology

The battery is a crucial component in EV systems and plays a key role for supplying energy to the electric motor. While different technical aspects have been existed in the battery technology, four main aspects, which are the type of battery, the charging pattern for lithium-ion battery, the battery ageing, and the battery cost, are pre-dominant and will be explained in this section by the reference of COTEVOS Project Deliverable 1.1 [8].

Types of Batteries

Batteries are considered as the largest barrier in the EV development due to their high prices and limited capacity-weight ratios. Therefore, it is a priority to develop the battery technology before focusing on other technologies. Various battery technologies that are already identified in the literature are listed below:

- Nickel-Metal Hydride Batteries (NiHM)
- Sodium-Nickel Chloride Batteries (NaNiCl)
- Lithium-Ion Batteries (Li-ion)
- Lithium-Metal Polymer Batteries (LMP)
- Zinc-Air Batteries (Zinc-Air)
- Lithium-Sulfur Batteries (Li-Sulfur)
- Lithium-Metal-Air Batteries (Li-Oxygen)
- Lithium-Air Batteries (Li-Air)

The most popular battery type used in EVs is the Li-ion battery that has higher energy density, longer lifetime, and high number of charge/discharge cycles. On the other hand, although Li-ion batteries currently dominate the battery market, there will be other promising technologies available in the battery market in the near future. Figure 3 presents expectations in the battery technology in the near future.

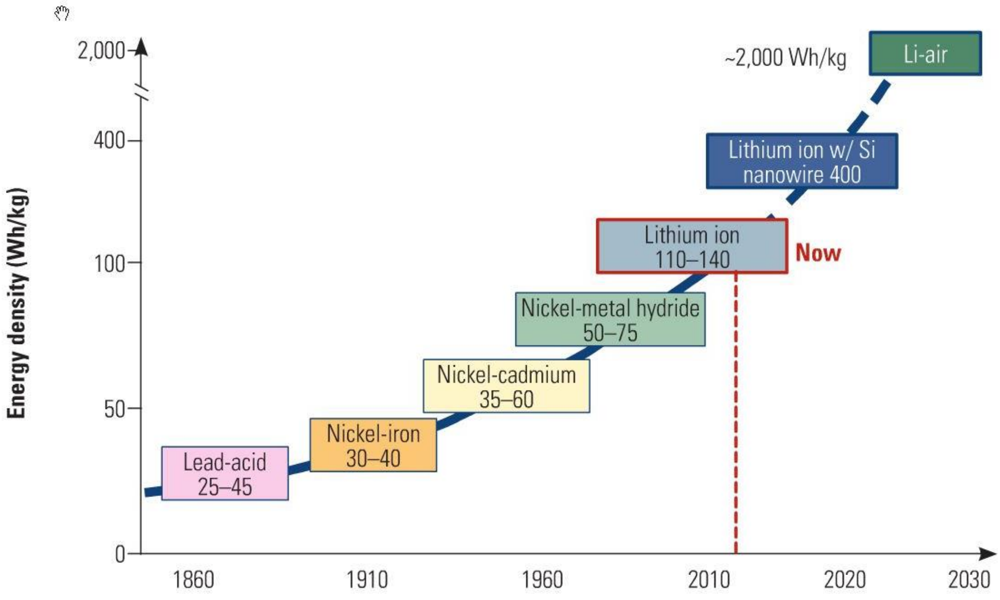


Figure 3. Expected Battery Technology in the Near Future [9]

Charging Pattern for Lithium-ion Battery

Charging process of Li-ion batteries must be carried out considering proper charging specifications in order to prevent overcharging. Therefore, 4.2 V/cell value must be applied during the charging process in order to optimize the battery lifetime and capacity.

State of Charge (SOC) is a parameter that represents the current battery capacity in percentage values. It directly affects the power transfer rate while the battery is in charging process. Figure 4 illustrates the charging curve of a battery depending on charging power over the SOC. Transferred power from the grid is almost constant until the 70% of SOC is reached, then the power starts to decrease dramatically until the battery is fully charged.

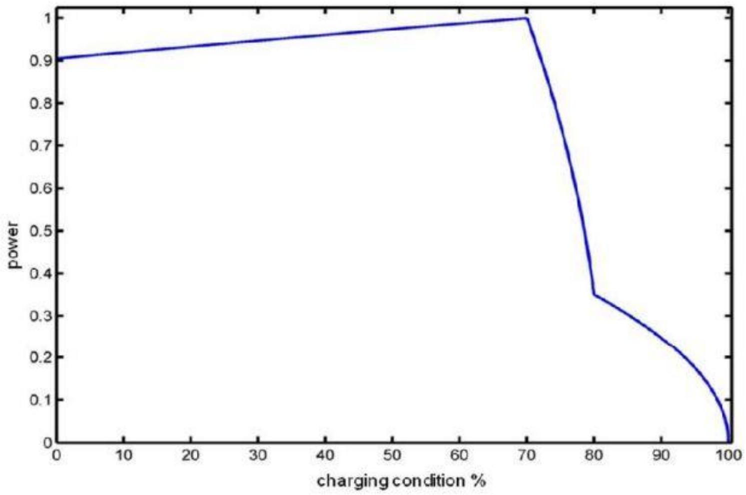


Figure 4. Charging Curve Depending on the SOC [10]

Battery ageing

The lifetime of a battery depends on various factors, which are briefly listed below:

- *Charging and discharging levels:* Deep discharging affects the battery life negatively. The optimum charge and discharge level is around 30%-40%.
- *Charging speed:* Slow charging increases the battery life.
- *Battery age:* The average lifetime of a battery is fifteen years. The performance decreases as the charging cycle increases.
- *Operation temperature:* Higher and lower temperatures reduces the battery life.

Battery Cost

The cost of a battery has probably been the most important aspect and ongoing issue from the perspective of EV manufacturers recently. The battery cost can be distinguished in two parts: Investment and degradation cost. Investment cost describes the initial cost while producing the battery. Degradation cost, on the other side, describes the cost of 1kWh-discharged energy with the assumed Depth of Discharge (DoD). Degradation cost differs between 180 and 380 €/kWh nowadays and will tend to decrease to lower rates in the future. Degradation cost is directly affected by the battery aging factors. Figure 5 shows the expectation of battery cost in the near future.

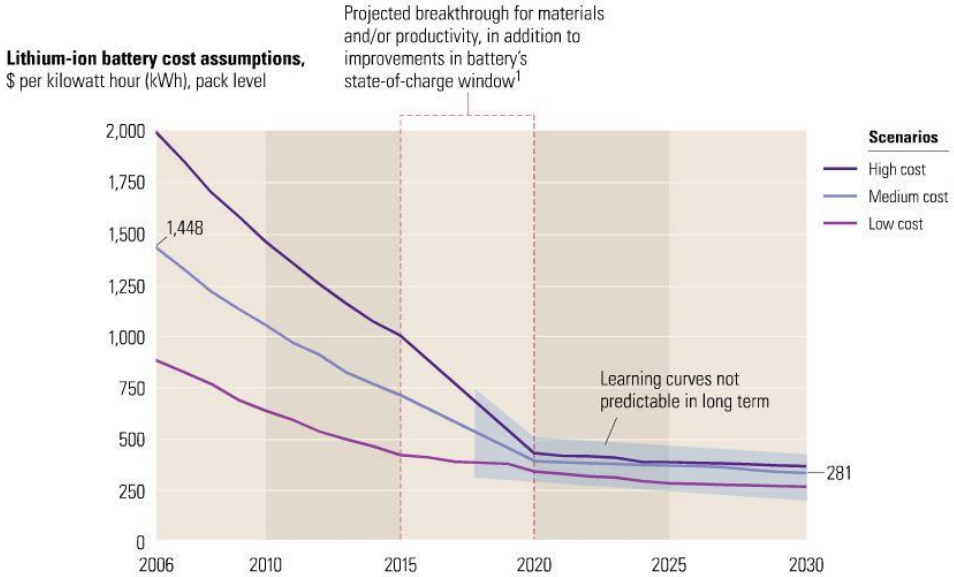


Figure 5. Cost Projections for Batteries in the Near Future [11]

2.1.3.3 Charging Technology

Various types of charging infrastructures with technical aspects will be explained in this section referred from G4V Project WP1.3 Report [10].

Three main types of charging technology are available for EV batteries. The first and most common one is the conductive charging type. In this type of charging, the battery is charged directly from the gird by using an external plug-in cable. Both AC and DC charging solutions are available in the conductive charging. Each type has different specifications. AC charging is simpler, but slower than DC charging. Having simple and cheap technology compared to other charging types makes the conductive charging method commonly used in EV charging sector.

Second type of charging is the inductive charging that is probably the most practical solution for EV users. In this type, wireless power transfer is taken into account between the parking lot (charger) and the battery. However, this technology is very expensive and inefficient (low power transfer efficiency) to be commercialized at least for today’s technology. Additionally, for the process of inductive charging, a common communication protocol must be developed between the charger and the battery in order to meet the standards and verify the secure energy transfer.

Third and final type of charging is the battery swap. This solution is based on exchanging empty batteries with fully charged ones at specific places. Despite the fact that the battery swap solution seems to diminish range problems and very convenient, a considerable amount of investment is needed in order to build battery swap stations distributed around cities. Additionally, EV manufacturers must agree on a common battery technology (a common battery to be installed in all EVs) so that the battery swap technology can be applied among all type of EVs efficiently.

According to Eşarj A.Ş., a company developing EV charging solutions in Turkey [12], four main charging solutions are available to be implemented at the customer side. Table 3 presents technical specifications for all offered solutions. All types are designed based on the AC charging solution due to low initializing costs and simple design.

Table 3. AC Charger Solutions [12]

	Wall-Box Charger V1		Wall-box Charger V2		Normal Charger
Unit power	***3.7 kVA***	***7.4 kVA***	***11 kVA***	***22 kVA***	***22 kVA***
Voltage	1 phase 230 V		3 phase 380V		3 phase 380V
Cables	1p + n + g		3p + n + g		3p + n + g
Current	16 A	32 A	16 A	32 A	32 A
Frequency	50 Hz		50 Hz		50 Hz
Plug type	Type 2		Type 2		Type 2
Charging mode	Mode 3 (EN/IEC 61851-1)		Mode 3 (EN/IEC 61851-1)		Mode 3 (EN/IEC 61851-1)
Overflow protection	20 A	32 A	20 A	32 A	32 A
Number of plugs	1		1		2

2.1.4 Future Trends and Market Availability

Future expectations on EV trend and details of the EV market are going to be explained in this section considering the world and Turkish EV market, respectively.

2.1.4.1 The EV Market and Trends over the World

As it is explained in Section 2.1.1, despite the first EV was invented in the mid of eighteenth century, the popularity of EVs has started to increase with the development of battery technology and the increment of fuel prices at the beginning of 21^{th} century. It is not wrong to point out that the EV market is in its infancy with a rapid development process nowadays [13].

Many popular car manufacturers like Nissan, Ford, Toyota, Honda, and Chevrolet have recently started to make investments on the EV sector and have produced their first EV models. Owing to first mass production of plug-in EVs, Nissan Leaf and Chevrolet Volt dominated the EV market in 2011. Besides, Nissan Leaf model became the world's all-time best selling highway capable EV based on March 2015 data [14]. On the other hand, Tesla Motors and BMW gained their popularities after producing promising EV models, Tesla S and BMW i3. In conclusion, more than 250 different EV models are currently available in the EV market, but 42% of the number of EV stories (commercials, magazines, etc.) mentions only from Tesla S and BMW i3 [15].

According to the questionnaire made among the motorist by the reporters of Automotive Trends [16], two thirds of motorists would consider purchasing an electric or hybrid car in the future. This questionnaire shows that EVs will play a vital role in the automotive industry and car market in the near future.

Despite the fact that the production rate of EVs is rapidly increasing, some encouraging/discouraging factors should be taken into account by EV manufacturers. Table 4 indicates that factors related to customer expenses are determined as fundamental factors on EV sales.

More than 712,000 plug-in EVs have been sold since 2003 based on December 2014 data in [14]. Most of EVs were sold in developed countries like USA, Japan, and Norway due to the high purchasing power and positive attitudes on EVs of their citizens. Additionally, most of developed countries have initiated some national policies aiming to increase the EV market share. Table 5 shows some developed countries (also called Electric Vehicle Initiative (EVI) countries) and their policies initiated on the finance, infrastructure, and Research, Development, and Deployment (RD & D) [17].

EV sales and market share in 2013 and 2014 are presented in Table 6 for developed countries. According to the Table, while the USA has the highest number of EV sales in the US automotive market, Norway has the biggest market share due to the difference in the market size between two countries. Additionally, the market share of plug-in EVs has increased in 2014 for all countries expect The Netherlands that, on the other hand, has substantially high penetration rate in 2014 as well. It is obvious that the number of EVs will increase and reach a remarkable value in the near future by looking only the sales rates between 2013 and 2014.

Table 4. Factors Affecting Customer Attitudes on EV Sales [16]

Encouraging Factors:		**Discouraging Factors:**	
Fuel economy (running costs)	56%	Not enough charging points	42%
Purchase price	52%	Purchase price	37%
Miles per full charge	44%	Range (miles per charge)	36%
Reliability	43%	Speed of recharging	35%
Reassurance on battery life	39%	Limited distribution of recharging points	32%

Figure 6 shows the EV mean deployment scenario between 2010 and 2050 in Ireland studied in Electric Vehicles Roadmap Report by Sustainable Energy Authority of Ireland [18]. According to Figure 6 and the report, by 2020 the EV contribution (BEVs and PHEVs) to the passenger car segment is 2.4%, growing to 60% by 2050 in the medium scenario. Additionally, as an alternative technology to EVs, H2 Fuel Cells car sales are going to reach 18% by 2050. Although the report studies the EV deployment in Ireland, similar trends and expectations in the EV deployment might occur for other countries as well.

Table 5. Current National Policy Initiatives [17]

Country	Finance	Infrastructure	RD & D
China	Purchase subsidies for vehicles of up to RMB 60,000.	---	RMB 6.95 billion for demonstration projects.
Denmark	Exemption from registration and road taxes.	DKK 70 million for development of charging infrastructure.	Focus on integrating Evs into the smart grid.
France	EUR 450 million in rebates given to consumers buying efficient vehicles, with 90% of that amount from fees on inefficient vehicles. Remaining 10% (EUR 45M) is a direct subsidy.	EUR 50 million to cover 50% of EVSE cost (equipment and installation).	EUR 140 million budget with focus on vehicle RD&D.
Germany	Exemption from road taxes.	Four regions nominated as showcase regions for BEVs and PHEVs.	Financial support granted for R&D for electric drivetrains, creation and optimization of value chain, information and communications technology (ICT), and battery research.
Italy	EUR 1.5 million for consumer incentives, ending in 2014.	---	---
Japan	Support to pay for ½ of the price gap between EV and corresponding ICE vehicles, up to YEN 1 million per vehicle.	Support to pay for ½ of the price of EVSE (up to YEN 1.5 million per charger).	Major focus on infrastructure RD&D.
The Netherlands	Tax reduction on vehicles amounting to 10-12% net of the investment.	400 charging points supported through incentives.	Focus on battery RD&D (30% of 2012 spending).
Spain	Incentives up to 25% of vehicle purchase price before taxes, up to EUR 6,000. Additional incentives of up to EUR 2,000 per EV/PHEV also possible.	Public incentives for a pilot demonstration project. Incentives for charging infrastructure in collaboration between the national government and regional administrations.	Five major RD&D programmers are operational with incentives for specific projects.
Sweden	EUR 4,500 for vehicles with emissions of less than 50 grams of CO_2/km. EUR 20 million for 2012-2014 super car rebate.	No general support for charging points besides RD&D funding (EUR 1 million in 2012).	EUR 2.5 million for battery RD&D.
United Kingdom	---	GBP 37 million for thousands of charging points for residential, street, railway, and public sector locations. Available until 2015.	The UK Technology Strategy Board has identified 60 collaborative R&D projects for low-carbon vehicles.
United States	Up to USD 7,500 tax credit for vehicles, based on battery capacity. Phased out after 200,000 vehicles from qualified manufacturers.	A tax credit of 30% of the cost, not to exceed USD 30,000 for commercial EVSE installation; a tax credit of up to USD 1,000 for consumers who purchase qualified residential EVSE. USD 360 million for infrastructure demonstration projects.	2012 budget of USD 268 million for battery, fuel cell, vehicle systems and infrastructure R&D.
Norway	No purchase taxes, Exemption from 25% VAT on purchase, No charges on toll roads.	Free municipal parking, Free access to bus lanes. A goal of 100,000 electric cars within 2020.	---

Table 6. Plug-in EV Sales and PEV Market Share in Developed Countries [14]

Country	PEV Sales		Growth	PEV Market Share	
	2013	2014	2013-2014	2013	2014
USA	172,000	291,332	69.4 %	0.62 %	0.72 %
Japan	74,124	108,248	46.0 %	0.85 %	1.06 %
China	28,619	83,198	190.7 %	0.08 %	0.23 %
The Netherlands	28,673	45,020	57.0 %	5.37 %	3.87 %
France	28,560	43,605	52.7 %	0.65 %	0.70 %
Norway	20,486	43,442	113.3 %	5.60 %	13.84 %
Germany	12,156	25,205	107.3 %	0.25 %	0.43 %
UK	9,982	~24,500	145.4 %	0.16 %	0.59 %
Canada	5,596	10,658	90.5 %	0.18 %	0.27 %
Sweden	3,138	8,076	157.4 %	0.57 %	1.53 %
Global Total (since 2003)	405,000	712,000	75.8 %	0.038 %	0.062 %

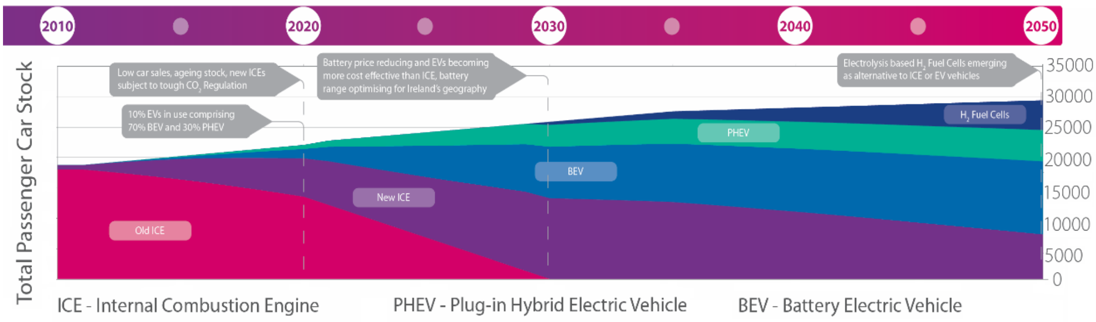


Figure 6. The EV Mean Deployment Scenario 2010 – 2050 in Ireland [18]

2.1.4.2 The EV Market and Trends in Turkey

EV sales have significantly increased in developed countries over the world in recent years. On the other hand, developing counties like Turkey are experiencing a much slower rate in the increase of EVs. It does not necessarily mean that EV market is not available in these countries; it only implies that EV sales in developing countries need some time to catch the sales in developed countries.

Renault Company made the first investment on EVs in Turkey by producing and releasing the Fluence Z.E. model at the end of 2011. Unfortunately, the company stopped the production of the car in 2014 because of low sales. Instead, Renault has been offering new models, Twizy and Zoe, since 2014. Besides, other companies like BMW, Toyota, Opel, etc. have recently offered their EV models into Turkish automotive market. Additionally, the most popular EV Company Tesla Motors is planning to make an investment aiming to bring its supercharger technology to Turkey in 2015 [19]. Tesla S and BMW i3, the most popular two EV models in the world, will most probably dominate the EV market in Turkey in the near future.

A survey made by Deloitte Company shows that most of customers are interested in EVs [20]. Table 7 presents that customer expectations from EVs are quite high. There are many factors evaluated as “very important” by survey participants while making decisions before purchasing EVs. Especially issues related to security and price have high importance value in the survey.

Only a few hundred EVs have been sold in Turkey according to reports on vehicle market evaluation released by Turkish Automotive Distributers’ Association (ADA) [21]. Even though the number of sales seems to be lower than the number of sales in developed countries, there are some governmental incentives and policies to support the EV sales in Turkey. Turkish government has decided to apply some discounts on excise duties applied in car sales regarding the decision of Council of Minister dated and numbered as 2011/1435 [22]. Normally, a typical excise duty for a light car is applied at the rate of 45%, but the rate of excise duties on EVs is classified between 3% and 15% based on the power of the electric motor. Addition to the reduction in duties, some incentive programs and action plans are prepared by Ministry of Development in order to increase the usage of EVs in Turkey, which are listed below [23]:

- 1511 - Priority Areas Research, Technology Development and Innovation Projects Support Program has been initiated by The Scientific and Technological Research Council of Turkey (TUBITAK) regarding the hybrid and battery EV technology.
- Action plans on three EV related topics:
  - Support the production of batteries for EVs aiming to spread alternative energy resources for cars.
  - Develop an incentive tax system aiming to encourage people to use the environmentally friendly vehicles.
  - Infrastructure activities to extend the usage of electric cars.

All of these incentives and policies are the evidence of a rapid development in the EV market in Turkey. Even though the number of EVs in Turkey is not as many as in developed countries, an appropriate environment that is sufficient for the advancement of EVs will occur in the following years.

Table 7. The Importance of Customer Expectations from EVs in Turkey [20]

Decision Factors:	Not important →									→ Very important
Security and reliability										◆
Consumption / charging cost									◆	
Total quality									◆	
Maintenance and repairing cost								◆		
Purchase price /annually leasing price								◆		
Performance and usage							◆			
Environmental issues (emission rate)							◆			
Secondary market						◆				
Brand popularity					◆					

2.2 Literature Review on Impacts of EVs on Distribution Networks

Developing electric motor industry, raising fossil fuel prices, and recent developments in battery technology have enlarged the momentum of the EV integration into power grids in recent years [2], [24]. Increasing the number of EVs creates various challenges regarding power grid issues to be contended. Considering the fact that charging will be mostly at LV levels [25], major effects of the EV integration will take place on LV distribution networks. This brings a requirement to assess and analyze impacts of EVs on LV distribution networks from the perspective of distribution companies.

Several methods have recently been applied for the evaluation of impacts of EVs on distribution networks. Almost all of them are based on the load flow simulation applied with either a deterministic or a probabilistic approach. Reference [26] focused on the assessment of distribution networks in Gothenburg city using a deterministic load flow simulation only on peak hours while the researcher of [27] studied impacts of EVs on network planning criteria using different large-scaled distribution networks both on peak and valley hours. Moreover, a deterministic 24-hour load flow approach was applied in [28] to analyze LV distribution networks in Malaysia, in [29] to analyze MV distribution networks in Bosnia-Herzegovina, and in [30] to analyze Pacific Northwest distribution networks, considering fixed plug-in and charging times. Reference [31] also obtained deterministic results from the load flow analysis using average PHEV profiles by sampling some EV parameters acquired from different sources. In general, considering various unpredictable variables on an EV load profile, applying the deterministic based load flow may create large gaps between simulations and real applications.

Due to such gaps, the probabilistic based load flow approach must be implemented while determining impacts of EVs on distribution networks in order to acquire more reasonable results. References [32] and [33] concentrated on the analysis of distribution networks applying both deterministic and probabilistic approaches on a simple generic distribution network and a detailed British generic LV distribution network, respectively. Moreover, researchers of [34] and [35] applied a comprehensive probabilistic approximation on unknowns of EV variables using National Household Travel Survey (NHTS) data applying Monte Carlo simulation on IEEE 123 node test feeder. Probabilistic based load flow approach was also performed in papers [36], [37], [38], and [39] as well.

This study mainly focuses on the assessment of impacts of EVs on LV distribution networks in Turkey using Monte Carlo based load flow simulation. Instead of analyzing impacts of EVs on a current test network as in [34], or on a generic network as in [33], two real pilot distribution networks have been analyzed in this study. The networks are chosen considering the differences on the socio-economic characteristic and load consumption of their customers, settlement types, and network structures. In addition to these two pilot networks, a generic distribution network has also been modelled and analyzed as a reference distribution network.

One of the most crucial challenges while assessing impacts of EVs using the probabilistic approach is the modeling of unknown variables related to EVs. EV plug-in time, SOC status, type of home charger, and battery characteristic of an EV have to be constructed and utilized with remarkable assumptions. Although various EV modelling methods have already been implemented with various assumptions in the literature, an extensive BEV model has been developed using well-defined probabilistic models and assumptions in this study. Instead of using general data representing the whole country as in [33] or making some general assumptions as in [39], the average daily traffic data for Ankara region are collected and used while modelling the EV plug-in time as a normal distribution function. Additionally, the survey data representing daily travel distances for Turkish people are modelled as a Weibull distribution in order to determine the SOC status of a battery at the beginning of the charging process. This approach gives more reliable results than the method associating the same travel distances to all EVs as in [36] and [40]. Moreover, the other two EV variables, capacity of the battery and home charger unit, are selected as 22 kWh and 3.7 kVA. It is assumed that they will be the most selected alternatives by the EV manufacturers and customers in Turkey in the near future.

CHAPTER 3

MODELLING AND DETERMINATION OF CASES

The modelling criteria of LV residential distribution networks, EVs, and residential loads will be explained in this chapter. The applied methodology and assumptions while modelling the distribution networks, residential loads, EVs, and other grid elements (lines, transformers, etc.) will be addressed in detail. Additionally, five cases studied will be described and the determination of cases will be explained in this chapter.

3.1 Modelling of LV Distribution Networks

Three different types of LV distribution networks are modelled and analyzed in the scope of this study. All three networks differ from each other in terms of the structure, location, and socio-economic nature of their customers. Two networks are chosen from actual network segments in Ankara [41], while an additional distribution network is modified from EDP design criteria [42] as a generic distribution network model for Turkey. The terminology of the distribution networks are identified as Network 1a (NW1a) and Network 1b (NW1b) for the first type, Network 2 (NW2) for the second type, and Network 3 (NW3) for the third type in this study.

The first type (NW1a and NW1b) of distribution network is a pilot network which is not well-designed (in terms of distribution planning standards) and has been operating for almost 20 years. The network supplies an apartment-type settlement region. Customers of this network are considered as middle class citizens having average incomes. The socio-economic nature of the customers may affect the possibility of EV ownership, which is taken into account while determining EV scenarios.

The second type (NW2) of distribution network is a relatively new and well-designed network operating in a villa-type settlement region. In addition to the network structure, economic condition of customers at this network is better and, therefore, the electricity consumption and EV purchasing power are expected to be higher than those in NW1.

The third type of distribution network is a generic LV distribution network model. Network 3 is a well-structured network and it is a good candidate while designing or planning a new distribution segment. Being different from the other types of networks, NW3 is modeled in more detail (only 4 residential customers lumped as a group) including the tapered LV lines (the distribution cable conductor size is reduced as the number of consumers downstream diminish with distance from the substation).

All three networks are three-phase distribution networks, but modelled as single-phase equivalents. Although customers of the networks are connected to different phases of the distribution system, they are considered as three-phase loads represented by single-phase equivalents. Hence, it is assumed that there is no unbalanced loading between the phases. Additionally, instead of modelling every load separately, residential customers are modelled as lumped loads in this study. The representation of the LV distribution network in a scaled group is a part of the modelling criterion while simulating the network. Details of distribution networks are explained in the following paragraphs while the simulation data for transformers and LV cables are presented in Appendix A.

Network 1:

Network 1 is a LV residential distribution network having 610 customers. This network is operating in Inonu neighborhood feeding Harb-iş-4 housing estate in Ankara. The MV/LV transformer of NW1 supplies thirty 5-storey buildings with 20 customers by eight outgoing main feeders.

Since the transformer in NW1 is 85% loaded at the moment and is going to be replaced soon, two different transformer ratings corresponding to two different networks (NW1a and NW1b) are utilized in simulations. The transformer in NW1a is assumed to be 800 kVA (operating at 70% loading rate in the peak hour) while the transformer in NW1b is 1000 kVA (operating at 55% loading rate in the peak hour). Single line diagram of NW1 are presented in Figure 7.

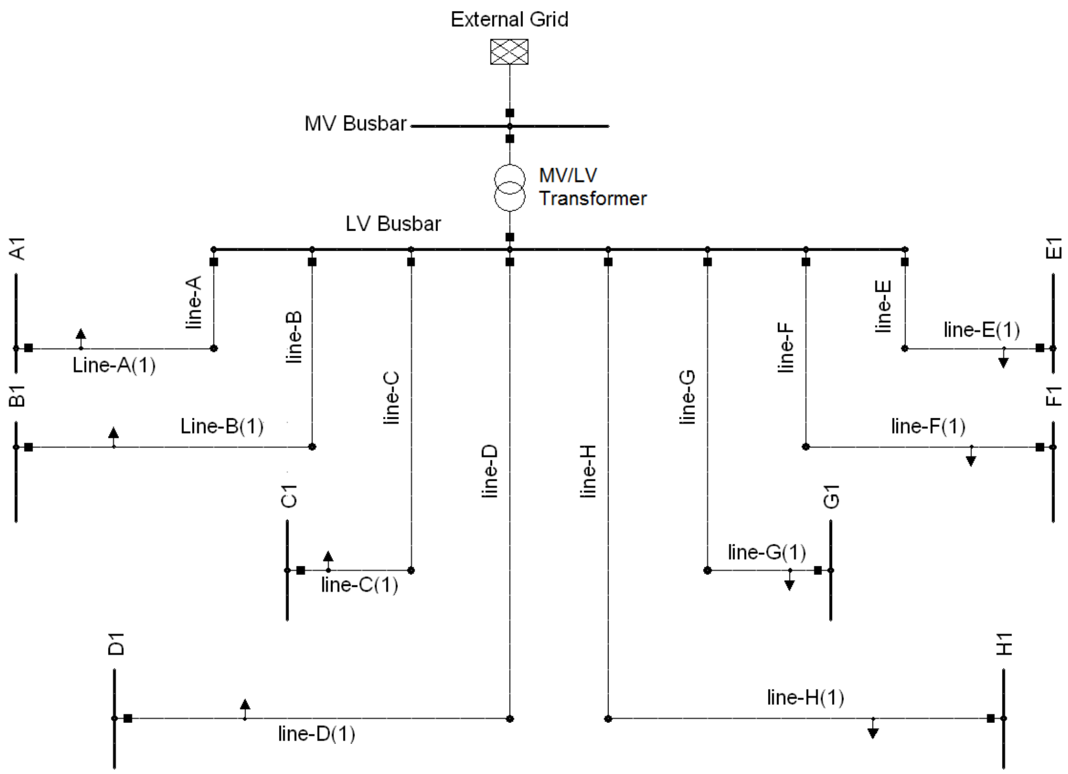


Figure 7. Single Line Diagram of Network 1

Each busbar in Figure 7 (A1, B1…, and H1) represents a group of loads fed by LV lines. Each LV line reaches to a distribution box which is a junction point between the main line (e.g., line-D) and the branch line (e.g., line-D(1)). Since the residential loads are distributed LV loads at branch lines, they are lumped and positioned at the 67% of the branch lines (based on expert knowledge). The characteristic of LV feeders and the number of customers are shown in Table 8.

Table 8. Feeder Characteristics and the Number of Customers in Network 1

Feeder	**Cable Type**	**Length (m)**	**Number of Customers**
A + A(1)	35 mm^2	200 + 50	60
B + B(1)	95 mm^2	150 + 66	80
C + C(1)	50 mm^2	100 + 60	60
D + D(1)	70 mm^2	250 + 50	100
E + E(1)	50 mm^2	250 + 60	60
F + F(1)	35 mm^2	100 + 30	40
G + G(1)	95 mm^2	290 + 30	100
H + H(1)	95 mm^2	400 + 70	110

Network 2:

Network 2 is also taken from an actual network and is operating in Ahmet Taner Kışlalı neighborhood in Çayyolu, Ankara. The network has a 1000 kVA MV/LV transformer (operating at 40% loading rate at the peak hour) supplying 392 customers living in separate houses (villa type settlement). Ten outgoing main feeders supply the residential loads. Single line diagram of NW2 is demonstrated in Figure 8.

Figure 8 shows that NW2 has ten outgoing main feeders supplying 17 main busbars. All of main feeders except T1, T2, and T3 supply two busbars having around 20 customers. Main lines in NW2 firstly reach to distribution boxes (e.g., the junction point between line-A and line-A(1)). Then, branch lines outgoing from the distribution box (e.g., line-A1) feed residential loads. If there are two busbars supplied by the same main feeder, an additional LV line (e.g., line-A2) is used from the existing distribution box to an additional distribution box. Finally, residential loads in the second busbars are also fed by branch lines (e.g., line-A2(1)). Since the number of customers is in considerable amount for voltage drop analysis, all residential loads are connected at the end of branch lines. The length of LV lines and the number of customers are given in Table 9.

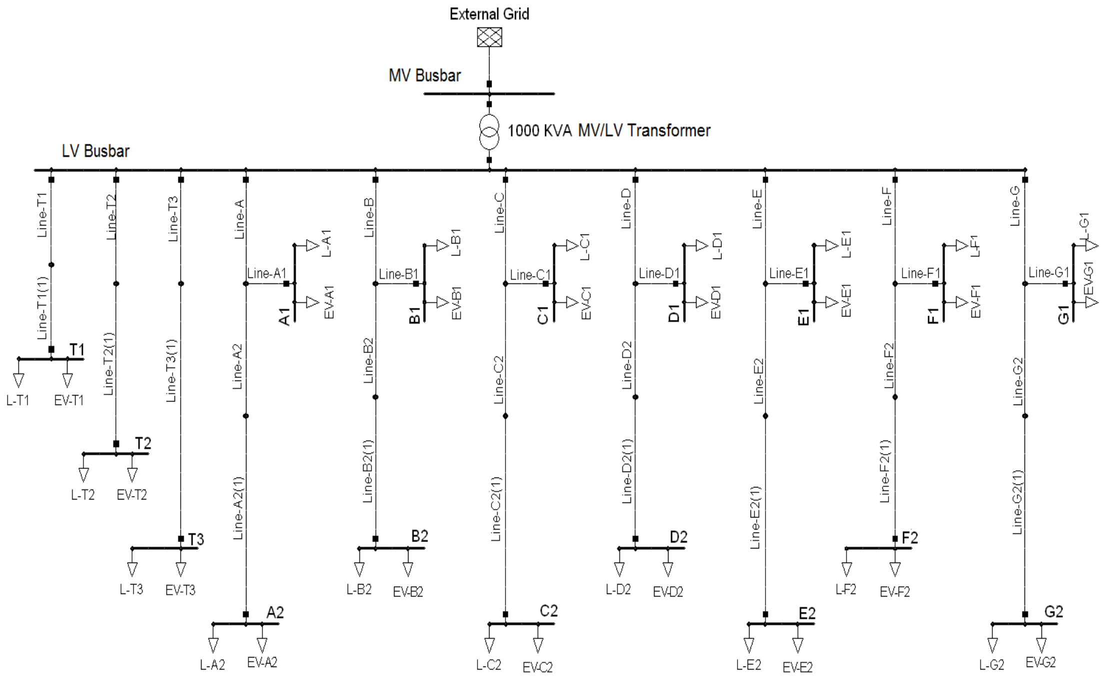


Figure 8. Single Line Diagram of Network 2

Table 9. Feeder Characteristics and the Number of Customers in Network 2

Feeder	Cable Type	Length (m)	Number of Customers
A + A1	150 mm^2	400 + 55	13
A2 + A2(1)	95 mm^2 + 95 mm^2	87 + 50	16
B + B1	120 mm^2	276 + 50	15
B2 + B2(1)	95 mm^2	131 + 50	16
C + C1	120 mm^2	237 + 50	17
C2 + C2(1)	95 mm^2	53 + 50	17
D + D1	120 mm^2	150 + 50	24
D2 + D2(1)	120 mm^2	93 + 50	18
E + E1	120 mm^2	165 + 50	20
E2 + E2(1)	120 mm^2	100 + 50	20
F + F1	120 mm^2	62 + 50	14
F2 + F2(1)	95 mm^2	200 + 50	12
G + G1	120 mm^2	120 + 50	24
G2 + G2(1)	95 mm^2	100 + 50	26
T1 + T1(1)	150 mm^2	110 + 10	30
T2 + T2(1)	150 mm^2	170 + 70	70
T3 + T3(1)	150 mm^2 + 95 mm^2	107 + 70	40

Network 3:

Network 3 is modelled based on the design criteria of EDP Distribution Company with some network modifications (to be used as a generic network in Turkey). The transformer is upgraded from 630 kVA to 1250 kVA and eight residential customers are divided in two groups (instead of four) at the end of branches. The modified network is presented to be a generic LV residential distribution network in Turkey while planning or constructing a new network. Presented as a NW3 distribution network, it includes 576 customers and is analyzed in two different loading rates:

48% (higher installed capacity) and 65% (lower installed capacity). In other words, two different load consumption rates as middle and high are considered for residential customers in NW3 in simulations. Single line diagram of the distribution network and the labeling of feeders are shown in Figure 9.

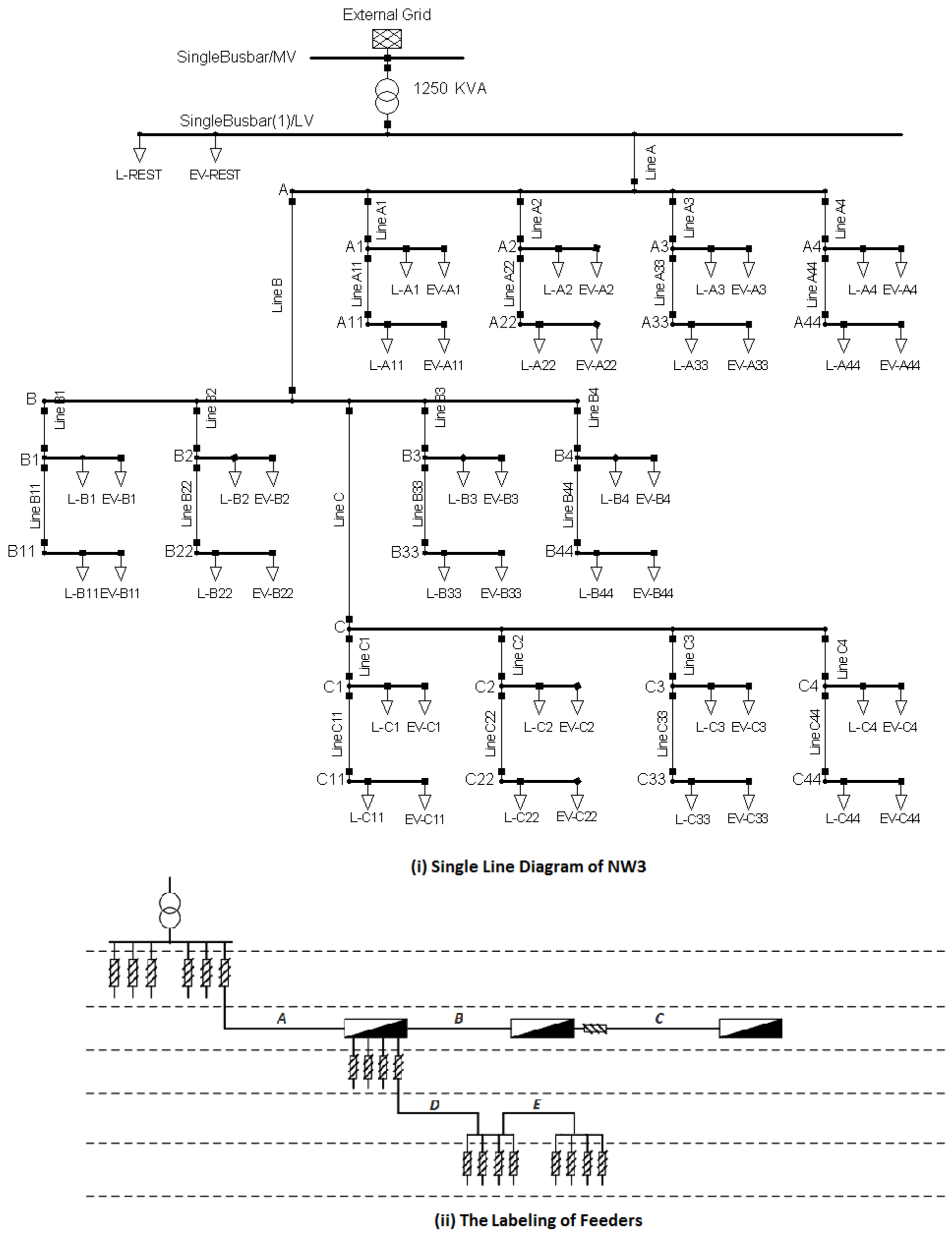


Figure 9. Single Line Diagram of Network 3

As it is illustrated in Figure 9, NW3 has 1250 kVA MV/LV transformer with six outgoing main feeders. Three distribution nodes (each one supplies 32 customers) are located at each feeder. In simulations, only elements of one main feeder (i.e., one branch) is modelled in detail, while the remaining elements are modelled as lumped loads directly connected to the main busbar. Results obtained for elements of the main feeder are also valid for corresponding elements located at other feeders due to the identical structure. Details of LV lines and the number of customers are demonstrated in Table 10.

Table 10. Feeder Characteristics and the Number of Customers in Network 3

Feeder	**Cable Type**	**Length (m)**	**Number of Customers**
A	185 mm^2	100	96
B	150 mm^2	100	64
C	120 mm^2	100	32
D	35 mm^2	50	8
E	35 mm^2	50	4

3.2 Modelling of LV Residential Loads

A LV load, from the perspective of distribution companies, is an amount of power measured by distribution companies during a period. Three different types of loads have been defined in the literature [43]: Residential, commercial, and industrial. In each type, every customer has a unique individual load curve based on daily, weekly or yearly periods and the load curve alters with the characteristic of customer demand. In this study, residential type of customers will be studied since selected pilot distribution networks are structured in residential areas.

In the distribution network planning, the total peak demand of customers is evaluated for each LV load area based on the socio-economic characteristic of customers. Three main parameters have to be taken into account while modelling a residential load: Demand factor, coincidence factor, and total peak demand. The demand factor defines the rate of maximum demand to the total installed capacity for a LV customer while the coincidence factor defines the ratio of peak demand in an individual customer to the complete system peak demand.

In Figure 10, the term “coincidence factor” is illustrated in terms of daily load curves for different number of LV customers. It is obvious that the value of total peak load per customer decreases when the number of customers supplied by a transformer increases. For instance, the total peak demand per customer drop from 22 kW to 15 kW (at the transformer side) when the number of customers increases.

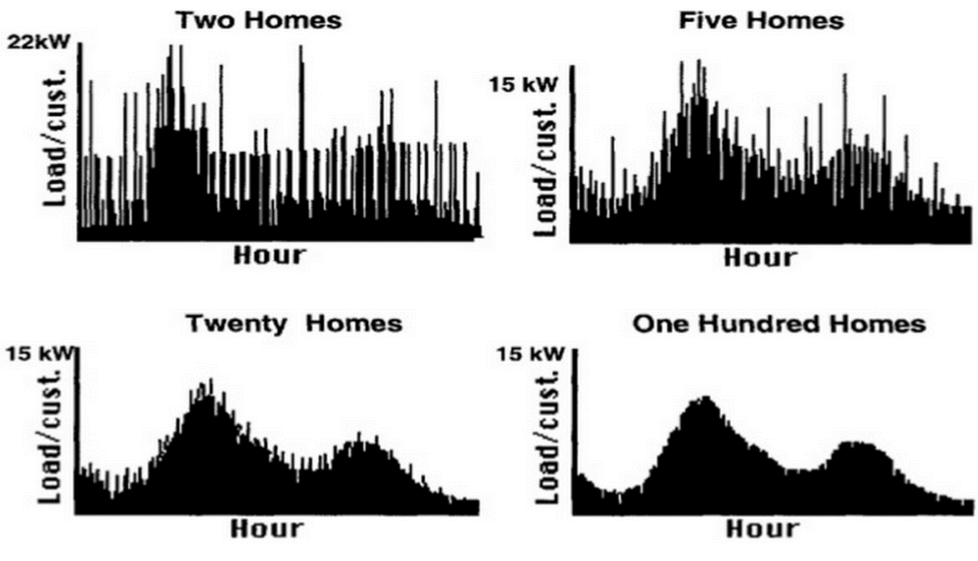


Figure 10. Daily Load Curves for Different Groups of Customers [43]

In this study, two different areas and two different peak demand values are determined for LV residential loads. A high-demand customer is assumed to have a total installed capacity of 8 kVA while a medium-demand customer has 6 kVA. In both cases, the power factor is taken as 0.95 lagging. The demand and coincidence factors are selected as 0.5 and 0.3, respectively, from the most possible scenario in [41].

After the determination of the peak demand, demand factor, and coincidence factor, the daily load curve of a residential customer has to be defined in the load flow simulation. In this study, residential loads are modelled using residential load profiles published by Republic of Turkey Energy Market Regulatory Authority [44]. The data are selected from the winter period (January 2015 on Monday). The modelling of the LV load is realized by associating the peak load value of a customer to 1 per unit (pu) value in the daily load curve. The load consumption of each customer are defined for each hour in the same manner. The daily load curve for a typical residential customer in Ankara is given in Figure 11.

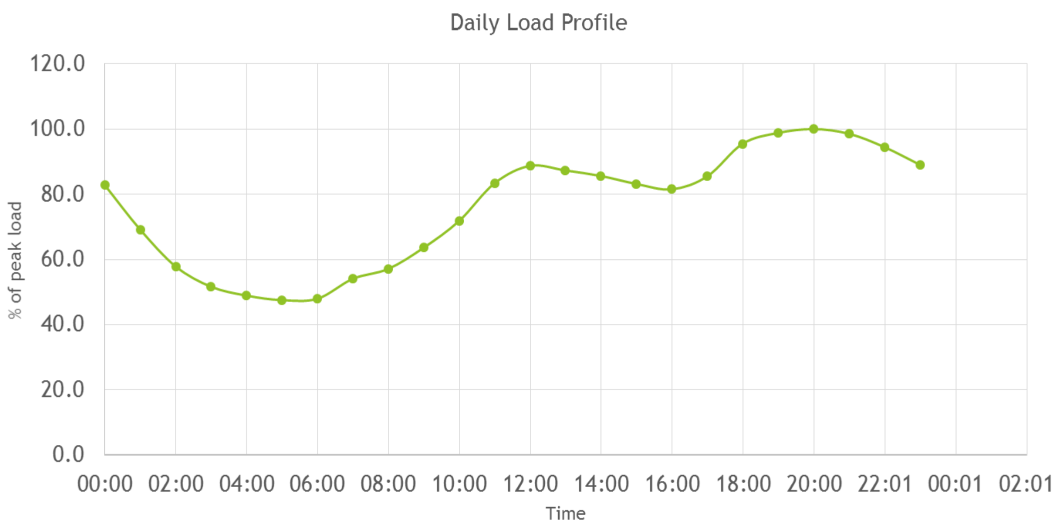


Figure 11. Daily Load Profile of a LV Residential Customer in Ankara

Due to the fact that the EV integration will affect distribution networks in Turkey in the near future, LV residential customers are not only determined on their current load consumption rates but also on their annual consumption growth rates (assuming the 2% annual load increase for a residential area). Hence, three distinctive load scenarios are applied regarding three different values of load increasing rates in this study as 10%, 20%, and 30%.

3.3 Modelling of EVs as LV Distributed Loads

Impacts of EVs on distribution networks are studied using the probabilistic load flow approach in this study. This approach is a quite reliable method due to the compatibility of modeling EV uncertainties in a probabilistic manner. In the assessment of different EV unknown variables, four pre-dominant probabilistic aspects must be taken into account while performing the simulation:

- Plug-in time
- Charge duration
- Type of home chargers
- EV penetration rates

A scenario approach is followed to represent different penetration rates due to the fact that the estimation of EV penetration is a cumbersome task. Therefore, as many researchers in the literature do, different EV penetration rates are implemented in various cases instead of applying a probabilistic model in this study.

Four types of home chargers with 3.7 kVA, 7.4 kVA, 11 kVA and 22 kVA power outputs are available for home charging systems in Turkey according to [12]. Since the cheapest and easiest solution is 3.7 kVA charging, EV owners will most probably prefer to apply this type of solution in their houses. Hence, 3.7 kVA charging units are assumed to be deployed in residential customers throughout this study.

Additionally, an average 3.6 kWh energy is determined for any charging process at each hour in this study due to the constant current (16 A) and variable voltage (changing between 220 and 230 V due to voltage values of residential customers) characteristic of battery charging.

In this study, the uncertainty in the two EV aspects is modelled using probabilistic functions to be deployed in Monte-Carlo based load flow approach namely: Plug-in time and Charge duration.

Plug-in Time:

The EV plug-in time is favorably correlated with home arrival habits of EV owners. Since pilot distribution networks are located in Ankara region, home arrival times have been estimated using the traffic density data for Ankara city. It is assumed that a vehicle that is on the road at any specific time will be plugged-in after half an hour, which is assumed to be the average trip duration between work and home in Ankara. Considering travel times and customer habits, this is a quite reliable assumption and estimation for Ankara.

Focusing on the mobility, Yandex traffic data are accumulated to determine hourly traffic densities in Ankara [45]. Density values are represented from 0 to the value that depends on the traffic density (the maximum value that is observed for Ankara is 8). According to Yandex tool, the zero value means that there is no traffic and when the value increases the traffic density increases as well.

Starting from 16:00 to 21:15, traffic density data are gathered using 15-minutes resolution for working days of a week. Then, the average of daily traffic densities (from 16:00 to 21:15) are calculated for each 15-minute periods. After that, home-arrival density values are determined by adding 30 minutes to each time frame. Finally, home arrival densities are calculated on a semi-hourly basis from 17:00 to 22:00 by adding previous two quarter-hourly density data. The calculation of traffic densities on a semi-hourly basis aims to create more accurate EV profiles. Traffic density data are given in Table 11 while the calculated data (on a semi-hourly basis) are presented in Table 12.

It can be inferred from Table 12 that almost half of the charging process tends to start between 18:30 and 20:00 in Ankara. If the plug-in trend of EVs is plotted using Matlab simulation tool, Normal Distribution (μ = 19:15, σ^2 = 1.5) Probabilistic Density Function (PDF) fits the plug-in curve. Therefore, EV plug-in times are modelled as a Normal Distribution function having 19.15 as the mean value and 1.5 hours as the standard deviation in the simulation tool. Figure 12 shows curves of N(19:15, 1.5) PDF and real data.

Table 11. Traffic and Home Arrival Densities for Ankara Region [45]

Traffic Time	Plug-in Time	Density	Traffic Time	Plug-in Time	Density
16:00	16:30	3.4	18:45	19:15	6.6
16:15	16:45	3.8	19:00	19:30	6.4
16:30	17:00	4.2	19:15	19:45	5.8
16:45	17:15	4.2	19:30	20:00	5
17:00	17:30	4.4	19:45	20:15	4
17:15	17:45	5	20:00	20:30	3.4
17:30	18:00	5.6	20:15	20:45	2.4
17:45	18:15	5.8	20:30	21:00	2
18:00	18:30	6	20:45	21:15	2
18:15	18:45	6.6	21:00	21:30	1.4
18:30	19:00	6.8	21:15	21:45	1

Table 12. Plug-in Time Densities on a Semi-Hourly Basis

Arrival Time	**Density**	**Plug-in Rate**
17:00	7.2	7.5 %
17:30	8.4	8.7 %
18:00	9.4	9.8 %
18:30	11.4	11.9 %
19:00	12.6	13.2 %
19:30	13.4	14 %
20:00	12.2	12.7 %
20:30	9	9.4 %
21:00	5.8	6.1 %
21:30	4	4.2 %
22:00	2.4	2.5 %

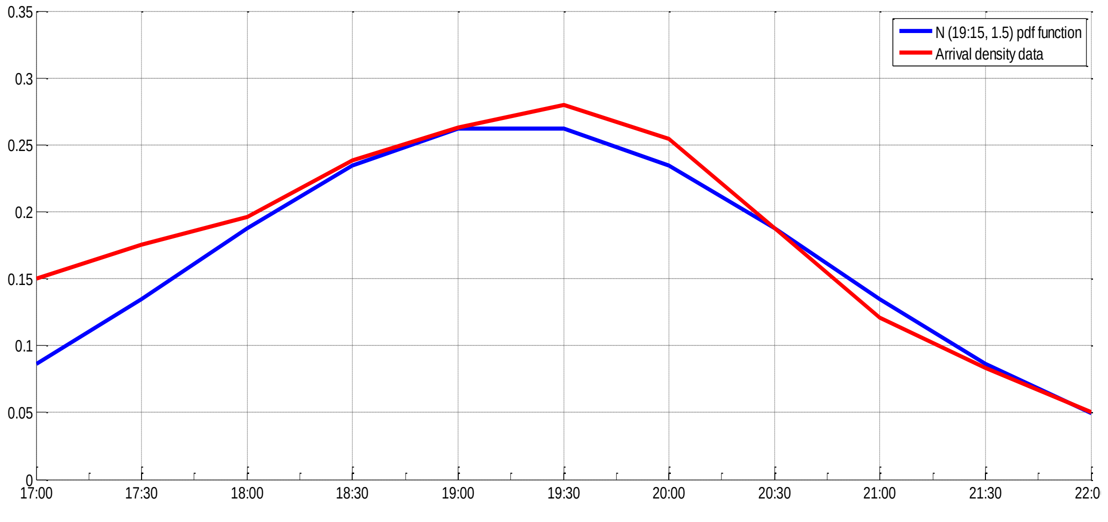


Figure 12. Normal Distribution PDF (μ = 19:15, σ2 = 1.5) and Home Arrival Data

Charge Duration:

Finally, yet importantly, the last unknown variable for the EV modelling is the charge duration. This variable depends on various characteristics of an EV and EV owner. There are four prominent characteristics in the determination of the charge duration for an EV, which are the daily travel distance, the charging habit, the type of EV and battery, and the charger type. All of four characteristics and their modelling process into the simulation are explained in the following paragraphs.

As it is mentioned at the beginning of this section, the charger type is selected as 3.7 kVA (3.6 kWh energy in average). Therefore, the characteristic of the charger type is determined by associating it to the fixed 3.7 kW home charger.

Considering all EV types in Turkish car market, BMW i3 and Renault ZOE are two BEVs that can currently be purchased from the EV market. Although they have the same battery capacity as 22 kWh [46] [47], the characteristic curve of the batteries is slightly different. Since the predictions of customer trends in the near future show that BMW i3 is one-step ahead than ZOE [15], the battery characteristic of BMW i3 is selected and deployed in simulations.

A further assumption is made for the charging habit in this direction: An EV starts to charge as soon as it is plugged-in (if there is no special tariff which will be explained in the following section) and not interrupted until it is fully charged.

Finally, the daily travel distance characteristic is utilized in order to calculate the charge duration of an EV. A survey made by Deloitte Company [20] (see Figure 13) is used to model daily travel distances in a probabilistic manner. The survey comprises total travel distances for Europe average, Turkey workday, and Turkey weekend.

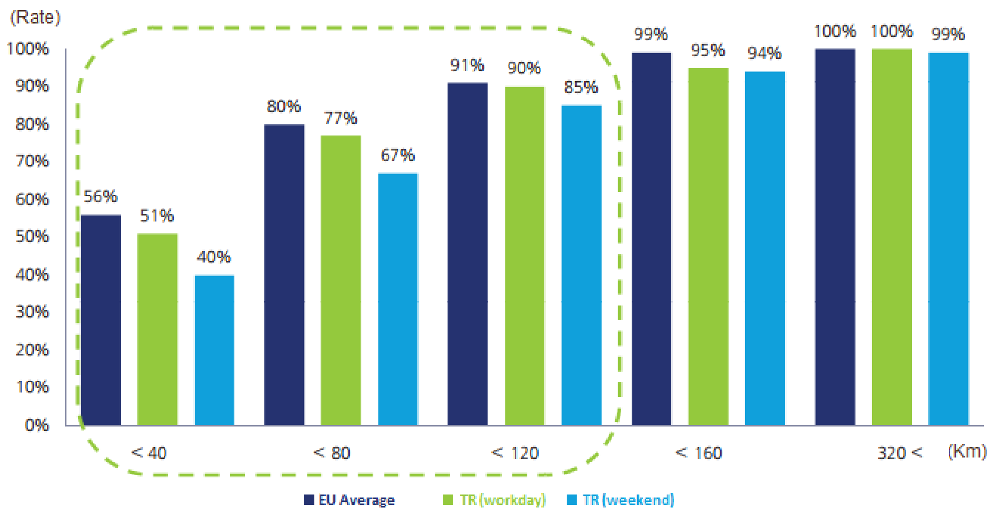


Figure 13. Daily Travel Distances between Home and Work [20]

It can be inferred from Figure 13 that almost 50% of travels terminate in less than 40 km for Turkish people in working days. It is obvious from the survey data that the probabilistic model of daily travel distances has to be modelled by adapting a Cumulative Density Function (CDF). After the evaluation of the curve of survey data, Weibull Distribution ($\lambda = 60$, $k = 1$) is found to fit the curve. Curves of Weibull CDF and survey data are shown in Figure 14.

The daily travel characteristic, having a curve as in Figure 14, delivers major information about the charge duration of an EV. On the other hand, the charge duration is also slightly affected by the charging characteristic of the battery. Section 2.1.3.2 explains the charging characteristic of a li-ion battery in general. Considering the battery and charging process of BMW i3 from the experimental usage, the battery current drop characteristic starts at the 85% of SOC and endures around one third of the total charging period. If the charging of a battery is adjusted to the 3.7 kVA charge, the linearized curve for the charging process will be obtained as in Figure 15. It can be inferred that an empty battery is fully charged in 9 hours. However, the injected power decreases after 6 hours and the battery needs 3 additional hours to become fully charged.

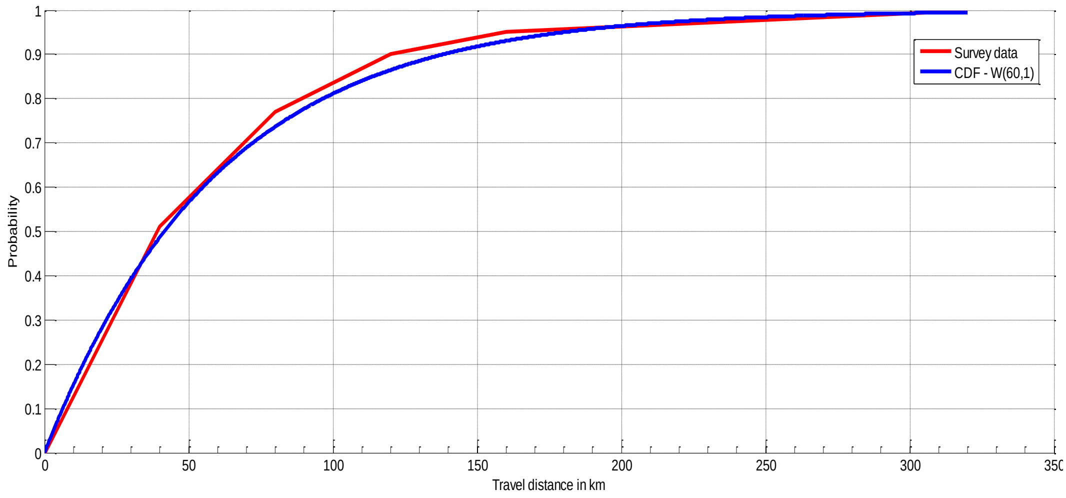


Figure 14. Weibull Distribution CDF (λ = 60, k = 1) and Survey Data

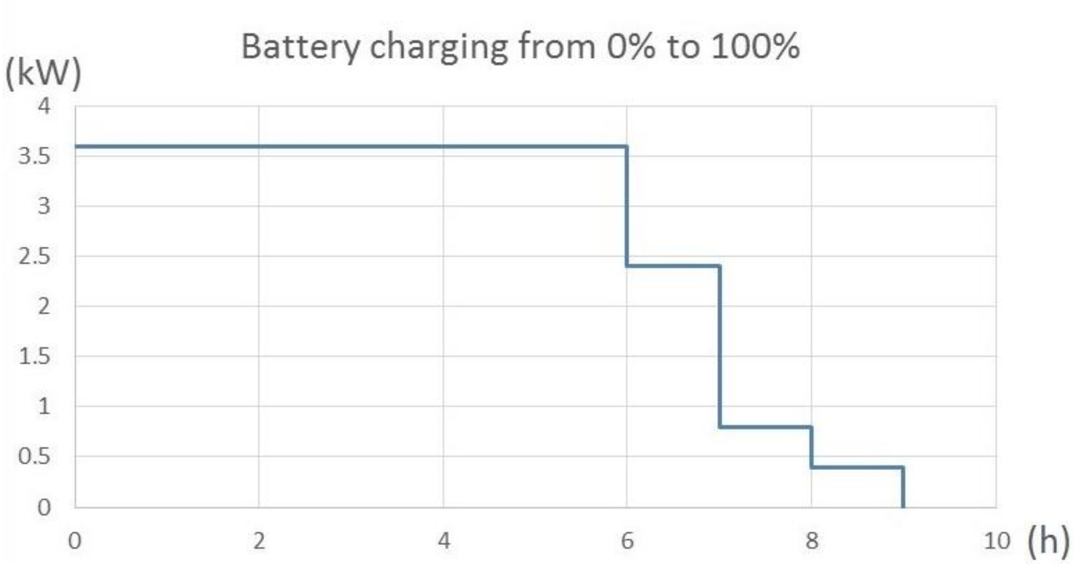


Figure 15. Injected Power from the Grid while Charging Process – Linearized

In conclusion, Weibull Distribution (see Figure 14) determines daily travel distances for each EV randomly in order to calculate the amount of the energy consumption. Moreover, Figure 15 defines the curve of the power absorbed from the grid. Using all modelling parameters and assumptions related to the charge duration of an EV, Table 13 is obtained and inserted in simulations.

Table 13. Charge Duration of an EV Regarding the Travel Distance

Travel Distance (TD) in Km	SOC of the Battery (%)	Charge Duration (h)
TD < 10	85-90	3
10 < TD < 20	70-80	4
20 < TD < 40	55-65	5
40 < TD < 60	40-50	6
60 < TD < 80	25-35	7
80 < TD < 100	10-20	8
100 < TD	100	9

3.4 Definition of Cases Studied

In order to assess the impact of EVs on LV distribution networks as well as other functions such as the rate of demand increase, existing structure, existence of multi-tariffs, various cases have been defined and studied. Since the definition of the cases is highly correlated with the Turkish electricity tariff used in distribution, some details about the current and new suggested multi-tariff system are explained in the following two paragraphs, respectively.

Two different electricity tariffs are currently applied in Turkey [48]. The first one is a one-time tariff that offers constant energy price to customers at any time of the day. The second one is a multi-time tariff that corresponds to three different time periods and energy prices. In multi-time tariff, energy price is higher during peak hours (17:00 – 22:00), lower during night hours (22:00 – 06:00), and moderate during day hours (06:00 – 17:00).

The period for suggested EV tariff has been determined by performing a specific load flow analysis using the daily load profile of residential customers. The daily loading curves of the transformer and LV lines present that an additional load must be integrate between 02:00 and 08:00 a.m. in order to avoid extreme violations on the network operation. Besides, considering average charging durations for EVs presented in Section 3.3, almost half of EVs need to be charged for around 5 hours. Hence, due to the low consumption period and EV charging durations in Turkey, the period between 02:00 and 08:00 is suggested as a new multi-tariff in this study (Chapter 4 is going to show the effectiveness of the new tariff).

In this study, five main cases are defined regarding time frames of the EV integration on distribution networks. They are identified considering the existing one-time and multi-time tariffs in Turkey including an additional suggested multi-tariff that will be the most appropriate period for the EV charging. Five cases are briefly given in the following paragraphs.

Case 1:

The first case is identified as the base case having regular one-time tariff. In Case 1, all EV owners plug in their EVs as soon as they arrive at homes. Plug-in times and charge durations are calculated for each EV regarding their probabilistic functions and assumptions explained in Chapter 3.3.

Case 2:

Case 2 is described considering the current multi-time electric tariff applied in Turkey. It is natural to assume that EV owners prefer to charge their EVs during the cheapest periods. Since the night tariff starts at 22:00, in this case, it is assumed that half of EV owners initiate the plug-in at 22:00. Therefore, EV plug-in times are set to 22:00 for the half of EV owners while others connect their EVs based on the distribution functions utilized in Case1.

Case 3:

Case 3 is also determined considering current three-time tariff applied in Turkey. In this case, all EV owners are assumed to choose night tariff and plug-in their vehicles at 22:00. This case represents an extreme situation concerning the customer behavior. Charge durations of EVs are calculated similar to Case 1. Briefly, Cases 2 and 3 intend to observe how the current multi-tariffs could respond to the EV penetration into distribution networks from the perspective of distribution companies.

Case 4:

Case 4 is identified regarding the most appropriate EV penetration period that can be applied on Turkish distribution networks. In Case 4, the aim is to charge EVs in off peak hours in order to avoid network problems in distribution systems. The off-peak hour is determined by analyzing the residential load curve given in Figure 11. It is found that 02:00 is the most appropriate hour (it stated in the beginning paragraphs of this section) to integrate EV loads into distribution networks due to not only the low loading rate, but also the sufficient time to charge an EV until the morning. Additionally, in Case 4, half of EV owners are assumed to use this new plug-in time.

Case 5:

Case 5 is defined in the same way that Case 4 is implemented. However, in Case 5, all EV owners are assumed to plug-in their EVs at 02:00 (as an extreme case). As a brief conclusion, Cases 4 and 5 intend to analyze how the suggested multi-tariff system will respond and be beneficial to the EV penetration into distribution networks from the perspective of distribution companies.

CHAPTER 4

SIMULATION AND RESULTS

The effects of EVs on LV distribution networks are investigated by applying Monte Carlo based load flow simulations in this study. This chapter will present the methodology and outcomes of the load flow analysis. Details of the Monte Carlo Simulations and the reporting methodology developed to present simulation results will be explained in Section 4.1. Besides, simulation results for each network model will be presented and discussed in Section 4.2 and 4.3, respectively.

4.1 Simulation Tool and Methodology

Digsilent PowerFactory simulation tool is used while analyzing effects of EVs on three distribution networks identified in Section 3.1. Additionally, Excel tool is used for generating reports showing results of each scenario. Details of the load flow simulation and the reporting mechanism will be stated in the following sections.

4.1.1 Monte Carlo Based Load Flow Simulations

DigSilent PowerFactory is selected as the load flow simulation tool in this study. This tool implements a balanced - positive sequence AC load flow with Newton-Raphson iteration method [49]. An algorithm is developed using Digsilent Programming Language (DPL) to execute the Monte Carlo based load flow analysis on an hourly basis. In the algorithm, hourly-based daily load profiles of each EV are created and associated to related busbars. The number of EVs at a specific busbar is determined using the EV penetration rate given as an input at the beginning of the algorithm. The algorithm flowchart is demonstrated in Figure 16.

In Figure 16, the first loop (yellow one) represents the creation of EV load profiles at a specific busbar. The number of loops (in the yellow one) equals to the number of EVs at a busbar, represented by NEV. According to Turkish Statistical Institute data [50], the number of vehicles is approximately equal to the number of residential customers in Ankara. Hence, with the assumption of "one vehicle for each customer", NEV is determined by multiplying the number of customers at a busbar with the specified EV penetration rate. If the calculated result (NEV) is not an integer, it is rounded up to the closest integer value. The second loop (green one) defines the repetition of the creation of EV load profiles for all busbars in the network. In this loop, the number of loops is equal to number of busbars (NB) in the network. The final loop (orange one) performs Monte Carlo trials which is determined as 200 (explained in the following paragraphs) in order to obtain more reasonable and accurate results based on the probabilistic distribution functions utilized.

The determination of the number of trials in Monte Carlo simulations is carried out by an additional compatibility assessment applied on probabilistic models in DigSilent PowerFactory simulation tool. In this assessment, the aim is to find the minimum adequate number of Monte Carlo trials that provides sufficient compatibility between probabilistic functions and real data. In Section 3.4, probabilistic functions for plug-in times and daily travel distances have already been identified as Gaussian and Weibull Distribution functions by the help of Matlab tool. Hence, same Gaussian and Weibull Distribution functions are modelled in Digsilent PowerFactory in order to check the accuracy of simulation results with the characteristic of real data. Monte Carlo simulations are performed with 100, 200, and 500 trials (five attempts in each one) in order to check the compatibility of probabilistic curves (Gaussian and Weibull) defined in simulations with the real (traffic and travel data) parameters.

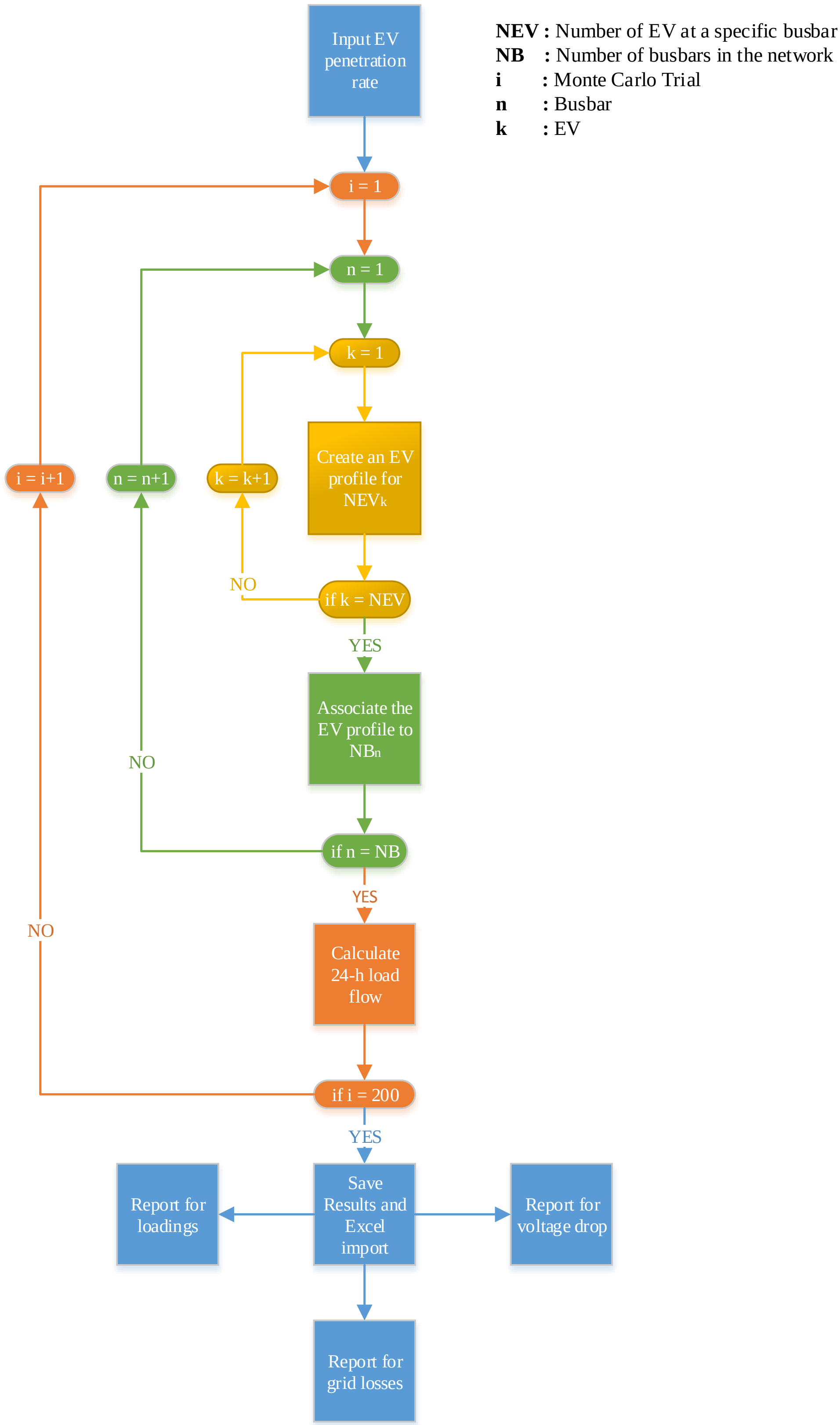


Figure 16. Algorithm Flowchart of the Load Flow Analysis

Figures 17 – 22 show curves of probabilistic functions procured from the compatibility analysis. Figures 17 and 18 present that there are quite significant distortions on Gaussian and Weibull curves, which makes 100 trials insufficient to be applied in simulations. On the other hand, Figures 19, 20, 21, and 22 present that 200 and 500 trials seem to fit the real data better and are acceptable to be implemented in the analysis. Therefore, having less execution time, Monte Carlo based load flow simulations are executed by applying 200 trials in this study.

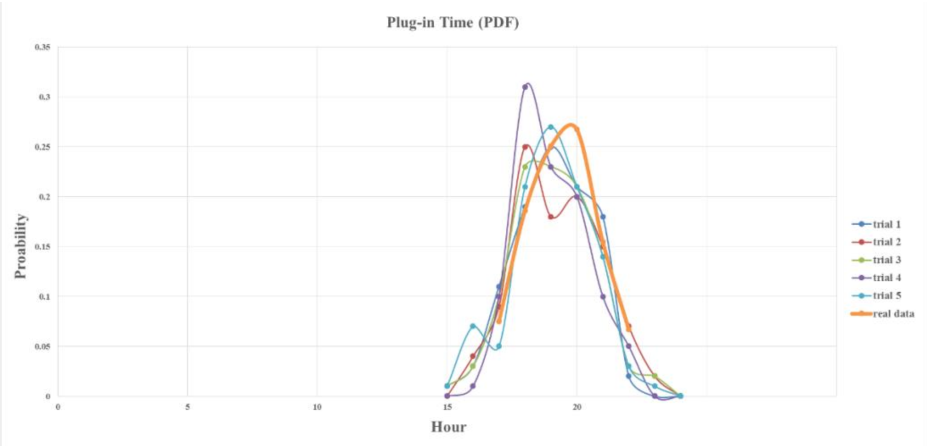


Figure 17. Compatibility Analysis for 100 Monte Carlo Trials: Plug-in Times

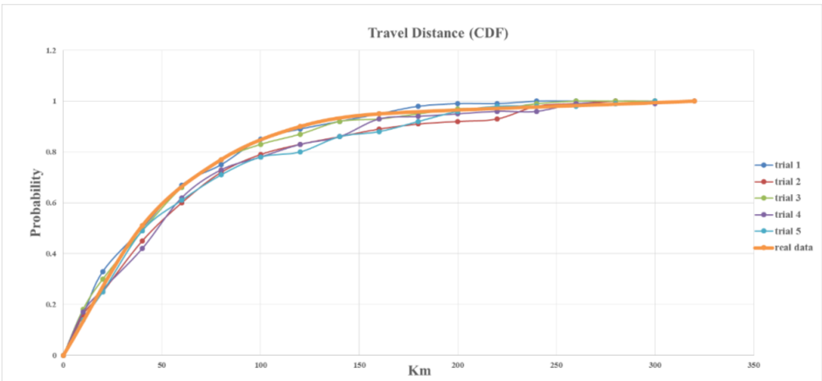


Figure 18. Compatibility Analysis for 100 Monte Carlo Trials: Daily Travel Distances

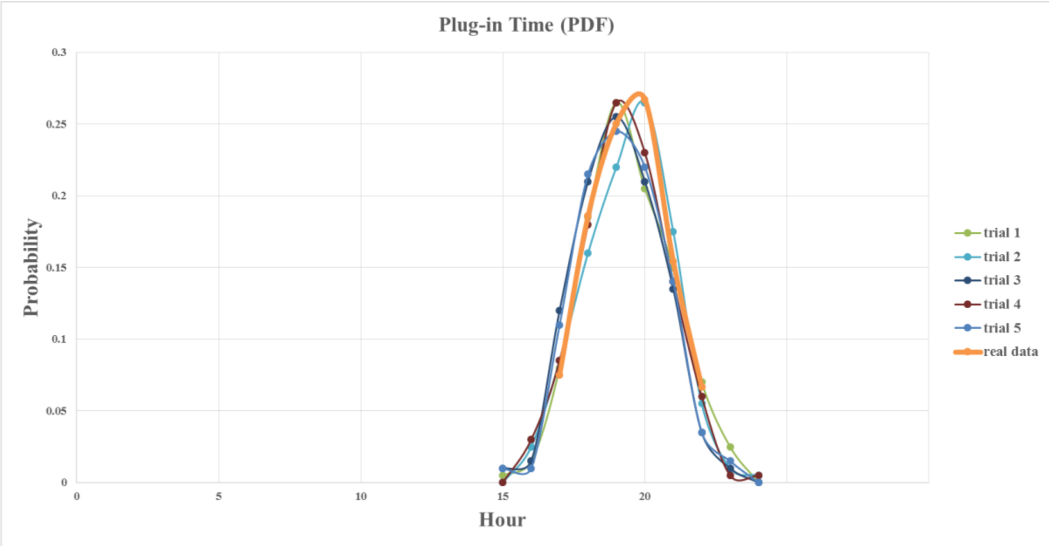


Figure 19. Compatibility Analysis for 200 Monte Carlo Trials: Plug-in Times

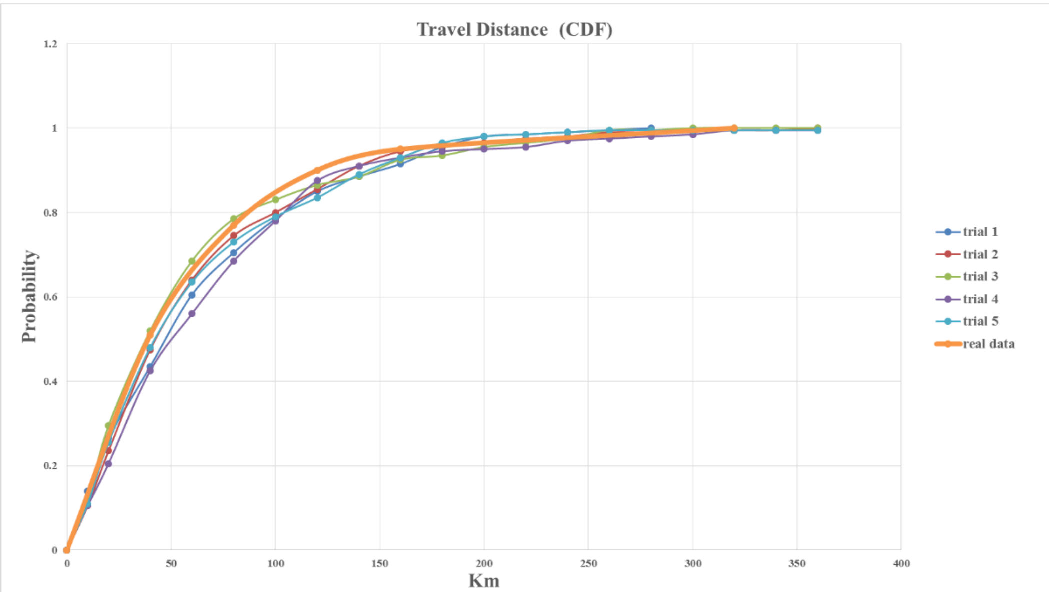


Figure 20. Compatibility Analysis for 200 Monte Carlo Trials: Daily Travel Distances

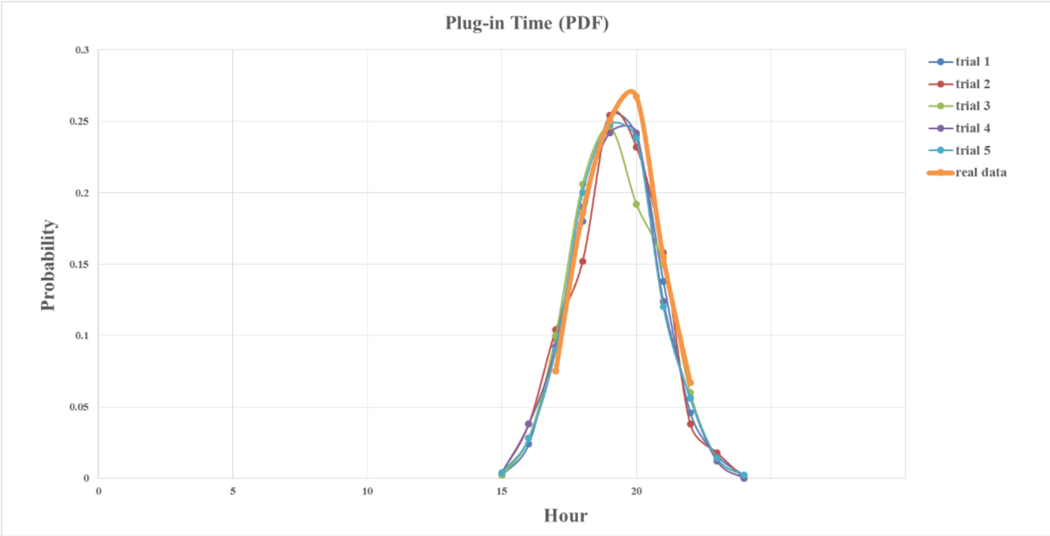


Figure 21. Compatibility Analysis for 500 Monte Carlo Trials: Plug-in Times

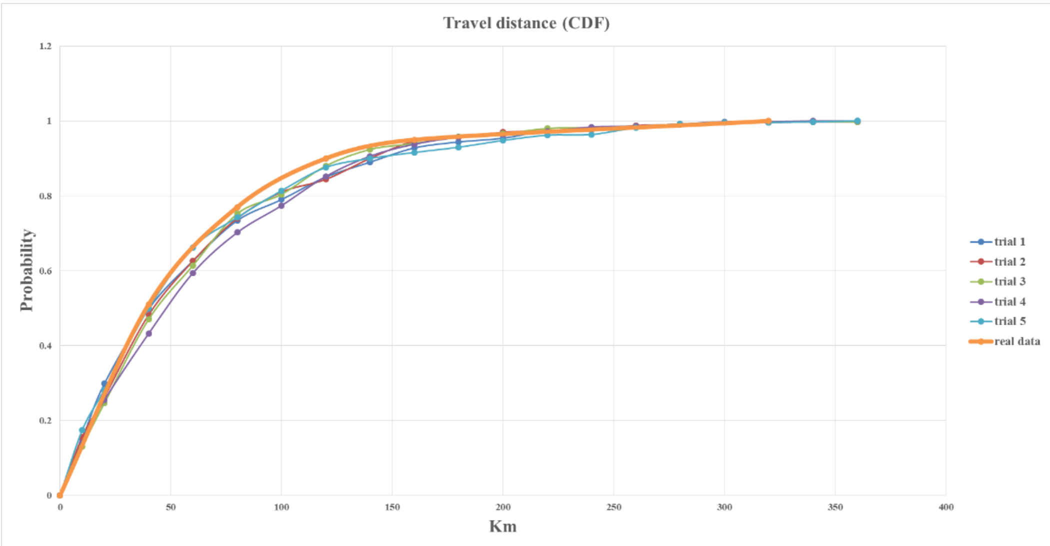


Figure 22. Compatibility Analysis for 500 Monte Carlo Trials: Daily Travel Distances

4.1.2 Reporting Methodology

Due to huge number of scenarios and simulations taken into account, it is necessary to develop a reporting format to simplify the interpretation of the results obtained from simulations. The results are presented in specified reports using MS Office Excel tool in this study. Presentation of the results is separated in two parts. The first part is the overview of distribution networks in terms of element overloads and voltage drops. In addition, increases in grid losses for various EV scenarios are also presented in this part. The second part, on the other hand, includes detailed reports for simulation results of each EV and load scenario showing incidence rates of each network element. In detailed reports, the incidence rate shows the probability of the event (in percent) occurred on a specific element. Details about the reporting methodology will be explained in the following paragraphs for the first and second parts, respectively.

Presentation of network overloads and voltage drops:

The overview of overloads and voltage drops on Network X can be observed using Table 14 for different cases and scenarios. Each box in Table 14 represents a separate scenario (various rates of load increase and EV penetration) acquired from simulations and has a detailed report. The classification of loading and voltage drop levels are explained in Table 15 and Table 16, respectively.

Table 14. Template Table for the Overview of Results obtained on Network X

Load	*X% load increase*			
EV Rate	*NO EV*	*x% EV*	*x% EV*	*x% EV*
CASE X1		**x**	**x**	**x** **x**
CASE X2			**x**	**x**

Table 15. Classification of Loading Levels

(green)	All grid elements are loaded less than 80% (Status: OK)
(grey)	Not studied (Status: EMPTY)
x (yellow)	x number of elements are loaded between 80% and 100% (Status: WARNING)
x (red)	x number of elements are loaded above 100% (Status: ALARM)
x (yellow) **y** (red)	x number of elements (y not included) are loaded between 80% and 100% and y number of elements are loaded above 100% (Status: ALARM)

Table 16. Classification of Voltage Drop Levels

(green)	Voltage value is greater than 0.95 pu. (Status: OK)
(grey)	Not studied (Status: EMPTY)
x (yellow)	Voltage values of x number of lines are between 0.95 and 0.9 pu. (Status: WARNING)
x (red)	Voltage values of x number of lines are less than 0.9 pu. (Status: ALARM)
x (yellow) **y** (red)	Voltage values of x number of lines (y not included) are between 0.95 and 0.9 pu and voltage values of y number of lines are less than 0.9 pu. (Status: ALARM)

Presentation of grid losses:

In the evaluation of grid losses, for the purpose of simplicity, changes in grid losses for each EV scenario from the value obtained for the base case (i.e., existing system with no EVs) will be presented and interpreted. As it is stated in the previous section, Monte Carlo based load flow simulations are performed applying 200 Monte Carlo trials. Therefore, increases in grid losses are presented in three categories (minimum, maximum, and average values) in order to consider and present all results obtained from Monte Carlo trials.

In the second part of the reporting (detailed results), simulation results for each network element are addressed based on probabilistic occurrences of overloads and critical voltage drops. Each box in Table 14 has a detailed report showing the status of each network element and their rate of occurrences. In addition, the most critical element in the network is presented with a supplementary hourly chart presenting the incidence rate of events for all elements. Furthermore, a labeling is developed to clarify the presentation of the reporting for each box, which is explained below:

- *NWx.Cy.Lz.EVt*: This label indicates the exact place of a box (a specific scenario) in the overview table of distribution networks (see Table 14). *NWx* represents the type of residential distribution network where *x* gets a value as 1a, 1b, 2 or 3. Cy represents the case where *y* gets a value from 1 to 5. *Lz* represents the rate of load increase where *z* get a value from 0 to 3 (0 for the current load, 1 for 10% annual load increase, etc.). Finally, *EVt* represents the percent EV penetration rate where *t* is between 0 to 100.

4.2 Simulation Results

Five cases, three types of residential distribution networks, four different rates of load increase, and various EV penetration rates that have already been defined in Chapter 3 are evaluated together in order to observe the impact of each factor in a reasonable and justifiable manner. Each network type is studied regarding overloads, voltage drops, and grid losses. The obtained results will be presented and explained in the following sections in terms of three different types of residential distribution networks.

4.2.1 Simulation Results for Network 1

As it is stated in Section 3.1, NW1 is a residential distribution network that is relatively old and not a well-planned network. The network is supplying an apartment type settlement region having customers which are assumed to be of middle class from a socio-economical point of view.

Network 1 has been studied with two different transformer capacities, namely NW1a and NW1b. Since the existing transformer is operating at 85% capacity, the current condition corresponds to a warning situation for the transformer. It is clear that this existing transformer is going to be replaced in very near future. Therefore, in simulations, two different ratings for the transformer are assumed. In the networks NW1a and NW1b, the transformers are assumed to be 800 kVA and 1000 kVA, respectively. In other words, initially, the transformer are assumed loaded at 55% and 70% of their ratings in NW1a and NW1b, respectively. Simulation results for NW1a and NW1b are presented under three categories as overloads, voltage drops, and increases in grid losses.

4.2.1.1 Loading of Network 1 Elements

Simulation results for overloads are obtained based on the transformer and line loading for networks NW1a and NW1b. Simulation results for both networks will be presented in the following paragraphs.

Table 17 shows the overview of NW1a based on loading conditions. It is seen that NW1a reflects at least one warning status for each EV scenario, which makes the network sensitive to the EV integration. At 10% load increase rate, critical overloads occur for Cases 1, 2, and 3 for 20% EV penetration scenario, but these overloads are eliminated in Cases 4 and 5 (applying the suggested multi-time tariff). At 20% and 30% load increases, on the other hand, statuses are observed as alarms almost for all cases and EV scenarios. In conclusion, a network having the similar characteristic as NW1a can be maintained as it is at low load increase rates and low EV penetration rates. Considering the increment of the residential loads and EV trends in Turkey, it can be inferred that elements for this type of networks can be operated under warning statuses for around ten years (assumed the demand in that region has saturated or close to saturation), and then some investments have to be initiated.

Table 17. Overview of NW1a in terms of Overloads

Load	***Cur.***	***10% Load Increase***				***20% Load Increase***				***30% Load Increase***			
EV Rate	*0 %*	*0 %*	*5 %*	*10 %*	*20 %*	*0 %*	*10 %*	*20 %*	*30 %*	*0 %*	*10 %*	*30 %*	*50 %*
Case 1			**1**	**2**	**3 2**	**1**	**2 1**	**5 2**	**3 5**	**1**	**3 1**	**3 5**	**9**
Case 2			**1**	**2**	**3 2**		**1 1**	**3 2**	**3 5**		**3 1**	**3 5**	**9**
Case 3			**1**	**2**	**3 2**		**1 1**	**4 3**	**3 5**		**3 1**	**1 7**	**9**
Case 4			**1**	**1**	**2**		**1**	**2 1**	**4 1**		**1 1**	**2 3**	**3 5**
Case 5					**2**		**1**	**1 1**	**3 2**		**1**	**4 3**	**1 8**

Each box in Table 17 also represents a separate analysis with detailed reports on the loading of NW1a elements. Despite the fact that there are several scenarios evaluated and implemented in this study, two scenarios (shown in black boxes in Table 17) are selected to be presented and discussed in this section.

In the overview table, it is seen that there are three warnings and two alarms in Scenario *NW1a.C1.L1.EV20*. In Table 18, on the other hand, results for the selected scenario can be observed by analyzing all network elements in detail. Since Monte Carlo based load flow simulations are performed with 200 trials (with an hourly basis load flow analysis), 4800 simulation results are generated for each network element. The assessment of the condition for each element is made based on the rate and number of events occurred on the element.

According to Table 18, the transformer and line-D are two network elements exceeding 100% loading rate while lines A, G, and H are loaded between 80% and 100% for Scenario *NW1a.C1.L1.EV20*. Although the probability of an alarm status for line-D (an underground cable) is very low, it should be considered by the network operator due to the possibility of an insulation fault that may occur at the cable. Additionally, it is obvious that the transformer in NW1a is the most critical element having the highest incidence rate. The hourly loading response of the transformer is given in Figure 23.

Table 18. Detailed Results of Overload Analysis for Scenario NW1a.C1.L1.EV20

Rate and Number of Events								
(100% > X > 80%)					(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
Line-A(1)	4800	0	0.000		Line-A(1)	4800	0	0.000
Line-B(1)	4800	0	0.000		Line-B(1)	4800	0	0.000
line-A	4800	186	3.875		line-A	4800	0	0.000
line-B	4800	0	0.000		line-B	4800	0	0.000
line-C	4800	0	0.000		line-C	4800	0	0.000
line-C(1)	4800	0	0.000		line-C(1)	4800	0	0.000
line-D	4800	761	15.854		line-D	4800	4	0.083
line-D(1)	4800	0	0.000		line-D(1)	4800	0	0.000
line-E	4800	0	0.000		line-E	4800	0	0.000
line-E(1)	4800	0	0.000		line-E(1)	4800	0	0.000
line-F	4800	0	0.000		line-F	4800	0	0.000
line-F(1)	4800	0	0.000		line-F(1)	4800	0	0.000
line-G	4800	28	0.583		line-G	4800	0	0.000
line-G(1)	4800	0	0.000		line-G(1)	4800	0	0.000
line-H	4800	363	7.563		line-H	4800	0	0.000
line-H(1)	4800	0	0.000		line-H(1)	4800	0	0.000
800KVA	4800	1301	27.104		800KVA	4800	660	13.750

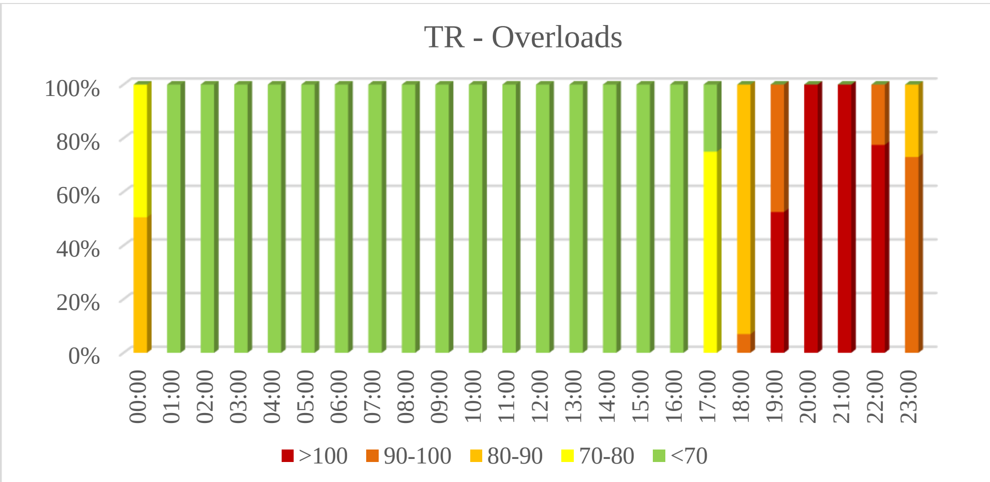


Figure 23. Hourly Loading Chart for the Transformer at NW1a.C1.L1.EV20

Figure 23 shows the rate of incidence of overloads occurring on the transformer for each hour. Besides, additional loading ranges and their probabilities are included in this chart. The occurance probability of each loading range can be evaluated on the operation of the transformer. For instance, at 19:00, the probability of being loaded between 90% and 100% is 0.5 for the transformer. Additionally, the transformer exceeds 100% loading between 19:00 and 22:00 due to the high EV plug-in period.

Simulation results for the second scenario (*NW1a.C4.L1.EV20)* in NW1a are presented in Table 19. This scenario is intentionally selected from the same column of Table 17 in order to compare both scenarios on different multi-tariff systems.

Table 19. Detailed Results of Overload Analysis for Scenario NW1a.C4.L1.EV20

Rate and Number of Events								
(100% > X > 80%)					(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
Line-A(1)	4800	0	0.000		Line-A(1)	4800	0	0.000
Line-B(1)	4800	0	0.000		Line-B(1)	4800	0	0.000
line-A	4800	0	0.000		line-A	4800	0	0.000
line-B	4800	0	0.000		line-B	4800	0	0.000
line-C	4800	0	0.000		line-C	4800	0	0.000
line-C(1)	4800	0	0.000		line-C(1)	4800	0	0.000
line-D	4800	47	0.979		line-D	4800	0	0.000
line-D(1)	4800	0	0.000		line-D(1)	4800	0	0.000
line-E	4800	0	0.000		line-E	4800	0	0.000
line-E(1)	4800	0	0.000		line-E(1)	4800	0	0.000
line-F	4800	0	0.000		line-F	4800	0	0.000
line-F(1)	4800	0	0.000		line-F(1)	4800	0	0.000
line-G	4800	0	0.000		line-G	4800	0	0.000
line-G(1)	4800	0	0.000		line-G(1)	4800	0	0.000
line-H	4800	0	0.000		line-H	4800	0	0.000
line-H(1)	4800	0	0.000		line-H(1)	4800	0	0.000
800KVA	4800	972	20.250		800KVA	4800	0	0.000

Table 19 presents that the alarm occurring on the transformer and line-D in the first scenario turns to warnings by changing the case (i.e., the time tariff). In addition, warning statuses on lines A, G, and H also disappear. In conclusion, NW1a can be maintained as it is under such a case and scenario despite of the warning conditions at some network elements (the transformer and line-D). Similarly, the most critical element for this scenario is also the transformer due to the high incidence rate. Hourly loading chart for the transformer is shown in Figure 24.

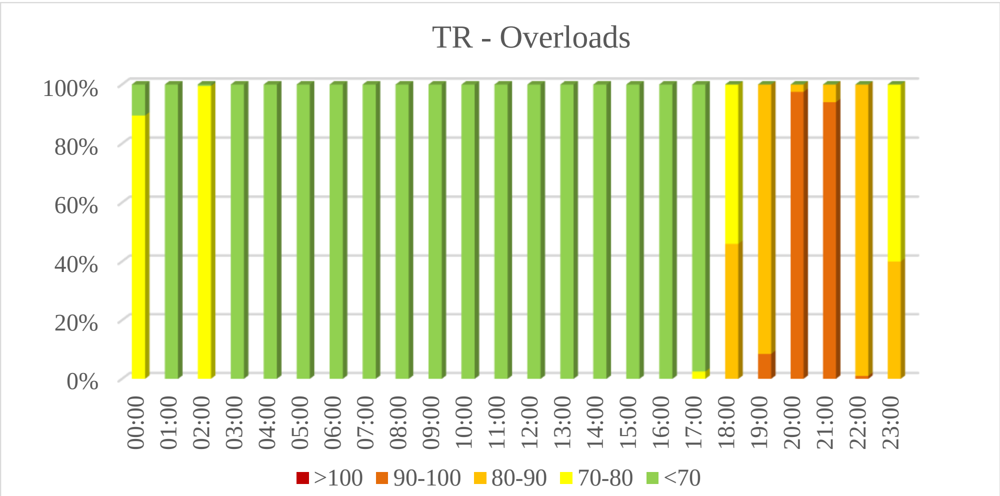


Figure 24. Hourly Loading Chart for the Transformer at NW1a.C4.L1.EV20

The overview of NW1b in terms of overloads is presented in Table 20. It is obvious that the number of warnings and alarms reduces in NW1b compared to NW1a. Network 1b is maintained without any overload in scenarios at 5% and 10% EV penetration rates and 10% load increase. Besides, the network can support 20% EV penetration rate for Cases 4 and 5. Similar to NW1a, some reinforcements on critical network elements are needed to be deployed in order to integrate higher EV rates (20% and more) on the network without any effect.

Table 20. Overview of NW1b in terms of Overloads

Load	***Cur.***	***10% Load Increase***				***20% Load Increase***				***30% Load Increase***			
EV Rate	*0 %*	*0 %*	*5 %*	*10 %*	*20 %*	*0 %*	*10 %*	*20 %*	*30 %*	*0 %*	*10 %*	*30 %*	*50 %*
Case 1				**1**	**4 / 1**		**3**	**5 / 2**	**3 / 5**		**4**	**4 / 5**	**9**
Case 2				**1**	**4 / 1**		**2**	**4 / 1**	**3 / 5**		**4**	**3 / 5**	**9**
Case 3				**1**	**4 / 1**		**2**	**3 / 3**	**3 / 5**		**4**	**1 / 7**	**9**
Case 4					**1**			**3**	**4 / 1**		**2**	**4 / 1**	**3 / 5**
Case 5					**1**			**2**	**3 / 2**			**4 / 3**	**1 / 8**

Similar to NW1a, each box in Table 20 represents a separate analysis (scenario) for NW1b elements. Two scenarios (shown in black boxes in Table 20) are selected and explained in this section in the same manner as it is explained in the previous paragraphs for NW1a.

Table 21 demonstrates five warnings and an alarm occurring on the transformer and lines A, D, G, and H for Scenario *NW1b.C1.L1.EV20*. It is clear that upgrading the transformer from 800 kVA to 1000 kVA in NW1 eliminates the transformer overloads for cases simulated. Instead, line-D becomes the most sensitive element in the network. Hence, the hourly loading chart is presented for line-D in Figure 25. Although incidence rate of overloads occurring on line-D at 20:00 is very low, this situation is not acceptable for distribution system operators and planners.

The second scenario is selected as *NW1b.C4.L1.EV20*, which demonstrates the differences between Cases 1 and 4. It can be inferred from Table 22 that the alarm status disappears and number of warning statuses reduces from four to one compared to the first scenario.

Table 21. Detailed Results of Overload Analysis for Scenario NW1b.C1.L1.EV20

Rate and Number of Events								
(100% > X > 80%)					(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
Line-A(1)	4800	0	0.000		Line-A(1)	4800	0	0.000
Line-B(1)	4800	0	0.000		Line-B(1)	4800	0	0.000
line-A	4800	190	3.958		line-A	4800	0	0.000
line-B	4800	0	0.000		line-B	4800	0	0.000
line-C	4800	0	0.000		line-C	4800	0	0.000
line-C(1)	4800	0	0.000		line-C(1)	4800	0	0.000
line-D	4800	739	15.396		line-D	4800	3	0.063
line-D(1)	4800	0	0.000		line-D(1)	4800	0	0.000
line-E	4800	0	0.000		line-E	4800	0	0.000
line-E(1)	4800	0	0.000		line-E(1)	4800	0	0.000
line-F	4800	0	0.000		line-F	4800	0	0.000
line-F(1)	4800	0	0.000		line-F(1)	4800	0	0.000
line-G	4800	18	0.375		line-G	4800	0	0.000
line-G(1)	4800	0	0.000		line-G(1)	4800	0	0.000
line-H	4800	340	7.083		line-H	4800	0	0.000
line-H(1)	4800	0	0.000		line-H(1)	4800	0	0.000
1000KVA	4800	662	13.792		1000KVA	4800	0	0.000

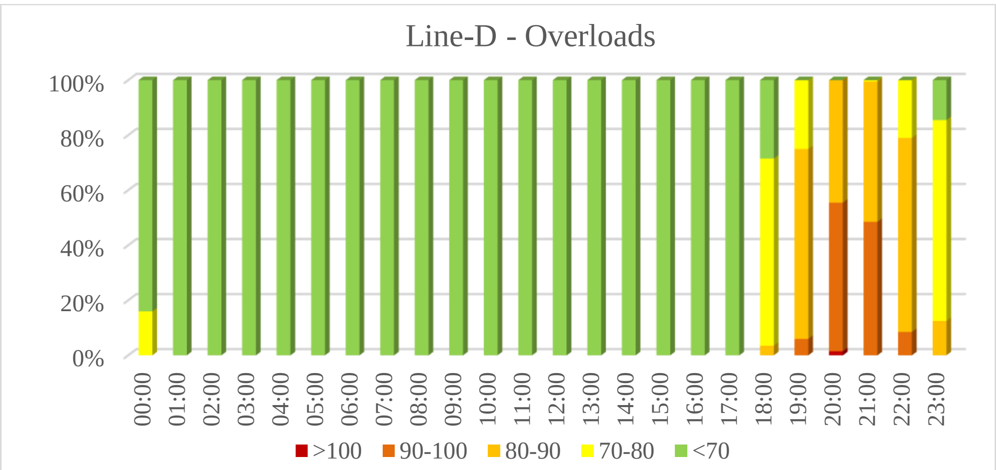


Figure 25. Hourly Loading Chart for Line-D at NW1b.C1.L1.EV20

Table 22. Detailed Results of Overload Analysis for Scenario NW1b.C4.L1.EV20

Rate and Number of Events								
(100% > X > 80%)					(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
Line-A(1)	4800	0	0.000		Line-A(1)	4800	0	0.000
Line-B(1)	4800	0	0.000		Line-B(1)	4800	0	0.000
line-A	4800	0	0.000		line-A	4800	0	0.000
line-B	4800	0	0.000		line-B	4800	0	0.000
line-C	4800	0	0.000		line-C	4800	0	0.000
line-C(1)	4800	0	0.000		line-C(1)	4800	0	0.000
line-D	4800	35	0.729		line-D	4800	0	0.000
line-D(1)	4800	0	0.000		line-D(1)	4800	0	0.000
line-E	4800	0	0.000		line-E	4800	0	0.000
line-E(1)	4800	0	0.000		line-E(1)	4800	0	0.000
line-F	4800	0	0.000		line-F	4800	0	0.000
line-F(1)	4800	0	0.000		line-F(1)	4800	0	0.000
line-G	4800	0	0.000		line-G	4800	0	0.000
line-G(1)	4800	0	0.000		line-G(1)	4800	0	0.000
line-H	4800	0	0.000		line-H	4800	0	0.000
line-H(1)	4800	0	0.000		line-H(1)	4800	0	0.000
800KVA	4800	0	0.000		800KVA	4800	0	0.000

According to Table 22, there is a warning status at a low incidence rate occurring only on line-D. Hence, it can be inferred that shifting the EV integration to 02:00 is an advantageous approach for NW1b instead of making a new investment. For this scenario, the hourly loading chart for line-D obtained from the analysis will not be presented in this study due to the low incidence rate.

4.2.1.2 Voltage Drops in Network 1

Simulation results obtained from the voltage drop analysis refer to voltage profiles of residential customers. Network 1 has eight main feeders outgoing from the transformer. Thus, results obtained from voltage drop analysis will cover busbars located at the end of these eight feeders using the methodology explained in Section 4.2. The overview of voltage conditions for NW1 is presented in Table 23.

Table 23. Overview of NW1 in terms of Voltage Drop

Load	***Cur.***	***10% Load Increase***				***20% Load Increase***					***30% Load Increase***				
EV Rate	*0 %*	*0 %*	*5 %*	*10 %*	*20 %*	*0 %*	*10 %*	*20 %*	*30 %*	*50 %*	*0 %*	*10 %*	*30 %*	*50 %*	*100 %*
Case 1	**1**	**1**	**2**	**4**	**5**	**1**	**5**	**5**	**4 1**		**2**	**5**	**4 1**	**1 4**	
Case 2			**1**	**4**	**5**		**5**	**5**	**4 1**			**5**	**4 1**	**1 4**	
Case 3			**1**	**4**	**5**		**5**	**5**	**4 1**			**5**	**4 1**	**1 5**	
Case 4			**1**	**2**	**4**		**3**	**5**	**5**			**5**	**5**	**4 1**	
Case 5			**1**	**1**	**4**		**1**	**4**	**5**			**2**	**5**	**2 3**	

As it is seen from Table 23, at least one warning status is observed for the each scenario studied. This means that at least one Monte Carlo trial makes the voltage under the limit value of 0.95 pu. Voltage drop problems may occur due to the fact that NW1 is a relatively old and not well-structured network. At 10% load increase, all scenarios are under the warning status for all cases. At 20% load increase, alarm statuses at 30% EV penetration rate are eliminated in Cases 4 and 5. However, it becomes harder to clear the voltage drop problems at higher EV penetration rates by applying the new multi-time tariff. Hence, higher load increase and EV penetration rates bring more voltage drop issues for residential customers.

Similar to table showing loading conditions, each box in Table 23 represents a scenario having a detailed report. Moreover, two scenarios (shown in black boxes) are selected to be presented and explained in this section, respectively.

Table 24. Detailed Results of Voltage Drop Analysis for Scenario NW1b.C1.L2.EV30

Rate and Number of Events							
(0.9 pu < X < 0.95 pu)				(X < 0.9 pu)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*	*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
A1	4800	1331	27.729	A1	4800	0	0.000
B1	4800	0	0.000	B1	4800	0	0.000
C1	4800	0	0.000	C1	4800	0	0.000
D1	4800	1394	29.042	D1	4800	0	0.000
E1	4800	1192	24.833	E1	4800	0	0.000
F1	4800	0	0.000	F1	4800	0	0.000
G1	4800	1052	21.917	G1	4800	0	0.000
H1	4800	2991	62.313	H1	4800	169	3.521

Table 24 presents the detailed results of voltage drop analysis for the first scenario. According to Table 24, five out of eight busbars (a group of customers) create warning statuses at high incidence rates. Due to the longer cable length and having higher number of customers, busbar H1 has an alarm status, which makes H1 as the most critical element in the network. Therefore, the hourly voltage drop chart is presented for busbar-H1 in Figure 26.

The voltage drop chart in Figure 26 includes additional voltage ranges in order to make a detailed assessment on the voltage characteristic of H1. According to Figure 26, the voltage value at H1 drops below the critical value (0.9 pu) at 20:00 and 21:00 hours with around 40% incidence rate. This information can be valuable for the distribution system operator in order to manage the transformer tap adjustments.

Voltage drop results for the second scenario are demonstrated in Table 25. The alarm status is disappeared in this scenario for H1 while the rate of the warning status increased surprisingly. The reason behind this increment is that the EV integration distributes among night hours by applying Case 4, which causes the voltage drops under 0.95 pu in night hours as well.

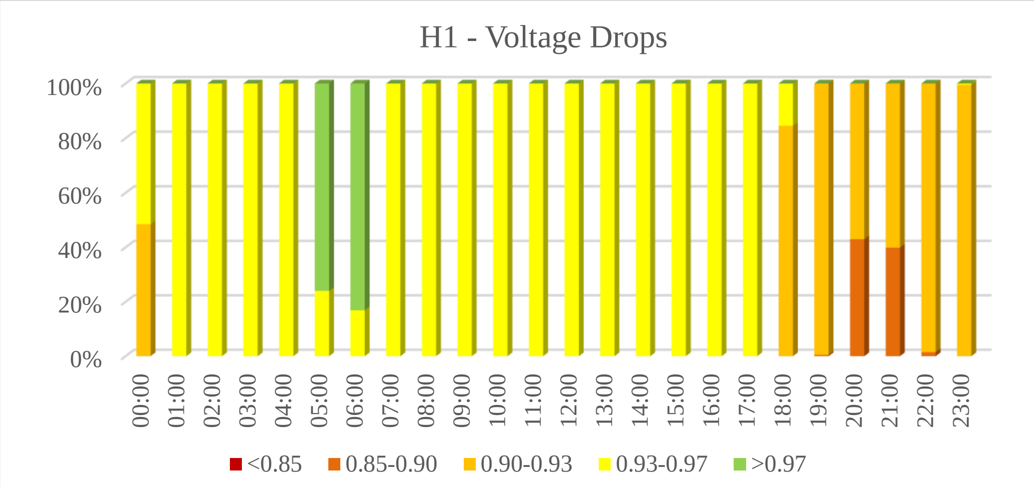


Figure 26. Hourly Voltage Drop Chart for H1 at NW1b.C1.L2.EV30

Table 25. Detailed Results of Voltage Drop Analysis for Scenario NW1b.C4.L2.EV30

Rate and Number of Events								
(0.9 pu < X < 0.95 pu)					**(X < 0.9 pu)**			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
A1	4800	1139	23.729		A1	4800	0	0.000
B1	4800	0	0.000		B1	4800	0	0.000
C1	4800	0	0.000		C1	4800	0	0.000
D1	4800	1346	28.042		D1	4800	0	0.000
E1	4800	750	15.625		E1	4800	0	0.000
F1	4800	0	0.000		F1	4800	0	0.000
G1	4800	470	9.792		G1	4800	0	0.000
H1	4800	3424	71.333		H1	4800	0	0.000

Having the highest incidence rate, voltage values of residential customers at H1 are presented in the form of hourly chart in Figure 27. The figure shows that voltage drops on H1 represent smooth profiles distributed among hours.

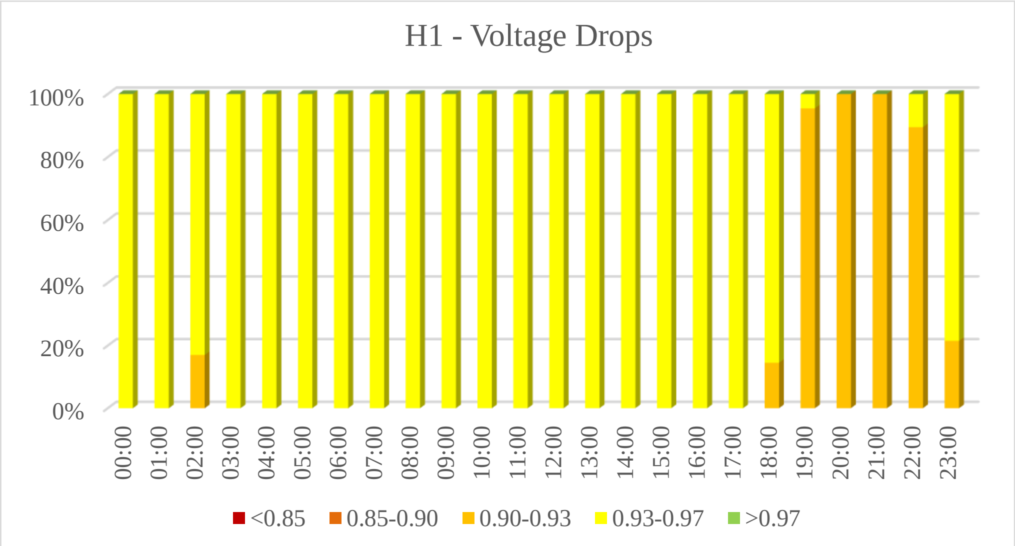


Figure 27. Hourly Voltage Drop Chart for H1 at NW1b.C1.L2.EV30

4.2.1.3 Evaluation of Grid Losses for Network 1

The evaluation of grid losses is studied by calculating the increases in grid losses after the EV integration on the network. The overview of grid losses is demonstrated in overview tables for NW1a and NW1b in this section, respectively. Furthermore, a financial assessment based on grid losses is presented in this section.

Table 26 demonstrates results of the loss increase analysis for NW1a considering the minimum, maximum, and average values. Naturally, when the EV penetration rate rises, grid losses rises as well. Moreover, cases studied directly affect grid losses due to having different plug-in times for EVs. The EV integration is shifted to less loaded hours by changing cases (i.e., from Case 2 to Case 4). Looking at Cases 1 and 4 in Table 26, it is inferred that the most efficient way for the operation of distribution networks is to integrate EVs during valley hours in order to diminish grid losses.

Table 26. Overview of NW1a in terms of Increases in Daily Grid Losses (in kWh)

Load		*10% Load Increase*			*20% Load Increase*			*30% Load Increase*		
EV Rate		*5 %*	*10 %*	*20 %*	*10 %*	*20 %*	*30 %*	*10 %*	*30 %*	*50 %*
Case 1	Min.	25.8	58.9	135.1	64.8	147.2	221.6	69.3	257.7	469.4
	Max.	45.5	85.8	185.6	94.3	196.1	293.1	98.5	319.8	594.5
	Avrg.	35.4	71.8	156.8	79.3	170.4	255.5	83.4	288.3	541.9
Case 2	Min.	25.4	53.6	124.3	44.6	119.1	210.7	65.1	232.2	459.8
	Max.	40.1	80.5	169.7	71.3	163.5	270.2	90	306	568.2
	Avrg.	32.9	66.6	145.7	56.9	142.4	238.4	76.8	269.2	511.4
Case 3	Min.	26	55.2	131.2	42.6	127.2	215.5	63.3	257.3	512.1
	Max.	39.4	80	175.6	69.7	165.5	275.2	88.5	315.4	613.4
	Avrg.	31.6	66.4	149.8	55.2	143.6	249.6	75	281.4	558.9
Case 4	Min.	20.4	43.9	104	33.7	94.9	171.7	49.3	188.3	374.3
	Max.	36.5	72.8	136.6	57.1	140.2	217.6	76.8	249	447.3
	Avrg.	27.6	56.2	121.2	45.2	113.4	190	64.9	219	410
Case 5	Min.	17.4	39.4	96.2	25.2	87.9	163.2	40.8	187.1	409.6
	Max.	27.3	56.5	127.2	46.8	120.9	219.2	66.1	249.1	490.9
	Avrg.	22.4	47.5	112.8	35.2	103.2	190	53.5	215.4	448.7

Cost analysis for NW1a is applied on two scenarios shown in black boxes in Table 26. In order to be consistent with the results of the overload analysis, same two scenarios are selected to be evaluated. Additionally, cost analysis is executed by importing System Marginal Prices (SMP) of Turkish Energy Market [51] in the analysis of grid losses. Hourly energy prices are multiplied with the simulation results obtained from the loss analysis in order to calculate minimum, maximum, and average daily costs.

The SMP data given in Figure 28 are implemented on the loss analysis in order to create an economical assessment for NW1a. Results obtained from the assessment are presented in Table 27 in TL basis. The data are recorded for two cases: Case 1 and Case 4. Since the detailed results for overload and voltage drop analyses are presented at 10% load increase and 20% EV penetration rates, Cases 1 and 4 for the same two scenarios are implemented in the cost analysis. According to Table 27, encouraging half of EV owners to plug-in their EVs at 02:00 yields a saving of 12.341 TL in average for NW1a in one day from the perspective of distribution companies. Despite the fact that this amount of saving seems as a low value, it may create respectable amount of savings considering all Ankara region. For instance, if there are 1,500 residential distribution transformers in Ankara, total savings may reach to 18,750 TL value (considering that each distribution region might save around 12.5 TL for one day) for just one day. In conclusion, the financial assessment on grid losses may guide distribution companies in their decisions for multi-tariff periods and the tariff to be applied.

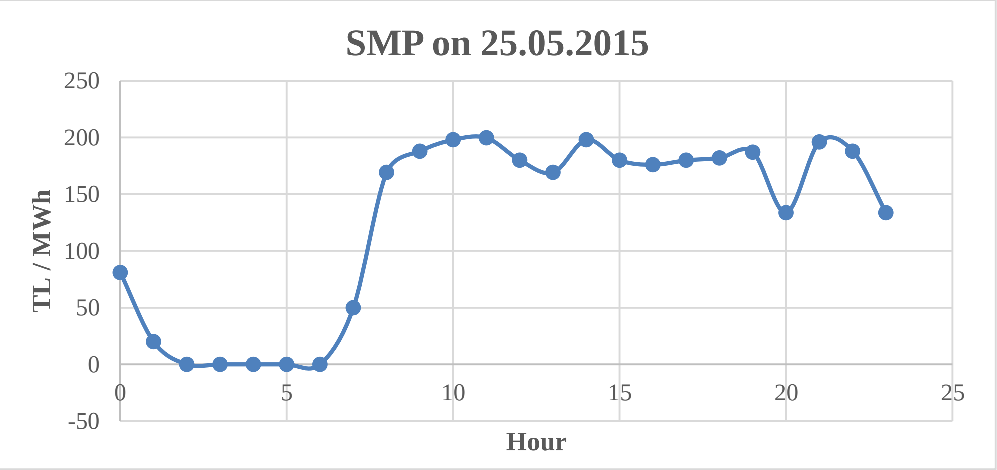


Figure 28. Daily SMP in Turkey on 25.05.2015

Upgrading the transformer from 800 kVA to 1000 kVA decreases the daily transformer losses (the efficiency of the transformer increases), therefore, total grid losses decreases in NW1b compared to NW1a. Results of the loss analysis for NW1b have similar characteristic as results for NW1a, presented in Table 28. Grid losses rises when the EV penetration rate rises due to the additional load integration on the distribution network. Similar to NW1a, same scenarios are analyzed for NW1b in order to make a comparative assessment regarding grid losses.

Table 27. Results for the Cost Analysis of Grid Losses in NW1a

Increases in the Cost of Daily Losses (TL Basis)			
	Case1	*Case4*	*Savings*
Min.	20.857	9.399	11.458
Max.	29.140	13.442	15.698
Avrg.	23.996	11.655	12.341

Table 29 demonstrates that applying Case 4 instead of Case 1 saves an average of 11.7 TL/day from the view of distribution companies. Similar to NW1a, this amount of saving can be used to calculate the total benefit for Ankara region by distribution companies. Moreover, a distribution company can assess the value of return after upgrading the transformer by the help of these outcomes.

Table 28. Overview of NW1b in terms of Increases in Daily Grid Losses (in kWh)

Load		*10% Load Increase*			*20% Load Increase*			*30% Load Increase*		
EV Rate		*5 %*	*10 %*	*20 %*	*10 %*	*20 %*	*30 %*	*10 %*	*30 %*	*50 %*
Case 1	Min.	23.8	54.4	122.7	63.3	128.8	214.3	62	237.7	472.1
	Max.	42.4	86.5	169.8	92.4	186.5	272.5	94.5	308.2	571.5
	Avrg.	34	69	149.1	75.8	163.6	245	80	275.8	518.9
Case 2	Min.		54.7	122.1	42.3	116.7	203.9	61	232.1	425.5
	Max.		75	162.8	69.2	156.2	261	90.1	286.6	551.8
	Avrg.		64.8	140	54.3	135.6	228.9	75	260.1	491.6
Case 3	Min.		53.2	126.3	40.3	115.8	210.7	62.2	242.3	498
	Max.		75	162.3	64.7	157.4	266.5	83.4	299.2	592.3
	Avrg.		63.1	143.5	52.4	137.9	239.4	71.9	268.9	537.5
Case 4	Min.		45.3	100.2	32.6	90.8	160.7	49.8	187.9	356.8
	Max.		64.1	131.2	54.8	127.4	207.7	73.7	239	426.1
	Avrg.		54.4	115.6	42.8	108.6	183	61.8	210.2	391.4
Case 5	Min.		38.3	93.1	25.3	80	153.9	42.3	176.9	386.4
	Max.		57.3	123.8	42.2	119.8	210.1	61.4	229.6	472.6
	Avrg.		46	108.2	33.5	99.6	182	51.2	205.6	432

Table 29. Results for the Cost Analysis Grid Losses in NW1b

Increases in the Cost of Daily Losses (TL Basis)			
	Case 1	*Case 4*	*Savings*
Min	19.434	9.408	10.026
Max	25.694	12.844	12.850
Avrg	22.796	11.082	11.714

4.2.2 Simulation Results for Network 2

Network 2 is a new and well-designed network compared to NW1. The network is structured in a villa type settlement region. Besides the network structure, the socio-economic nature of its customers is different, therefore, higher load consumptions and EV penetration rates are considered for the assessment of impacts of EVs on NW2. Overloads, voltage drops, and grid losses acquired for NW2 are presented in the following sections, respectively.

4.2.2.1 Loading of Network 2 Elements

Table 30 demonstrates loading of the transformer and LV cables for NW2. According to the table, there are no warnings or alarms for all 10% load increase scenarios. Moreover, only a few events occur at 20% and 30% load increase rates. At the same value of forecasted increase in the load demand, NW2 performs much better overload conditions than NW1 due to being a well-structured network. On the other hand, warnings and alarms are observed frequently at high EV penetration rates. Alarm statuses occurred at 50% EV integration rates are eliminated in Case 4 (applying the new multi-tariff for half of customers). In overall, considering the rate of EV and load increase, NW2 seems to be maintained for more than ten years without any investment if additional loads (except EVs) are not integrated to the network.

Detailed reports obtained from the overload analysis of NW2 elements are demonstrated by listing three scenarios in the following paragraphs. Unlike the previous loading tables for NW1a and NW1b, three scenarios are examined in order to show also the effect of customer preferences on the suggested multi-tariff. Since Scenarios *NW2.C5.L2.EV50* and *NW2.C4.L2.EV50* have distinctive responses to the same EV integration and load increase rates, the percentage of the usage the new multi-tariff is a substantial outcome for the network operation. Details of three scenarios will be delivered in the following paragraphs.

Table 30. Overview of NW2 in terms of Overloads

Load	***Cur.***	***10% Load Increase***				***20% Load Increase***					***30% Load Increase***					
EV Rate	*0 %*	*0 %*	*5 %*	*10 %*	*20 %*	*0 %*	*20 %*	*30 %*	*50 %*		*0 %*	*30 %*	*50 %*		*100 %*	
Case 1							**1**	**1**	**1**	**1**		**1**	**1**	**1**	**2**	**3**
Case 2							**1**	**1**	**1**	**1**		**1**	**1**	**1**	**3**	**3**
Case 3							**1**	**1**	**1**	**1**		**1**	**1**	**1**	**2**	**5**
Case 4									**1**				**1**		**1**	**1**
Case 5									**1**				**1**	**1**	**2**	**3**

In Table 31, the base case (no specific tariff) is evaluated in Scenario NW2 (*NW2.C1.L2.EV50)*. Due to the villa type settlement (distributed residential houses), there are higher numbers of LV lines in NW2 compared to NW1. On the other hand, only two elements reflects overloads occurred on the transformer and line-T2, which shows that the reliability of the network is higher than the reliability in NW1. Additionally, the transformer is the most critical element of NW2 as it is observed from Table 31. Therefore, distribution companies should consider upgrading firstly the transformer in case of a network reinforcement.

Figure 29 presents that the transformer is loaded over 100% rate at 20:00 and 21:00 for Case 1. The MV/LV transformer operates at various loading rates in different hours due to the high EV penetration rate. For instance, five different loading rates can be observed between 17:00 and 23:00 for the transformer. Hence, it is suggested that distribution companies should distribute the EV integration between hours or try to integrate an additional transformer operating in peak hours.

Table 31. Detailed Results of Overload Analysis for Scenario NW2.C1.L2.EV50

Rate and Number of Events								
(100% > X > 80%)					(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
Line-A	4800	0	0.000		Line-A	4800	0	0.000
Line-A1	4800	0	0.000		Line-A1	4800	0	0.000
Line-A2	4800	0	0.000		Line-A2	4800	0	0.000
Line-A2(1)	4800	0	0.000		Line-A2(1)	4800	0	0.000
Line-B	4800	0	0.000		Line-B	4800	0	0.000
Line-B1	4800	0	0.000		Line-B1	4800	0	0.000
Line-B2	4800	0	0.000		Line-B2	4800	0	0.000
Line-B2(1)	4800	0	0.000		Line-B2(1)	4800	0	0.000
Line-C	4800	0	0.000		Line-C	4800	0	0.000
Line-C1	4800	0	0.000		Line-C1	4800	0	0.000
Line-C2	4800	0	0.000		Line-C2	4800	0	0.000
Line-C2(1)	4800	0	0.000		Line-C2(1)	4800	0	0.000
Line-D	4800	0	0.000		Line-D	4800	0	0.000
Line-D1	4800	0	0.000		Line-D1	4800	0	0.000
Line-D2	4800	0	0.000		Line-D2	4800	0	0.000
Line-D2(1)	4800	0	0.000		Line-D2(1)	4800	0	0.000
Line-E	4800	0	0.000		Line-E	4800	0	0.000
Line-E1	4800	0	0.000		Line-E1	4800	0	0.000
Line-E2	4800	0	0.000		Line-E2	4800	0	0.000
Line-E2(1)	4800	0	0.000		Line-E2(1)	4800	0	0.000
Line-F	4800	0	0.000		Line-F	4800	0	0.000
Line-F1	4800	0	0.000		Line-F1	4800	0	0.000
Line-F2	4800	0	0.000		Line-F2	4800	0	0.000
Line-F2(1)	4800	0	0.000		Line-F2(1)	4800	0	0.000
Line-G	4800	0	0.000		Line-G	4800	0	0.000
Line-G1	4800	0	0.000		Line-G1	4800	0	0.000
Line-G2	4800	0	0.000		Line-G2	4800	0	0.000
Line-G2(1)	4800	0	0.000		Line-G2(1)	4800	0	0.000
Line-T1	4800	0	0.000		Line-T1	4800	0	0.000
Line-T1(1)	4800	0	0.000		Line-T1(1)	4800	0	0.000
Line-T2	4800	100	2.083		Line-T2	4800	0	0.000
Line-T2(1)	4800	0	0.000		Line-T2(1)	4800	0	0.000
Line-T3	4800	0	0.000		Line-T3	4800	0	0.000
Line-T3(1)	4800	0	0.000		Line-T3(1)	4800	0	0.000
1000KVA	4800	1005	20.938		1000KVA	4800	417	8.688

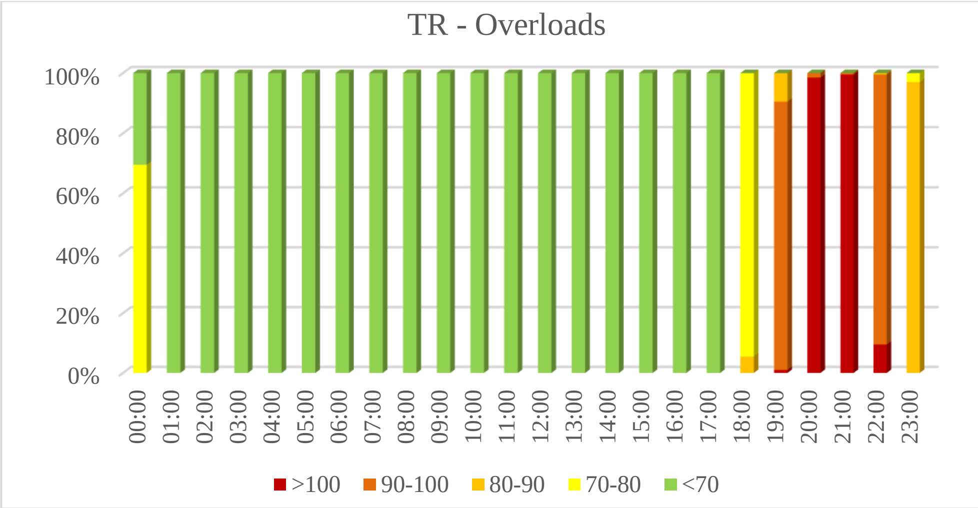


Figure 29. Hourly Loading Chart for the Transformer at NW2.C1.L2.EV50

Table 32 demonstrates detailed results of overload analysis for Scenario *NW2.C4.L2.EV50* that is created by applying the new multi-tariff system to half of EV owners. According to the table, the alarm status occurred on the transformer in Case 1 is eliminated for this scenario. In addition, the warning status occurred on the loading of line-T2 is cleared. Hourly loading chart of the most critical element (the transformer) is demonstrated in Figure 30.

Table 32. Detailed Results of Overload Analysis for Scenario NW2.C4.L2.EV50

Rate and Number of Events								
(100% > X > 80%)					**(X>100%)**			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
1000KVA	4800	274	5.708		1000KVA	4800	0	0.000
All other elements (lines)	4800	0	0.000		All other elements (lines)	4800	0	0.000

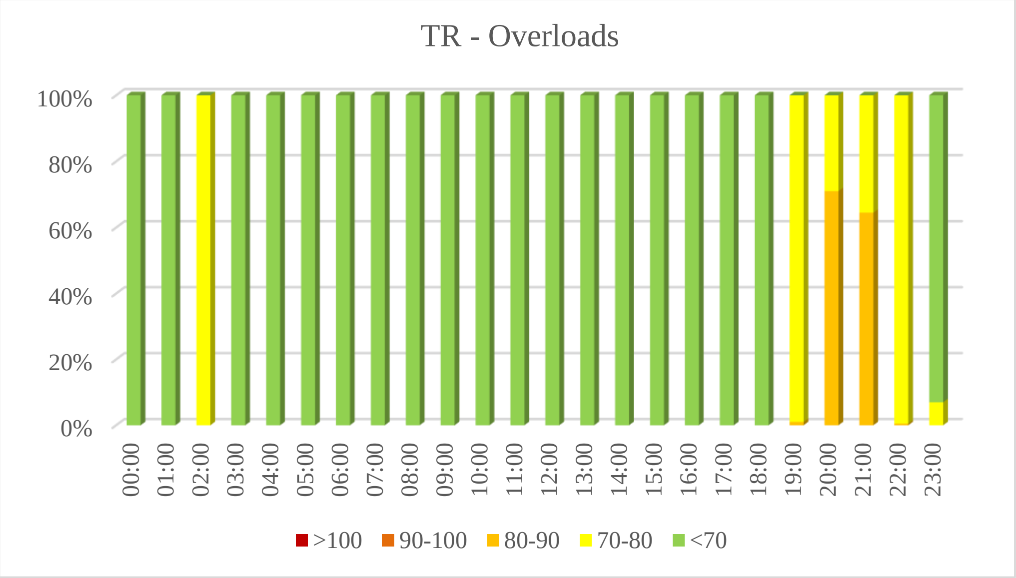


Figure 30. Hourly Loading Chart for the Transformer at NW2.C4.L2.EV50

The third scenario selected from Table 30 is *NW2.C5.L2.EV50*. This scenario is evaluated to observe the effect of EVs on NW2 considering customer preferences on the new multi-tariff. Table 33 shows that the warning status occurred at line-T2 is cleared compared to the base scenario. Even if the rate of incidence of overloads diminishes, there is still an alarm on the transformer loading. This assessment shows the extreme case and delivers that the suggested multi-tariff system becomes insufficient at high EV penetration rates if all EV owners prefer to use the suggested multi-tariff.

Figure 31 displays transformer overloads on an hourly basis. According to the figure, critical overloads for the transformer accumulate at 02:00, 03:00, and 04:00 due to the high EV integration on the network (starting at 02:00). On the other hand, the transformer operates under the 70% loading rate at all remaining hours.

Table 33. Detailed Results of Overload Analysis for Scenario NW2.C5.L2.EV50

Rate and Number of Events								
(100% > X > 80%)					(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
1000KVA	4800	474	9.875		1000KVA	4800	200	4.167
All other elements (lines)	4800	0	0.000		All other elements (lines)	4800	0	0.000

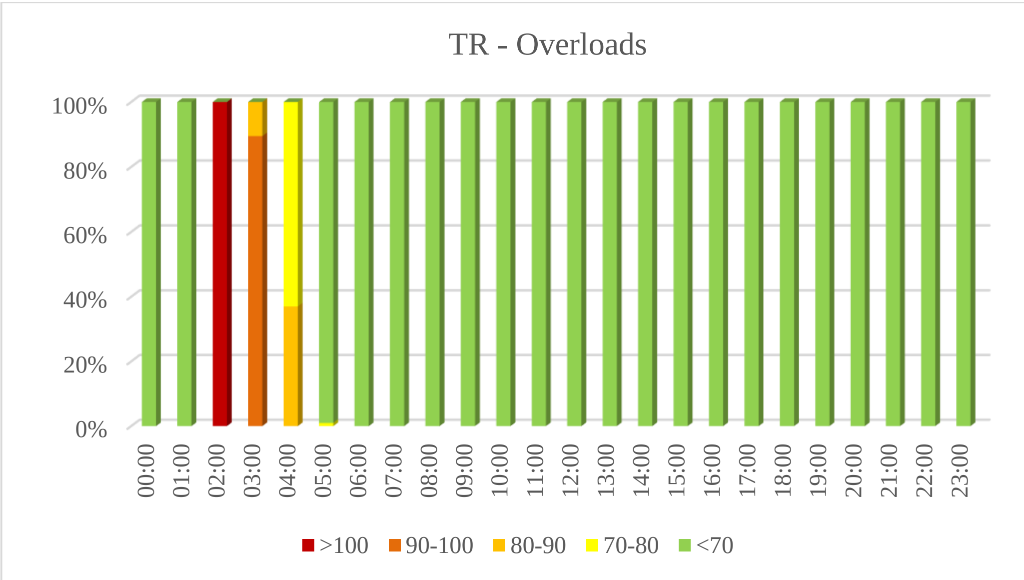


Figure 31. Hourly Loading Chart for the Transformer at NW2.C5.L2.EV50

4.2.2.2 Voltage Drops in Network 2

Results of voltage drop analysis are gathered regarding voltage profiles of residential customers in NW2. This network has ten main feeders supplying seventeen busbars (a group of customers). Therefore, simulation results are presented for seventeen busbars by applying the methodology explained in Section 4.2.

The overview of voltage drops for NW2 is presented in Table 34. Similar to overloads, voltage profiles seem in a good condition at low load increase and EV penetration rates. At 20% load increase, voltage values of residential customers start to appear as under warnings. Even if the voltage does not drop under 0.9 pu, high number of warnings is observed at 50% EV integration rate. It can be summarized from Table 34 that low EV penetration levels have no wide impacts on voltage profiles while high EV penetration rates create mostly warning statuses on the operation of NW2. Two scenarios, *NW2.C1.L2.EV50* and *NW2.C1.L2.EV50*, are selected from the same column to be explained in this section.

Table 34. Overview of NW2 in terms of Voltage Drops

Load	***Cur.***	***10% Load Increase***				***20% Load Increase***					***30% Load Increase***				
EV Rate	*0 %*	*0 %*	*5 %*	*10 %*	*20 %*	*0 %*	*10 %*	*20 %*	*30 %*	*50 %*	*0 %*	*10 %*	*30 %*	*50 %*	*100 %*
Case 1								**1**	**3**	**12**			**8**	**13**	**14** **1**
Case 2								**1**	**4**	**13**			**8**	**13**	**14** **3**
Case 3								**1**	**6**	**13**			**8**	**14**	**11** **6**
Case 4										**3**			**1**	**5**	**13**
Case 5										**5**				**6**	**15**

Results of voltage drop analysis for Scenario *NW2.C1.L2.EV50* are demonstrated in Table 35. Despite the fact that twelve busbars are under the warning status, some of them have very low incidence rates. The most critical element in Table 35 is T2 that also has the highest incidence rate of voltage drop among LV busbars (see Table 31). Hence, it is obvious that there is a distinctive correlation between the voltage drop at the specific busbar and the loading of the corresponding line (e.g., line-T2 and busbar-T2).

Table 35. Detailed Results of Voltage Drop Analysis for Scenario NW2.C1.L2.EV50

Rate and Number of Events							
(0.9 pu < X < 0.95 pu)				(X < 0.9 pu)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*	*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
A2	4800	806	16.792	A2	4800	0	0.000
T3	4800	0	0.000	T3	4800	0	0.000
T2	4800	904	18.833	T2	4800	0	0.000
T1	4800	0	0.000	T1	4800	0	0.000
A1	4800	559	11.646	A1	4800	0	0.000
B2	4800	791	16.479	B2	4800	0	0.000
B1	4800	349	7.271	B1	4800	0	0.000
C2	4800	577	12.021	C2	4800	0	0.000
C1	4800	265	5.521	C1	4800	0	0.000
D2	4800	166	3.458	D2	4800	0	0.000
D1	4800	1	0.021	D1	4800	0	0.000
E2	4800	356	7.417	E2	4800	0	0.000
E1	4800	1	0.021	E1	4800	0	0.000
F2	4800	0	0.000	F2	4800	0	0.000
F1	4800	0	0.000	F1	4800	0	0.000
G2	4800	547	11.396	G2	4800	0	0.000
G1	4800	0	0.000	G1	4800	0	0.000

Being the most sensitive element, voltage drops at T2 are demonstrated in Figure 32 based on the hourly chart. Figure 32 shows that even if the rate of the warning status is around at 20% (see Table 35), the voltage value does not drop under 0.93 pu for T2. Therefore, since 0.93 pu is acceptable on the operation of the distribution systems, the distribution system operator may operate NW2 without any reinforcements (in terms of voltage conditions).

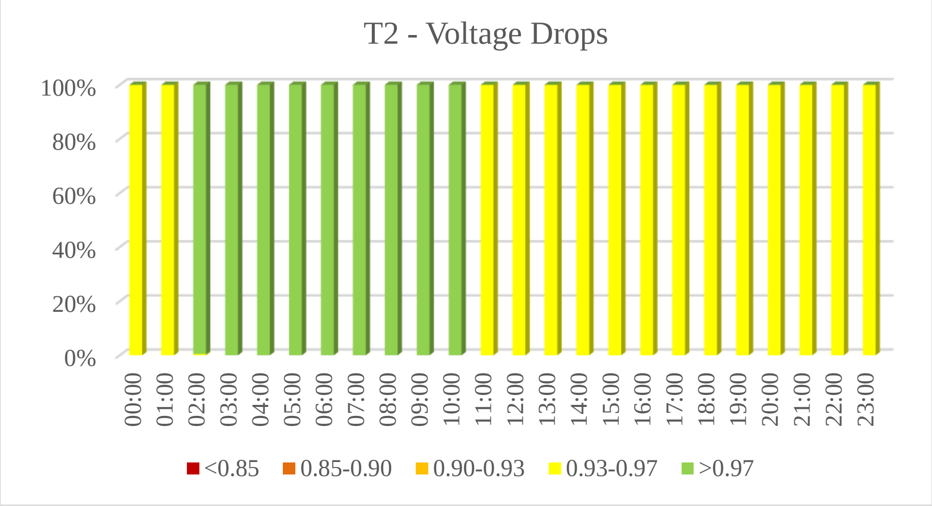


Figure 32. Hourly Voltage Drop Chart for T2 at NW2.C1.L2.EV50

Voltage conditions of NW2 customers for the second scenario (*NW2.C4.L2.EV50)* are presented in Table 36. The number of warnings occurred in NW2 reduces from twelve to three after applying Case 4. Furthermore, incidence rates of warnings for busbars A2, B2, and T2 decrease considerably. Due to the possibility of being recovered by the tap management of the transformer, low incidence rates occurring for the voltage drop characteristic of a LV busbar can be negligible on the operation of the network. Therefore, voltage drops occurred at A2 and B2 may not require any network reinforcement.

Since T2 is the most critical network element (based on voltage drops), voltage drop results for T2 are presented in an additional hourly chat in Figure 33. According to Figure 33, it is obvious that voltage drops at T2 are distributed among hours of the day.

Table 36. Detailed Results of Voltage Drop Analysis for Scenario NW2.C4.L2.EV50

Rate and Number of Events							
(0.9 pu < X < 0.95 pu)				(X < 0.9 pu)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*	*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
A2	4800	15	0.313	A2	4800	0	0.000
T3	4800	0	0.000	T3	4800	0	0.000
T2	4800	129	2.688	T2	4800	0	0.000
T1	4800	0	0.000	T1	4800	0	0.000
A1	4800	0	0.000	A1	4800	0	0.000
B2	4800	16	0.333	B2	4800	0	0.000
B1	4800	0	0.000	B1	4800	0	0.000
C2	4800	0	0.000	C2	4800	0	0.000
C1	4800	0	0.000	C1	4800	0	0.000
D2	4800	0	0.000	D2	4800	0	0.000
D1	4800	0	0.000	D1	4800	0	0.000
E2	4800	0	0.000	E2	4800	0	0.000
E1	4800	0	0.000	E1	4800	0	0.000
F2	4800	0	0.000	F2	4800	0	0.000
F1	4800	0	0.000	F1	4800	0	0.000
G2	4800	0	0.000	G2	4800	0	0.000
G1	4800	0	0.000	G1	4800	0	0.000

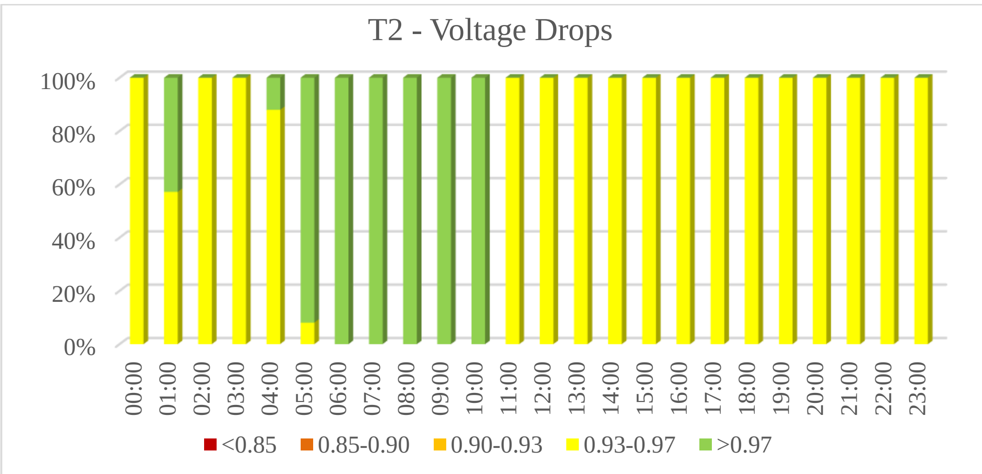


Figure 33. Hourly Voltage Drop Chart for T2 at NW2.C4.L2.EV50

4.2.2.3 Evaluation of Grid Losses for Network 2

Results obtained from the assessment of grid losses are presented as increases in grid losses for NW2 including the financial assessment as well. The overview of NW2 in terms of increases in daily grid losses is demonstrated in Table 37 while results for the financial assessment are presented in Table 38, respectively. The SMP of Turkish Energy Market (see Figure 28) is used while evaluating the cost of grid losses.

Table 37. Overview of NW2 in terms of Increases in Daily Grid Losses (in kWh)

Load		*10% Load Increase*			*20% Load Increase*			*30% Load Increase*		
EV Rate		*5 %*	*10 %*	*20 %*	*20 %*	*30 %*	*50 %*	*30 %*	*50 %*	*100 %*
Case1	Min.	5.8	12.7	31.7	35.6	60.5	120.1	67.5	130	323.9
	Max.	12.5	23.2	45.9	51.9	83.5	151.5	87.1	163	396.6
	Avrg.	9.2	19	39.7	44.6	72.1	135.2	77.2	145.2	362.7
Case2	Min.				33.8	59.3	117.6	63.5	120.5	318.5
	Max.				49	79.5	148	82.9	152.4	383.5
	Avrg.				41.6	67.8	129.1	72.7	137.2	347.5
Case3	Min.				35.8	59.8	122.5	60.3	128.2	373.2
	Max.				47.4	79.7	152.3	86.6	161.6	433.7
	Avrg.				41	69	137.5	73.5	145	403.5
Case4	Min.				27.9	47.2	88.2	48.8	96.4	232.2
	Max.				38.2	61.4	114.1	62.8	118.9	286.4
	Avrg.				33.1	53.9	101	57.5	107.6	260.6
Case5	Min.				24.3	44.9	90.6	43.9	95	295.3
	Max.				34.6	59.5	116.7	63.7	125.6	367.7
	Avrg.				29.3	50.9	105.1	52.9	109.9	325.1

Table 37 demonstrates increases in grid losses obtained for NW2 for cases considered. Grid losses increase as the EV integration rate increases. Compared to

NW1, grid losses in NW2 are considerably low. As an example, the increase in daily loss value at 50% EV penetration rate in Table 37 is approximately similar to the increase in daily loss value at 30% EV penetration for NW1.

The cost analysis for NW2 creates an economical picture of the network in terms of grid losses. Cases 1 and 4 are compared regarding increases in the cost of gird losses. Table 38 demonstrates that applying Case 4 instead of Case 1 saves daily around 12 TL from the perspective of distribution companies. This amount of saving is almost equal to the saving in NW1, thus similar economic arguments can be made for NW2. On the other hand, it must be noted that EV penetration rate in the financial assessment for NW1 is at 30% while the EV penetration rate in this assessment is at 50%.

Table 38. Results for the Cost Analysis of Grid Losses in NW2

Increases in the Cost of Daily Losses (TL Basis)			
	Case 1	*Case 4*	*Savings*
Min.	18.233	7.642	10.591
Max.	23.263	10.474	12.788
Avrg.	20.904	9.097	11.807

4.2.3 Simulation Results for Network 3

Network 3 is a generic distribution network in terms of the network design or planning as it has already been explained in Section 3.1. This network includes a detailed network model and tapered lines. Network 3 includes six main feeders having the same connectivity structure. Therefore, the analysis of this network is performed by modeling only one main feeder (i.e., branch) in detail and considering the others as lumped loads. In the same manner, the results are generated only for the transformer and elements of the selected and modelled branch. In this model, if an event (warning or alarm) occurs at a specific element located in the selected branch, it also occurs at the corresponding element of other branches.

Network 3 is analyzed based on two customer consumption rates: Medium-demand (as in NW1) and high-demand (as in NW2). The aim of using two different load consumption rates is to observe impacts of EVs on the network by comparing simulation results with those obtained from two real networks. Overloads, voltage drops, and grid losses obtained for NW3 are presented in the following sections.

4.2.3.1 Loading of Network 3 Elements

The overview of NW3 in terms of element overloads is shown in Table 39. The results are presented for the transformer and LV lines of the selected branch. Only Cases 1 and 4 are evaluated for NW3 since many scenarios have already been analyzed for NW1 and NW2. According to Table 39, at low EV integration rates (up to 25%), NW3 can be maintained without any overload. However, when the EV penetration rate rises, some warnings or alarms occur on NW3 elements. In order to understand the response of elements in the network, the worst scenario is selected and presented this section.

The transformer, line A, and line B are three elements reflecting warnings and alarms for Scenario *NW3.C1.L3.EV100* shown in Table 40. Since lines A and B are connected to the selected branch in modelling, it is obvious that the corresponding lines in other branches will also face same overloads. Clearly seen from Table 40, the transformer is the most critical element. Hence, the hourly loading chart of the transformer is presented in Figure 34. It is obvious from the figure that overloads for NW3 occur at the high EV charging periods.

General comment that can be inferred from results of the analysis is that overloads occur only at the transformer and feeders A and B (for all branches) at high EV penetration rates. Therefore, the network reinforcement must firstly be applied on these components.

Table 39. Overview of NW3 in terms of Overloads

Load		***Cur.***	***10% Load Increase***			***20% Load Increase***			***30% Load Increase***			
EV Rate		*0 %*	*0 %*	*25 %*	*50 %*	*0 %*	*25 %*	*50 %*	*0 %*	*25 %*	*50 %*	*100 %*
Medium Load Demand (as in NW1)	*Case 1*				**1 1**			**1 1**		**1**	**1**	**3**
	Case 2											
	Case 3											
	Case 4				**1**			**1**		**1**	**1**	**1**
	Case 5											
High Load Demand (as in NW2)	*Case 1*			**1**	**1 1**		**1**	**1 1**		**1 1**	**2**	**3**
	Case 2											
	Case 3											
	Case 4			**1**	**1**		**1**	**1**		**1 1**	**1**	**3**
	Case 5											

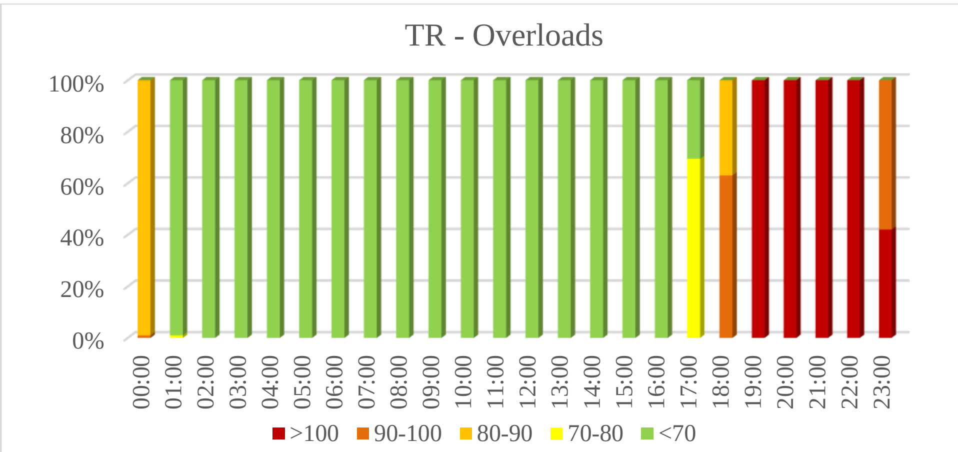


Figure 34. Hourly Loading Chart for the Transformer at NW3.C1.L3.EV100

Table 40. Detailed Results of Overload Analysis for Scenario NW3.C1.L3.EV100

Rate and Number of Events							
(100% > X > 80%)				(X>100%)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*	*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
Line A	4800	1296	27.000	Line A	4800	916	19.083
Line A1	4800	0	0.000	Line A1	4800	0	0.000
Line A11	4800	0	0.000	Line A11	4800	0	0.000
Line A2	4800	0	0.000	Line A2	4800	0	0.000
Line A22	4800	0	0.000	Line A22	4800	0	0.000
Line A3	4800	0	0.000	Line A3	4800	0	0.000
Line A33	4800	0	0.000	Line A33	4800	0	0.000
Line A4	4800	0	0.000	Line A4	4800	0	0.000
Line A44	4800	0	0.000	Line A44	4800	0	0.000
Line B	4800	804	16.750	Line B	4800	335	6.979
Line B1	4800	0	0.000	Line B1	4800	0	0.000
Line B11	4800	0	0.000	Line B11	4800	0	0.000
Line B2	4800	0	0.000	Line B2	4800	0	0.000
Line B22	4800	0	0.000	Line B22	4800	0	0.000
Line B3	4800	0	0.000	Line B3	4800	0	0.000
Line B33	4800	0	0.000	Line B33	4800	0	0.000
Line B4	4800	0	0.000	Line B4	4800	0	0.000
Line B44	4800	0	0.000	Line B44	4800	0	0.000
Line C	4800	0	0.000	Line C	4800	0	0.000
Line C1	4800	0	0.000	Line C1	4800	0	0.000
Line C11	4800	0	0.000	Line C11	4800	0	0
Line C2	4800	0	0.000	Line C2	4800	0	0.000
Line C22	4800	0	0.000	Line C22	4800	0	0.000
Line C3	4800	0	0.000	Line C3	4800	0	0.000
Line C33	4800	0	0.000	Line C33	4800	0	0.000
Line C4	4800	0	0.000	Line C4	4800	0	0.000
Line C44	4800	0	0.000	Line C44	4800	0	0.000
1250KVA	4800	1674	34.875	1250KVA	4800	1400	29.167

4.2.3.2 Voltage Drops in Network 3

Voltage drop results for NW3 are presented in Table 41 considering two different load demand scenarios for residential customers. Table 41 demonstrates that the rate of EV integration reaching up to 50% does not cause any warnings or alarms on NW3 in terms of voltage drops of residential customers. However, warning statuses are observed at many busbars at 100% EV penetration rate, which can be eliminated by applying Case 4.

Table 41. Overview of NW3 in terms of Voltage Drops

Load		***Cur.***	***10% Load Increase***			***20% Load Increase***			***30% Load Increase***			
EV Rate		*0 %*	*0 %*	*25 %*	*50 %*	*0 %*	*25 %*	*50 %*	*0 %*	*25 %*	*50 %*	*100 %*
Medium Load Demand (as in NW1)	*Case 1*											**16**
	Case 2											
	Case 3											
	Case 4											
	Case 5											
High Load Demand (as in NW2)	*Case 1*											**18**
	Case 2											
	Case 3											
	Case 4											
	Case 5											

Voltage drop results for Scenario *NW3.C1.L3.EV100* are presented in Table 42 in order to evaluate the voltage status of NW3 customers in detail. It is obvious that, the furthest element from the transformer (e.g., C11) has the highest incidence rate. In addition, similar groups have similar incidence rates (e.g., B11 and B22).

Table 42. Detailed Results of Voltage Drop Analysis for Scenario NW3.C1.L3.EV100

Rate and Number of Events								
(0.9 pu < X < 0.95 pu)					(X < 0.9 pu)			
Element Name	*Total results*	*Number of Warn.*	*% of Warn.*		*Element Name*	*Total results*	*Number of Alarms*	*% of Alarms*
A	4800	0	0.000		A	4800	0	0.000
B	4800	0	0.000		B	4800	0	0.000
C	4800	137	2.854		C	4800	0	0.000
C4	4800	357	7.438		C4	4800	0	0.000
C44	4800	481	10.021		C44	4800	0	0.000
C3	4800	358	7.458		C3	4800	0	0.000
C33	4800	485	10.104		C33	4800	0	0.000
C2	4800	361	7.521		C2	4800	0	0.000
C22	4800	487	10.146		C22	4800	0	0.000
C1	4800	357	7.438		C1	4800	0	0.000
C11	4800	493	10.271		C11	4800	0	0.000
B1	4800	1	0.021		B1	4800	0	0.000
B11	4800	19	0.396		B11	4800	0	0.000
B2	4800	1	0.021		B2	4800	0	0.000
B22	4800	24	0.500		B22	4800	0	0.000
B3	4800	3	0.063		B3	4800	0	0.000
B4	4800	0	0.000		B4	4800	0	0.000
B33	4800	25	0.521		B33	4800	0	0.000
B44	4800	28	0.583		B44	4800	0	0.000
A1	4800	0	0.000		A1	4800	0	0.000
A2	4800	0	0.000		A2	4800	0	0.000
A3	4800	0	0.000		A3	4800	0	0.000
A4	4800	0	0.000		A4	4800	0	0.000
A11	4800	0	0.000		A11	4800	0	0.000
A22	4800	0	0.000		A22	4800	0	0.000
A33	4800	0	0.000		A33	4800	0	0.000
A44	4800	0	0.000		A44	4800	0	0.000

4.2.3.3 Evaluation of Grid Losses for Network 3

As it is stated in previous sections, in simulations of NW3, one branch has been modeled in detail while others have been integrated as lumped loads. This approximation does not bring out any problem in the analysis of overloads and voltage drops. Hence, if an alarm or warning occurs on a specific line at the modelled branch, it will occur on the corresponding line of other branches as well. Unfortunately, this approximation applied in overload and voltage drop analysis creates some gaps on the analysis of grid losses. Since LV lines for other branches have not been modelled in the simulation, the losses in these LV lines have not been considered for the results of grid losses. Hence, a new calculation method that is explained in the following paragraph is developed and implemented in the calculation of the daily cost of grid losses for NW3.

Firstly, all LV residential loads for NW3 are connected to the LV busbar of the transformer without any line and EV (named as no-line analysis), and the daily cost of grid losses are calculated. Then, another daily cost analysis is performed (the regular calculation applied for NW1 and NW2) for the detailed model of one branch integrated to NW3 (named as no-EV analysis). The daily cost of losses for modelled one branch is calculated by subtracting the result of no-line analysis from the results of no-EV analysis. After that, the daily cost of all line losses is calculated by multiplying one branch result with the number of branches (without EVs and considering all branches). The daily cost of grid losses is calculated by adding the daily cost of transformer losses with the daily cost of all line losses. Similarly, the same approach is implemented for Scenarios *NW3.C1.L3.EV50* and *NW3.C4.L3.EV50* in order to calculate the daily cost of grid losses. Finally, increases in the daily cost of grid losses are calculated for two scenarios. The simulation results are shown in Table 43.

As it is seen from Table 43, it is clear that the daily economic benefit may reach up to around 20 TL by applying the new multi-tariff in NW3. Similar comments and suggestions can be made for distribution companies as in two previous cost analyses applied for NW1 and NW2.

Table 43. Results for the Cost Analysis of Grid Losses in NW3

Increases in the Cost of Daily Losses (TL Basis)			
	Case 1	*Case 4*	*Savings*
Min.	31.770	13.860	17.909
Max.	43.320	19.711	23.608
Avrg.	36.703	16.836	19.867

4.3 Discussion of Simulation Results

Loading conditions of network components obtained from simulations present valuable information to distribution system planners while making investments or reinforcements on distribution networks by indicating overloads or critical conditions. Additionally, incidence rates of element overloads give opinions about the operational capacity and upgrading period of network components.

Looking at the results of overload analysis, each EV scenario studied creates at least one warning status on the operation of NW1a. The most critical element is the transformer that has the highest incidence rate of overloads (in the form of warning or alarm). The transformer is subject to at least one warning status for all EV scenarios (especially during EV plug-in hours). After upgrading the transformer (NW1b), line-D becomes the most eligible element in the network, which brings line-D a priority on the investment plans. On the other hand, NW2 having a well-designed network structure can be operated without any violations at low load increase rates and EV penetration rates. At higher load increase rates, overloads start to appear on NW2 elements. Finally, NW3, being a generic distribution network, faces a few overloads only at high EV penetration rates (i.e., more than 25%).

MV/LV transformers face the biggest impact of the EV integration on distribution networks in terms of overloads. In the general view, transformers initially loaded at or above the value of 70% must be upgraded in the coming 10 years while the transformer loaded at 55% or lower rates can be maintained more than 10 years without any overload under the expected rate of increase in EV penetration rates. Hence, considering the high number of MV/LV transformers in Ankara, distribution system planners should carefully define the operational condition of each transformer in order to determine the replacement and investment period. In addition to the transformer loading, 70 mm^2 (or lower) LV cables feeding 100 or more residential customers might be overloaded for 20% EV integration scenario in the coming decade. Therefore, the new design criteria for a LV main feeder outgoing from MV/LV transformer (taking the EV integration into account) must be at least 185 mm^2 for 100 customers, 150 mm^2 for 75 customers, and 120 mm^2 for 50 customers.

Simulation results of voltage drop analysis show the response of the voltage status at the end of LV lines to various EV scenarios. Distribution system operators may consider these results while dealing with the voltage coordination in the network. Hourly chart table acquired from the voltage drop analysis can be a valuable information for the determination of the transformer tap adjustment.

Network 1, being a relatively old distribution network (structured using old network design criteria), reflects at least one warning status for all EV and load scenarios. The increase in the EV penetration and load demand increases voltage drop problems occurring at residential customers. On the other hand, low EV uptake levels have no wide impacts on voltage profiles of residential customers in NW2. In addition, even high EV penetration rates create mostly warning statuses on the NW2 operation due to well-designed LV lines. Unsurprisingly, NW3, suggested as a generic network, includes the warning status only at the worst scenario.

As a general outcome obtained from the assessment of voltage drop analysis, well-designed networks can support higher EV integration without any voltage violation. The simulation results indicate that the length of a LV line must not exceed 300 meters in a distribution area. Otherwise, the voltage value of a residential customer (located at the 300 or higher meters of the LV line) might drop under 0.9 pu. Additionally, the tap rate of the transformer might be regulated (to increase the voltage level at the end customers) for old distribution networks in the following years.

Increases in grid losses in distribution networks for various EV scenarios are also analyzed in this study. Simulation results present the calculation and comparison of daily grid losses for various EV integration scenarios. Additionally, distribution companies can obtain a financial assessment in terms of grid losses for different cases. Total savings after applying the proposed multi-tariff systems are calculated using the SMP data observed in Turkish electric market. This calculation helps distribution companies to calculate the fee of the new multi-tariff in Ankara.

Grid losses, as expected, are highly correlated with the level of loading in the network. Networks NW1a and NW1b generate similar results in terms of grid losses due to having the same network structure but different transformer sizes. On the other hand, the increase in grid losses for NW2, a well-structured network, is considerably lower than the increase in NW1 losses. In conclusion, implementation of well-designed LV lines and charging of EVs during valley hours are the most efficient ways to diminish grid losses in a distribution network.

The financial assessment of grid losses for each distribution network presents that distribution companies achieve considerable amount of savings based on grid losses by encouraging EV owners to charge EVs after 2 a.m. According to the simulation results, total savings for the 20% EV penetration scenario may reach up to 20,000 TL for just one day in Ankara region.
It is also observed from the simulation results that many violations (warnings and alarms) occurred in the network for various EV scenarios can be eliminated by

changing the tariff system. This means that implementing new multi-tariff system (such that the lowest energy price is applied between 02:00 – 08:00) instead of the old one (22:00 – 06:00) decreases network overloads and voltage problems as well as the total grid losses. Changing the time tariff not only reduces the grid losses but also delays some investments from the perspective of distribution companies.

In regions where the load growth has saturated (as in network NW1 and NW2), the 10% increase in the total demand is expected to occur in approximately 5 – 10 years. This increase would originate from the increase in the living standards and wealth of residential customers. Considering that the EV penetration rate will not exceed the 10% value in 10 years, there will not be any critical overload on the network operation if the MV/LV transformer is initially loaded much under the value of 80%. On the other hand, in case of the occurrence of 20% EV penetration rate, network overloads can be eliminated by applying the suggested multi-tariff. Since the biggest impact of EVs occurs on the MV/LV transformers, all transformers operating on LV distribution networks should carefully be monitored and scheduled by distribution companies.

In areas where the load growth of residential customers has not been saturated yet, a higher rate of natural load demand increase (i.e., 20% or higher load increase rate) also contributes to total load demand. Hence, there will be some overloads (warnings and alarms) on the MV/LV transformer for even 10% EV penetration rates. Therefore, the investment periods and plans for these networks must be rearranged and the transformer of the networks might be upgraded in approximately 10 years. Additionally, at higher EV penetration rates, some LV lines having high number of residential customers might face overload problems.

CHAPTER 5

CONCLUSION

Environmental and economic concerns increase investments and interests on the electrification of transportation sector mainly on EVs that had once lost his momentum in the mid-of 20th century. An EV is a vehicular technology that uses an electric motor instead of conventional combustion engine for propulsion. Mainly, an EV deals with three technical quantities as the driving/motor technology, the battery technology, and the charging technology.

The driving technology of an EV involves all pieces related to motor and internal material. Despite the fact that the driving technology depends on the type of EV, the main aim behind an EV technology is to efficiently deploy the electric power for propulsion in order to reduce CO_2 emissions and provide cheap transportation. Hence, the internal energy efficiency in an EV is considerably higher than the conventional cars, which is an encouraging factor in the EV development.

Directly related to the driving range, the battery is the most crucial component in EV due to the high prices and limited capacity-weight ratio. Batteries are considered in four main technical issues in the EV technology which are the type, charging pattern, aging, and cost. The Li-ion battery technology has the highest popularity between various battery types due to higher energy density, longer lifetime, and high number of charge/discharge cycles. Li-ion batteries absorb constant power during the charging process until they reach the current drop characteristic value where the power decreases exponentially (trickle charging) until the completion of the charging process. Additionally, the battery aging depends on various factors like the level of charging/discharging, the charging speed, the battery age, and the operation temperature. As the final technical aspect, the battery cost is tending to decline in the EV market with the development of the Li-ion battery technology.

Three different types of charging infrastructure are available in the EV charging technology. The first and most common technology is the conductive charging where the battery is charged by using an external plug-in cable directly from the gird. The conductive charging has AC and DC solutions with slow and fast charging options. The second type of charging is the inductive charging that applies wireless power transfer between the parking lot (charger) and battery. However, this technology is quite expensive and very inefficient to be implemented in real applications for today's technology. The third and final type of charging is the battery swap based on exchanging empty batteries with fully charged ones at specific stations. Although the battery swap seems to diminish range problems and very convenient, a considerable amount of investment is needed to be made in order to use this technology in an efficient way. In conclusion, having a simpler and cheaper technology compared to other charging solutions makes the conductive charging (particularly AC) commonly used in the EV charging sector.

Developed and developing countries including Turkey have recently initiated many governmental programs aiming to increase sales of EVs. The sales of EVs tend to increase over the world with recent initiative programs and developments, which bring a requirement to assess the impacts of EVs on power grids. In consequence of the fact that EVs are mostly charged at low voltage levels, the first and major effect of the EV integration will occur on low voltage distribution networks. Hence, an assessment from the perspective of distribution companies is required regarding impacts of EVs on LV distribution networks, which defines the scope of the thesis.

Three different residential LV network models, two of them belonging to actual network segments in Ankara corresponding to two different socio-economic regions and one being generic, have been developed with their customer attributes and network connectivity in the scope of the thesis. Different scenarios and cases have been applied to all of these sample networks. Implemented scenarios involve different penetration rates of EVs among residential customers, different load demand increase rates, and different multi-tariff mechanisms.

An extensive EV model has also been developed using probabilistic models. Gaussian distribution function for EV plug-in times and Weibull distribution function for daily travel times in Ankara (to determine the state-of-charge status of battery at the beginning of charging process) are adapted and implemented in Digsilent PowerFactoy simulation tool. Monte Carlo based load flow simulations are performed in order to evaluate the response of the distribution networks to various EV scenarios. Furthermore, the daily load curve (on an hourly basis) have also been employed in simulations to investigate the operational acceptability of the network in terms of the following criteria: Transformer and line/cable loading level, voltage drops, and grid losses.

A methodology (based on the overview of each network and detailed evaluation for network components) is developed in order to present the simulation results in terms of three criteria. Simulation results indicate, for each LV network and scenario, the network component for which one of the operational criteria fails and the year it should be replaced or upgraded. Another outcome of this methodology is that it gives a general insight to system planners about the additional investments required for each EV penetration rate in the coming years.

It has been also observed from simulation results that the existing multi-tariff time periods and the tariffs currently applied in Turkey have to be revised or reorganized. Starting the lowest tariff period at 2.00 a.m. instead of the existing 22.00 p.m. would provide a much more economical operating scheme for distribution companies due to reduced total losses in the network and delayed investments.

In a deregulated environment, distribution companies in Turkey are obliged to periodically submit their long-term investment plans to the regulatory agency for approval. Up to now, they have prepared their investment plans based only on the forecasted load growth without any EV effect. Considering the high numbers of LV distribution networks in Ankara, submitted plans have an important role on the operation of distribution networks properly in the following years. In addition, approved expenditures on network investments are reflected to fees of the current tariffs by the regulatory agency. Hence, the distribution network planning must widely be determined and applied by distribution system planers. The methodology presented in this study will clearly help and guide the planners in distribution companies to prepare more realistic and accurate investment plans and develop more economical and effective multi-tariff systems.

REFERENCES

[1] Guarnieri, M., "Looking back to electric cars," in *History of Electro-Technology Conference (HISTELCON)*, 2012 IEEE , September 2012.

[2] E. Ulrich, R. Helmolt, "Sustainable transportation based on EV concepts: a brief overview," *Elsevier Energy & Environmental Science,* vol. 3, no. 6, pp. 689 - 699, June 2010.

[3] IEEE Smart Grid Webinars, “Electric Vehicles and the Smart Gird,” November 2014.

[4] Samuel E. de Lucena, “A Survey on Electric and Hybrid Electric Vehicle Technology,” Electric Vehicles â€ “The Benefits and Barriers, Dr. Seref Soylu (Ed.), ISBN: 978-953-307-287-6, September 2011.

[5] TVA, “Types of Electric Vehicles,” [Online]. Available: http://www.tva.com/environment/technology/car_vehicles.htm. [Accessed 1 July 2015].

[6] TDK, “EV/HEV/PHEV MLCC Application Spotlight,” [Online]. Available: http://www.mouser.com/pdfdocs/TDK-MLCC-Automotive.pdf. [Accessed 1 July 2015].

[7] Mike Salisbury, “Air Quality and Economic Benefits of Electric Vehicles in Arizona,” SWEEP Project, September 2013, [Online]. Available: http://www.swenergy.org/publications/transportation. [Accessed 1 July 2015].

[8] COTEVOS Project D1.1, "Report on the needs for interoperability between EVs and electrical power system," 2014, [Online]. Available: http://cotevos.eu/publications/. [Accessed 1 July 2015].

[9] A. Mansoor, EPRI, "Emerging Technologies Enable "No Regrets" Energy Strategy," January 2013, [Online]. Available: http://www.powermag.com/emerging-technologies-enable-no-regrets-energy-strategy/. [Accessed 1 July 2015].

[10] Grid for Vehicles (G4V) project WP 1.3 report, "Parameter Manual," November 2010, [Online]. Available: http://www.g4v.eu/datas/Parameter_Manual_WP1_3_RWTH_101216.pdf. [Accessed 1 July 2015].

[11] M. Quarterly, "Electrifying cars: How three industries will evolve," June 2009, [Online]. Available: http://www.mckinsey.com/insights/manufacturing/electrifying_cars_how_three_industries_will_evolve. [Accessed 1 July 2015].

[12] Eşarj Elektrikli Araçlar Şarj Sistemleri A.Ş., "Charger Units," [Online]. Available: https://esarj.com/urunler. [Accessed 1 July 2015].

[13] International Economic Development Council, "Analysis of the Electric Vehicle Industry," 2013, [Online]. Available: http://www.iedconline.org/clientuploads/Downloads/edrp/IEDC_Electric_Vehicle_Industry.pdf. [Accessed 1 July 2015].

[14] Wikipedia, "Electric car use by country," [Online]. Available: http://en.wikipedia.org/wiki/Electric_car_use_by_country. [Accessed 1 July 2015].

[15] Prime Research, report on “World Car Trends 2014 - Smart Efficiency and Digital Intelligence,” April 2014, [Online]. Available: www.world-car-trends.com/download.php. [Accessed 1 July 2015].

[16] John Whittaker, “Automotive Trends 2015 – Changing Lanes: Understanding consumer attitudes and future trends in the UK motoring industry,” March 2015, [Online]. Available: http://futurethinking.com/wp-content/uploads/2015/03/Automotive-Trends-2015.pdf. [Accessed 1 July 2015].

[17] “GLOBAL EV OUTLOOK: Understanding the Electric Vehicle Landscape to 2020,” April 2013, [Online]. Available: http://www.iea.org/publications/globalevoutlook_2013.pdf. [Accessed 1 July 2015].

[18] Sustainable Energy Authority of Ireland (SEAI), “Electric Vehicles Roadmap,” December 2011.

[19] Tesla Motors, “Supercharger,” [Online]. Available: http://www.teslamotors.com/supercharger. [Accessed 1 July 2015].

[20] Deloitte Turkey, a survey report on “Elektrikli araçlar yolda… Dönüşüme hazır mısınız?,” 2011. [Online]. Available: http://www2.deloitte.com/content/dam/Deloitte/tr/Documents/manufacturing/otomotiv_sektoru_tuketici_arastirmasi.pdf. [Accessed 1 June 2015].

[21] ODD, reports on “Passenger Car and Light Commercial Vehicle Market Evaluation,” [Online]. Available: http://www.odd.org.tr/web_2837_2/neuralnetwork.aspx?type=35&language_id=2. [Accessed 1 July 2015].

[22] Republic of Turkey - Ministry of Science, Industry and Technology, "Automotive Industry Report," January 2014, [Online]. Available: http://sanayipolitikalari.sanayi.gov.tr/Public/DownloadSectorReport/1076?pid=34&yid=2. [Accessed 1 July 2015].

[23] Republic of Turkey - Ministry of Development, "Tenth Development Plan 2014-2018: Automotive Industry Working Group Report," 2014, [Online]. Available: http://www.osd.org.tr/yeni/wp-content/uploads/2014/09/2014-10.Plan-Otomotiv-Sanayi-%C3%96%C4%B0K-Raporu.pdf. [Accessed 1 July 2015].

[24] F. Salah, J. P. Ilg, C. M. Flath, H. Basse, C. V. Dinther, "Impact of electric vehicles on distribution substations: A Swiss case study," *Elsevier Applied Energy*, vol. 137 (2015), pp. 88-96, October 2014.

[25] P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau, L. M. Cipcigan, N. Jenkins, "Predicting Electric Vehicle impacts on residential distribution networks with Distributed Generation," in *Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE*, September 2010.

[26] S. Babaei, D. Steen, Le Anh Tuan, O. Carlson, L. Bertling, "Effects of Plug-in Electric Vehicles on distribution systems: A real case of Gothenburg," in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES*, October 2010.

[27] L. Pieltain Fernández, T. G. S. Román, R. Cossent, C. M Domingo, P. Frías, " Assessment of the Impact of Plug-in Electric Vehicles on Distribution Networks," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 206-213, February 2011.

[28] H. T. Chin, C. K. Gan, K.A. Ibrahim, "The impact of electric vehicle charging on a residential low voltage distribution network in Malaysia," in *Innovative Smart Grid Technologies - Asia (ISGT Asia), 2014 IEEE*, May 2014

[29] A. Bosovic, M. Music, S. Sadovic, “Analysis of the impacts of plug-in electric vehicle charging on the part of a real medium voltage distribution network,” in *Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2014 IEEE PES*, October 2014.

[30] K. Schneider, C. Gerkensmeyer, M. Kintner-Meyer, R. Fletcher, "Impact assessment of plug-in hybrid vehicles on pacific northwest distribution systems," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, July 2008.

[31] S. Shafiee, M. Fotuhi-Firuzabad, M. Rastegar, "Investigating the Impacts of Plug-in Hybrid Electric Vehicles on Power Distribution Systems," *IEEE Transactions on Smart Grid*, vol.4, no.3, pp.1351-1360, September 2013.

[32] E. Valsera-Naranjo, D. Martinez-Vicente, A. Sumper, R. Villafafila-Robles, A. Sudria-Andreu, "Deterministic and probabilistic assessment of the impact of the electrical vehicles on the power grid," in *Power and Energy Society General Meeting, 2011 IEEE*, July 2011.

[33] P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau, L. M. Cipcigan, N. Jenkins, "Electric vehicles' impact on British distribution networks," *IET Electrical Systems in Transportation*, vol.2, no.3, pp.91-102, September 2012.

[34] M. S. ElNozahy, M. M. A. Salama, "A Comprehensive Study of the Impacts of PHEVs on Residential Distribution Networks," *IEEE Transactions on Sustainable Energy*, vol.5, no.1, pp.332-342, January 2014.

[35] S. ElNozahy, M. M. A. Salama, "Studying the feasibility of charging plug-in hybrid electric vehicles using photovoltaic electricity in residential distribution systems," *Elsevier Electric Power Systems Research*, vol.110, pp.133-143, May 2014.

[36] L. Trovao, H. M. Jorge, "Power demand impacts of the charging of Electric Vehicles on the power distribution network in a residential area," in *Energetics (IYCE), Proceedings of the 2011 3rd International Youth Conference on*, July 2011.

[37] L. Kelly, A. Rowe, P. Wild, "Analyzing the impacts of plug-in electric vehicles on distribution networks in British Columbia," in *Electrical Power & Energy Conference (EPEC), 2009 IEEE*, October 2009.

[38] E. Valsera-Naranjo, A. Sumper, R. Villafafila-Robles, D. Martinez-Vicente, "Probabilistic Method to Assess the Impact of Charging of Electric Vehicles on Distribution Grids," *Energies Journal*, vol. 5, pp. 1503-1531, May 2012.

[39] J. R. Aguero, P. Chongfuangprinya, S. Shengnan, Xu Le, F. Jahanbakhsh, H. L. Willis, "Integration of Plug-in Electric Vehicles and distributed energy resources on power distribution systems," in *Electric Vehicle Conference (IEVC), 2012 IEEE International*, March 2012.

[40] R. M. Oviedo, Z. Fan, S. Gormus, P. Kulkarni, "A residential PHEV load coordination mechanism with renewable sources in smart grids," Elsevier Electrical Power and Energy Systems, vol. 55 (2014), pp. 511-521, October 2013.

[41] Power System Analysis Group, Report on "Low Voltage Pilot Network Studies: Digsilent Simulation Results," TUBITAK UZAY, April 2011.

[42] Grid for Vehicles (G4V) project D5.3 report, “Report with the recommendations for the grid planning and operation,” October 2011, [Online]. Available: http://www.g4v.eu/datas/reports/G4V_WP5_D5_3_recommendations_grid_infrastructure.pdf. [Accessed 1 July 2015].

[43] H. Lee Willis, Power Distribution Planning Reference Book, New York: Marcel Dekker, Inc., 2004.

[44] EPDK, Load profiles for Distribution companies for 2015, 2014, [Online]. Available: http://www.epdk.gov.tr/index.php/elektrik-piyasasi-dairesi/36. [Accessed 1 July 2015].

[45] Yandex traffic data for Ankara region, 2015, [Online]. Available: https://harita.yandex.com.tr/11503/ankara/?l=trf. [Accessed 1 July 2015].

[46] BMW i3, “Technical Data,” [Online]. Available: http://www.bmw.com/com/en/newvehicles/i/i3/2013/showroom/technical_data.html. [Accessed 1 July 2015].

[47] Renault Zoe, “Technical Specifications,” [Online]. Available: http://www.media.renault.com/download/media/specialfile/45115_1_5.aspx. [Accessed 1 July 2015].

[48] EPDK, “Dağıtım Lisansı Sahibi Tüzel Kişiler ve Görevli Perakende Satış Şirketlerinin Tarife Uygulamalarına İlişkin Usul ve Esaslar,” 2012, [Online]. Available: http://www.epdk.org.tr/index.php/component/content/article/29-icerik/tuketiciler-icerik/1833-tuketiciler-elk#mevzuat. [Accessed 1 July 2015].

[49] DigSilent, Digsilent PowerFactory Version 15 User Manual.

[50] Turkish Statistical Institute, “Main Statistics,” 2014, [Online]. Available: http://www.turkstat.gov.tr/UstMenu.do?metod=temelist. [Accessed 1 July 2015].

[51] Turkish Market & Financial Settlement Center, “General Reports,” 2015, [Online]. Available: https://rapor.pmum.gov.tr. [Accessed 1 July 2015].

APPENDIX A

TECHNICAL DATA OF LV DISTRIBUTION NETWORKS USED IN LOAD FLOW SIMULATIONS

Data for transformers and LV cables used in the simulation are given below in Tables 44 and 45.

Table 44. Input Data for Transformers

	630 kVA	**800 kVA**	**1000 kVA**	**1250 kVA**
Relative short-circuit voltage-Uk (%)	4.5	6	6	6
Copper losses (kW)	8	9.7	12.2	14
No load current (%)	1.6	1.5	1.4	1.4
No load losses (kW)	1.35	1.52	1.6	1.95

Table 45. Input Data for LV Cables

	4x35 mm^2	**4x50 mm^2**	**4x70 mm^2**	**4x95 mm^2**	**4x120 mm^2**	**4x150 mm^2**	**4x185 mm^2**
Rated current (kA)	0.157	0.184	0.227	0.275	0.313	0.353	0.4
Resistance (Ohm/km)	0.524	0.387	0.268	0.193	0.153	0.124	0.091
Reactance (mH/km)	0.211	0.212	0.2	0.198	0.2	0.2	0.192
Capacitance ($\mu F/km$)	0.261	0.342	0.397	0.458	0.5	0.5	0.5