SHURA
ENERGY TRANSITION CENTER

TRANSPORTATION SECTOR TRANSFORMATION: INTEGRATING ELECTRIC VEHICLES INTO TÜRKİYE'S DISTRIBUTION GRIDS

About SHURA Energy Transition Center

SHURA Energy Transition Center, founded by the European Climate Foundation (ECF), Agora Energiewende, and Istanbul Policy Center (IPC) at Sabancı University, contributes to the decarbonisation of the energy sector via an innovative energy transition platform. It caters to the need for a sustainable and broadly recognized platform for discussions on technological, economic, and policy aspects of Türkiye's energy sector. SHURA supports the debate on the transition to a low-carbon energy system through energy efficiency and renewable energy by using fact-based analysis and the best available data. Taking into account all relevant perspectives by a multitude of stakeholders, it contributes to an enhanced understanding of the economic potential, technical feasibility, and the relevant policy tools for this transition.

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Acknowledgements

We would like to thank Enerjisa Enerji (Oğuzcan Samsun, Erdem Özgüner, Mutlu İpteç, Furkan Şarkir) to support development of methodology, determination of assumptions and valuable contributions to the report. An earlier draft of this report was discussed with the Department of Energy Transition of EPDK in stakeholder consultation meeting that took place in April 2024, we are grateful for feedbacks provided. We would also like to thank the valuable stakeholder groups of the energy and transport sectors for evaluating the results of the study at a public stakeholder consultation meeting organized in May 2024. SHURA Director Alkım Bağ Güllü has reviewed the report and provided comments and feedback. We are grateful for all the reviews, opinions and feedback provided.

SHURA Energy Transition Center is grateful to the generous funding provided by the ECF.
This report can be downloaded from www.shura.org.tr
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Design

Tasarımhane Tanıtım Ltd. Şti.

ISBN 978-625-6956-47-6

Disclaimer

This report and the assumptions made within the scope of the study have been drafted based on different scenarios and market conditions as of 2024. Since these assumptions, scenarios, and the market conditions are subject to change, it is not warranted that the forecasts in this report will be the same as the actual figures. The institutions and the persons who have contributed to the preparation of this report cannot be held responsible for any commercial gains or losses that may arise from the divergence between the forecasts in the report and the actual values.

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LIST OF ABBREVIATIONS

AA	Anadolu Ajansı (Anadolu Agency)
AC	Alternative Current
AFIR	Alternative Fuels Infrastructure Regulation
BAU	Business-as-Usual
BEV	Battery Electric Vehicle
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CapEx	Capital Expenditure
CO_2	Carbon Dioxide
CPO	Charging Point Operators
C-SUV	C Segment Sport Utility Vehicle
DC	Direct Current
DLMP	Distribution Locational Marginal Pricing
DSO	Distribution System Operator
EDAŞ	Elektrik Dağıtım Anonim Şirketi (Electric Distribution Corporation)
EENS	Expected Energy Not Supplied
EI	Electrical Index
ELDER	Electricity Distribution Services Association
EMRA	Energy Market Regulatory Authority
EPDK	Enerji Piyasaları Düzenleme Kurumu (Energy Market Regulatory Authority)
EU	European Union
EV	Electric Vehicle
EVAM	Electric Vehicle Allocation Multiplier
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions

GIS	Geographic Information System
HV	High Voltage
IRA	Inflation Reduction Act
km	Kilometer
kVA	Kilovolt-Ampere
kW	Kilowatt
kWh	Kilowatt-hour
LDV	Light Duty Vehicles
LMP	Locational Marginal Pricing
LPG	Liquefied Petroleum Gas
LV	Low Voltage
MENR	Ministry of Energy and Natural Resources
Mt	Million Tons
MV	Medium Voltage
MVA	Megavolt-Ampere
MW	Megawatt
Net0	Net zero
NEVI	National Electric Vehicle Infrastructure
ODMD	Otomobil Distribütörleri ve Mobilite Derneği (Automotive Distributors and Mobility Association)
OECD	Organisation for Economic Co-operation and Development
ÖTV	Özel Tüketim Vergisi (Special Consumption Tax)
p.u.	Per Unit
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
RDI	Relative Development Index
SAIFI	System Average Interruption Frequency Index
SOC	State-of-Charge
TEHAD	Türkiye Elektrikli ve Hibrid Araçlar Derneği (Turkey Electric and Hybrid Vehicles Association)
TL	Turkish Lira
TM	Trafo Merkezi (Substation)
TOGG	Türkiye's Automobile Joint Venture Group
TR	Transformer
TÜİK	Turkish Statistical Institute
TWh	Terawatt-hour
US	United States
V2G	Vehicle to Grid
YEK-G	Renewable Energy Resources Certificates

Key Messages

- In 2035, integrating 11 million EVs (including LDVs) into Türkiye's distribution grid will necessitate an additional 12% (BAU scenario; 5 million EV and an additional 3.5%) investment beyond the expected expenditures required to meet non-EV load growth. This integration will result in a 41% reduction in emissions from passenger vehicles, preventing a total of 20 million tons of CO_2 from being released into the atmosphere.

- Developing investment strategies for distribution grids with a focus on e-mobility is crucial. Integrating electric vehicles into distribution grids, balancing system reliability and capital allocation to DSOs for e-mobility loads, as well as allocating dedicated transformer capacity for e-mobility loads and planning new transformers for other types of loads, can effectively facilitate this transition. Consequently, a collaborative approach involving stakeholders from the energy sector, automotive industry, regulatory bodies and research institutions is required to ensure the smooth integration of electric vehicles into the grid while maintaining reliability standard.

- Smart (and controlled) charging allows for the utilisation of renewable energy for EV charging, preventing renewable curtailment and facilitating greater integration of renewable energy into the grid. If flexibility mechanisms enabling controlled and smart charging are implemented, the impact of EV charging on the distribution systems can be mitigated, potentially deferring or even reducing grid investments.

- The implementation of smart charging strategies encourages cost-effective and grid-friendly charging, particularly during periods of low grid load or high availability of renewable energy sources. Time-varying tariffs, aligned with actual electricity production and delivery costs, can incentivize charging activities during off-peak hours, benefiting both EV owners and overall grid stability. The introduction of time-of-use tariffs tailored for EV users can capitalize on the inherent flexibility of EV charging. These tariffs are likely to emerge naturally and evolve as the market becomes more competitive with the increasing adoption of renewable energy and EVs, incentivizing energy suppliers to develop innovative pricing offers.

Executive Summary

A. Introduction

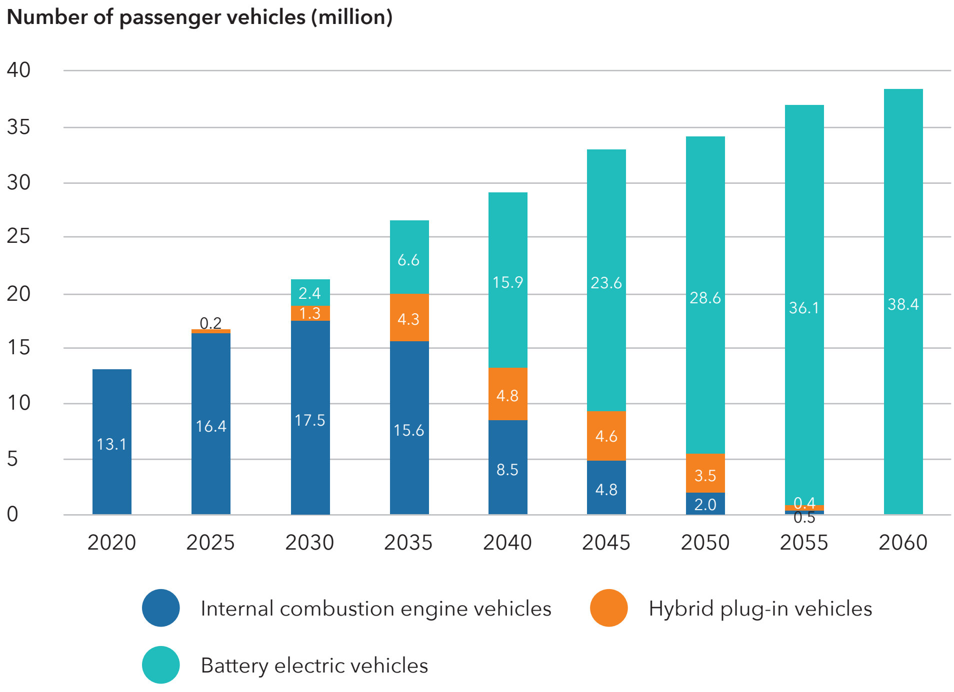
Electrification is a crucial component of the energy transition for decarbonising end-use sectors. Given the global net-zero targets and from an energy system perspective, electrification is the most effective strategy to reduce emissions and enhance energy efficiency in the transportation sector. Reflecting this urgency, global electric vehicle (EV) sales are increasing, driven by policies supporting the development of various types of EVs and the expansion of charging infrastructure. By the end of 2023, the total number of EVs in the global vehicle stock exceeded 40 million, with projections indicating approximately 350 million EVs worldwide by 2030.

In October 2021, Türkiye ratified the Paris Agreement and declared its commitment to achieving a net-zero emissions economy by 2053. This ambitious target necessitates a transition from fossil fuels to renewable energy, particularly in energy-intensive sectors such as industry, buildings, and transportation. At the end of 2022, the electricity consumption rate in the transportation sector's final energy consumption was a mere 0.4% in Türkiye. The Turkish transport sector is highly dependent on oil products, mainly diesel oil, gasoline, and liquefied petroleum gas (LPG). Consequently, the transportation sector, which is the third most energy-consuming sector after buildings and industry sector, has the highest reliance on fossil fuels, contributing approximately 22% of Türkiye's carbon dioxide (CO_2) emissions. Over 90% of these emissions originate from road transportation, highlighting the significant impact that transitioning to electric mobility could have.

As of the end of 2023, Türkiye had approximately 80,735 fully battery electric vehicles (BEV) and 5,906 plug-in hybrid electric vehicles (PHEV), representing a small but rapidly growing segment of the total vehicle fleet. Projections based on SHURA's net-zero emissions pathway[1] indicate that by 2035, Türkiye should have around 11 million EVs, including light-duty vehicles (LDVs) (see Figure 1). This growth in the number of EVs demands an estimated 37 terawatt-hours (TWh) of electricity annually.[2]

[1] SHURA, 2023. Net Zero 2053: A Roadmap for the Turkish Electricity Sector. https://shura.org.tr/wp-content/uploads/2023/05/Net-Zero-EN.pdf
[2] This is calculated considering 20 kWh/100km consumption for EVs and 104 kWh/100km for LDVs. The average daily distance for EVs and LDVs are assumed 40 km and 100 km, respectively.

Figure 1. The evolution of passenger vehicles based on SHURA's net-zero emissions pathway



B. Objectives

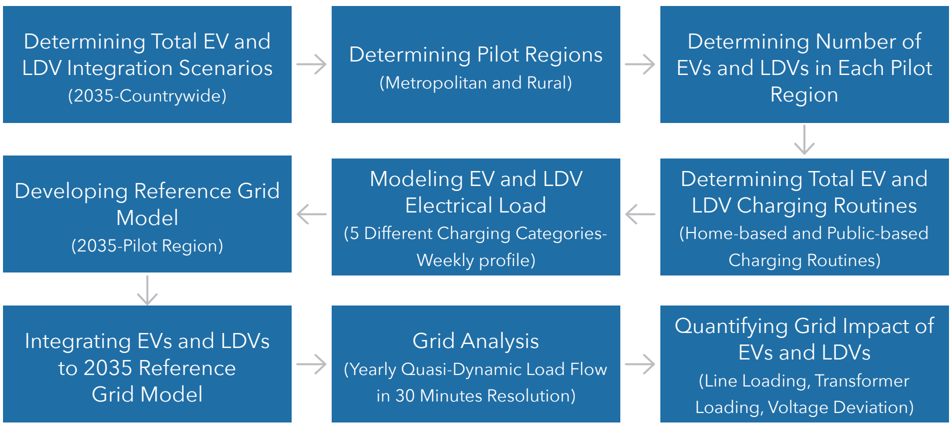
SHURA's 2019 study "Transport Sector Transformation: Integrating Electric Vehicles into Türkiye's Distribution Grids" demonstrated that 2.5 million EVs (representing 10% of the vehicle stock in 2030) could be integrated to Türkiye's distribution grid with minimal additional investments and limited impact on the operation of the distribution grids, as measured through maximum loading increments and voltage violations. Given the accelerated EV growth and its incremental effects on Türkiye's power grid in recent years, this new study is needed to update the general context and set sound targets for the EV ecosystem, as well as to propose innovative actions for the power grid.

The purpose of this study is to comprehensively examine the implications of electrifying the transportation sector in Türkiye. Based on analyses of two major electricity distribution grids, the study investigates the additional investment requirements arising from e-mobility, highlights countermeasures such as smart charging mechanisms to facilitate EV integration, and proposes policy recommendations for the smooth integration of e-mobility loads into the Turkish power system. In this context, the study presents an in-depth analysis of the integration of electric vehicles and LDVs into Türkiye's distribution grid, projecting to the year 2035. The study addresses the implications of increased e-mobility on grid infrastructure and proposes strategic solutions to mitigate potential challenges.

C. Methodology

In this study conducted by SHURA Energy Transition Center, **two main scenarios are considered: the SHURA net-zero scenario (Net0 Scenario), projecting an EV fleet of 11 million, and the business-as-usual scenario (BAU) projecting an EV fleet of 5 million by 2035.** Additionally, various sensitivity cases are explored, including the impact of excessive EV charging during holiday periods, the implementation of time-of-use tariffs and EV smart charging mechanisms, the adoption of Vehicle-to-Grid (V2G) technology, and the effects of excessive charging along highways. Furthermore, the study accounts for two main charging routines: home-based charging and public-based charging. Figure 2 illustrates the initial phase, which involves forecasting the market outlook, scenarios and grid impact analysis for the evolution of the total number of EVs and LDVs throughout Türkiye between 2024 and 2035.

Figure 2. Key steps in the methodology

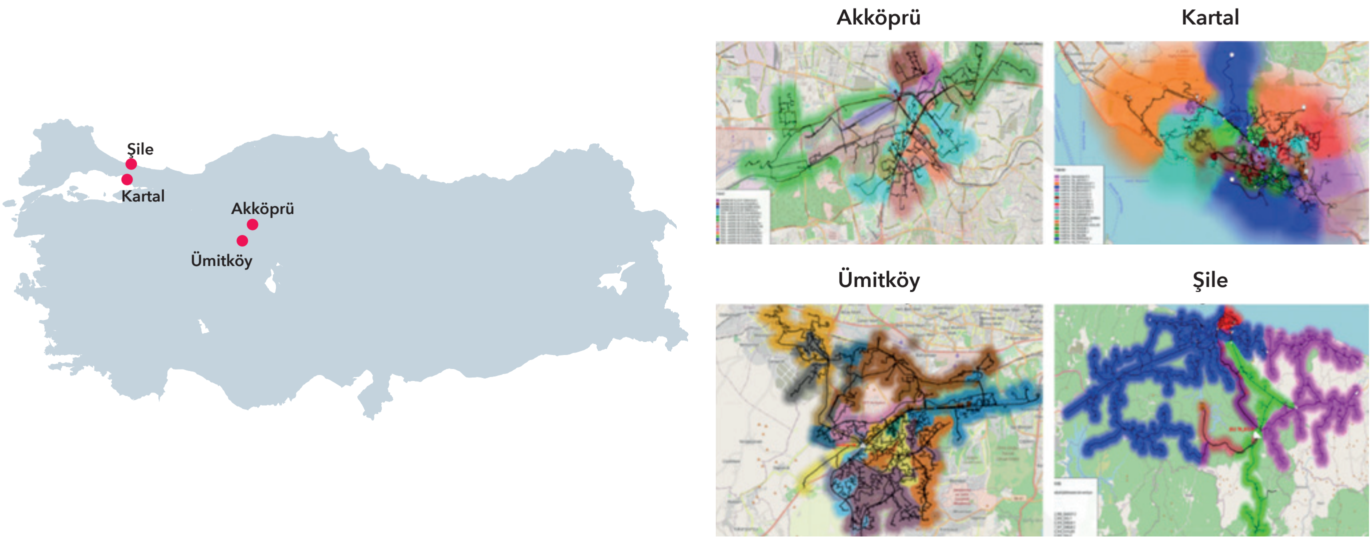


The studies are conducted in four pilot regions (Table 1) strategically selected from two distinct Distribution System Operators (DSOs)—BAŞKENT and AYEDAŞ DSOs. These pilot regions (Akköprü, Ümitköy, Kartal, and Şile) encompass 14% of Türkiye's population and contribute to approximately 13% of the nation's total energy consumption (Figure 3).

Table 1. Distribution companies and corresponding pilot HV substations

DSO	Pilot HV Substations	Region Type	Substation Installed Capacity (MVA) Year 2023
AYEDAŞ	Kartal	Metropolitan-Developed	200
	Şile	Rural	125
BAŞKENT	Akköprü	Metropolitan-Developed	300
	Ümitköy	Metropolitan-Developing	300

Figure 3. The MV grid model of the pilot regions – Current system, year 2023



D. Results and Discussion

The necessary level of electrification in the transport sector to meet Türkiye's climate target for 2053 requires 11 million EVs by 2035 according to SHURA's Net0 scenario.

By 2035, with 11 million EVs in operation according to SHURA's net-zero pathway, Türkiye is expected to see a significant reduction in CO_2 emissions. Specifically, CO_2 emissions will be reduced by 20 million tons (Mt), representing a 41% decrease in emissions from passenger cars.

Based on the findings from this study, **integrating 11 million EVs (including LDVs) into Türkiye's distribution grid will necessitate an additional 12% investment beyond the expected expenditures required to meet non-EV load growth.** For Business-as-Usual (BAU) scenario, which deals with integration of 5 million EVs (including LDVs) up to year 2035, e-mobility load asks for 3.5%

more investment. **Notably, the estimated investments for e-mobility do not account for potential benefits and savings from optimized EV charging.**

The main driver of this investment requirement is the impact of the low voltage (LV) system, particularly on MV/LV transformers and medium voltage (MV) line investment plans. In other words, the predominant burden imposed by e-mobility loads on the distribution grid comes from a distribution system reliability perspective. This necessitates proactive measures from distribution system planners, capital expenditure (CapEx) providers, and policymakers and regulatory authorities such as the Energy Market Regulatory Authority (EMRA) and the Ministry of Energy and Natural Resources (MENR) in Türkiye. Based on these findings, the investment prerequisites to accommodate the anticipated e-mobility load of 11 million EVs in Türkiye's metropolitan areas are as follows:

- 10% more MV/LV transformer investment on top of what should be invested up to year 2035;
- 16% more MV lines investment on top of what should be invested up to year 2035;
- 12% more investment costs on top of what should be invested up to year 2035.

For 5 million EVs, which corresponds to BAU scenario, the investment requirements are as follows:

- 3% more MV/LV transformer investment on top of what should be invested up to year 2035;
- 5% more MV line investment on top of what should be invested up to year 2035;
- 3.5% more investment on top of what should be invested up to year 2035.

In addition to regular charging behaviours and their associated impacts on the grid and investment requirements, the study investigates the effects of extensive charging on special days, such as periods preceding religious holidays (sensitivity case I). In such cases, simulation results indicate that the average loading of transformers serving e-mobility loads in residential areas surges to 97%, compared to the typical 40% under normal conditions. Similarly, the average loading of MV/LV transformers supplying public charging stations increases from 36% under normal conditions to 78% during periods of extensive charging. **Addressing such overloading through investment alone is not considered a rational solution. Instead, the deployment of controlled and smart charging mechanisms is essential to manage the increased load efficiently. This approach will ensure the reliability and sustainability of the distribution grid without necessitating disproportionate capital expenditures.**

To optimize grid integration, one smart charging scenario considered in this study (sensitivity case II) involves shifting EV charging to times when local renewable-based generation dominates the energy mix. By implementing load shifting mechanisms, e-mobility loads can be moved to less congested hours. For instance, in sensitivity case II, overloading is caused by the simultaneous charging of 385 EVs (alternative current (AC) type 2, 3.7 kilowatt (kW)), resulting in the loading of 11 MV/LV transformers beyond 90%. By postponing 56% of the charging load (219 EVs), the overloading on the MV/LV transformers is alleviated.

Additionally, targeting hours with low loads and high renewable generation helps avoid renewable energy curtailments. EV loads can be shifted to periods when renewable energy is abundant, such as noon for solar power and night for wind energy. **This strategy allows for the utilisation of renewable energy for EV charging, preventing renewable curtailment and facilitating greater integration of renewable energy into the grid.**

Under both home-based and public-based charging routines, the benefits of synergies between renewable energies, flexibility measures such as storage, and EV charging are evident. **If flexibility mechanisms enabling controlled and smart charging are implemented, the impact of EV charging on the distribution systems can be mitigated, potentially deferring or even reducing grid investments.**

Figure 4. The loading of a 630-kVA MV/LV transformer feeding e-mobility loads – Uncontrolled charging profile vs smart (controlled) charging

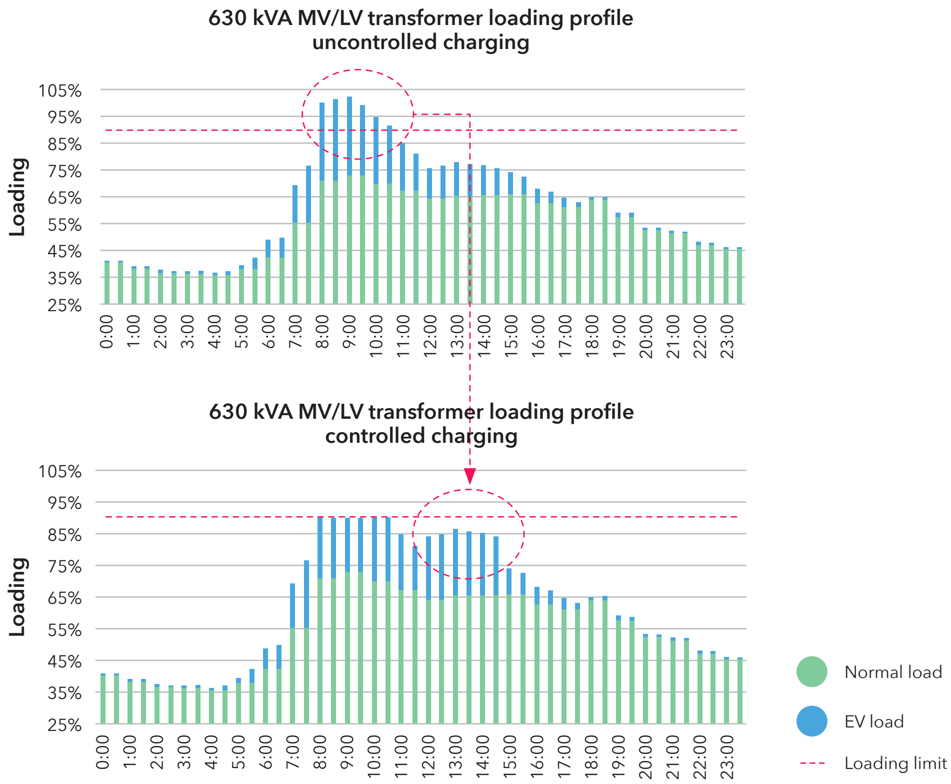


Figure 5. The impact of e-mobility loads on a portion of the distribution system in the Akköprü region: Smart (controlled) vs uncontrolled charging

Uncontrolled charging **Controlled charging**

V2G mechanisms can also be considered as controlled charging/discharging mechanisms, where certain levels of EV charging demand are met by V2G-ready EVs. In the conducted simulation (sensitivity case III), the same condition, overloading 11 MV/LV transformers with simultaneous charging of 385 EVs (AC type 2, 3.7 kW), is alleviated by serving only 25% of the e-mobility load through other available cars. Although a certain level of infrastructure and market mechanisms is required for the realisation of V2G, it can be an effective approach to limit the impact of e-mobility loads on distribution systems and defer required investments.

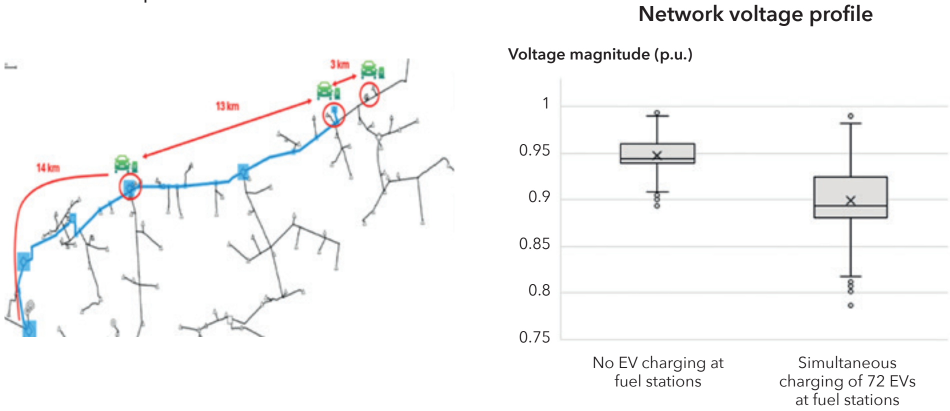
Figure 6. The impact of V2G on a portion of the Akköprü distribution grid

385 AC2 EVs charging **385 AC2 EVs charging, 94 EV discharging**

Another option when smart charging mechanisms are unavailable is simple controlled charging, where local automation solutions contribute to managing the e-mobility load. For instance, in the case of charging along highways (sensitivity case IV), coordinating charging across consecutive charging points on one weak feeder is a challenging task. As depicted in Figure 7, if all charging plugs at fuel stations are loaded with e-mobility loads (100 kW direct current (DC)), the voltage drop in the network becomes inevitable. Such conditions can occur during holiday periods when people are traveling with their EVs, and most of the charging points will be occupied.

To maintain the voltage within permissible operational levels, investments in reinforcing feeding conductors may be a solution. However, as such cases may happen only a few days per year, operational measures such as controlled charging are also viable solutions.

Figure 7. Typical charging along highways and the voltage profile of the network depicted



Here, based on the loading level of the feeder or the voltage magnitude drop resulting from e-mobility loads, simultaneous charging can be limited.

Smart charging mechanisms are essential to save system costs, particularly in avoiding grid investments that may seem unrealistic to cover maximum capacity needs. Implementing smart charging solutions involves advanced metering and automated charging responses to pricing signals. **Initially, time-of-use and/or dynamic pricing mechanisms are required, which can then evolve into flexibility aggregation mechanisms through aggregators to harness EV flexibility at specific hours.**

An additional step involves establishing local flexibility markets, enabling aggregated flexibility trading with DSO coordination. Developing region-specific pricing strategies to manage e-mobility loads effectively is advised. Flexibility markets and locational marginal pricing should be leveraged to reflect the true cost of local technical constraints.

Establishing synergies between EV charging, renewable energy integration, and energy storage can enhance overall grid efficiency and resilience, supporting the transition to a more sustainable energy system. Coordinating the planning of EV charging infrastructure with grid capacity is crucial to ensure optimal deployment and cost-efficiency. Strategic planning is essential to anticipate and mitigate potential grid impacts.

E. Priority Areas for Transforming Türkiye's Transportation Sector

Drawing from the findings of this study, five priority areas have been outlined for energy policymakers, the market regulator, distribution grid companies, the automotive industry, charging technology developers and investors, urban planners, and academia.

1. Accelerate the market for EVs and charging services in parallel:

- Purchase Incentives: Implementing purchase incentives such as price rebates or tax deductions may stimulate EV sales significantly. These incentives should be strategically combined with measures aimed at phasing out internal combustion vehicles.

- Government Leadership: Public institutions should take a proactive role in fostering the EV market. This includes setting ambitious targets, providing regulatory support, and investing in research and development to advance EV technology.

- Electrification of Public and Fleet Vehicles: Subsidies or incentives can encourage fleet operators to transition to electric vehicles.

- Charging Infrastructure: Public authorities should invest in the deployment of charging stations in strategic locations, such as urban centres, highways, and parking facilities. Public-private partnerships can also incentivize businesses to install charging infrastructure on their premises.

- Phased Approach: While critical in the early stages of market development, EV incentives should be gradually phased out to establish a sustainable and competitive market. This allows for a smooth transition and ensures the long-term viability of the EV market.

2. Develop E-mobility-oriented distribution grid ınvestment strategies:

- Collaborative Approach: To accommodate 11 million EVs by 2035, the distribution grid will require at least a 12% increase in investment beyond the planned expenditure for non-EV load growth, which is assumed to rise by an average of 5% annually. The primary challenge lies in the LV grid's constraints, impacting overall reliability. This necessitates additional investments, particularly in LV systems, which affects MV and LV transformers and lines in a cascading manner. Policymakers and regulatory authorities, such as MENR and EMRA, should allocate specific e-mobility-related capital expenditures (CapEx) to DSOs to cope with these challenges. Alternatively, as a low-cost, temporary solution, they could relax reliability criteria, such as Customer Average Interruption Duration Index (CAIDI) and Customer Average Interruption Frequency Index (CAIFI) limits, to soothe EVs' integration into the distribution grid. Achieving a trade-off between maintaining reliability and dedicating CapEx for e-mobility is crucial. This optimisation should be coordinated by MENR, EMRA, and DSOs or their association, the Electricity Distribution Services Association (ELDER). Additionally, allocating specific transformer capacity for e-mobility loads and planning new transformers for other load types can effectively pave the way for this transition. Ultimately, a collaborative approach is essential to ensure seamless integration of EVs into the grid while maintaining reliability standards, involving stakeholders from the energy sector, automotive industry, regulatory bodies, and research institutions.

3. Develop time-specific and region-specific charging measures

- **Development of time-varying charging price strategies:** The implementation of smart charging strategies encourages cost-effective and grid-friendly charging, particularly during periods of low grid load or high availability of renewable energy sources. Time-varying tariffs, aligned with actual electricity production and delivery costs, can incentivize charging activities during off-peak hours, benefiting both EV owners and overall grid stability. The introduction of time-of-use tariffs tailored for EV users can capitalize on the inherent flexibility of EV charging. These tariffs are likely to emerge naturally and evolve as the market becomes more competitive with the increasing adoption of renewable energy and EVs, incentivizing energy suppliers to develop innovative pricing offers.

- **Introduction of time-of-use network pricing:** Volumetric time-of-use pricing of power networks is an essential condition to ensure efficient utilisation of existing grid capacity through distributed energy resources. Compared to other network tariff designs where the cost of using power networks is based on the annual peak demand capacity (so-called demand charges), a predominantly volumetric design is more suitable for flexible electrified end-uses such as EVs.

- **Development of region-specific charging price strategies:** The adoption of e-mobility can pose challenges to the distribution grid, such as line/transformer overloading and voltage drops, although these issues vary by region. Overloading tends to be more pronounced in certain areas and can be alleviated by directing e-mobility loads to less congested feeders through settlement mechanisms and regional pricing strategies. This necessitates the establishment of flexibility markets within distribution systems to aggregate flexibility, demand response, V2G, and peer-to-peer options, ultimately enhancing grid resilience and reliability.

4. Plan, develop, and ımplement smart charging mechanisms to limit the ımpact of e-mobility loads on distribution grids

- Grid-integrated planning of EV charging infrastructure: Charging infrastructure planning should involve detailed mapping of expected charging demand matched with maps of available or planned grid capacity. This approach enables grid- and cost-optimal deployment of charging infrastructure. DSOs should provide information on grid capacity, such as hosting capacity maps, to facilitate informed decision-making during the planning process.

- Deployment of intelligent technologies to support grid-friendly EV uptake: Global pricing trials have shown that smart charging mechanisms optimize EV integration into the power system. These technologies include advanced metering systems and automated charging that responds to pricing signals. Charging infrastructure, both current and future, should incorporate smart functionality, even if not immediately utilized. This is particularly important for workplaces and public stations, where many EVs charge for extended periods. Mandating smart functionality can ensure control over peak-hour usage, maximizing the potential for optimized charging.

- Establishment of synergies between EV charging, renewable energy integration, and energy storage: A comprehensive approach to energy and transportation planning is essential for the cost-efficient integration of EVs into the grid and realizing their benefits. In the medium to long term, nuanced pricing structures, such as efficient market mechanisms, are necessary to integrate renewables and effectively manage flexible loads, like EVs, efficiently. For instance, incentivizing EV charging during peak solar generation periods through price adjustments can optimize grid utilisation and alleviate technical constraints, such as voltage fluctuations caused by excess solar energy generation. This benefits EV owners and enhances grid stability. Additionally, enhancing the implementation of time-varying network pricing and maximizing the efficiency of existing infrastructure are crucial for deferring costly grid investments.

- Development of local automation schemes to manage the impact of simultaneous and excessive charging: In addition to smart charging mechanisms, integrating local automation capabilities into current and future charging infrastructure is essential. These automation features enable control over and the limitation of simultaneous charging events, which significantly affect the reliable operation of distribution systems.

5. **Assess, develop, and implement new business models for EV charging:** Despite the global progress in EV charging infrastructure, creating a sustainable business case remains a significant challenge for many companies. Public support programs are crucial to facilitate the commercialisation of the EV charging market. In Türkiye, EV charging infrastructure policies should focus on transitioning to commercial operations, with subsidies tied to the number of EVs and gradually reduced. Separating installation cost subsidies from operational costs promotes viability. Monitoring and sharing charging point utilisation data is crucial for informed decision-making. Public-private co-funding models can address low-capacity locations, and electricity network companies might ensure regional coverage through public tenders. Battery-assisted chargers offer flexibility, allowing relocation based on demand and energy storage during peak hours. These strategies would enhance the efficiency and sustainability of EV charging infrastructure.

1. Introduction

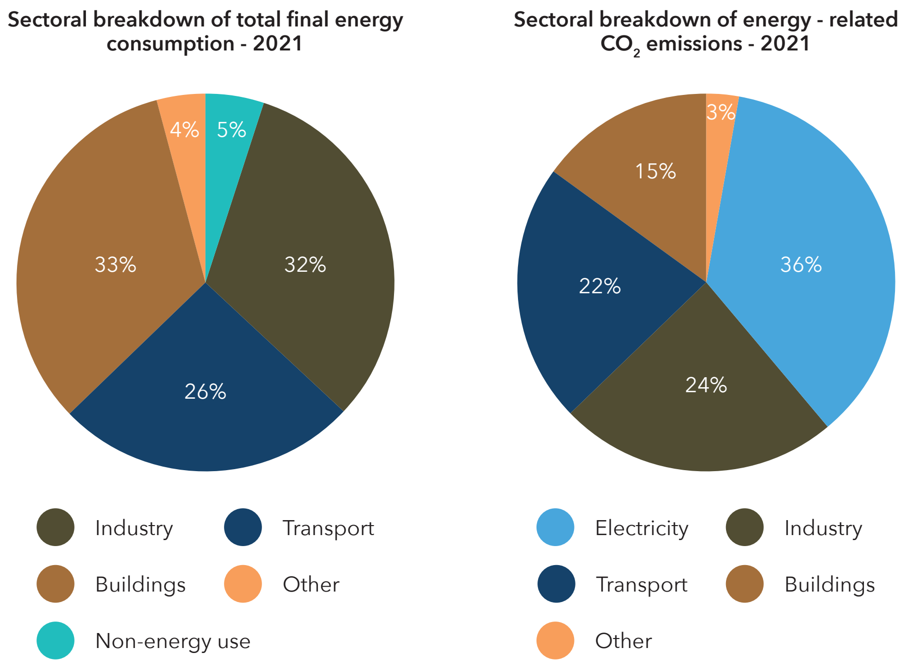
In October 2021, Türkiye ratified the Paris Agreement and subsequently declared its commitment to achieving net-zero emissions by 2053. This ambitious target necessitates a transition from fossil fuels to a renewable energy-based system as well as the decarbonisation of energy-intensive sectors such as industry, buildings, and transportation. Additionally, the target requires a shift towards energy-efficient, low-carbon, and high value-added production methods for industry. While ensuring supply security, economic access to energy, and emissions mitigation are crucial factors in Türkiye's energy transition, numerous policies are being rapidly developed to address these concerns. Among the most significant strategies within the context of electrification are those that aim to promote the direct (e.g., using electric vehicles (EV) or heat pumps in buildings) or indirect (e.g., through synthetic fuels or green hydrogen obtained by electrolysis) use of electricity. The power system is, therefore, the backbone of Türkiye's efforts to achieve its net zero (Net0) emissions target and decarbonize its economy.

Türkiye's commitment to renewable energy is exemplified by surpassing its 2023 target outlined in the 11th Five-Year Development Plan, in which it targeted renewables contributing over 40% to the electricity generation mix.[3] Today, approximately 42.3% of Türkiye's total electricity supply is currently sourced from renewables, with hydropower claiming a substantial share. The alignment between the transportation sector and an increasingly renewable-powered electricity grid has set the stage for a transformative shift towards sustainable and decarbonized transportation in Türkiye.

The transportation sector plays a significant role in Türkiye's energy landscape, constituting 26% of the country's total final energy demand (see Figure 8).[4] This sector, positioned as the third-largest consumer after the buildings and industry sectors. Notably, the transportation sector contributes approximately 22% of Türkiye's carbon dioxide (CO_2) emissions, with over 90% of these emissions originating from road transportation.[5] This substantial carbon footprint is primarily attributed to the sector's reliance on oil products, which constitute about 99% of its energy mix. In contrast, electricity accounts for a mere 0.4%, and renewables represent just 0.5% of the total energy mix[6] of the transportation sector.

[3] T.C. Cumhurbaşkanlığı Strateji ve Bütçe Başkanlığı, 2023. ON İKİNCİ KALKINMA PLANI (2024-2028). https://www.sbb.gov.tr/wp-content/uploads/2023/12/On-Ikinci-Kalkinma-Plani_2024-2028_11122023.pdf
[4] TMMOB Makina Mühendisleri Odası, n.d. ULAŞTIRMA SEKTÖRÜNDE ENERJİ VERİMLİLİĞİ. https://www.mmo.org.tr/sites/default/files/c9882bbac1c7093_ek.pdf
[5] SHURA, 2018. Türkiye ulaştırma sektörünün dönüşümü: Elektrikli araçların Türkiye dağıtım şebekesine etkileri. https://shura.org.tr/wp-content/uploads/2019/12/SHURA-2019-12-Turkiye-Ulastirma-Sektorunun-Donusumu-Elektrikli-Araclarin-Turkiye-Dagitim-Sebekesine-Etkileri.pdf)
[6] Enerji ve Tabii Kaynaklar Bakanlığı, 2024. Ulusal Enerji Denge Tabloları. https://enerji.gov.tr/eigm-raporlari

Figure 8. Breakdown of total final energy consumption and energy-related CO_2 emissions in Türkiye, 2021[7,8]



Source: IEA

To address the necessity of decarbonisation in the transportation sector, various strategies are being explored, including enhancing energy efficiency, electrification, and transitioning to carbon-neutral alternatives. EVs are gaining widespread adoption globally due to their manifold benefits, ranging from contributing to cleaner urban environments to facilitating electricity load management and achieving greater overall efficiency.

The global EV fleet surpassed 26 million units by the end of 2022.[9] The number of EVs in different countries along with associated geographical distribution are depicted in Figure 9 and Figure 10, respectively.

[7] IEA, n.d. Türkiye. https://www.iea.org/countries/turkiye/emissions
[8] IEA, n.d. Türkiye. https://www.iea.org/countries/turkiye/energy-mix
[9] IEA, 2024. Global EV Data Explorer. https://www.iea.org/data-and-statistics/data-tools/global-ev-data-explorer

Figure 9. The number of EVs in different countries

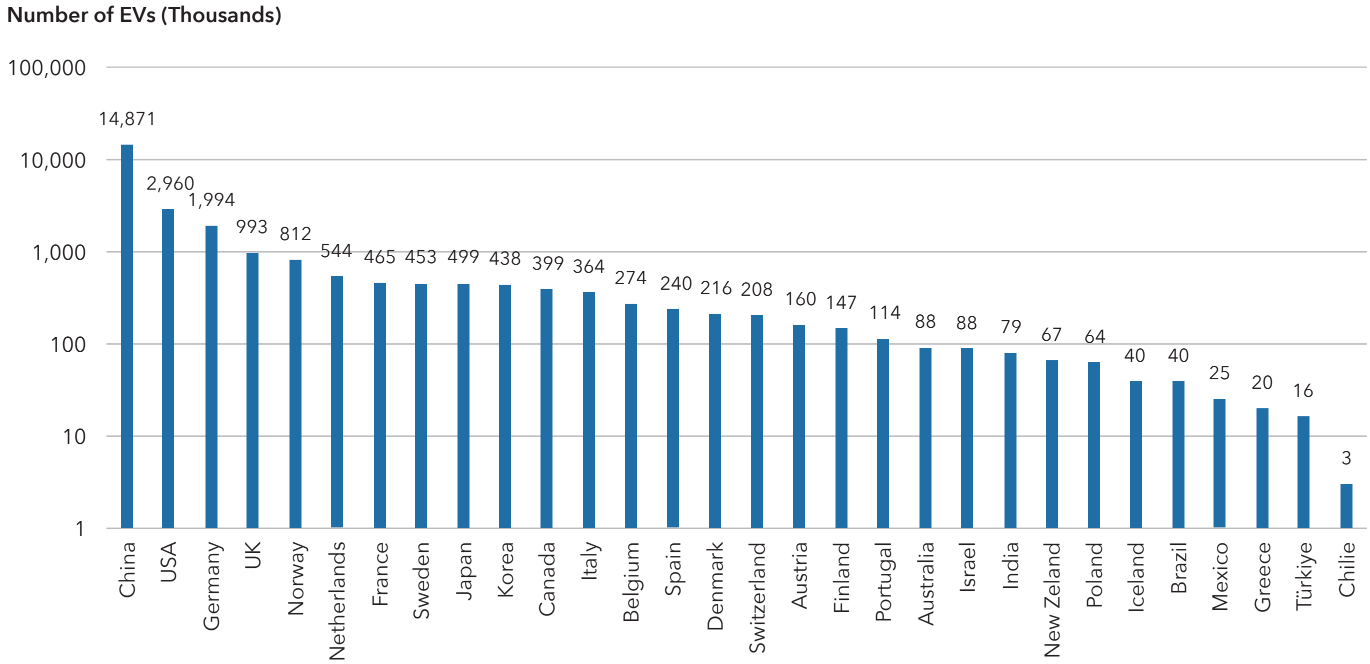
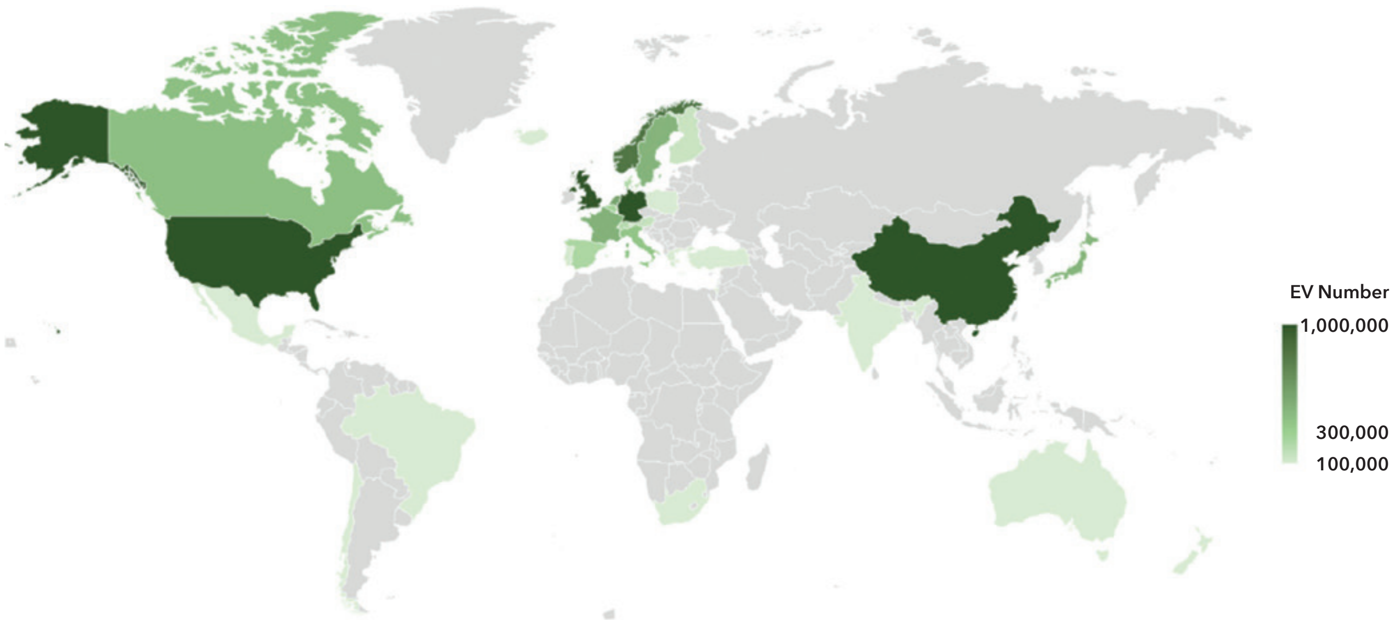


Figure 10. The geographical distribution of EVs in different countries



Within the Turkish context, the EV landscape is evolving, with 80,735 fully battery-powered EVs (BEV) and approximately 5,906 plug-in hybrid electric vehicles (PHEV) recorded by the end of 2023, accounting for 0.5% of the total vehicle fleet.[10] The geographical distribution of EVs and charging sockets across Türkiye are illustrated in Figure 11 and Figure 12, respectively. Albeit from a low base, rapid growth is projected for the share of EVs in the evolution of passenger vehicles based on SHURA's net-zero emissions pathway depicted in Figure 13.

Figure 11. The geographical distribution of electric vehicles in Türkiye – Year 2023

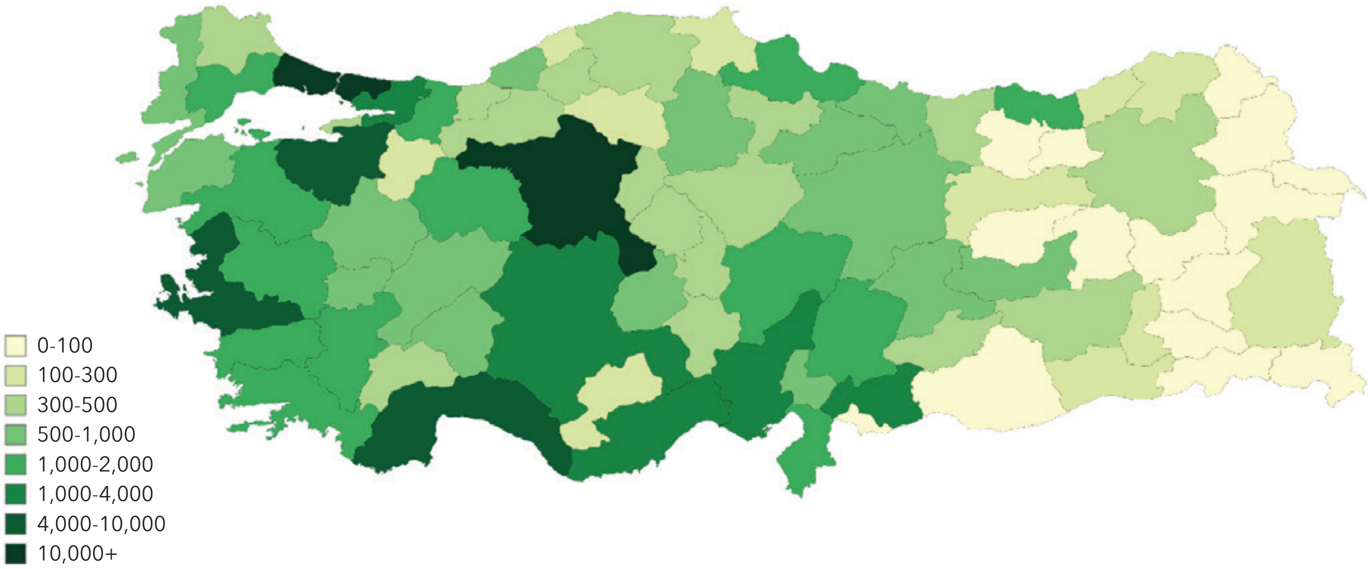
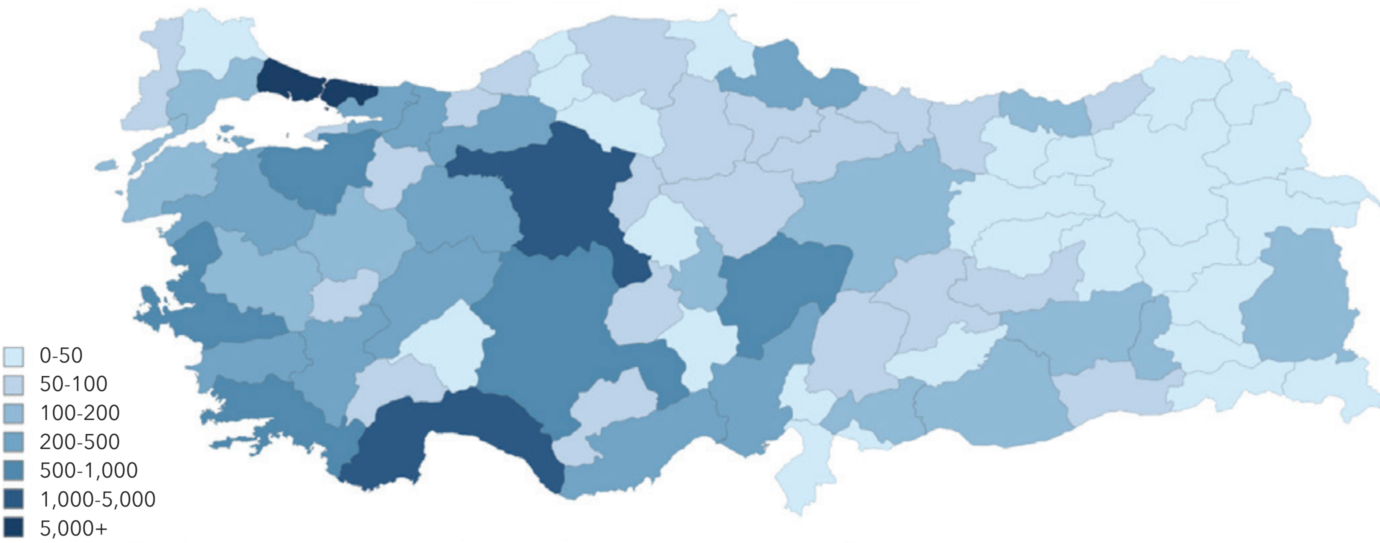
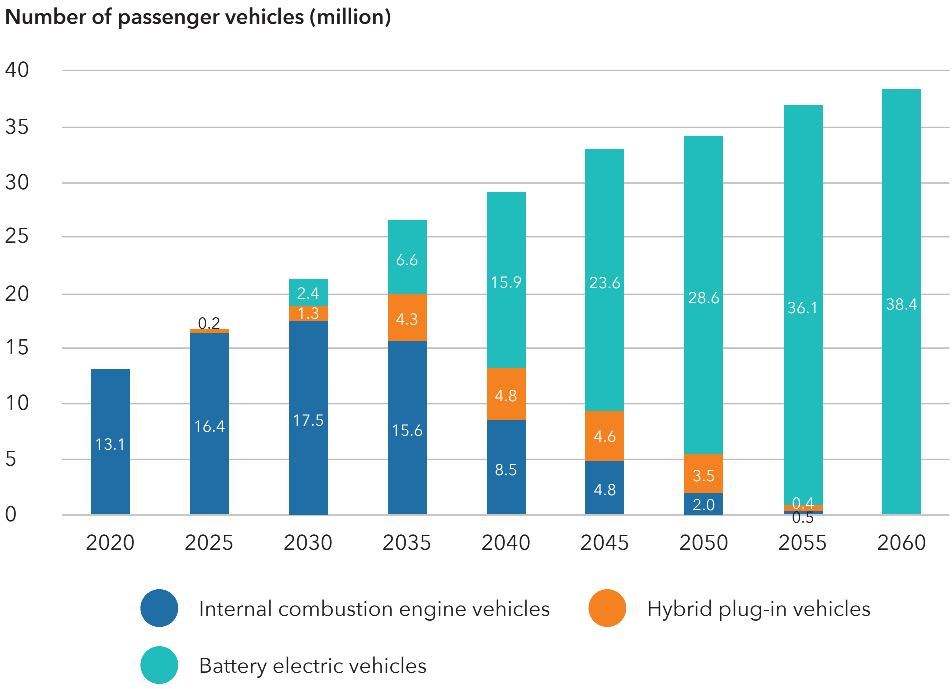


Figure 12. The geographical distribution of charging sockets in Türkiye – Year 2023



[10] European Commission, n.d. European Alternative Fuels Observatory. https://alternative-fuels-observatory.ec.europa.eu/

Figure 13. The evolution of passenger vehicles based on SHURA's net-zero emissions pathway



For the purposes of this study, both BEVs and PHEVs are collectively referred to as EVs, excluding unplugged hybrid vehicles from consideration. This burgeoning EV fleet in Türkiye, which is projected to evolve from 80,735 EVs in 2023 to around 11 million EVs in 2035, demands an estimated 37 terawatt-hours (TWh) of electricity annually.[11] However, the scope of electrification is not confined to passenger cars alone; buses, mini-buses, and various other forms of road-based public transport, including two/three-wheelers, present ample opportunities for electrification. Moreover, the potential for electrifying road freight and city logistics further underscores the multifaceted role of electric mobility. The success of electric mobility, particularly in contributing to low-carbon transitions and improved air quality, however, hinges on the concurrent decarbonisation of the power sector.

While EVs and a conventional internal combustion engine vehicle share the common goal of transporting passengers and freight, they diverge significantly in terms of energy utilisation. Traditional vehicles rely on a petrol tank and a 12-volt battery, fuelled by non-renewable crude oil products. Their one-way operating principle involves fuel combustion and motor drive generation controlled by an alternator and fuel injector. In contrast, an EV features an electric motor, a battery pack, a charger, and an AC-DC inverter to regulate the motor. The EV's battery pack, rechargeable wherever electricity is available,

[11] This is calculated considering 20 kWh/100km consumption for EVs and 104 kWh/100km for LDVs. The average daily distance for EVs and LDVs are assumed 40 km and 100 km, respectively

presents a dynamic energy storage system, offering flexibility that can be used to optimize charging according to grid or user needs (smart charging). With "vehicle-to-grid (V2G)" solutions coming closer to market, stored electricity can be also redirected to the grid and serve as a distributed energy source.

While conventional vehicles can refuel in minutes, EVs' charging time varies from minutes to hours, contingent on charging technology and battery size. Factors such as charging business models, electricity pricing signals, and driving habits influence when an EV is charged throughout the day. On average, an EV drives approximately 35 kilometers (km) per day.[12] An EV owner charging the vehicle upon returning home in the evening can amass enough power to cover 300 km overnight, allowing for a more flexible charging duration of 1–2 hours to accommodate average day trip distances.[13] Such flexibility allows for optimized charging hours and mitigates potential impacts on evening electricity load profiles, as simultaneous charging patterns during peak hours could lead to unmanageable loads. Fast-charging EVs at workplaces or public locations could shift the daily load, though not necessarily coinciding with peak periods. This scenario poses a challenge to grid management, necessitating strategic planning to handle exacerbating potential load profile.

Charging EVs also involves a number of opportunities for efficient energy consumption based on the real-time energy generation mix, showcasing opportunities for sustainable sourcing during periods of ample renewable energy, such as sunny summer days or periods of high wind production overnight. Using stored solar energy harvested from rooftop solar photovoltaic (PV) panels—for example, discharging the stored energy for night charging—adds another layer of flexibility. Recognizing EVs as not just transport vehicles but also as flexibility resources offers benefits for both the transportation and power sectors. Understanding and planning for these synergies is of paramount importance for the effective load management of power grids. Power grids, traditionally designed around peak demand periods, must anticipate the evolving EV landscape and should envision proper countermeasures to cope with the impact of EVs on the power grid. Regulations from policymakers and regulatory authorities such as the Ministry of Energy and Natural Resources (MENR) and Energy Market Regulatory Authority (EMRA) play a crucial role in shaping the charging service landscape, emphasizing the need for updated policies and frameworks in the rapidly evolving EV ecosystem.[14]

In SHURA's 2019 report, "Transport Sector Transformation: Integrating Electric Vehicles into Türkiye's Distribution Grids," SHURA estimated that 2.5 million

[12] TÜİK, 2023. Taşıt-kilometre İstatistikleri, 2021.https://data.tuik.gov.tr/Bulten/Index?p=Tasit-kilometre-Istatistikleri-2021-49527
[13] HedefFilo, n.d. ELEKTRİKLİ ARAÇ LİSTESİ. https://ev.hedeffilo.com/ev-nedir/elektrikli-arac-listesi
[14] EMRA last published a charging service regulation on 2 April 2022.

EVs (representing 10% of the vehicle stock in 2030) could be integrated to Türkiye's power grid with almost no additional investments and limited impact on the operation of the power grid (measured by maximum loading increment and voltage violations). With accelerated EV growth and its incremental effects on Türkiye's grid in recent years, this new study has been needed to update the general context and envision sound targets for the EV ecosystem and innovative actions for the power grid.

The purpose of this study is to comprehensively examine the implications of electrifying the transportation sector on two major electricity distribution grids in Türkiye, investigating the additional investment requirements of e-mobility, highlighting the countermeasures (such as smart charging mechanisms) to ease EV integration, and proposing proper policy recommendations for the smooth integration of e-mobility loads into the Turkish power system. The pilot regions account for approximately 14% of the total population and a corresponding share of the overall electricity demand. Out of the 21 total distribution system operators (DSO), the investigation centres on two significant distribution networks. The research framework, as illustrated in Figure 14, targets the year 2035, evaluating two principal scenarios: the Net0 pathway and the business-as-usual (BAU) scenario. The Net0 scenario aligns with the Net0 pathway articulated by SHURA Energy Transition Center,[15] envisioning the integration of around 11 million EVs and light duty vehicles (LDVs)[16] by 2035. In contrast, the BAU scenario incorporates projections from the Ministry of Science, Industry, and Technology in Türkiye, anticipating 1.6 million EVs and LDVs by 2030. Extrapolating this trend to 2035 estimates the presence of 5 million EVs and LDVs.[17]

Figure 14. The framework of the conducted study

Target Year
- Year 2035

Scenarios
- Business-as-usual (BAU)
- Net-zero pathway (Net0)

Pilot Region
- Metropolitan
- Rual

Analysis Time Frame
- Weekly time frame
- 30-minute time steps

Charging Routine
- Home-based charging
- Public-based charging

Sensitivities
- Excessive charging at holiday times
- Smart charging mechanisms
- Vehicle to grid impact
- Charging at highway

Key Performance Indices
- MV and LV branches overloding
- Voltage drop/raise
- MV/LV transformer loading and capacity factor
- Investment requirements

[15] SHURA, 2023. Net Zero 2053: A Roadmap for the Turkish Electricity Sector. https://shura.org.tr/wp-content/uploads/2023/05/Net-Zero-EN.pdf
[16] Here, the term "passenger cars and light duty vehicles" refers to vehicles weighing less than 3.5 tons. https://www.hedeffilo.com/blog/ticari-hafif-ticari-ve-binek-arac-nedir-farklari-nedir
[17] This report does not include electric heavy-duty vehicles such as delivery and long-haul trucks and buses.

This study concentrates on four pilot regions—Kartal, Akköprü, Ümitköy, and Şile—selected from BAŞKENT and AYEDAŞ DSOs, encompassing both metropolitan and rural areas across the country. Simulations in this study operate on a weekly timeframe, covering both weekday and weekend profiles, utilizing 30-minute time steps to capture the intricacies of direct current (DC) fast charging technology. Two distinct charging routines are considered: home-based charging, predominantly occurring at residential charging points, and public-based charging, including a higher share of charging at publicly accessible charging points. Beyond the primary scenarios of BAU and Net0, four additional sensitivity analyses are conducted to evaluate the impact of EVs and LDVs under varying conditions. Central to this investigation is the exploration of the impact of EVs and LDVs on the power grid through comprehensive computer simulations. The study goes further to identify the investment requirements necessary to mitigate the impact of electrifying the transportation sector on the power grid. This holistic approach ensures a thorough understanding of the multifaceted challenges and opportunities posed by the electrification of the transportation sector in Türkiye by 2035. This study examines both the proper countermeasures (such as smart charging mechanisms) to ease EV integration and policy recommendations for the smooth integration of e-mobility loads into the Turkish power system.

This report is organized as follows: Section 2 deals with the recent global developments and accelerating policies to roll out transportation section electrification. Afterwards, in Section 3, the current situation of Türkiye's transportation sector, including the current market and EV policies, is presented. The methodology is outlined in Section 4, and the results and discussion are detailed in Section 5. The report concludes with Section 6, which outlines the priority areas for DSOs, power system planners, EV manufacturers, and charging infrastructure planners and licensors relevant to Türkiye's transportation sector transformation.

2. EV Grid Integration in The Global Context

The global market for electric vehicles (EVs) is maturing quickly. In 2022, EVs accounted for almost a quarter of new vehicle registrations in China, 19% of new vehicle registrations in Europe, and 7% in the United States.[18] This is two to three times higher than EV registrations in 2020 in the mentioned regions. National and local policies targeting the tailpipe emissions of road transport vehicles, such as the European carbon dioxide (CO_2) standards for light duty vehicles (LDVs)[19] and the LDV greenhouse gas (GHG) emissions regulations in the United States (US),[20] further contributed to this growth, resulting in a growing global EV fleet over the past decade.

With a continuously growing fleet, challenges and opportunities arise with regard to the integration of the EV fleet into the power grid. If additional demand from EVs remains unmanaged, this could lead to substantial cost increases to meet EVs' power and delivery needs, as EVs would likely be charged during existing peak periods, thus exacerbating peak demands. If this transition is not managed carefully, the associated growth in electricity demand will lead to higher costs for consumers, the power system, and the environment and may slow down the transition to a cleaner road transportation sector.[21,22] Smart or managed EV charging can help overcome many of these challenges and utilize EV charging to provide optimum system flexibility. Smart charging is a key tool to reduce the consumption of electricity from fossil fuels and integrate more variable renewables into the grid by charging EVs when there is sufficient renewable energy available. In doing so, smart charging can maximize carbon emissions reductions and reduce the need for costly and unnecessary upgrades of the power grid.[23] While smart charging of EV fleets has been studied from the user benefits point of view,[24]

[18] Monteforte, M., Bernard, Y., Bieker, G., 2023. EUROPEAN VEHICLE MARKET STATISTICS 2022/23. https://theicct.org/publication/european-vehicle-market-statistics-2022-23/

[19] European Commission, n.d. CO_2 emission performance standards for cars and vans. https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/co2-emission-performance-standards-cars-and-vans_en#:~:text=From%202035%20onwards%2C%20the%20EU,of%20its%20registered%20new%20vehicles.

[20] EPA, 2023. Light-Duty Vehicle Greenhouse Gas Regulations and Standards. https://www.epa.gov/regulations-emissions-vehicles-and-engines/light-duty-vehicle-greenhouse-gas-regulations-and

[21] Das, H.S., Rahman, M.M., Li, S., Tan, C.W., 2020. Electric vehicles standards, charging infrastructure, and impact on grid integration: A technological review. doi: 10.1016/j.rser.2019.109618

[22] Ashfaq, M., Butt, O., Selvaraj, J., Rahim, N., 2021. Assessment of electric vehicle charging infrastructure and its impact on the electric grid: A review. doi: 10.1080/15435075.2021.1875471.

[23] Hildermeier, J., Rosenow, J., Hogan, M., Wiese, C., Jahn, A., Kolokathis, C., 2019. Smart EV Charging: A Global Review of Promising Practices. doi: 10.3390/wevj10040080.

[24] Hildermeier, J., Burger, J., Jahn, A., Rosenow, J., 2022. A Review of Tariffs and Services for Smart Charging of Electric Vehicles in Europe. doi: 10.3390/en16010088.

it is important to better understand the value that EVs can have as flexible assets for the power system[25] and for power networks in large EV markets.[26,27]

This section reviews policies for smart EV grid integration in key global EV markets as an important context for the developments in Türkiye (2.1.). We define smart and bidirectional EV charging and discuss its benefits as well as the key building blocks to unlock these, such as tariff design and grid planning (2.2.).

2.1 Policy framework for EV grid integration in the EU and U.S.

While EV policy frameworks in large global EV markets have been targeting EV uptake, there is increasing awareness among policymakers of the need to enable optimal grid integration of EVs into power markets to minimize costs and maximise the benefits of road transportation electrification.

In the European Union (EU), the Alternative Fuels Infrastructure Regulation (AFIR), which entered into force on 13 April 2024, requires the building of essential public charging networks starting from 2025.[28] It sets targets for installed capacity and density for both light and heavy duty EVs. All new charging infrastructure is required to be smart, e.g., able to measure and communicate consumption, an important condition to allow optimized charging. In addition, recently agreed energy market reforms are likely to improve the demand-side flexibility regulatory framework. This includes:

- A lower threshold for aggregated flexibility resources, e.g., EVs, to participate in flexible markets,
- Higher transparency requirements for grid operators to disclose grid information, facilitating market access for aggregators,
- Encouraging Distribution System Operators (DSOs) to remove the capital expenditure (CapEx) bias towards leaner operations, using flexibility resources such as EVs,
- Requirements for detailed demand forecasts, including those from EV charging, for grid (investment) planning, and
- Encouraging national energy regulators to introduce time-varying tariffs.

[25] IEA, 2023. Grid Integration of Electric Vehicles - A manual for policy makers. https://iea.blob.core.windows.net/assets/21fe1dcb-c7ca-4e32-91d4-928715c9d14b/GridIntegrationofElectricVehicles.pdf
[26] Anwar, M., Muratori, M., 2022. Assessing the value of electric vehicle managed charging: a review of methodologies and results. doi: 10.1039/D1EE02206G.
[27] Xue, L., Jian, L., Ying, X., Xiaoshi, L., 2020. Quantifying the Grid Impacts from Large Adoption of Electric Vehicles in China. https://www.wri.org/research/quantifying-grid-impacts-large-adoption-electric-vehicles-china
[28] European Union, 2023. REGULATIONS. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1804

That said, previous provisions concluded in 2019 and designed to advance demand-side flexibility in national legislation have not been fully implemented, and the rollout of smart meters has been slow in some European countries such as Germany.[29]

Recently revised European building regulations necessitate that residential and non-residential buildings be fitted with charging infrastructure for EVs and pre-cabling, respectively, and present an important opportunity to accelerate residential and workplace charging.[30] The regulation's requirements to enable smart and, where appropriate, bi-directional charging, sets fundamental conditions to better use EVs' flexibility when charging at homes or workplaces.[31]

In the United States, EV sales increased by 70% in 2022.[32] Americans bought nearly 1.4 million EVs in 2023. This brings the share of EVs in the U.S. vehicle market to 9%, up from 5.9% in 2022.[33] EV adoption is being further stimulated by various federal programs: the Inflation Reduction Act (IRA) supports EV adoption with tax credits for light duty EVs, used EVs, commercial EVs, and EV charging infrastructure.[34] The US Department of Transportation's National Electric Vehicle Infrastructure (NEVI) Program provides states with over US $7 billion in funding to deploy charging stations and an interconnected network to facilitate data collection, access, and reliability.[35] Federal and state environmental policies are also stimulating EV adoption. Research is showing that with advanced EV adoption, states can unlock value from using EVs' flexibility in the power system.[36] On the energy policy side, it is crucial to

[29] smartEn, 2022. The implementation of the Electricity Market Design to drive demand-side flexibility. SmartEn Monitoring Report. https://smarten.eu/report-the-implementation-of-the-electricity-market-design-2022-smarten-monitoringreport/

[30] European Commission, n.d. Energy Performance of Buildings Directive. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

[31] "Member States shall ensure that the recharging points referred to in paragraphs 1, 2 and 4 of this Article are capable of smart recharging and, where appropriate, bi-directional recharging and that they are operated on the basis of non-proprietary and non-discriminatory communication protocols and standards, in an interoperable manner, and in compliance with any European standards and delegated acts adopted pursuant to Article 21(2) and (3) of Regulation (EU) 2023/1804." Art 14 (6). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401275

[32] IEA, 2023. Global EV Outlook 2023. Paris. https://www.iea.org/ reports/global-ev-outlook-2023.

[33] EV VOLUMES, 2024. Global EV Sales for 2023. https://ev-volumes.com/news/ev/global-ev-sales-for-2023/

[34] The White House, 2024. FACT SHEET: Biden-Harris Administration Announces New Actions to Cut Electric Vehicle Costs for Americans and Continue Building Out a Convenient, Reliable, Made-in-America EV Charging Network. https://www.whitehouse.gov/briefing-room/statements-releases/2024/01/19/fact-sheet-biden-harris-administration-announces-new-actions-to-cut-electric-vehicle-costs-for-americans-and-continue-building-out-a-convenient-reliable-made-in-america-ev-charging-network/

[35] U.S. Department of Energy, 2021. National Electric Vehicle Infrastructure (NEVI) Formula Program. https://afdc.energy.gov/laws/12744#:~:text=The%20U.S.%20Department%20of%20Transportation%E2%80%99s,collection%2C%20access%2C%20and%20reliability.

[36] A case study for the state of Colorado is showing that smart EV grid integration can unlock between US $300 and 900 of savings, roughly 3.5% of the total system value. This is enough to cover all households in the state with L2 chargers, illustrating that the benefits of efficient EV charging can cover the costs of the transition. Source: RAP research in progress, unpublished.

advance customer-focused programs, e.g., time-varying rates, to help secure the benefits of vehicle flexibility.

2.2 Optimised EV charging – controlled, smart and bidirectional (V2G)

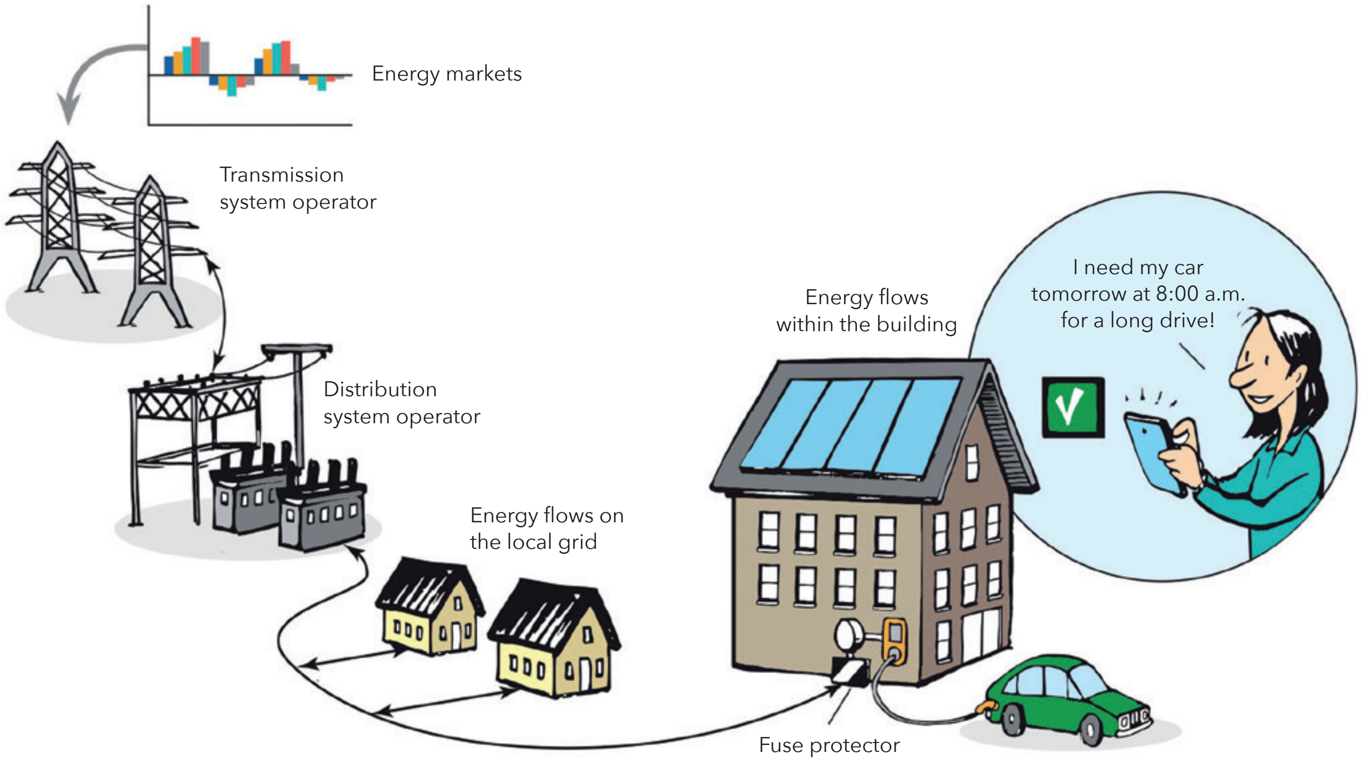
The system costs of EV grid integration can be mitigated by optimally integrating EVs into grids: that is, shifting EV charging to use existing grid capacities optimally and using EVs as resources for power grids by enabling demand-response services. We discuss some options for optimizing charging below. These range from smart unidirectional charging to bidirectional charging (V2G), also analysed in the sensitivity analysis (Section 5.2.2. and 5.2.3.), and include controlled automated charging if other smart charging options are not available.

2.2.1 Smart (unidirectional) charging

When the charging of EVs is optimised to lower costs, to accommodate the integration of renewable energy sources, and to minimise the impact on the power grid, this is called 'smart charging'.[37] The elements of smart EV grid integration is depicted in Figure 15. Smart charging adapts charging to signals, optimally using EVs' given flexibility windows. It can deliver significant cost savings to consumers by using time-varying tariffs, which offer lower electricity prices at certain times of day, or by rewarding flexibility through bonus payments. Technology and automation make smart charging user-friendly. Smart charging is a tool to make existing resources, e.g., power generation assets, grid infrastructure, and EV batteries, more efficient. EVs use electricity that is stored in their batteries, which can potentially optimise the way in which EVs are charged. Signals from the grid (or, smart building) to steer charging can cover a range of grid levels and time horizons, e.g., to prevent temporal congestion in a distribution or transmission system, to coincide with an increase in forecasted renewable energy supplies, or to relieve pressure on a substation in the neighbourhood when capacity limits are approaching.

[37] Burger, J., Hildermeier, J., Jahn, A., Rosenow, J., 2022. The time is now: smart charging of electric vehicles. https://www.raponline.org/knowledge-center/time-is-now-smart-charging-electric-vehicles/, p. 6.

Figure 15. Elements of smart EV grid integration. Source: RAP



2.2.2 Bidirectional charging (V2G)

Additional value can be generated from a specific form of smart charging, bidirectional charging (V2G). This method allows electricity to flow both into and out from a battery, enabling electric vehicles to act as power sources for a building or the grid (hence the name vehicle-to-grid, or V2G). Making better use of these existing batteries creates a new role for EVs, contributes to resource efficiency and resilience, and avoids the need for additional energy system investments.[38] Conservative estimates indicate that with the growth of EV batteries and the deployment of V2G technology, the short-term storage needs in the EU power system can be met.[39]

[38] Burger, J., 2023. Enabling two-way communication: Principles for bidirectional charging of electric vehicles https://www.raponline.org/knowledge-center/enabling-two-way-communication-principles-for-bidirectional-charging-of-electric-vehicles/.

[39] Xu, C., Behrens, P., Gasper, P., Smith, K., Hu, M., Tukker, A. & Steubing, B., 2023. Electric vehicle batteries alone could satisfy short-term grid storage demand by as early as 2030. https://doi.org/10.1038/s41467-022-35393-0

Both smart unidirectional and bidirectional charging require signals to optimize charging. These can be locational price signals from the grid or price signals from energy markets. If these are not available, in other models, load control or load shifting can be performed by DSOs to optimise charging. To distinguish this from smart (user-centric, price-based) charging, we use the term ‘controlled charging’.

To enhance smart grid integration and reap its benefits, two crucial elements are planning and pricing. DSOs must include detailed forecasts of EV charging demand into their investment strategies to anticipate the needed charging capacity and avoid distribution grids becoming a bottleneck for EV roll-out. Additionally, the improved transparency of distribution grids offers aggregators the option to optimize EV charging. The other element that allows optimal grid integration of EVs is cost-reflective pricing of both energy and networks to ensure EV users receive a strong signal to optimize charging. How these elements can be incorporated into a policy framework for smart EV charging is further discussed in Section 6 (priority areas).

3. Current Situation of EVs in Türkiye

3.1 Passenger car market

As of the close of 2021, road vehicles accounted for a substantial 92.7% of total passenger transport, with the remaining 7% primarily from the aviation sector—a mode of transport experiencing significant growth in Türkiye. A parallel trend is observed in freight transport, where road vehicles dominated with a staggering 90% share, followed by aviation at 6%, and maritime transport at 4%.[40] In terms of energy intensity, road transport emerges as the most energy-demanding mode, constituting 94.3% of total emissions from the transportation sector in 2021.[41] The increasing demand for energy in the transportation sector is propelled by rising per capita income levels, a growing population, and Türkiye's significant role as the 13th largest automotive producer globally and the fourth largest in Europe.

In 2023, Türkiye experienced a notable production surge, with a total of 1,468,393 road vehicles manufactured, including 952,667 automobiles—reflecting a remarkable 9% growth compared to 2022. Impressively, 70% of these vehicles were exported, highlighting Türkiye's standing in the global automotive market.[42] As of January 2024, the registered passenger car count reached approximately 15.3 million, contributing to a total of 28 million road vehicles on Turkish roads. This comprehensive figure encompasses 4.5 million small trucks, 5.1 million motorcycles, and 2.2 million tractors trailing behind passenger vehicles.[43] The passenger car ownership rate, currently at 179 per 1,000 people, is relatively low compared to the Organisation for Economic Co-operation and Development (OECD) countries like Germany and the United States (US). Nevertheless, ownership rates are rapidly escalating, with passenger cars accounting for seven out of ten vehicles sold in Türkiye, resulting in 951,782 new registrations in 2023.

Breaking down fuel composition, gasoline vehicles consume 28.9% of all fuel consumed in Türkiye, while liquefied petroleum gas (LPG) and diesel vehicles collectively consume the majority of fuel, 33.3% and 35.5%, respectively, as of the end of January 2024.[44] Notably, the share of EVs and hybrid vehicles in the overall car stock is around 2%.[45] This shift in fuel preferences is propelled

[40] T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2023. Ulaştırma Türlerine Göre Taşınan Yolcu ve Yük Miktarı. https://cevreselgostergeler.csb.gov.tr/ulastirma-turlerinegore-tasinan-yolcu-ve-yuk-miktari-i-85789 , 2021
[41] SHURA, 2023. Net Zero 2053: A Roadmap for the Turkish Electricity Sector. https://shura.org.tr/wp-content/uploads/2023/05/Net-Zero-EN.pdf
[42] OSD, 2024. ÖZET DEĞERLENDİRME – 2023/2022. https://www.osd.org.tr/saved-files/PDF/2024/01/15/2023-12-OSD%20%C3%96zet%20Rapor.pdf
[43] TÜİK, 2024. Motorlu Kara Taşıtları, Ocak 2024. https://data.tuik.gov.tr/Bulten/Index?p=Motorlu-Kara-Tasitlari-Ocak-2024-53453
[44] TÜİK, 2024. Motorlu Kara Taşıtları, Ocak 2024. https://data.tuik.gov.tr/Bulten/Index?p=Motorlu-Kara-Tasitlari-Ocak-2024-53453
[45] TÜİK, 2024. Motorlu Kara Taşıtları, Ocak 2024. https://data.tuik.gov.tr/Bulten/Index?p=Motorlu-Kara-Tasitlari-Ocak-2024-53453

by the cost advantages of LPG and diesel over gasoline, coupled with the longer driving distances achieved by diesel cars per litre of fuel. However, the narrowing price gap between diesel and gasoline, currently less than a 4% difference in price per litre, raises uncertainties about the future prospects of diesel in Türkiye.

3.2 EV market evolution

Electric vehicles (EVs) offer various benefits for the energy system. Compared to a conventional vehicle with an internal combustion engine, an EV is two to three times more efficient. Provided that the electricity demand of an EV is supplied with renewable energy sources, it can also contribute to increasing renewable energy's share in the energy system and, therefore, result in lower emissions, contributing to a clean urban environment. An EV also functions as a mobile battery storage system. It can provide grid services like flexibility, for instance, by selling demand response to the grid and integrating variable renewable energy sources like wind and solar power.

In Türkiye, the first incentive for EV sales was introduced in 2011 through a reduction in the so-called Special Consumption Tax (Özel Tüketim Vergisi, ÖTV). Depending on the power capacity of the battery electric vehicle (BEV), the ÖTV was set between 3% and 15%. According to the recently published incentives, the ÖTV bases for battery-powered cars have been changed. However, no change was made in the ÖTV rates of electric vehicles. According to this regulation, the base limit for EVs with an engine power not exceeding 160 kilowatts (kW) was increased from 700,000 TL to 1,250,000 TL. The tax base limit for EVs with an engine power exceeding 160 kW was increased from 750,000 TL to 1,350,000 TL. If the engine power of an electric vehicle does not exceed 160 kW and the base value does not exceed 1,250,000 TL, consumers will be expected to pay 10% ÖTV. For electric cars with the same engine power but with a base value exceeding 1,250,000 TL, the consumer will have to pay 40% ÖTV.[46]

EV sales continued to grow throughout 2021 (AA, 2021; TEHAD, 2021). Despite the continuous increase in sales in recent times, the share of EVs in the automotive market is still below 1%. Since the end of 2022, Türkiye has aimed to achieve a faster increase in sales with the introduction of Türkiye's Automobile Joint Venture Group (TOGG) vehicles to the market. For EV purchases in Türkiye, there are no incentive mechanisms applied in many regions, especially in Europe. However, tax regulations provide a tax advantage to EVs compared to their fossil fuel counterparts. The tax rates, which have been in effect since 2011, were increased with a new regulation

[46] HedefFilo, n.d. Elektrikli Araç ÖTV İndirimi ve ÖTV İndirimli Araçlar. https://ev.hedeffilo.com/ev-gundem/blog/elektrikli-arac-otv-indirimi-ve-otv-indirimli-araclar

in February 2021 (from 3% to 10% for vehicles with a motor power not exceeding 85 kW, from 7% to 25% for vehicles with a motor power from 85–120 kW, and from 15% to 60% for vehicles with a motor power exceeding 120 kW). This regulation, driven by luxury and imported vehicle sales, has led to downward revisions in sales projections that were driving growth in the EV market in recent periods. Despite the effects of this change, over 2,000 EVs were sold in 2021, bringing the total to over 6,000 vehicles.

According to data released by the Automotive Distributors and Mobility Association (ODMD)[47] in November 2023, Türkiye experienced a notable surge in the sales of cars and light commercial vehicles from January–November 2023. This period saw a remarkable 60.8% increase compared to the same timeframe in the previous year, with sales reaching a total of 1,073,982 units. In contrast, during the same period in 2022, sales stood at 668,063 units, indicating a significant growth trajectory. In November alone, there was a substantial 39.8% uptick in car and light commercial vehicle sales compared to the corresponding period in the previous year, with sales figures reaching 115,040 units. Notably, during the first eleven months of the year, electric cars accounted for 7.1% of total car sales in Türkiye, while hybrid cars held a share of 10.6%. This demonstrates a growing interest and adoption of eco-friendly vehicle options among Turkish consumers. These impressive figures can be attributed to various factors, including dedicated incentives and the contributions of electric vehicle manufacturers to the Turkish EV market. Manufacturers have been actively promoting EV adoption through incentives, infrastructure development, and technological advancements, resulting in notable growth in recent years. The evolution of electric vehicles in Türkiye is visually depicted in Figure 16, illustrating a consistent and substantial increase in the number of EVs from 2020 to the end of 2023. While there may be differing projections regarding the future growth of EVs in Türkiye, Table 2 provides an overview of the available projections for reference. These projections indicate a promising trajectory for the continued expansion of the electric vehicle market in Türkiye.

[47] Enerji Günlüğü, 2023. Türkiye otomobil satışlarında elektriklilerin payı arttı. https://www.enerjigunlugu.net/turkiye-otomobil-satislarinda-elektriklilerin-payi-artti-56779h.htm

Figure 16. The recent evolution of EVs in Türkiye

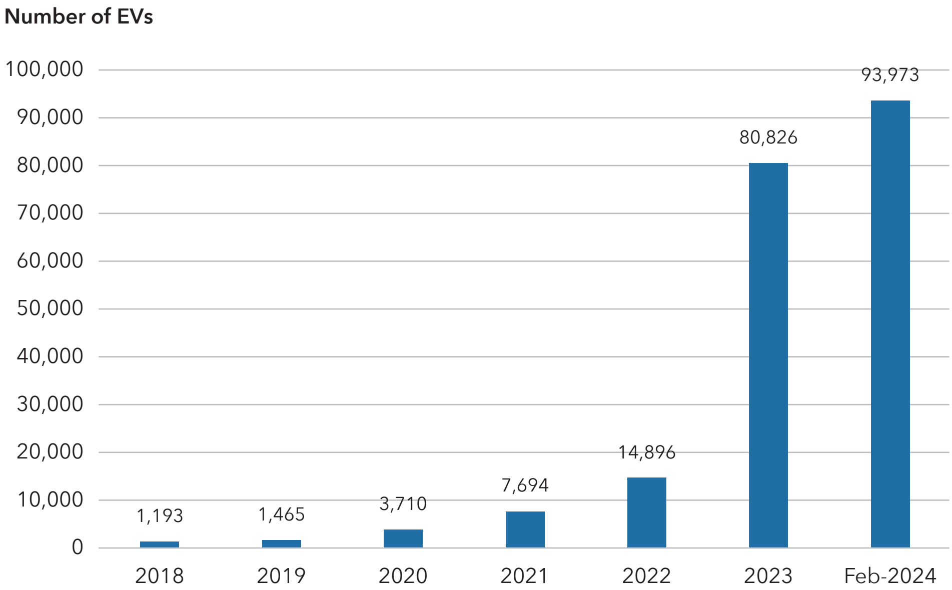


Table 2. EV projections for Türkiye from different associations

	Ministry of Science, Industry, and Technology	EMRA	SHURA Net-Zero Study
2025	270,000	361,893	237,626
2030	1,600,000	1,679,600	3,758,252
2035	-	4,214,273	10,941,664

3.3 The evolution of charging infrastructure

The infrastructure of EV charging networks plays a key role in increasing energy efficiency and reducing Türkiye's carbon footprint as EVs lay the foundation for an environmentally friendly transportation system. Türkiye's geographical location and energy infrastructure present a unique opportunity to support the widespread use of EVs. In this context, the development of Türkiye's EV charging infrastructure, strengthened by both public incentive policies and private sector participation, has the potential to position the country among the leaders of sustainable transportation in the future.

Efforts are currently underway to establish the necessary infrastructure for charging EVs. Mechanisms are being developed to incentivize the installation and proliferation of charging stations in both urban and rural areas, aiming to provide adequate infrastructure to meet the daily charging needs of EV users. Additionally, the use of renewable energy sources is being encouraged to support the use of more environmentally friendly and sustainable energy sources for charging EVs. Furthermore, various efforts are being made to develop and popularize energy storage technologies. In this regard, policymakers and regulatory authorities such as Energy Market Regulatory Authority (EMRA) are developing various regulations and policies aimed at promoting the widespread use and adoption of EVs and improving the country's charging infrastructure.

In line with these efforts, regulations have been put in place by EMRA to quickly publish the Charging Service Regulation and secondary regulations to establish a comprehensive charging network covering the entire country. These regulations aim to ensure that EV users are provided with quality, continuous, and uninterrupted charging services. The regulation covers provisions related to charging network operator licenses, the licensing process, the formation and development of the charging network, the rights and obligations of license holders, installation and operation of charging stations, pricing, monitoring, rights and obligations of EV users, inspections, and sanctions.

Within these regulations, companies can operate charging networks under the obtained charging network operator license. License holders can operate their own charging stations or allow third parties to operate charging stations with certificates issued by them. License holders are required to establish a charging network within six months of obtaining the license, consisting of at least fifty charging units in at least five different districts. Individuals or companies wishing to operate charging stations can do so by obtaining certificates from licensed companies. Significant regulations have also been implemented to increase the number of fast charging stations and to ensure that electric vehicle users have easy access to charging service prices and information. Additionally, EMRA monitors complaints filed by EV users against charging network operators, ensuring that complaints are resolved satisfactorily.

In Türkiye, the price of charging services is applied in terms of the unit energy cost transferred to the vehicle, and no additional fees are charged. Comparatively, in many other countries, charging services are priced based on minutes, with various rates combining minute and unit energy costs, as well as additional fees such as initial charging fees. The application of pricing based on the unit energy cost in Türkiye, without charging additional fees, has facilitated the comparison of charging service prices by companies and contributed to the development of the electric vehicle market.

Another significant regulation introduced by policymakers and regulatory authorities such as EMRA is the requirement for all EVs to be able to receive charging services from charging stations (full interoperability). In some other countries, some charging network operators only serve their own subscribers, and some EV manufacturers only install charging stations for their own vehicles. In Türkiye, charging stations provide charging services to EVs regardless of brand or model, promoting optimal use of charging stations and efficient utilisation of national resources in investments.

Following the issuance of secondary regulations, license applications started to be accepted as of 18 April 2022. There has been considerable interest from investors in this area. Accordingly, while only five companies were engaged in charging service activities in the market before the establishment of the legal infrastructure, today, there are 172 licensed companies. In the coming period, policymakers and regulatory authorities such as the Ministry of Energy and Natural Resources (MENR) and EMRA will continue to grant charging network operator licenses to companies that meet the license requirements.

One of the determining factors for the widespread adoption of EVs inside a country is the status of publicly available charging facilities. In Türkiye, the widespread deployment of charging infrastructure in provinces and districts is of great importance for the rapid spread of EVs. At the beginning of 2023, there were 14,896 electric vehicles in Türkiye, whereas as of today (April 2024), this number has reached 93,973. As a result of investments made by charging network operators, the number of charging points (sockets) across Türkiye, which was 3,081 (2,706 AC (Slow) and 375 DC (Fast)) at the beginning of 2023, has increased to 17,233 (11,412 AC (Slow) and 5,821 DC (Fast)) as of 1 April 2024. As the number of electric vehicles rapidly increases, the simultaneous increase in charging points is a positive development for the advancement of the e-mobility ecosystem, increasing the drivers' likelihood of finding a place to charge. In Türkiye, there are 5.4 electric vehicles per socket. The European average ratio is 13.75 EVs per socket.

The widespread adoption of EVs plays an important role in reducing carbon emissions by reducing the share of vehicles powered by fossil fuels, which contribute to environmental pollution. Efforts are being made to ensure the healthy and sustainable development of the electric vehicle ecosystem with the continued support and cooperation of the public, and significant steps are being taken towards creating an environmentally friendly and innovative transportation system. The contribution of the widespread adoption of electric vehicles to these goals is expected to increase as the electricity used by electric vehicles comes from clean and renewable energy sources. Therefore, it is anticipated that establishing a strong connection between the charging service market and electricity generated from renewable energy sources will contribute significantly to Türkiye's climate goals. In this context, the concept of a "green charging station," where all the electricity supplied to electric vehicles is produced from renewable energy sources, has been added to the regulations, and these charging stations are also displayed on EMRA's website and the Charge@TR mobile application.

In addition to green charging stations, which certify that all the electricity supplied to EVs comes from renewable energy sources, it is currently possible to install integrated electric storage facilities alongside renewable energy production facilities to meet the electricity needs of any charging station. In this context, integrated charging stations with electric storage and renewable energy production facilities, as well as green charging stations with Renewable Energy Resources Certificates (YEK-G), can provide sustainable and environmentally friendly charging services for EVs. It is envisaged that establishing a strong connection between electricity supplied from renewable energy sources and the charging services market will contribute significantly to Türkiye's efforts to achieve its climate goals.

One of the most important initiatives in this field is the aforementioned Charge@TR, which is a mobile support application where EV users can view publicly available charging locations on a socket and station basis, and access current and secure information. With this application, EV users can easily and comfortably travel to any desired location. Thus, in addition to the environmental advantages of EVs, the aim is to enable real-time tracking of charging service prices tailored to the features of vehicles, considering their advanced technological features.

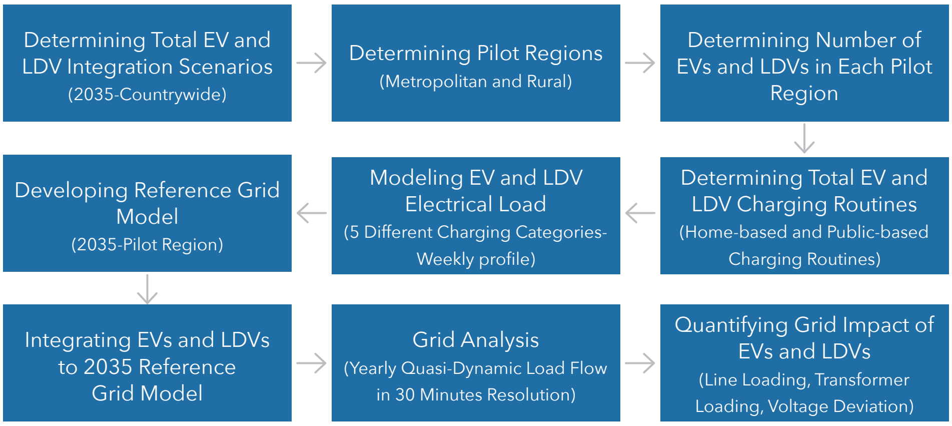
Additionally, a website containing information about charging stations and where charging services are provided has been made accessible to the public. The website provides information such as the location of charging stations, socket information, station addresses, and network operators. As a result, all EV users can access information about charging stations through EMRA's website[48]. Furthermore, continuous monitoring is being conducted to ensure the healthy development of the charging service market, examining the qualifications of charging stations established nationwide, the prices applied at the stations, developments in other countries, good practices in the field, factors disrupting competition, and factors affecting market development.

[48] EMRA, n.d. Serbest Erişim Platformu- Şarj@TR.
https://www.epdk.gov.tr/Detay/Icerik/1-3428/enerji-donusumuserbest-erisim-platformu--sarj@tr

4. Methodology

This section delineates the methodology employed and the foundational data utilized to project the total number of electric vehicles (EVs) and charging points in Türkiye. Additionally, it elucidates the key procedural steps in the methodology devised to model the grid integration of EVs within selected distribution areas across the country. Figure 17 illustrates the initial phase, which involves forecasting the market outlook and scenarios for the evolution of the total number of EVs and light duty vehicles (LDV) throughout Türkiye between 2024 and 2035.

Figure 17. Key steps in the methodology



Subsequently, specific pilot regions were chosen, encompassing both rural and metropolitan areas. This strategic selection allows for a more nuanced examination of the impact of EVs and LDVs on distribution grids. For the chosen pilot regions, the proportion of EVs and LDVs within the total number of vehicles in Türkiye were computed under various scenarios. The ensuing steps encompass:

1. **Determining EVs' and LDVs' charging routines:** Analysing both home and public charging routines to comprehend the charging behaviour of electric vehicles in diverse settings.

2. **Calculating equivalent electrical loads and associated profiles:** Quantifying the equivalent electrical load and developing associated profiles for EVs and LDVs to integrate them into the electrical grid.

3. **Developing the reference model:** Establishing a baseline distribution grid model for year 2035, denoted as the 'Reference Model', specifically designed for the chosen pilot regions.

4. **Integrating EVs and LDVs into the reference model:** Incorporating EVs and LDVs into the reference model to simulate their presence and interaction within the distribution grid.

5. **Conducting a grid analysis:** Performing a comprehensive analysis of the distribution grid, considering integrated EVs and LDVs, to assess the potential impact on various parameters.

6. **Quantifying grid impact:** Evaluating the impact of EVs and LDVs on the grid by examining line and transformer loading, voltage deviation, and identifying potential e-mobility-oriented investment requirements for both medium voltage and low voltage grids.

Detailed explanations of each of these steps are provided in the subsequent sections to offer a comprehensive understanding of the methodology and its implications for the grid integration of electric vehicles in Türkiye.

4.1 EVs and LDVs projections in Türkiye

The initial phase involved outlining the scenarios for EVs and LDVs in Türkiye. This study considers two main integration scenarios: the net-zero pathway (Net0) and the business-as-usual (BAU) scenario.

The Net0 scenario aligns with the net-zero pathway outlined by SHURA Energy Transition Center.[49] Currently, Türkiye exhibits relatively low passenger mobility levels, averaging 7,890 km/person in 2020,[50] compared to the European Union (EU) average of 13,498 km/person in 2019. Looking forward, SHURA's net-zero pathway anticipates a doubling of passenger transport with increasing income per capita, leading to a 45% share of passenger cars in total passenger-km by 2053. Despite a projected 121% increase in passenger car-km, this share is expected to remain below EU averages due to the growing availability of low-carbon public options. Figure 18 and Figure 19 illustrate the projections for EVs and LDVs based on this scenario. As the target year of the present study is year 2035, the total number of electric vehicles, including Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicle (PHEVs) and light duty vehicles, is broken down in Figure 20.

[49] SHURA, 2023. Net Zero 2053: A Roadmap for the Turkish Electricity Sector. https://shura.org.tr/wp-content/uploads/2023/05/Net-Zero-EN.pdf
[50] TÜİK, 2022

Figure 18. EV projection based on the Net0 pathway

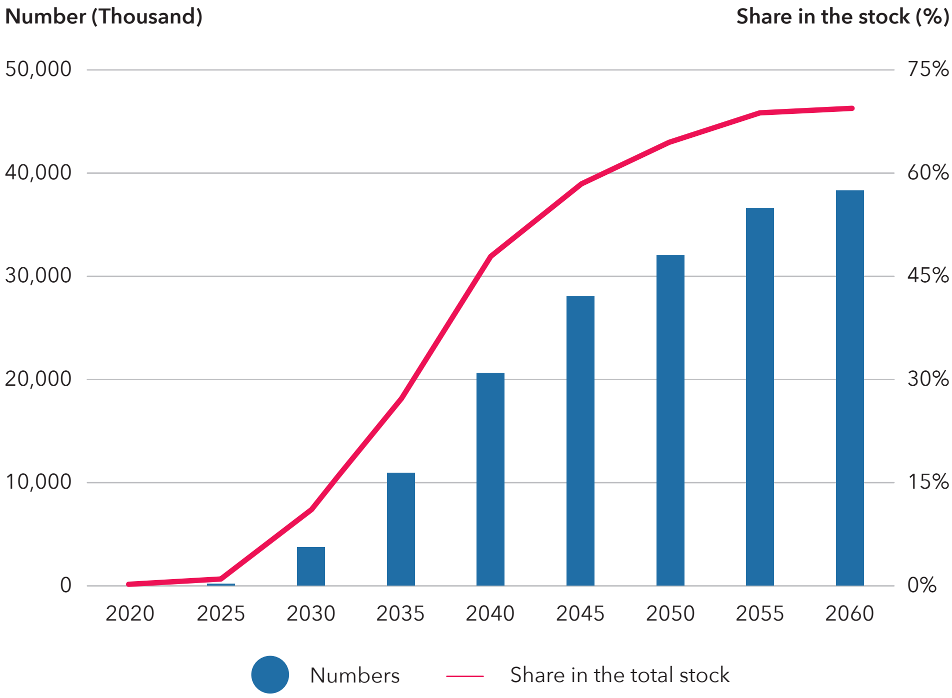


Figure 19. LDV projection based on the Net0 pathway

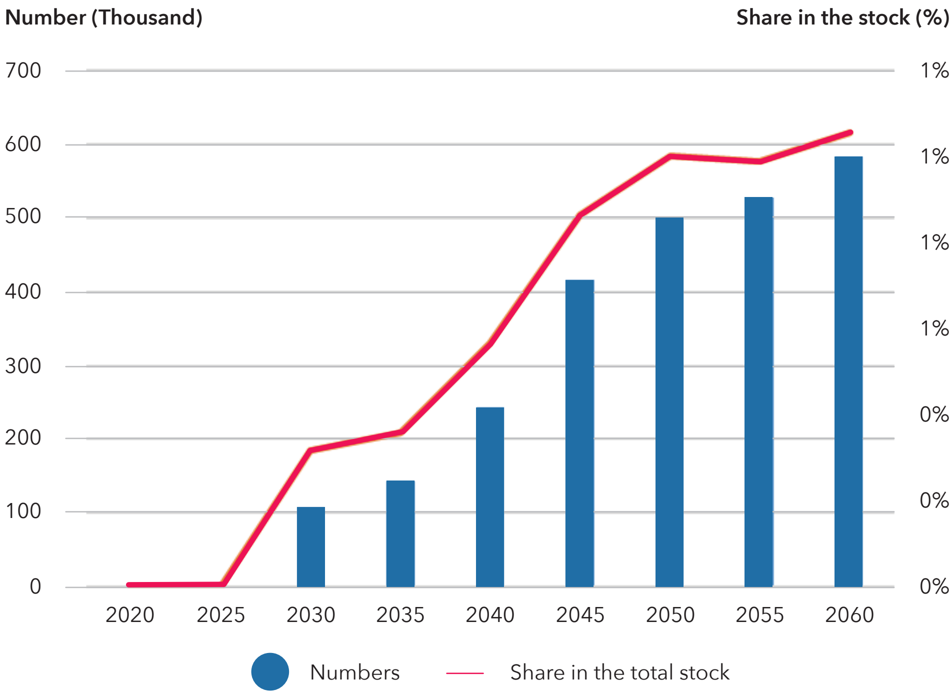
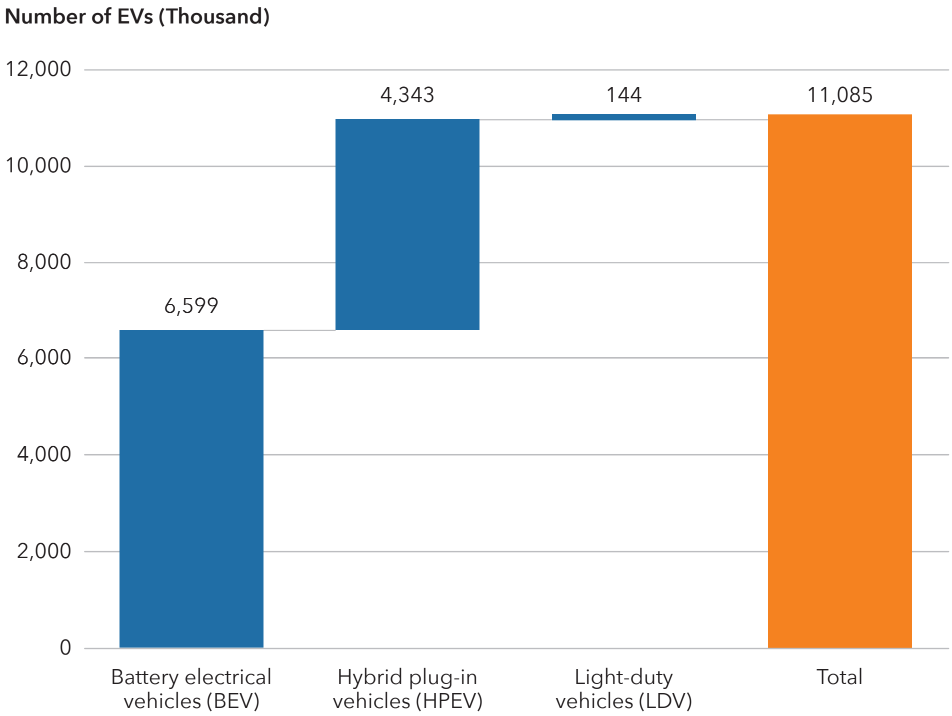


Figure 20. Breakdown of the EV fleet in year 2035 under the Net0 pathway



Conversely, the BAU scenario incorporates projections from the Ministry of Science, Industry, and Technology in Türkiye. Notably, the country incentivizes electric vehicle adoption through significant tax advantages, including a special consumption tax corresponding to motor power, starting at 10%. Compared to internal combustion engines, there is a fourfold advantage when comparing the upper limits of the special consumption tax for electric vehicles. Additionally, a 75% discount is applied to the annual motor vehicle tax, contributing to a remarkable surge in electric vehicle sales. The number of newly registered electric vehicles in Türkiye rose from 247 in 2019 to 3,587 in 2021, reaching 80,043 by the end of 2023. This upswing signifies a timely initiation of the transition to EVs, which is expected to persist with the introduction of domestically produced vehicles. According to Ministry projections, the number of EVs is expected to reach 1.6 million by 2030, aligning with the moderate growth scenario from a previous SHURA study (see Figure 21). Extrapolating this trend to the target year of 2035 reveals the anticipated evolution of EV and LDV numbers (see Figure 22).

Figure 21. The EV fleet trend based on the BAU scenario

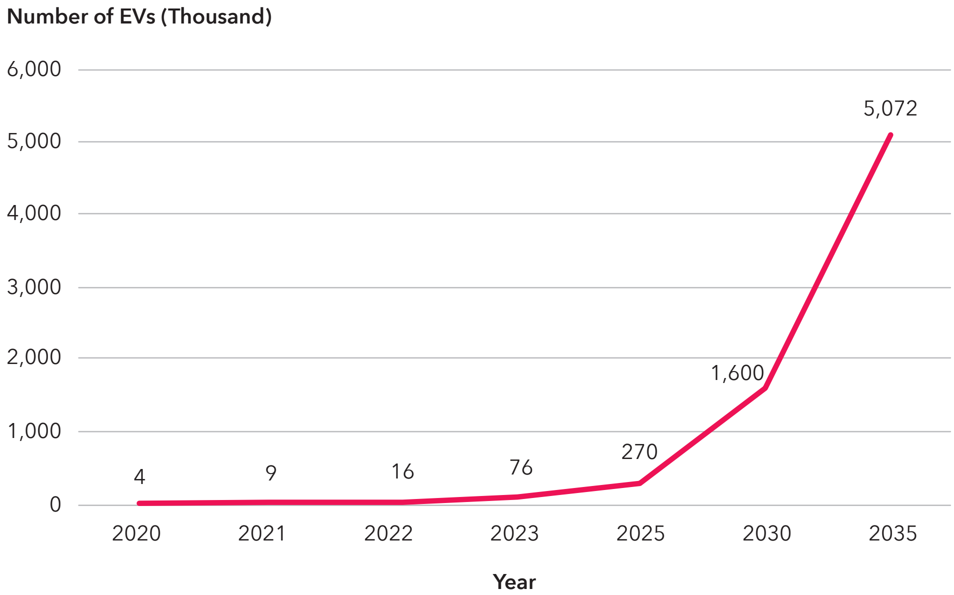
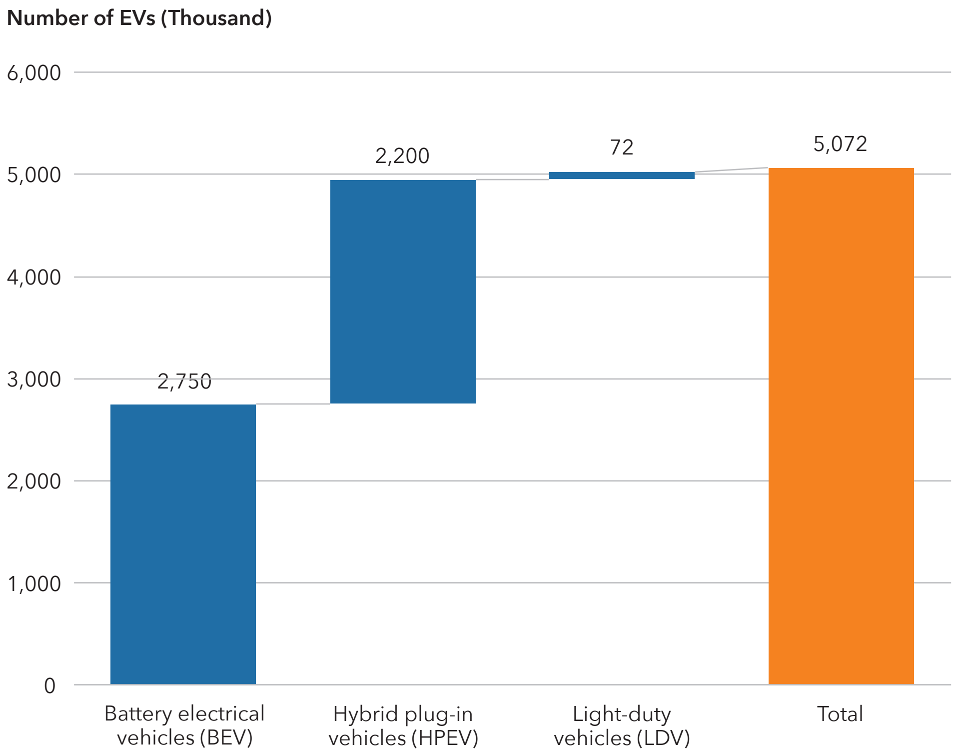


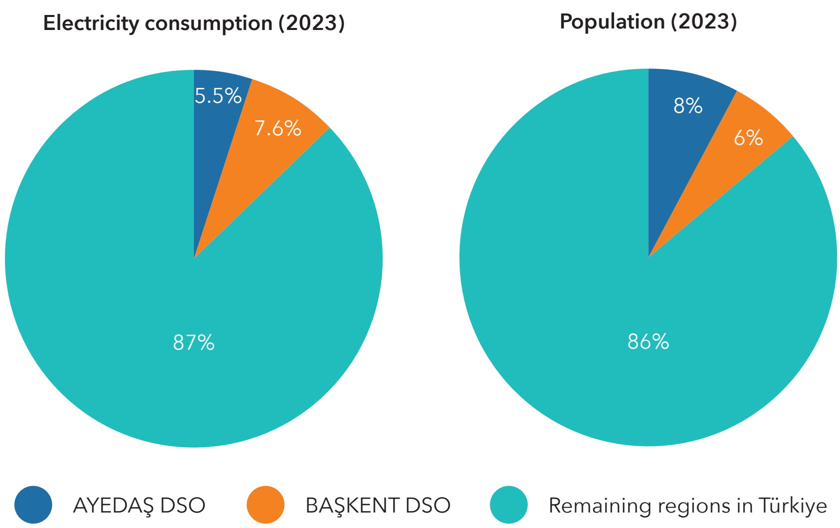
Figure 22. Breakdown of the EV fleet in year 2035 under the BAU scenario



4.2 Pilot Regions and the number of EVs in each region

The investigation into the impacts of EVs and LDVs on distribution grids was conducted within carefully chosen pilot distribution regions in Türkiye. These pilot regions were strategically selected from two distinct Distribution System Operators (DSOs)—BAŞKENT and AYEDAŞ DSOs. These DSOs provide distribution services across different territories in Türkiye. The distribution of BAŞKENT and AYEDAŞ customers in relation to all electricity customers in Türkiye is graphically presented in Figure 23. Simultaneously, Figure 23 illustrates the population distribution in these pilot regions. Notably, these pilot regions encompass 14% of Türkiye's population, contributing to approximately 13% of the nation's total energy consumption.

Figure 23. Shares of population and electricity consumption of pilot regions in Türkiye



Four specific high voltage (HV) substations were chosen from the pilot regions, as detailed in Table 3. The selected HV substations cater to both metropolitan and regional areas, covering diverse landscapes. The chosen metropolitan regions consist of both relatively developed areas, which is the case for the selected pilot regions Kartal and Akköprü, and regions in the developmental stage, for which the region of Ümitköy was selected, alongside a rural region, Şile. The pilot regions are depicted in Figure 24.

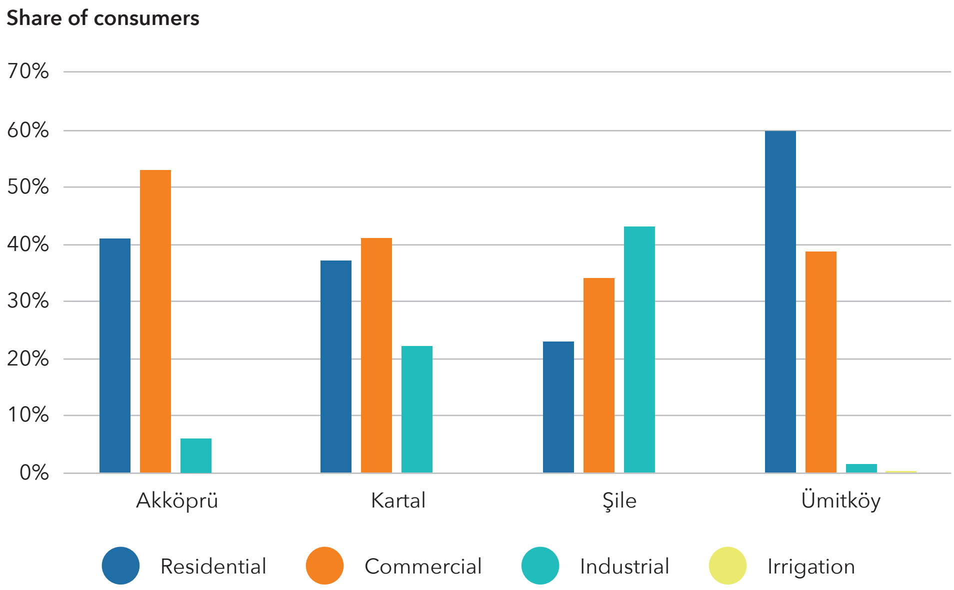
Figure 24. The pilot regions under study

Figure 25 shows the consumer breakdown within the pilot regions, highlighting the proportions of various consumer types. This breakdown encompasses diverse loads, including residential and commercial consumers. Given the diverse range of loads, coupled with the significant share of the pilot regions in terms of total population and electricity consumption, it is reasonable to assert that these selected pilot regions are representative of the diversity in EV usage across Türkiye.

Table 3. Distribution of companies and corresponding pilot HV substations

DSO	Pilot HV Substations	Region Type	Substation Installed Capacity (MVA) Year 2023
AYEDAŞ	Kartal	Metropolitan-Developed	200
	Şile	Rural	125
BAŞKENT	Akköprü	Metropolitan-Developed	300
	Ümitköy	Metropolitan-Developing	300

Figure 25. Breakdown of consumers in pilot regions, 2023



After identifying the pilot regions, the next step involved breaking down the total number of EVs in Türkiye as determined under the Net0 and BAU scenarios to assess the number of EVs in the pilot regions. As the real number of EV registrations in the pilot regions was not available, the number of EVs in each region was estimated through several indices:

- **Electrical Index (EI):** This index reflects the share of high voltage/medium voltage (HV/MV) transformer installed capacity in each pilot substation within the total installed capacity across Türkiye. The assumption here is that the share of total capacity, measured in Mega Volt Amper (MVA), in pilot HV substations could serve as an indication of the proportion of EVs and LDVs in that specific region.

- **GDP Index (GDP):** The Gross Domestic Product per capita of the cities in which the pilot regions are situated is factored in as a multiplier. This factor plays a role in estimating the total number of EVs and charging points in the pilot regions and utilizes GDP per capita from 2021.[51]

- **Relative Development Index (RDI):** The Relative Development Index is also considered as another multiplier.[52] This index encompasses various socio-economic factors specific to the pilot regions, providing a comprehensive perspective on regional development.

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[51] TÜİK, İl bazında gayrisafi yurt içi hasıla, iktisadi faaliyet kollarına göre, cari fiyatlarla, NACE Rev.2, 2004-2021.
[52] İlçelerin Sosyo-Ekonomik Gelişmişlik Sıralaması Araştırması (2004), Bülent Dincer, Metin Özaslan, DPT, Nisan 2004.

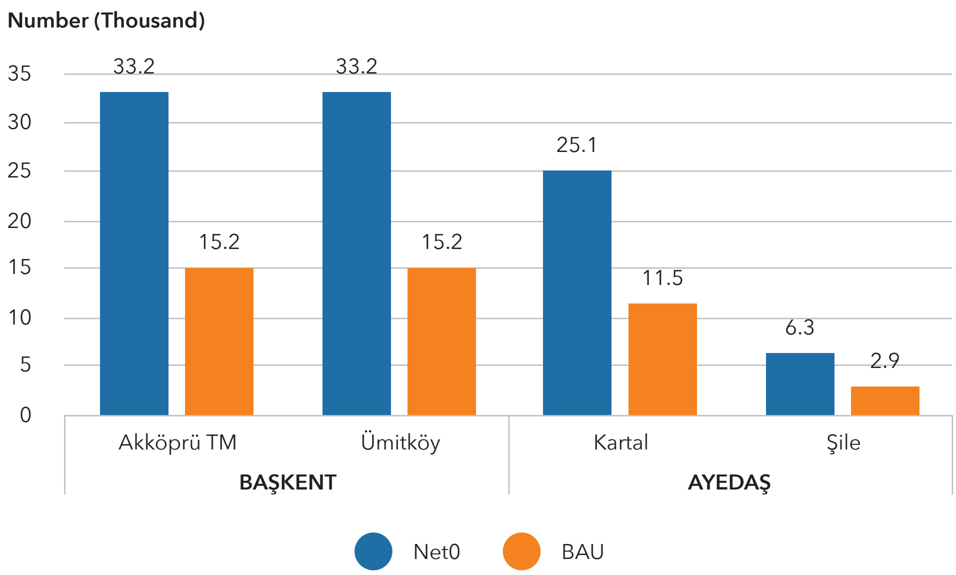
- **EV Allocation Multiplier (EVAM):** This multiplier is derived by multiplying the aforementioned indices–EI, GDP, and RDI. EVAM reflects the interplay of electrical infrastructure, economic indicators, and regional development in determining the allocation of EVs.

The calculated EVAM values for the pilot regions, along with the total number of EVs and LDVs determined through this comprehensive approach, are presented in detail in Table 4. Figure 26 visually presents these values. This multi-index approach ensures a nuanced and thorough assessment of the distribution and impact of EVs across the identified pilot regions in Türkiye. Note that although the number of EVs and LDVs in Akköprü and Ümitköy are almost the same, the distribution system configuration of these regions is quite different. It is interesting to investigate the same number of EVs and LDVs within a different distribution configuration.

Table 4. EVAM factors in the pilot regions

Total EV and LDV Countrywide - 2035 [Thousands]		Substation Name	Region	Province	Electrical Index (EI)	GDP Index (GDP)	Relative Development Index (RDI)	EV Allocation Multiplier (EVAM)	Total EV and LDV Pilot Regions - 2035 [Thousands]	
Net0	BAU								Net0	BAU
11,085	5,072	Akköprü	BAŞKENT	Ankara	0.00192	1.357	1.14767	0.0030	33.2	15.2
		Ümitköy		Ankara	0.00192	1.357	1.14767	0.0030	33.2	15.2
		Kartal	AYEDAŞ	İstanbul	0.00128	1.633	1.08283	0.0023	25.1	11.5
		Şile		İstanbul	0.00080	1.633	0.43313	0.0006	6.3	2.9

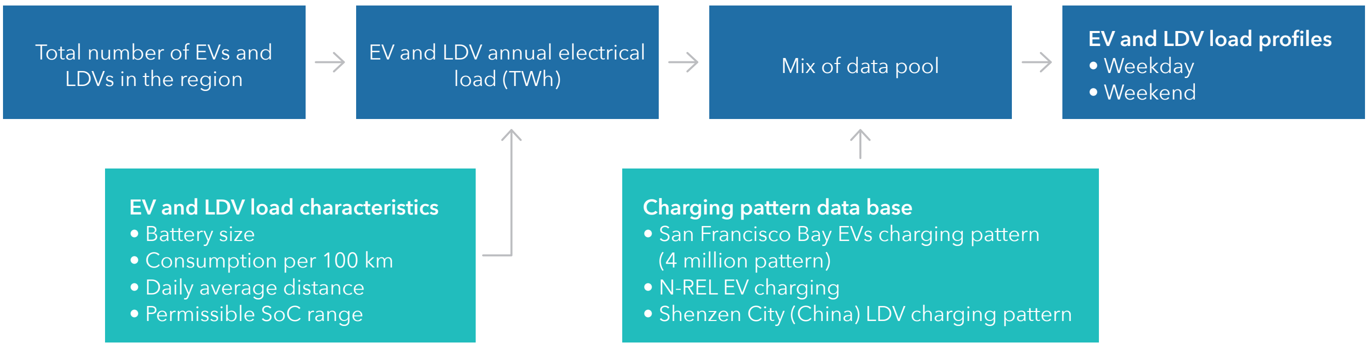
Figure 26. Number of EVs and LDVs in each pilot region – year 2035



4.3 EV and LDV modelling and charging routines

The load modelling approach for EVs and LDVs is illustrated in Figure 27. Beginning with the determined number of EVs and LDVs in each pilot region, the energy consumption associated with these vehicles was first estimated. Subsequently, charging habits, including home, workplace, and public charging habits, were identified, and an associated charging pattern was generated. Applying the energy consumption data to the estimated charging profile for each pilot region enables the calculation of the charging pattern. This calculation spans weekly time frames to cover both weekday and weekend profiles and utilizes 30-minute time steps to capture the dynamics of DC fast charging technology. This modelling approach provides a detailed understanding of how EVs and LDVs consume energy and follow charging patterns within the specified pilot regions, ensuring a nuanced depiction for precise grid impact assessments.

Figure 27. EV and LDV load modelling approach



The computation of energy consumption for EVs and LDVs involved a set of well-considered assumptions regarding the permissible charging range, average battery size, and the overall efficiency of these vehicles. The specific assumptions guiding this calculation are outlined in detail in Table 5. Notably, the determinations pertaining to EV battery size, average efficiency, and the permissible range are derived from an extensive analysis of 257 different models.[53] For LDVs, 18 different commercially available and in service LDVs were considered.[54] Figure 28 visually represents the range of variation observed in battery size, average efficiency, and the permissible range for both EVs and LDVs. The associated average values extracted from this variation were then utilized as the foundational parameters of this study. This comprehensive approach ensures that the assumptions made regarding EV and LDV characteristics are representative of the diverse range of models available on the market, providing a robust foundation for subsequent energy

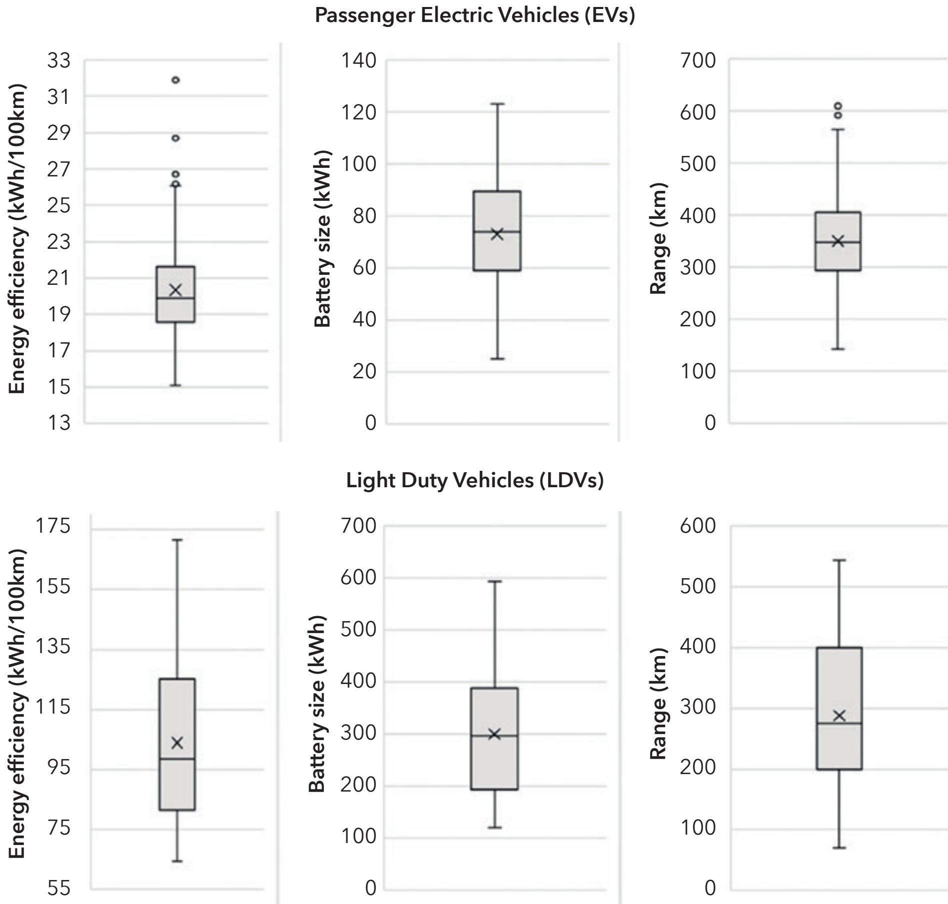
[53] Electric Vehicle Database, n.d. Current and Upcoming Electric Vehicles. https://ev-database.org/
[54] MotorWatt, n.d. Electric Buses & Vans. https://ev.motorwatt.com/ev-database/database-electric-buses

consumption calculations. The average daily distance in Türkiye is from the Turkish Statistical Institute (TÜİK).[55]

Table 5. List of assumptions for EVs and LDVs

Category	Parameter	Value
Battery	Minimum State-of-Charge (SOC)	0.2
	Minimum State-of-Charge (SOC)	0.2
EVs	Average battery capacity (kWh)	70
	Average consumption (kWh/100 km)	20
	Average range (km)	350
	Average daily distance in Türkiye (km)	40
LDVs	Average battery capacity (kWh)	300
	Average consumption (kWh/100 km)	104
	Average range (km)	288
	Average daily distance in Türkiye (km)	100

Figure 28. The range of variation observed in battery size, average efficiency, and the range for both EVs and LDVs



[55] TÜİK, 2023. Taşıt-kilometre İstatistikleri, 2021. https://data.tuik.gov.tr/Bulten/Index?p=Tasit-kilometre-Istatistikleri-2021-49527

With the assumptions in Table 5 in place, the approach presented in Figure 29 was used to calculate the average energy per charging, and consequently, the annual electrical load of EVs and LDVs was calculated. The results are reported in Table 6.

Figure 29. Annual energy consumption of EVs and LDVs

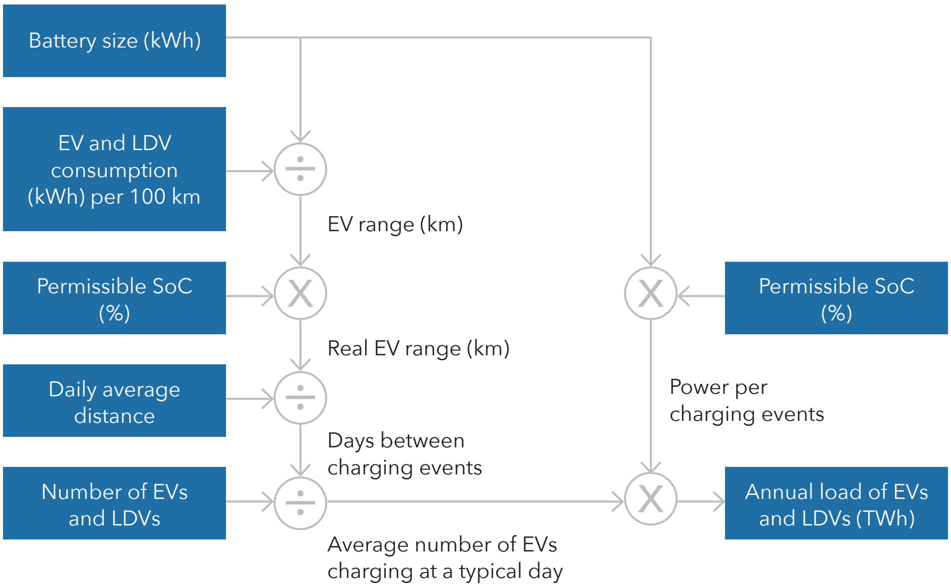


Table 6. Annual electricity consumption of EVs and LDVs

Category	Parameter	Value
EVs	Average power per charging event (kW)	49
	Days between consecutive charging events	6
	Annual Load (TWh)	31.9
LDVs	Average power per charging event (kW)	210
	Days between consecutive charging events	2
	Annual Load (TWh)	5.4

Once the annual consumed energy was calculated, charging patterns associated with different charging habits appear. The main dataset used for EVs examines the charging habits of 38,000 drivers over 3.9 million sessions, which was collected in 2019 in the San Francisco Bay Area in California, United States (US).[56] Drivers' charging behaviours were grouped into 16 different clusters, the associated distribution of which is depicted in Figure 30 and recorded in Table 7.

[56] Powell, S., Cezar, G. V., Rajagopal, R., 2022. Scalable probabilistic estimates of electric vehicle charging given observed driver behavior. doi: 118382.

Figure 30. Dendrogram illustrating charging behaviours

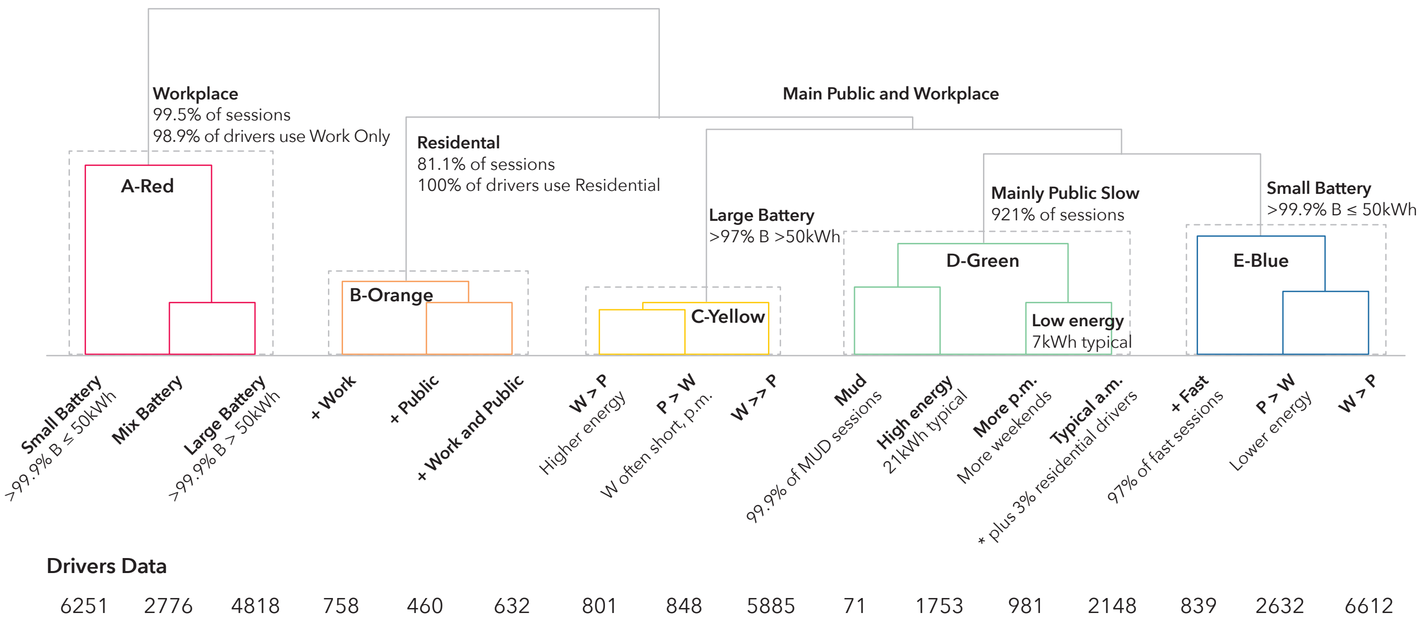


Table 7. Main charging clusters and representative charging groups

Clusters	Description	Detail	Representative Charging Group
Cluster 1		Small Battery (<50kW)	Workplace AC Type 2
Cluster 2	Using workplace charging almost exclusively	Mixed Battery	Workplace AC Type 2
Cluster 3		Large Battery (>50kW)	Workplace AC Type 2
Cluster 4		With workplace charging	Home AC Type 1
Cluster 5	Using significant amount of residential charging	With public charging	Home AC Type 1
Cluster 6		With work + public charging	Home AC Type 1
Cluster 7		Higher workplace charging than public charging	Workplace AC Type 2
Cluster 8	Large battery that uses public charging	Higher public charging than workplace charging	Public AC Type 2
Cluster 9		Much higher workplace charging than public charging	Workplace AC Type 2
Cluster 10		Multi-unit dwelling	Home AC Type 2
Cluster 11	Using predominantly public slow charging	High energy	Public AC Type 2
Cluster 12		More charging at p.m.	Public AC Type 2
Cluster 13		More charging at a.m.	Public AC Type 2
Cluster 14		Fast charging	Public DC Type 3
Cluster 15	Small battery that uses public charging	High public charging	Public AC Type 2
Cluster 16		High workplace charging	Workplace AC Type 2

The initial set of 16 distinct charging habits, as outlined in Table 7, is streamlined into five primary representative charging groups for enhanced manageability and profiling of charging behaviours. This reduction facilitates a more practical analysis of charging habits. The charging distribution for each of these clusters is visually represented in Figure 31. The details regarding the ratings and characteristics of these representative charging groups are provided in Table 8.[57] Note that the ratings used in Table 8 are considered to be the average ratings of the EVs. Particularly, for DC fast charging technology— albeit the fast-growing trend in the ratings—100 kW represents the average rating as the EV fleet in this study includes EVs with small battery capacities.

To further enrich the dataset, the U.S. Department of Energy's Electric Vehicle Infrastructure Projection Tool is incorporated.[58] Additionally, for LDVs, a substantial data pool of 17,000 LDVs is considered.[59] This dataset is sourced from the Chinese city of Shenzhen, renowned for having the first and largest fully electric bus network for public transit. The inclusion of these additional data sources contributes to a more robust understanding of charging habits and patterns for both EVs and LDVs in the study, enhancing the overall reliability and applicability of the findings.

[57] SHURA, 2019. Transport sector transformation: Integrating electric vehicles into Turkey's distribution grids. https://shura.org.tr/wp-content/uploads/2019/12/SHURA-2019-12-Transport-Sector-Transformation.Integrating-Electric-Vehicles-Into-Turkeys-Distribution-Grids.pdf
[58] U.S. Department of Energy, n.d. Electric Vehicle Infrastructure Toolbox. https://afdc.energy.gov/evi-pro-lite
[59] Wang, G., Xie, X., Zhang, F., Liu, Y., Zhang, D., 2019. bCharge: Data-Driven Real-Time Charging Scheduling for Large-Scale Electric Bus Fleets. https://ieeexplore.ieee.org/document/8603191

Figure 31. The charging distribution of each cluster

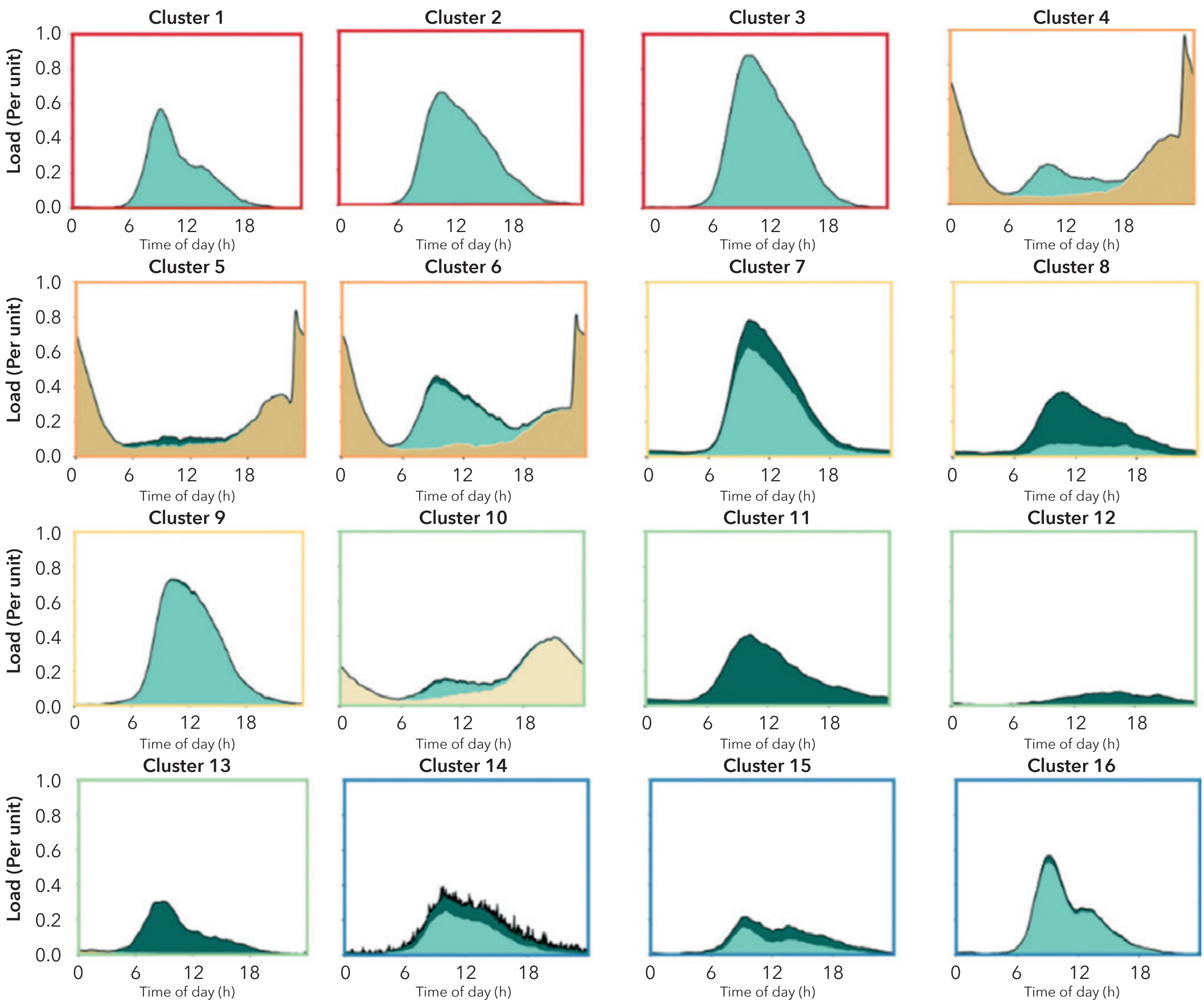


Table 8. The ratings and characteristics of the representative charging groups

Charging Technology	Rating (kW)	Charging Speed
AC1 – home (AC1 H)	2.3	Slow
AC2 – home (AC2 H)	3.7	Medium
AC2 – work (AC2 W)	22	Medium
AC2 – public (AC2 P)	22	Medium
DC3 – public (DC3 P)	100	Fast

This study incorporates two distinct charging routines: home-based charging and public-based charging. In the home-based charging routine, EVs are predominantly charged at residential charging points, whereas the public-based charging routine involves charging at publicly accessible charging points. Türkiye exhibits a high urbanisation rate, and a significant portion of its population resides in multifamily houses. Despite the prevalence of such living arrangements, it is anticipated that by 2035, over a quarter of all EV owners will have a home charging station. In workplaces, it is assumed that there will be one charger for every two EVs by 2025, one for every ten EVs by 2030, and one for every fifteen EVs by 2035. These assumptions reflect the expected growth in charging infrastructure to accommodate the increasing adoption of electric vehicles over the coming years.

The charging profiles obtained through the methodology outlined in Figure 27 primarily represent the home-based charging routine. To model the public-based charging routine, it is assumed that 40% of the energy obtained from AC2 (22 kW) home-type charging and 40% of the energy from AC2 (22 kW) public-type charging will be sourced from DC3 (100 kW) public charging stations. This assumption reflects a realistic distribution of energy consumption across different charging infrastructure types and aligns with the evolving landscape of charging technologies.

Employing the previously outlined methodology and assumptions, the charging profiles for both EVs and LDVs in each pilot region are meticulously calculated. This involves considering two integration scenarios—BAU and Net0—across two types of days (weekday and weekend) and two charging routines (home-based and public-based). Consequently, for each pilot region, a total of eight distinct charging profiles are generated, offering a comprehensive understanding of diverse charging behaviours. As an illustrative example, a specific charging pattern for the Akköprü region is presented in Figure 32–27. These profiles span weekly time frames, capturing both weekday and weekend charging dynamics, and employ 30-minute time steps to precisely reflect the nuances of DC fast charging technology.

In Figure 32, the home-based charging routine for a typical weekday under the BAU scenario is depicted. By contrasting this with the same scenario under Net0 conditions (comparing Figure 32 and Figure 33), a noticeable increase in the peak load of EVs and LDVs is observed, rising from approximately 10 megawatt (MW) to 20 MW. This elevation in the peak load is a direct consequence of the increased number of EVs and LDVs in the Net0 scenario compared to the BAU scenario. Figure 33 and Figure 34 further illustrate the comparison between home-based and public-based charging routines, where the number of DC fast charging events increases. Consequently, the peak of the charging profile rises from 20 MW to around

25 MW. This observation distinctly highlights the alteration in patterns when transitioning from a home-based routine to a public-based routine. Finally, Figure 35 portrays the charging pattern during the weekend, showcasing considerable changes in the charging profile when compared to the weekday pattern (Figure 34).

Figure 32. The charging profile of Akköprü, home-based charging routine, weekday, year 2035, BAU

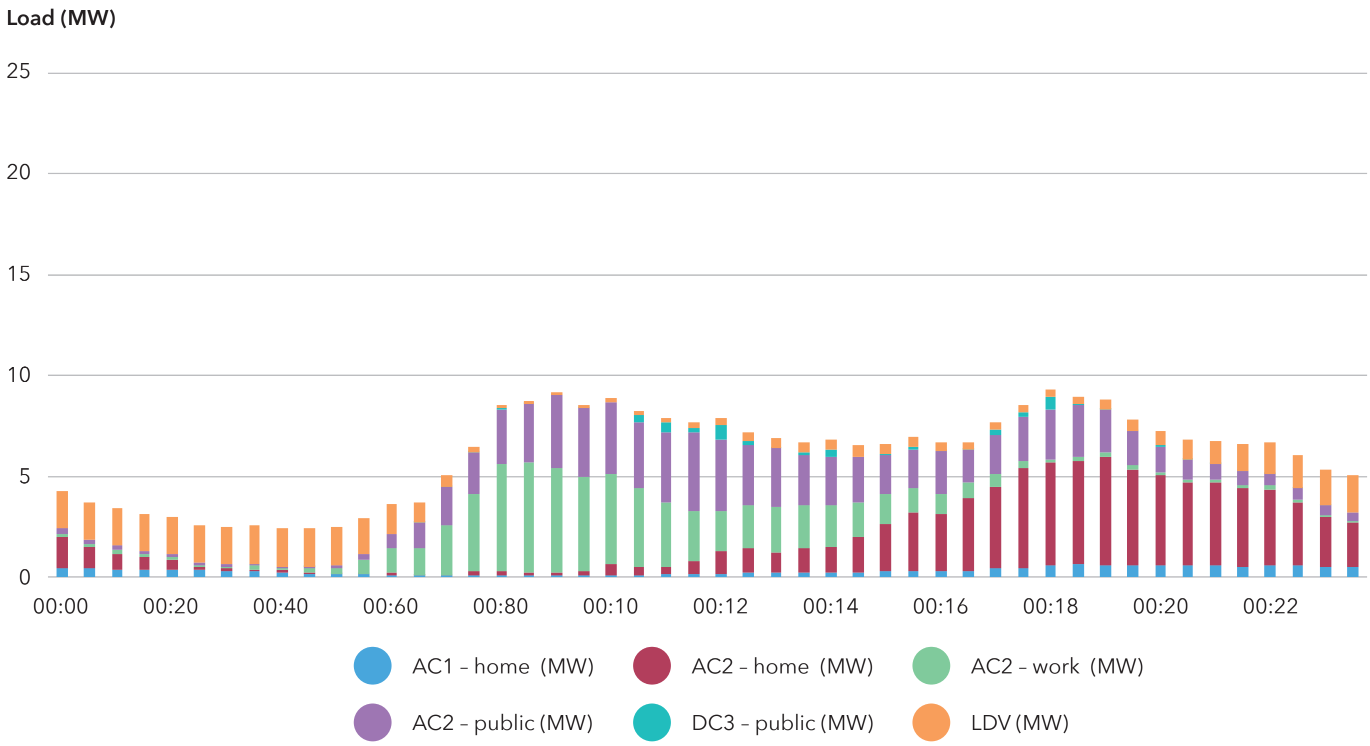


Figure 33. The charging profile of Akköprü TM, home-based charging routine, weekday, year 2035, Net0

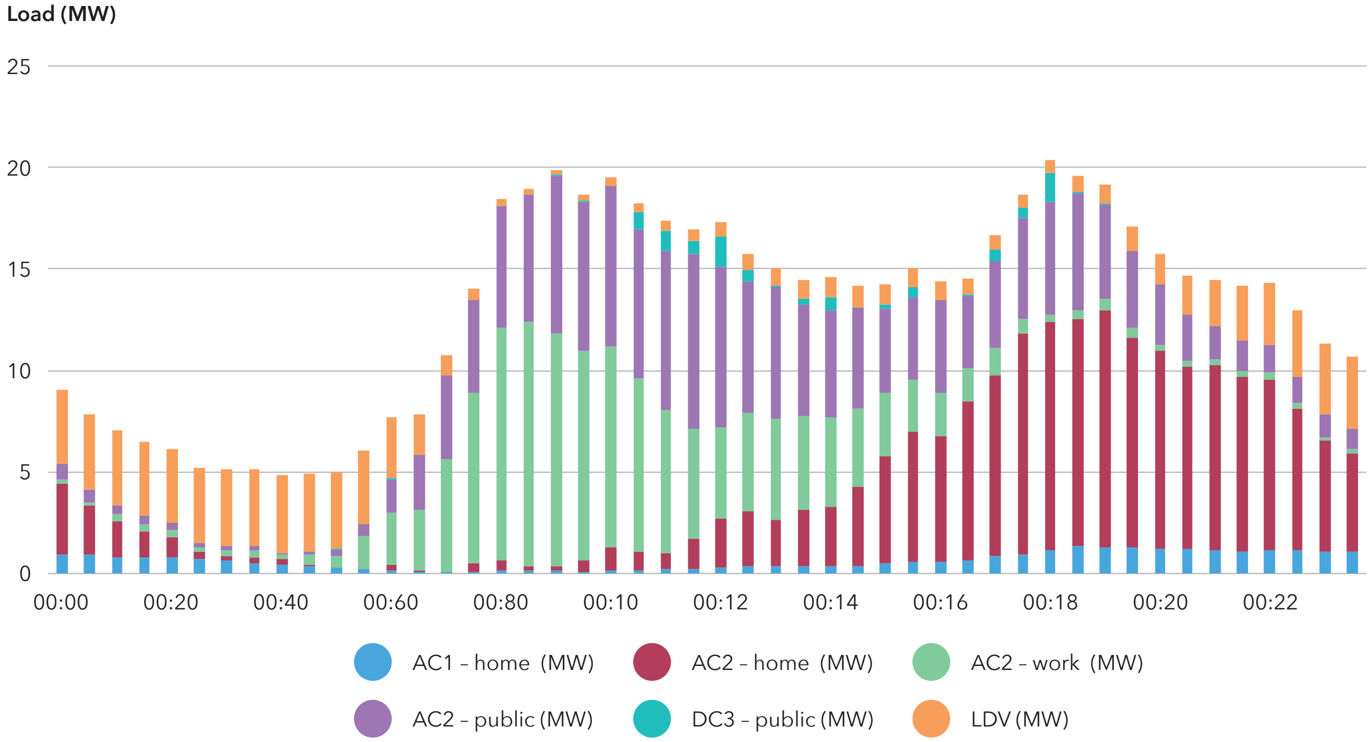


Figure 34. The charging profile of Akköprü TM, public-based charging routine, weekday, year 2035, Net0

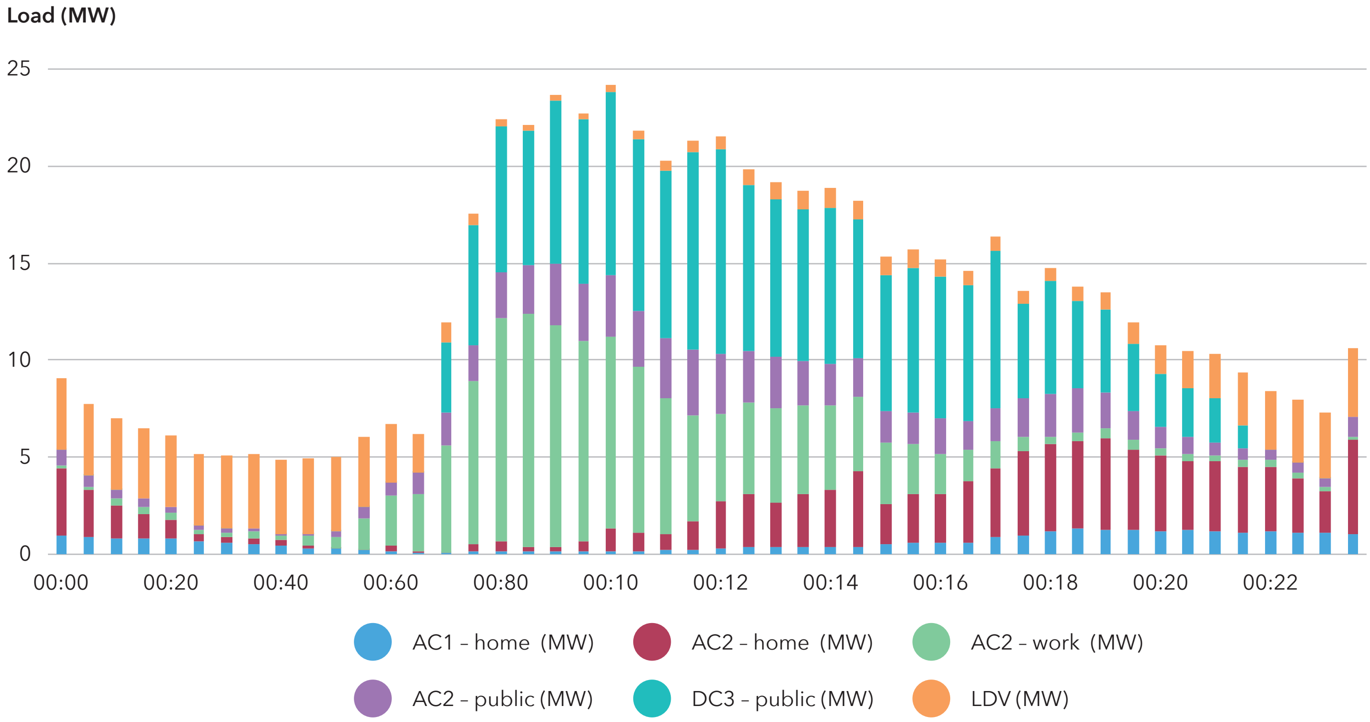
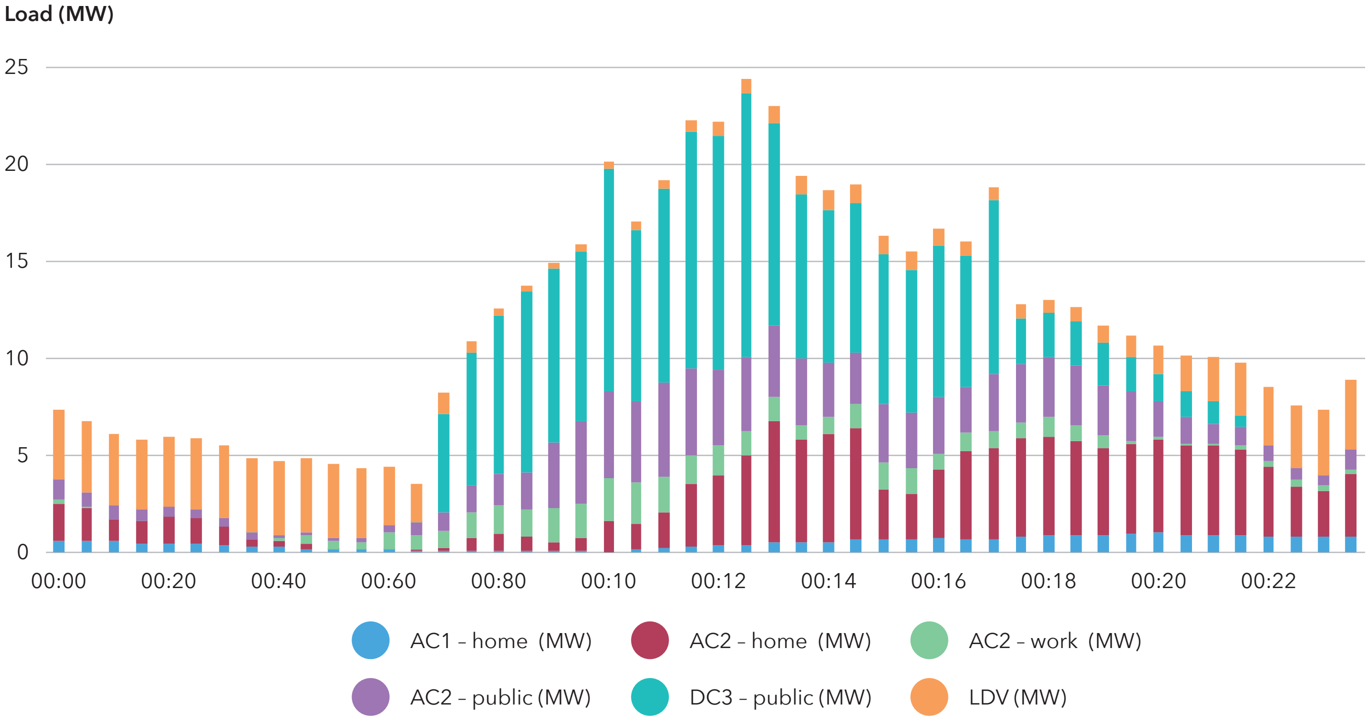


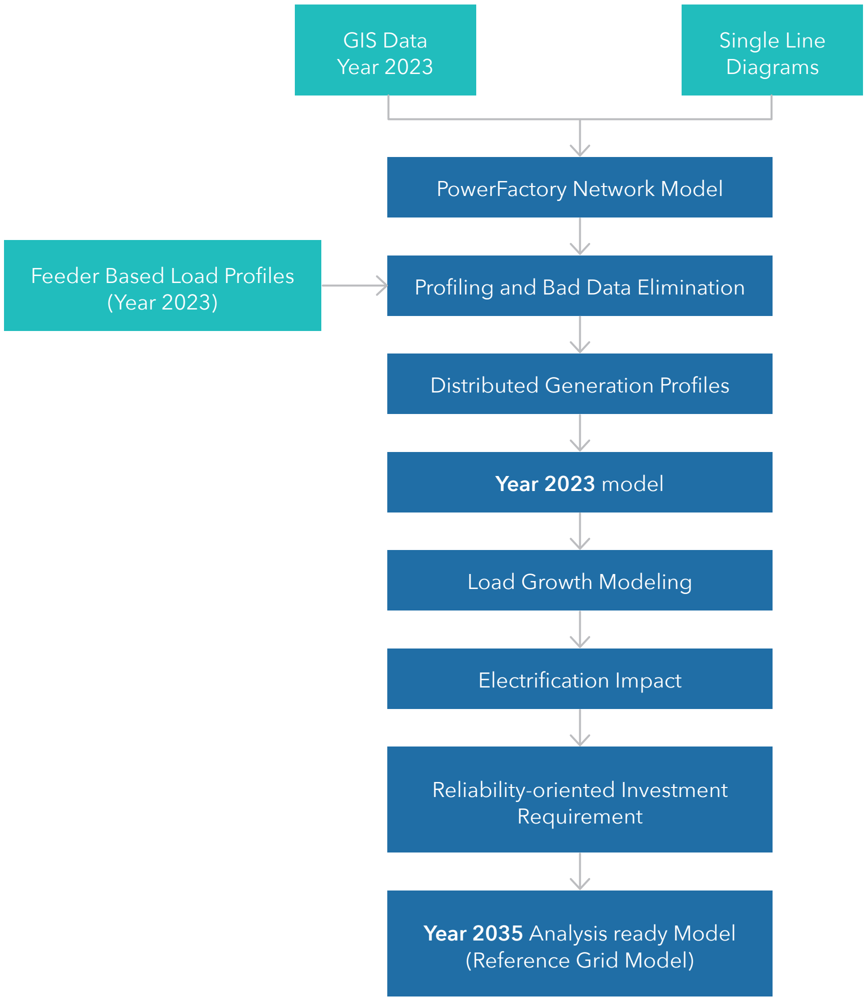
Figure 35. The charging profile of Akköprü TM, public-based charging routine, weekend, year 2035, Net0



4.4 Development of the reference grid model

To evaluate the influence of EVs on the pilot distribution regions, medium voltage (MV) reference grid models have been formulated up until the year 2035. In crafting these models, it was assumed that there is no EV charging load within the reference grid model, effectively characterizing it as a non-EV reference grid model. This assumption stems from the consideration that the BAU scenario, which forms the basis of this study, reflects the ongoing trend of EV integration into the distribution system. The procedural framework for developing the reference grid model is visually represented in Figure 36. This approach ensures a comprehensive understanding of the baseline distribution grid conditions, enabling a clear distinction between the non-EV reference grid model and subsequent scenarios incorporating EV charging loads.

Figure 36. The reference grid model development approach

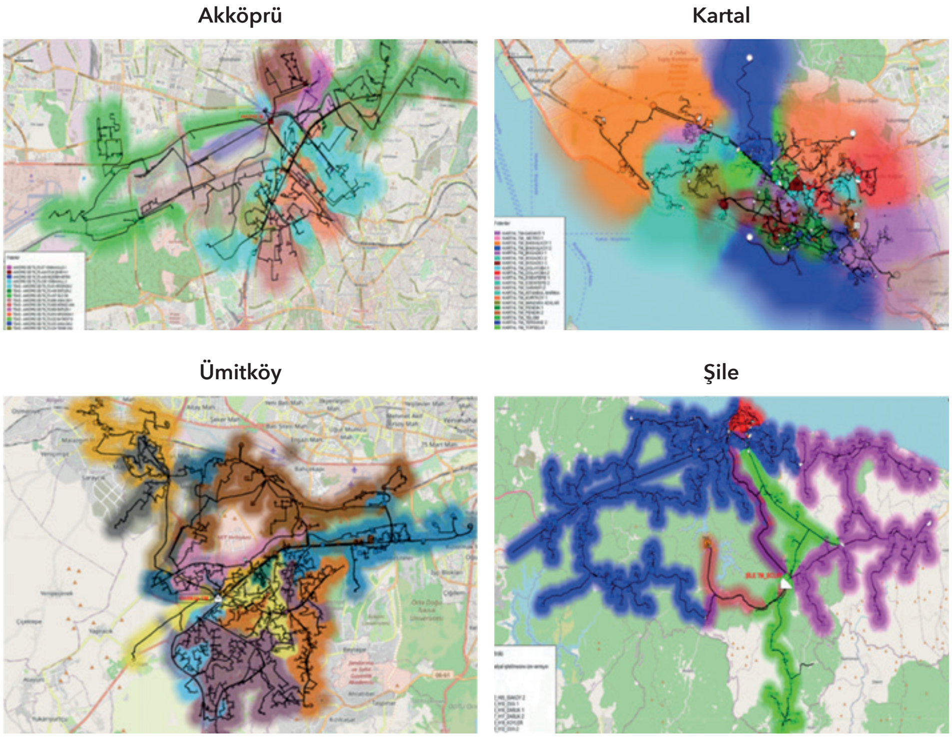


The following steps were performed to develop the reference grid model for each pilot region:

- **Year 2023 model development:** The geographical information system (GIS) data and single-line diagrams associated with the distribution network of the pilot regions were sourced from the relevant DSO. This acquired data was then meticulously transformed into the network model within the DIgSILENT PowerFactory environment. In conjunction with the network data, load profiles originating from feeders were also obtained and imported into the model to simulate the loading conditions of lines and transformers. In this process, the acquired load profiles underwent filtering and scrutiny for potential inaccuracies or anomalies. If downstream load data be available, it was directly utilized. Alternatively, if downstream data is unavailable, measurements from the feeder were scaled to match the downstream load, adjusting for the capacity of associated medium voltage/low voltage (MV/LV) transformers.

Additionally, the model considered various customer types on the low voltage (LV) side of the MV/LV transformers. Daily load characteristics, as identified by EMRA[60] for each distribution company, were incorporated into the model. These characteristics encompass residential, commercial, industrial, irrigation, and lighting loads for typical seasonal weekdays. By integrating these factors, the grid model for the year 2023 was established, providing a baseline for projecting loads towards the year 2035 and determining necessary investments. The MV grid model of the pilot regions pertaining to year 2023 is depicted in Figure 37, where the feeders serving different regions are separated by different colours. The current status of the network, considering MV line loading, MV/LV transformer loading, and voltage levels, is depicted in Figure 38, Figure 39, and Figure 40, respectively. Notably, the annual average loading of MV/LV transformers hovers between 30% and 40%, while for MV lines, the annual average loading level is approximately 15%. While this might initially suggest available capacity for new loads, subsequent sections will illustrate that despite this apparent vacancy, there remains a need for investment to ensure the secure operation and reliability of the distribution grid.

Figure 37. The MV grid model of the pilot regions – Current system, year 2023



[60] EPDK, Load profiles of consumer groups

Figure 38. MV/LV transformer loading level – Current system, year 2023

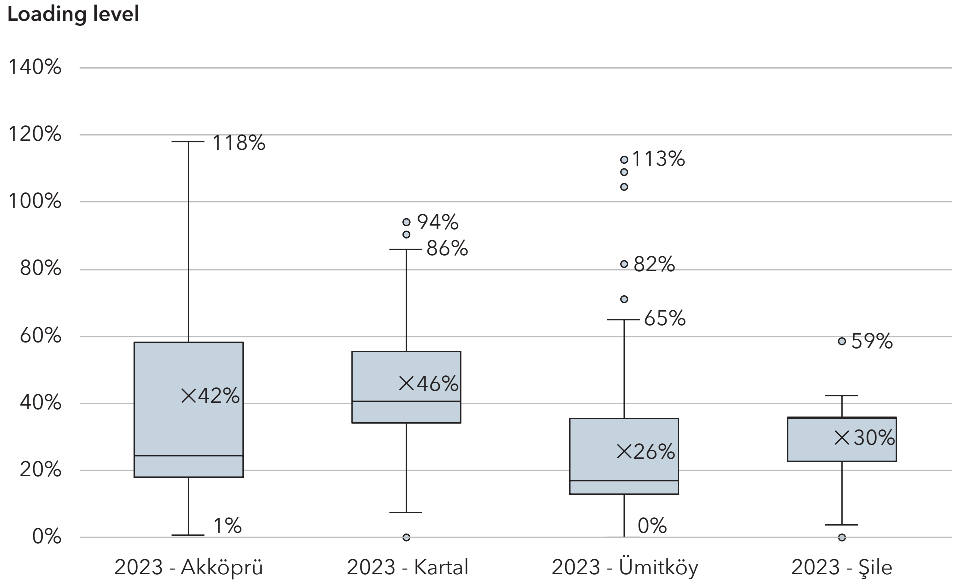


Figure 39. MV lines loading level – Current system, year 2023

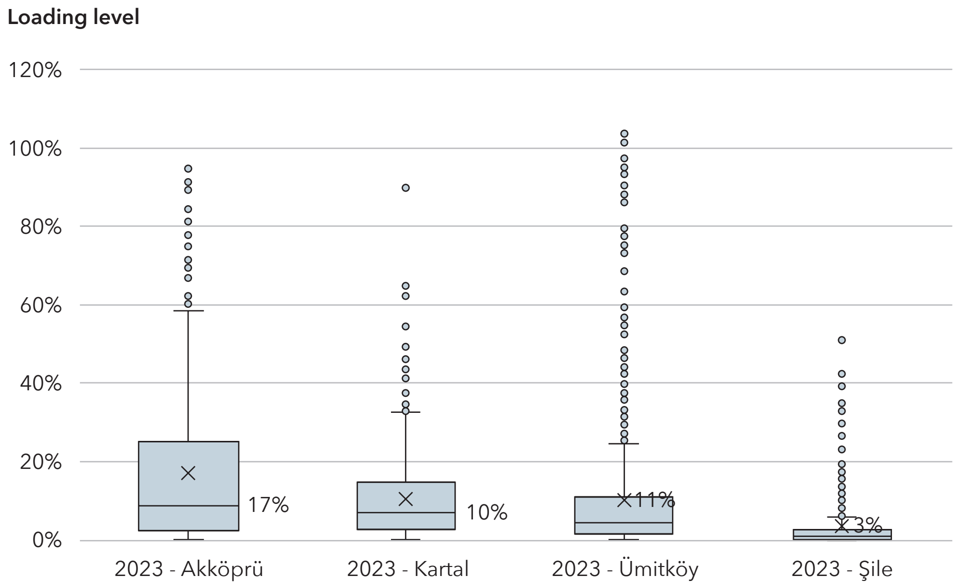
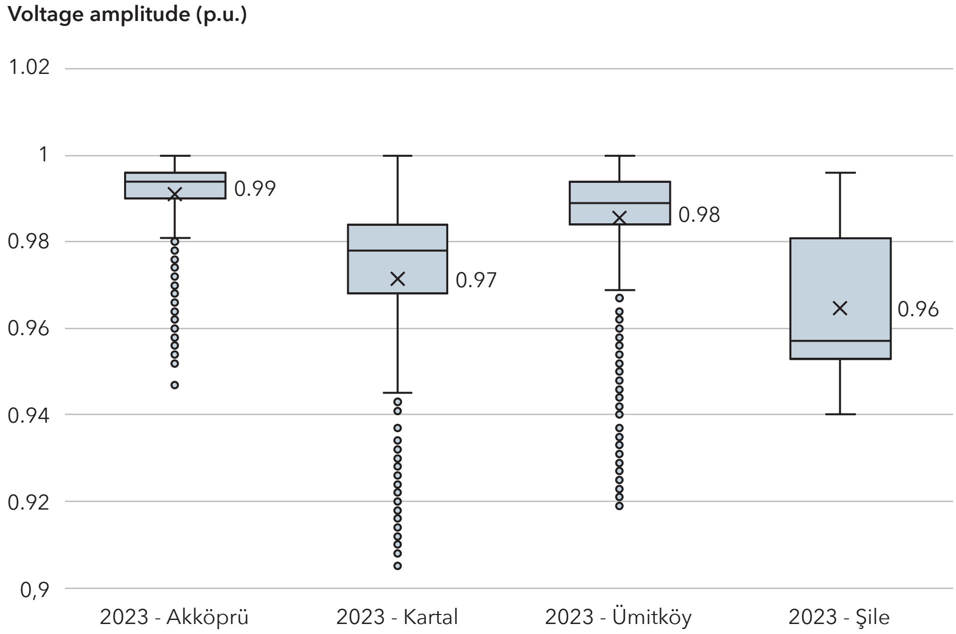


Figure 40. Voltage profile of pilot regions – Current system, year 2023



- **Load growth modelling:** To determine annual load curves for HV substations supplying the pilot regions, we scaled their current (2023) load curve to the target year (2035) and incorporated the annual demand increase rate. The annual average demand increase ratio, as per SHURA Energy Transition Center figures, was estimated to be ≈3% (Figure 41). While this 3% average serves as a representative value for the entire country, metropolitan areas often experience demand increments exceeding the national average, as indicated by DSO figures. Consequently, this study adopts a 5% annual increase in the average demand for metropolitan areas and 3% for rural areas. This percentage encompasses the demand growth for existing loads (vertical growth), the addition of new loads (horizontal growth), and the impact of electrification, excluding EV charging demand. It is crucial to note that this analysis considers an electrification rate of 7% (average). The associated impact on the load profile is visually represented in Figure 42 for a typical week and in hourly resolution. This figure reflects the changes in the load profile resulting from the electrification of various sectors, contributing to a comprehensive understanding of the evolving demand landscape.

Figure 41. The annual average increase in demand based on SHURA Energy Transition Center figures

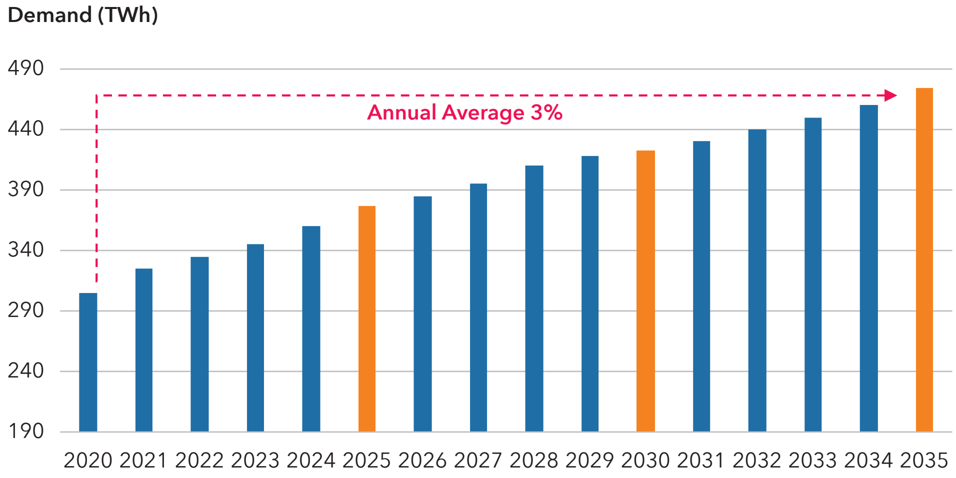
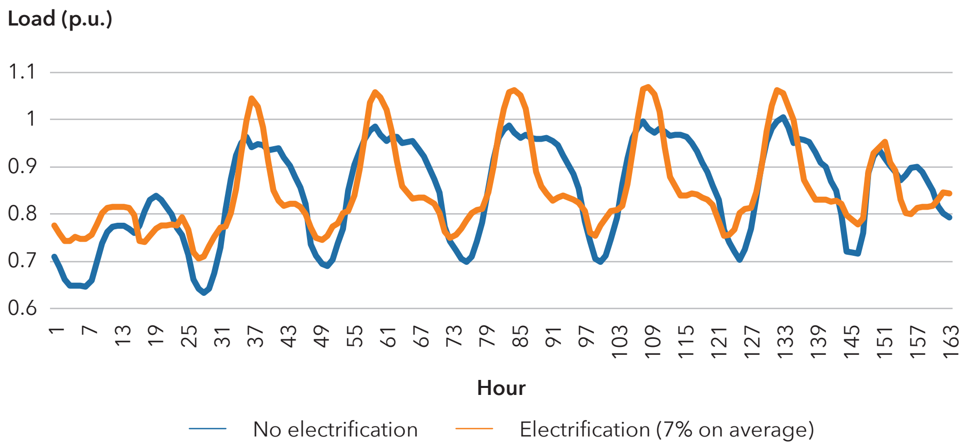


Figure 42. The impact of electrification on the load profile for a typical week, in hourly resolution



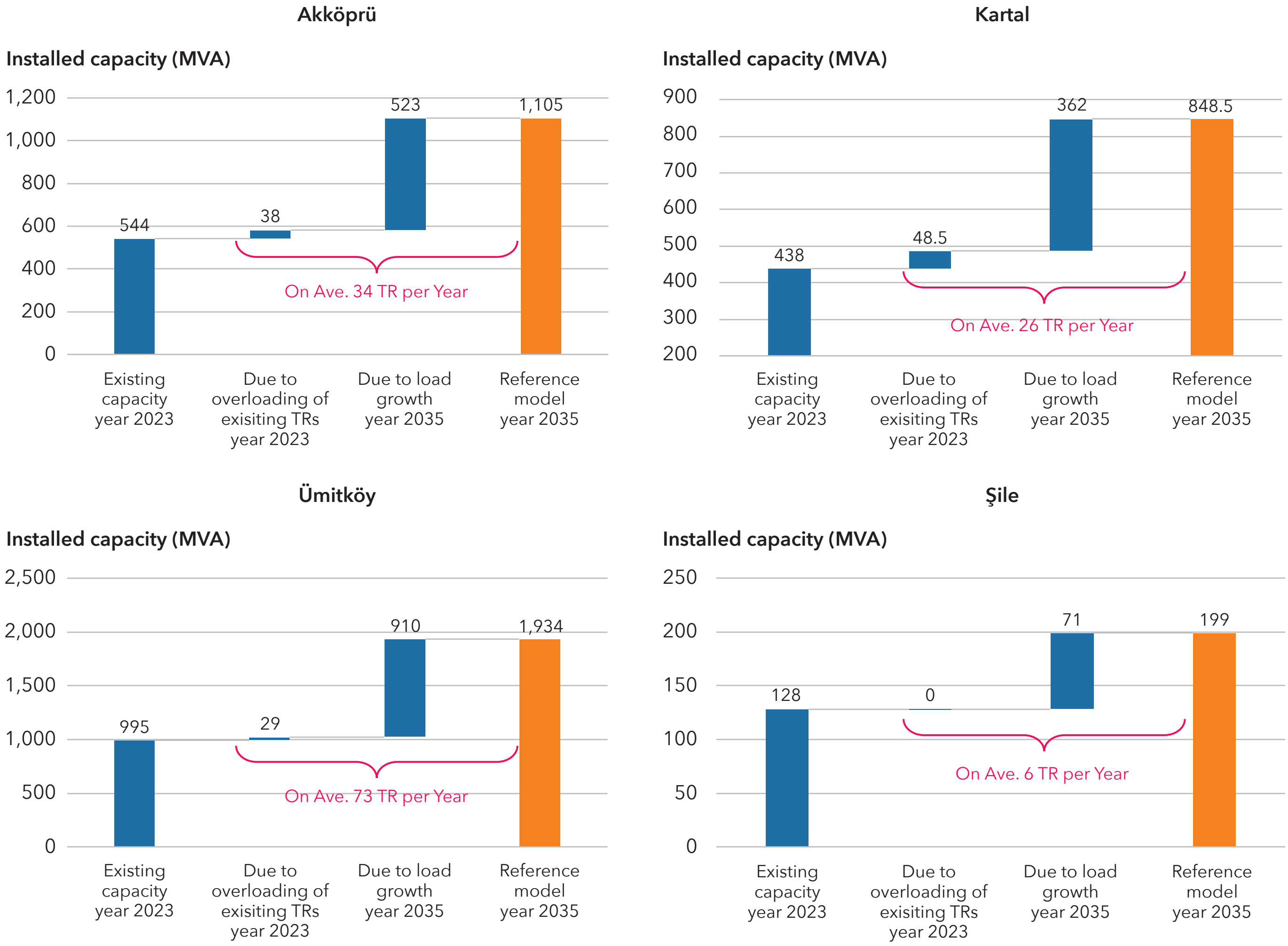
- **Investment requirements to build a reference grid model (Year 2035, excluding e-mobility loads):** Employing the aforementioned annual average load growth rate, the identification and implementation of investments and grid reinforcements were crucial steps to transform the existing 2023 model into a reference grid model for the year 2035. There are several drivers behind these grid reinforcement requirements: overloading of existing branches, overloading of MV/LV transformers, voltage drops at consumer points, N-1 contingency at the primary distribution network, and most importantly, reliability constraints essential for grid operation. DSOs typically consider reliability constraints based on the number of customers and feeding points on a MV lateral. While detailed reliability analyses, calculating indices like the Customer Average Interruption Duration Index (CAIDI), Customer Average Interruption

Frequency Index (CAIFI), and Expected Energy Not Supplied (EENS) are commonly conducted by DSOs, a rule of thumb is often applied. DSOs generally regard 16 units of 1.6 MVA MV/LV transformers (totalling around 25 MVA capacity) on a lateral as the upper limit to maintain reliability constraints. In this study, the grid reinforcement requirements are approached systematically. In cases of overloaded MV branches or MV/LV transformers, the introduction of parallel elements was contemplated. Subsequently, an assessment of voltage drops and N-1 contingency at the primary distribution network was performed, and if needed, investments in MV lines were envisioned. In the final stage, the number of MV/LV transformers on the laterals was scrutinized. If reliability constraints were violated, lateral splits were implemented—either into two or three laterals—as necessary to maintain the specified reliability standards. It is essential to note that the reinforcements considered at this stage are exclusively associated with the MV grid. The assumption is made that any new MV/LV transformer introduced to the system is facilitated by the associated LV system, standardized by the Turkish Electricity Distribution Corporation.[61] However, it is crucial to highlight that the investments resulting from the integration of EVs and LDVs are calculated at both the MV and LV levels. The outcomes of these calculations will be presented in Section 5 for comprehensive insights into the impacts of the integration of EVs and LDVs on both grid levels.

The required amount of MV/LV transformer investment for each pilot region is depicted in Figure 43. As can be seen from Figure 43, the average number of MV/LV transformer investments in the pilot regions is around 30 transformers per year, which is very close to the DSO figures. The number of MV/LV transformer investments in the Ümitköy region is relatively high due to the region's dense development, characterized by high-rise buildings.

[61] TEDAŞ, 2015. ALÇAK GERİLİM DAĞITIM PANOLARI TEKNİK ŞARTNAMESİ. https://www.tedas.gov.tr/FileUpload/MediaFolder/cc6ffb86-7888-4606-a962-c706c7ef6722.pdf

Figure 43. The required amount of MV/LV transformer investments for building a 2035 reference grid model

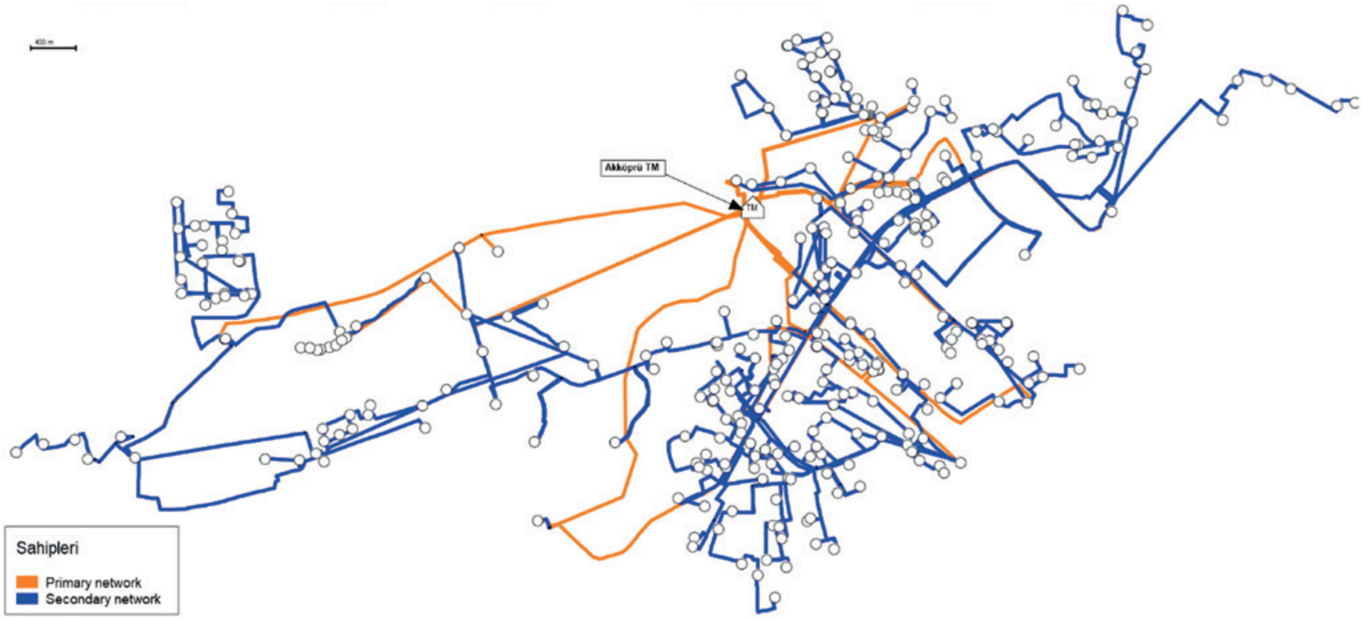


The investment requirements for MV lines to accommodate load growth until the year 2035 are outlined in Table 9. The available MV line length in the Akköprü region is 210 kilometers (km) as of the year 2023. Considering the previously discussed load growth scenario and, consequently, factoring in the MV/LV transformer growth detailed in Figure 43, an additional 64 km of MV lines would be necessary to address the impact of load growth. Within this 64 km, 27 km is attributed to overloading at the primary distribution network post-load growth, 35 km is due to secondary distribution network overloading, and 13 km is associated with reliability criteria. Here, the primary network pertains to the branches connecting the main substations and laterals, while the secondary network encompasses only the laterals feeding the distribution transformers. The primary and secondary network configuration for the Akköprü region is illustrated in Figure 44. Calculating reinforcements for the primary network is relatively straightforward due to its radial nature and a lower number of junctions compared to the secondary network. The secondary network, however, is more significantly influenced by site constraints. Given the unknowns and uncertainties related to the secondary network, relying solely on network analysis for reinforcement calculations might not capture all the necessary investments. In addressing this challenge, the ratio between the secondary and primary networks operated by Enerjisa DSOs is examined to establish an average coefficient. This coefficient is then used to derive more realistic investments for the secondary network. Considering these factors, the annual average MV line investment across all pilot regions hovers around 2.3% of available lines, aligning with figures reported by the DSOs.

Table 9. The required amount of MV line investments for building the 2035 reference grid

Item	Length (km)			
	Akköprü	Kartal TM	Ümitköy	Şile
Available MV Lines - Year 2023	**210**	**307**	**688**	**462**
Total Network Expansion Requirement - Year 2035	**64**	**68**	**171**	**57**
Primary Network Investment (From grid analysis)	27	31	58	15
Overloading-based Secondary Network Investment (From grid analysis)	24	33	46	12
Reliability-based Secondary Network Investment (From grid analysis)	13	2	67	18
Voltage Drop-based Secondary Network Investment (From grid analysis)	0	2	0	12
Secondary/primary ratio	0,9	1,1	0,8	0,8
Existing secondary/primary ratio (Enerjisa DSOs average based on current network topology considering site constraints)	3,3	3,3	3,3	3,3
Expected secondary network expansion considering site constraints/requirments (applying 3.3 ratio)	88,7	99,5	186,9	49,5
Additional secondary network expansion on top of expansion calculated from grid analysis	52,2	62,3	73,8	7,5
Total Investment up to Year 2035	**103,5**	**125,9**	**177,3**	**34,5**
Total Line Length at Year 2035	**314**	**433**	**865**	**497**
Annual Average Line Investment from 2023 to 2035	**9**	**10**	**15**	**3**
Annual Average Line Investment rate	**3,3%**	**2,9%**	**2%**	**0,6%**

Figure 44. Primary and secondary networks in Akköprü



The additional investment requirements to build a reference grid model based on 2023 data corresponds to 37 million Turkish Liras (TL) in new investments per year for the Akköprü region (in real 2023 prices). The details of the investment costs are presented in Table 10. The costs of MV/LV transformers and MV lines are calculated based on BAŞKENT EDAŞ and AYEDAŞ data.

Table 10. The required amount of MV line investments for building the 2035 reference grid

Pilot Region			Akköprü	Kartal	Ümitköy	Şile
MV/LV Transformer (LV busbar included)	Available at Year 2023	Capacity (MVA)	544	438	995	128
	Invested up to Year 2035	Capacity (MVA)	561	410	939	71
		Cost (million TL, 2023)	**285**	**209**	**550**	**63**
	Investment per Year	Capacity (MVA)	47	34	78	6
		Cost (million TL, 2023)	**24**	**17**	**46**	**5**
MV Lines	Available at Year 2023	Length (km)	210	307	688	462
	Invested up to Year 2035	Length (km)	114	115	177	35
		Cost (million TL, 2023)	**164**	**166**	**255**	**50**
	Investment per Year	Length (km)	10	10	15	3
		Cost (million TL, 2023)	**14**	**14**	**21**	**4**
Total Investment up to 2035 (million TL, 2023)			**449**	**375**	**805**	**113**
Required Investment per Year (million TL, 2023)			**37**	**31**	**67**	**9**

4.5 Charging stations, sizing and placement

After constructing the reference grid model for the year 2035, the computed EV and LDV loads from Section 4.3 are distributed among the charging points within the distribution system's service area. Charging points are categorized as follows: Charging at Workplace (AC2W), AC charging at Public Places (AC2 P), DC fast public charging (DC3 P), and Charging at Home (AC1 H and AC2 H). Public charging primarily caters to commercial and public applications, intending to function similarly to traditional gasoline service stations.[62] Currently, many charging points are strategically placed along highways or at points of interest like shopping centres, providing drivers with the convenience of charging their vehicles while engaged in activities such as work, eating, or shopping.[63] Therefore, it is assumed that public charging points will be located at existing gas stations along main boulevards and at shopping centres within the pilot regions. Concerning workplace charging, it is presumed that there is suitable infrastructure allowing all EVs to be charged during working hours, such as within a Technopark. The installed capacity of public charging points and the number of plugs in each pilot region are detailed in Table 11 and Table 12, respectively. This distribution ensures the comprehensive allocation of the calculated load to different charging categories, reflecting the diverse charging scenarios and infrastructure assumptions considered in the study.

Table 11. The installed capacity of public charging points in each pilot region

Substation Name	Number of EVs - Year 2035 [Thousands]		Total Station Capacity (kW)											
	BAU	Net0	BAU						Net0					
			Home-based Charging Routines			Public-based Charging Routines			Home-based Charging Routines			Public-based Charging Routines		
			AC2 Work-place	AC2 Public	DC3 Fast Public	AC2 Work-place	AC2 Public	DC3 Fast Public	AC2 Work-place	AC2 Public	DC3 Fast Public	AC2 Work-place	AC2 Public	DC3 Fast Public
Akköprü	14,97	32,76	5,500	8,900	2,500	5,500	3,700	9,500	12,050	19,600	5,400	12,050	8,103	20,810
Ümitköy	14,97	32,76	5,500	8,914	4,758	5,500	3,722	9,508	11,983	19,549	5,500	11,983	8,103	20,810
Kartal	11,33	24,79	4,200	6,700	1,900	4,200	2,714	7,230	9,195	14,676	4,200	9,195	5,925	15,795
Şile	2,83	6,20	1,050	1,650	500	1,050	704	1,800	2,298	3,616	1,089	2,298	1,547	3,941

[62] Borges, J., Loakimidis, C., Ferrao, P., 2010. Fast charging stations for electric vehicles infrastructure. https://www.researchgate.net/publication/271435550_Fast_charging_stations_for_electric_vehicles_infrastructure

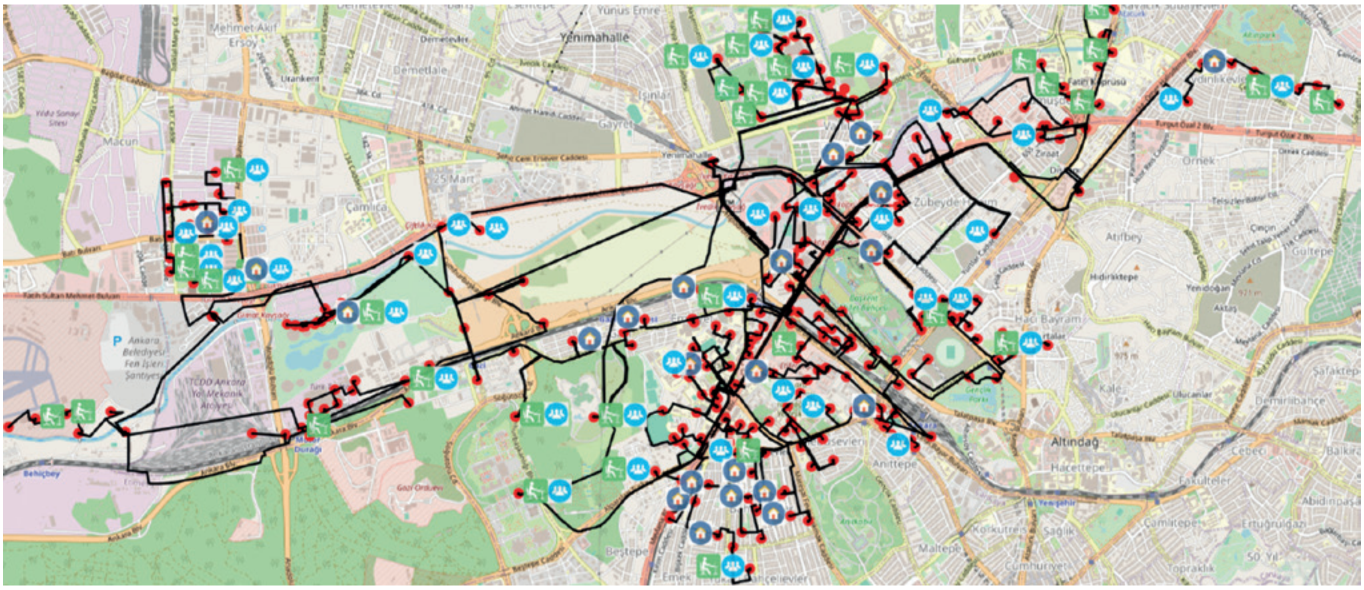
[63] https://lisans.epdk.gov.tr/epvys-web/faces/pages/lisans/elektrikSarjAgilsletmeci/sarjlstasyonuOzetSorgula.xhtml

Table 12. The number of public charging points in each pilot region

Substation Name	Number of EVs - Year 2035 [Thousands]		Total Station Capacity (kW)											
	BAU	Net0	BAU						Net0					
			Home-based Charging Routines			Public-based Charging Routines			Home-based Charging Routines			Public-based Charging Routines		
			AC2 Work-place	AC2 Public	DC3 Fast Public	AC2 Work-place	AC2 Public	DC3 Fast Public	AC2 Work-place	AC2 Public	DC3 Fast Public	AC2 Work-place	AC2 Public	DC3 Fast Public
Akköprü	250	405	26	56	250	174	26	547	897	547	379	217	8,103	20,810
Ümitköy	250	407	44	47	250	163	44	557	894	557	370	192	8,103	20,810
Kartal	191	305	18	36	191	140	18	413	667	413	295	148	5,925	15,795
Şile	48	75	5	10	48	31	5	96	150	96	75	40	1,547	3,941

Based on the surveys conducted and the available databases, the annual capacity factor of public charging stations is around 20%. For workplaces, assuming a 45-hour work week under which the charging would be performed, the annual capacity factor is around 26%. These capacity factors are used to determine the installed capacity of public charging stations. Home-based charging points are assumed to be distributed to transformers, which mainly supply residential consumers with respect to the installed capacity of MV/LV transformers. The charging points in the Akköprü region are depicted in Figure 45.

Figure 45. Locational distribution of the electric vehicle charging points in the Akköprü region



4.6 Sensitivity analysis

A sensitivity analysis was performed on top of the considered scenarios to evaluate the impact of EVs and LDVs in conditions other than those assumed for the main scenarios, BAU and Net0. The cases investigated are presented in Table 13. They include extreme charging patterns due to holidays, optimized charging (smart and bidirectional), and the impact of simultaneous highway charging.

Table 13. The sensitivity cases considered in this study

No.	Key parameter	Main Question
Case I	Excessive charging at holiday times	What is the impact of simultaneous and concentrated charging on the grid?
Case II	Smart Charging Mechanisms	What is the smart charging potential of EV charging through optimally using EVs' flexibility windows?
Case III	Vehicle to Grid Impact	What is the impact of bidirectional EV (dis-) charging on the grid?
Case IV	Charging at highway	What is the impact of increased charging along highways on the grid?

In Case I, the analysis explores the impact of heightened charging activities preceding specific occasions, such as religious holidays. It considers a scenario in which individuals engage in charging even if their vehicles already possess a certain level of charge. This anticipates the likelihood of increased charging demand as people prepare for extended periods of travel or usage during religious holidays. The study aims to understand and assess the potential strain on the charging infrastructure and grid during these specific events, contributing valuable insights into grid management strategies and infrastructure planning to accommodate such distinctive charging patterns.

In Case II, the effects of redistributing the load of EVs and LDVs to less congested hours within the grid are investigated. This involves exploring the potential benefits and challenges associated with introducing contractual agreements that offer flexibility in charging patterns, enabling a more balanced and efficient utilisation of the grid resources. This flexibility can be achieved through different mechanisms such as implementing time-of-use tariffs, dynamic pricing mechanisms, and smart contracts. By assessing the impact of these flexibility measures, the study aims to provide insights into optimizing the distribution of EV and LDV loads, minimizing grid congestion during peak hours, and promoting a more sustainable and resilient electric mobility infrastructure.

Case III thoroughly examines the repercussions of vehicle to grid (V2G) discharging, specifically focusing on its impact at the LV distribution system level. The primary objective is to assess how the integration of

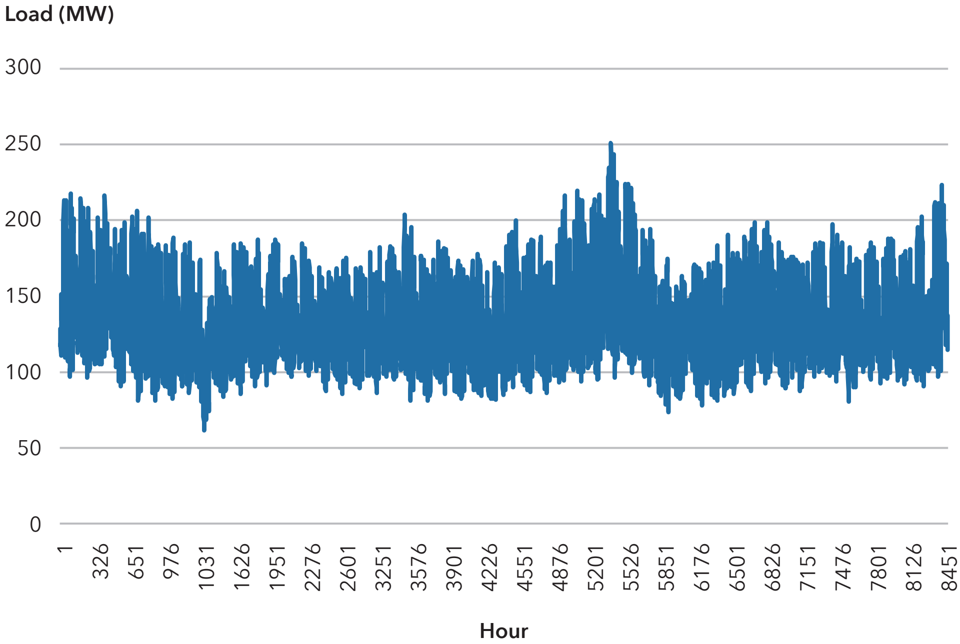
V2G discharging can play a pivotal role in mitigating congestion within the distribution system and potentially deferring the need for additional investments. By analysing the bidirectional flow of energy from electric vehicles back to the grid, the research aims to provide a comprehensive understanding of the potential benefits. These include optimizing grid performance, reducing congestion, and strategically postponing infrastructure investments. This investigation contributes valuable insights into the strategic implementation of V2G discharging as a solution to address distribution system challenges, ultimately enhancing overall grid resilience and sustainability.

Case IV explores the ramifications of EV charging at roadside stations, where the charging infrastructure is supplied through an extended and potentially weaker feeder. Additionally, the investigation considers the effects of simulated DC fast charging scenarios. By examining the impact of charging activities along highways, particularly those serviced by long and potentially less robust feeders, the research aims to understand the implications for the distribution network. This includes assessing the potential challenges associated with extended feeder lengths and the impact of rapid DC fast charging technology. The findings from this analysis will provide insights into optimizing charging infrastructure along highways and improving the resilience of the distribution system to accommodate these specific charging scenarios.

4.7 Grid analysis and key performance indices

Upon establishing the reference grid model for the year 2035 and integrating the EV and LDV fleet, a comprehensive grid analysis is undertaken for each pilot distribution region individually. This analysis aims to assess the impact of EVs and LDVs on the pilot grids. The grid analysis encompasses a quasi-dynamic load flow analysis for the entire year 2035 in which the EV and LDV loads are modelled on a weekly basis with a 30-minute resolution. Figure 46 provides insights into the annual active load observed from the high voltage (HV) substation in Akköprü, presented in hourly resolution. The simulation studies are executed using the DigSilent PowerFactory software, allowing for a detailed examination of the grid's behaviour under the influence of integrated EVs and LDVs. This approach facilitates a thorough understanding of the dynamic interactions between the vehicle fleet and the distribution network, aiding in the identification of potential challenges and the formulation of effective solutions.

Figure 46. The annual load seen from Akköprü HV substation



The conducted studies incorporate a comprehensive set of key performance and impact indices to assess the impacts of EVs and LDVs on the distribution grid. The considered indices are as follows:

- **Overloadings on MV and LV branches (%):** A branch is deemed overloaded if its loading at any given hour approaches the thermal loading capacity, set at 90%. This index serves as a critical measure of the distribution system's ability to handle the additional load imposed by EVs and LDVs.

- **Voltage drops on MV and LV busbars (%):** Voltage drops exceeding 10% of the nominal voltage during any hour are considered indicative of an under-voltage issue. Monitoring and analysing these voltage drops are crucial for ensuring the stability and reliability of the distribution network.

- **Capacity factors of MV feeders and MV/LV transformers (%):** Calculated on an annual basis, capacity factors provide insights into the utilisation levels of MV feeders and MV/LV transformers. This index aids in understanding the efficiency and load-carrying capabilities of these network components.

- **Investment requirements (MV lines, LV lines, and MV/LV transformers):** The study evaluates the investment needs for MV lines, LV lines, and MV/LV transformers. This includes determining the additional infrastructure required to accommodate the growing demands posed by EVs.

Operational violations, such as overloads and under-voltage occurrences, are recorded for both scenarios, namely no-EV uptake and EV uptake scenarios (BAU and Net0). This comparison allows for a thorough assessment of the impact of EVs and LDVs on the grid operational integrity. The calculated capacity factors offer insights into the adequacy of the existing infrastructure, guiding future investment decisions. This comprehensive approach ensures a holistic understanding of the grid's performance under different scenarios, aiding in the formulation of effective strategies for EVs' and LDVs' grid integration.

5. Results and Discussion

This section presents the simulation studies on the pilot regions. In Section 5.1, the results of the analysis are presented. Section 5.2 shows the results of the sensitivity analysis. In Section 5.3, a brief discussion on the findings is presented.

5.1 Impact on the distribution grids

The grid analyses are conducted considering the key performance indices discussed in Section 4.7, the reference grid model developed in Section 4.4, and electric vehicles' (EVs') and light duty vehicles' (LDVs') charging profiles calculated in Section 4.3. The loading levels of the medium voltage / low voltage (MV/LV) transformers under different EV integration scenarios for the Akköprü region are depicted in Figure 47. Here, to effectively illustrate the results of the grid analysis and emphasize the impact of EVs and LDVs, the MV/LV transformers are categorized into two distinct groups:

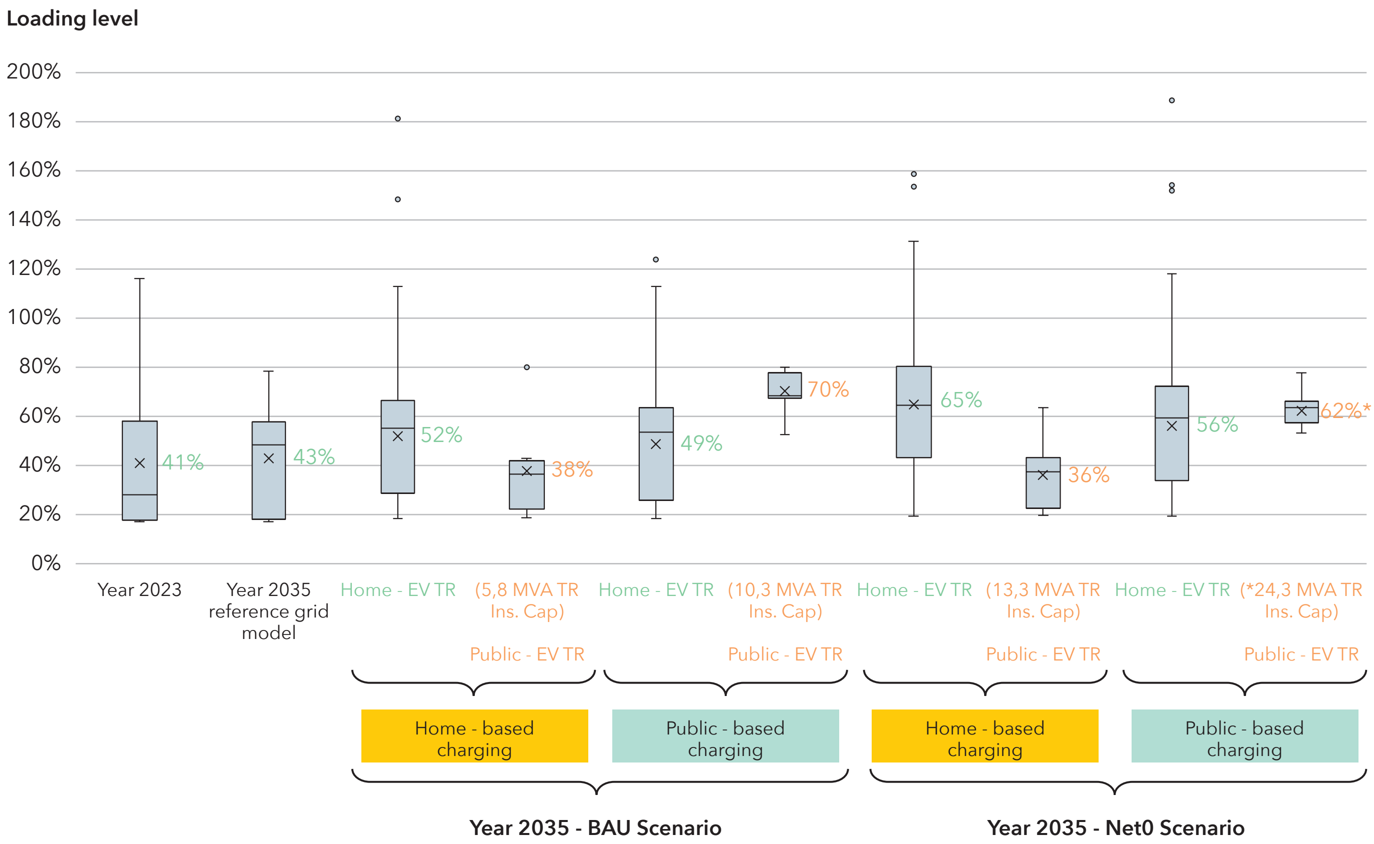
- **Non-EV TR:** This category comprises MV/LV transformers within the 2035 reference grid model that will not cater to EVs and LDVs following their integration into the grid.

- **Home-EV TR:** These transformers are designated to supply charging points located in residential areas and homes, encompassing AC1 and AC2 home types.

- **Public-EV TR:** This group encompasses MV/LV transformers designated to supply power to charging points situated in workplaces and public charging stations (AC2 and DC3). These transformers are usually installed for EVs and LDVs.

The initial results for the Akköprü region are depicted in Figure 47. In Figure 47, the annual average loading of MV/LV transformers in the year 2023 stands at approximately 42%. Looking ahead to the reference grid model in 2035, this average loading remains close to that of 2023, reflecting the envisioned investment levels aimed at achieving the standard operational level for distribution systems (refer to Figure 43). Notably, in the reference grid model for 2035, the average loading of potential Home-EV transformers holds significant importance, given their role in accommodating EVs. Examining Figure 47 further, the annual average loading of Home-EV transformers will see a notable increase from 43% in the absence of EVs (reference grid model) to 52% and 65% under the home-based charging routines in the business-as-usual (BAU) and net zero (Net0) scenarios, respectively. These figures represent the maximum values for the average loading of Home-EV transformers, primarily because the home-based charging routine predominantly focuses on charging at residential locations. In contrast, under public-based charging routines, the increment in average loading of Home-EV transformers is less pronounced compared to the reference grid model. This is attributed to the fact that most EVs are charged at public locations in this scenario. Consequently, the average loading of public-EV transformers stands at around 70% for the BAU scenario and 62% for the Net0 scenario under public-based charging routines. It is important to note that the average loading percentage is based on the installed capacity of transformers. In the BAU scenario, 10.3 megavolt-ampere (MVA) of MV/LV transformers are installed under public-based charging routines. However, for the Net0 scenario, this number increases to 24.3 MVA. Therefore, while the loading level appears lower in the Net0 scenario compared to BAU, it is crucial to consider the loading percentage relative to the installed capacity for a comprehensive understanding of the grid's condition.

Figure 47. The loading level of MV/LV transformers in the Akköprü region



The impact of EVs on average loading and overloading of the MV/LV transformers in the pilot regions is presented in Figure 48 and Figure 49, respectively. As seen in the figures, in all regions EV uptake increases the average loading of transformers, on average 7% under the BAU scenario and 17% under the Net0 scenario. In addition, some overloading are observed that should be mitigated either through investment or through EV charging management mechanisms, say smart charging. In addition, the difference between the loading level increments under the home-based and public-based charging routines are depicted in Figure 49. As can be seen, the impact of e-mobility loads on the annual average loading level of the MV/LV transformers for the home-based charging routine is more than that of the public-based charging routine. The main reason is that, in the case of the home-based charging routine, the e-mobility loads will be integrated with the already available MV/LV transformers, which are also loaded by residential loads. However, for the public-based charging routine, in most cases, the charging stations will be connected to the distribution grid through their own transformer.

Figure 48. Transformers' loading levels after EV uptake: Net0 Scenario, Home-based charging routine

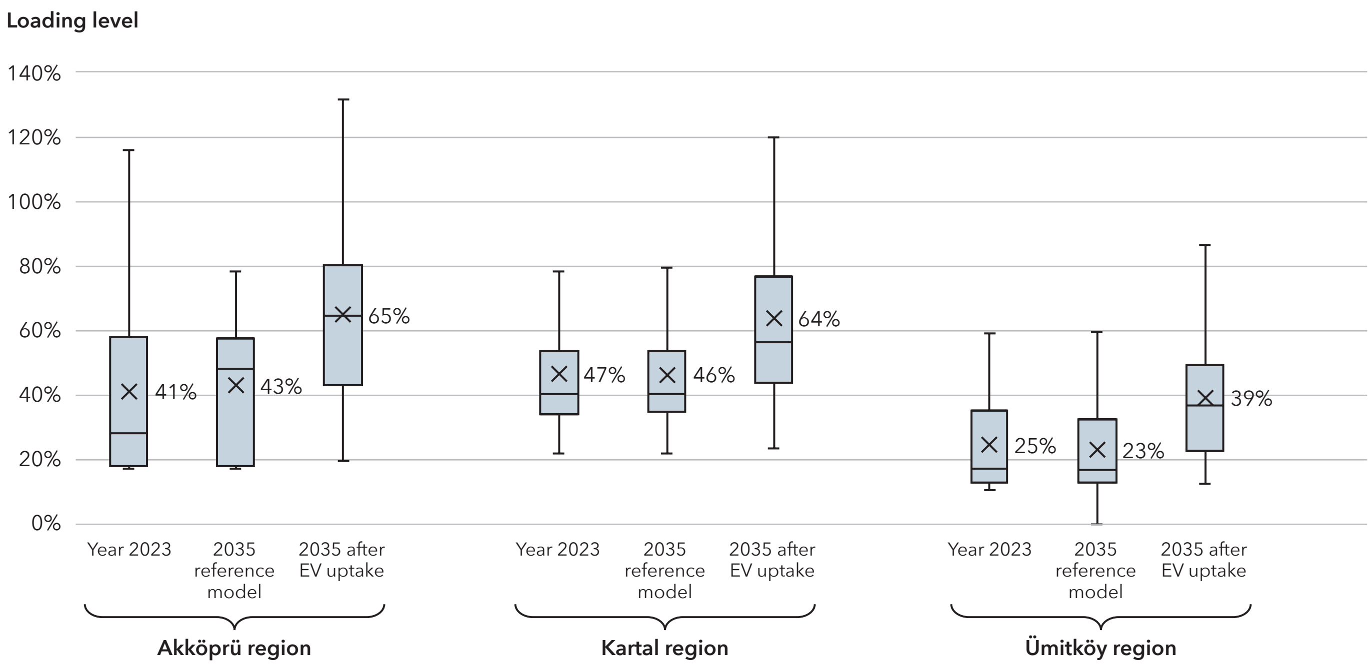


Figure 49. Increase in transformers' loading after EV uptake – Home-based charging routine

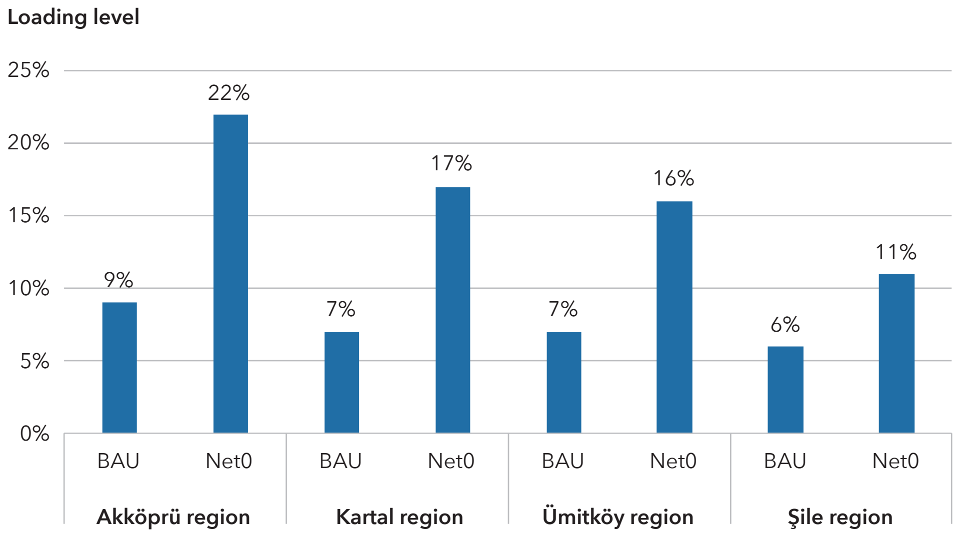
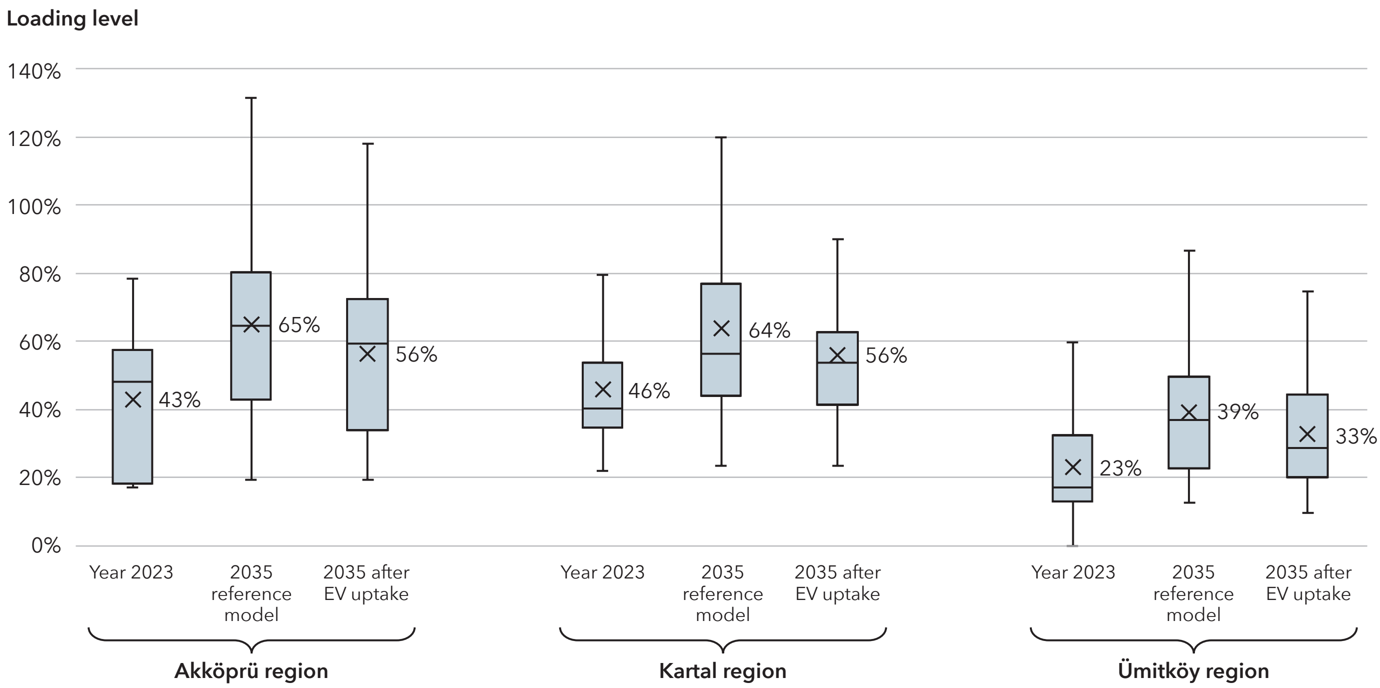
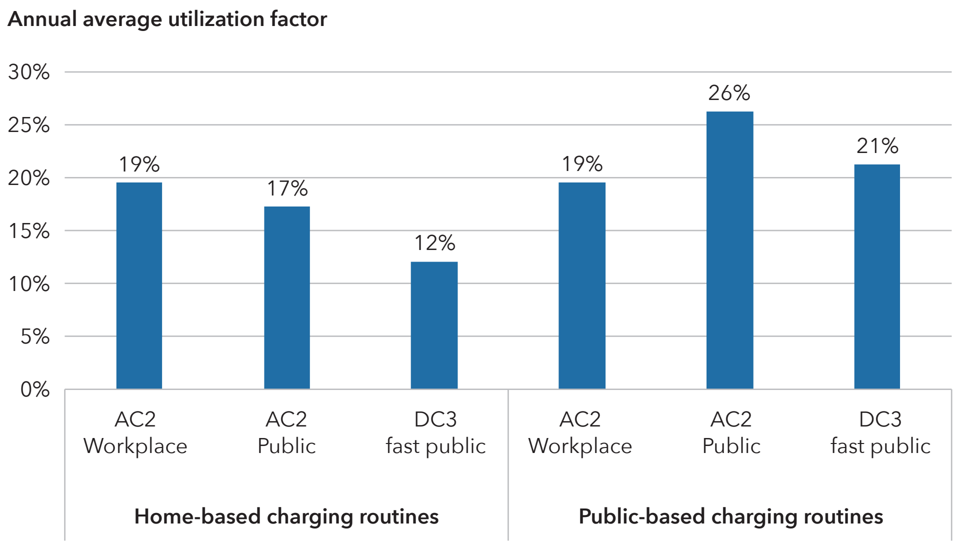


Figure 50. Impact of EV loading of the MV/LV transformers: Home-based charging vs public-based charging



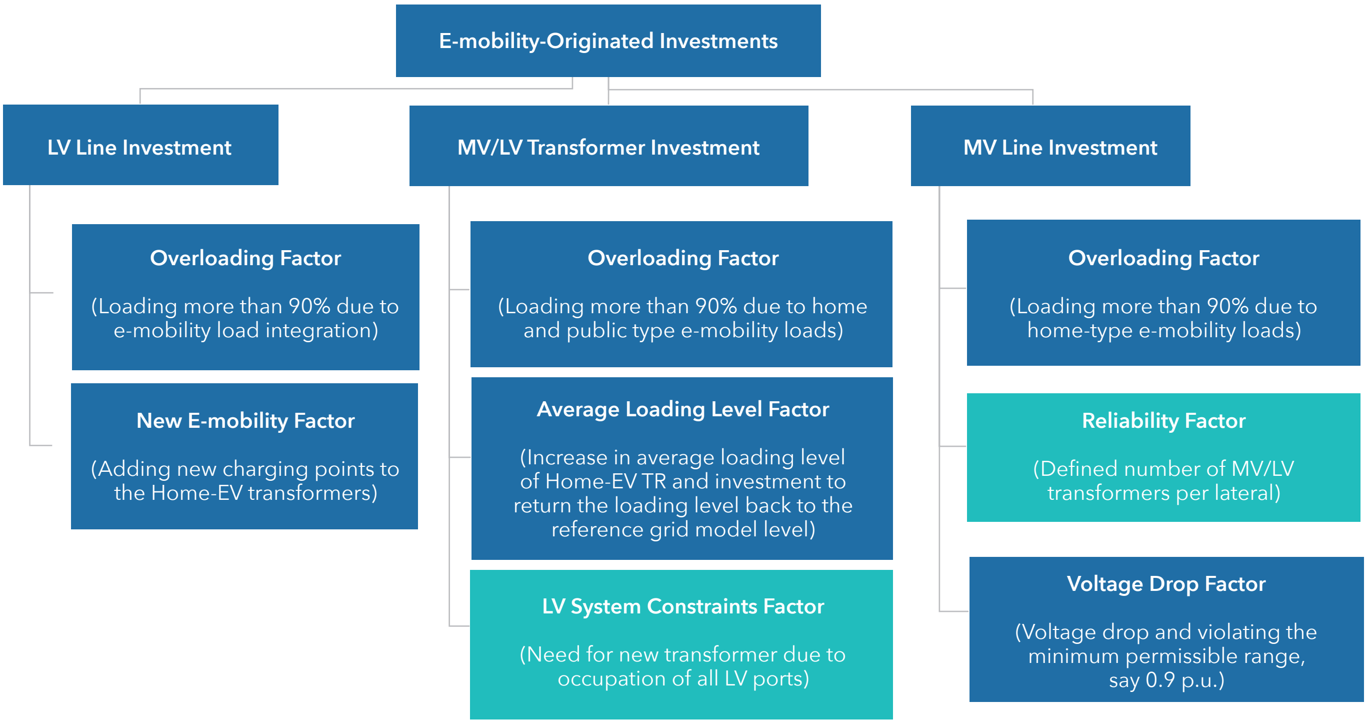
The annual average utilisation factor of public charging infrastructures under the Net0 scenario is reported in Figure 51. According to Figure 51, the average utilisation factor of the charging infrastructure at workplaces is around 19%. This is in part due to the fact that, considering an 8–9-hour workday for five days per week, the workplace charging infrastructure cannot deliver more than 2,340 hours of charging services in a year, which is around 26% of one year. Considering the coincidence effect (based on the profiles presented in Section 4.3), the utilisation factor is reduced to 19%. For an AC2 public charging point, the utilisation factor varies from 17% under the home-based charging routine to 26% for the public-based charging routine. For DC3 fast charging, the utilisation factor is 12% and 21% for home-based and public-based charging routines. Note that as the charging duration of the AC2 public charging infrastructure is longer than that of DC3 fast charging infrastructure, the associated utilisation factor is also higher than that of the DC3 fast charging stations.

Figure 51. The annual average utilisation factor of public charging infrastructure



The required investments to cope with the impact of EVs and LDVs on the distribution system should be evaluated from different views. The required investments in e-mobility are depicted in Figure 52.

Figure 52. Required investments in e-mobility



As can be seen from Figure 52, the investments in e-mobility are divided into three main categories. Starting from the LV system, which is the bottom line of EV uptake, a bottom-to-top approach is paved to investigate the impact of e-mobility load integration into the distribution systems. A typical LV network seen from a 1,000-kVA MV/LV transformer is depicted in Figure 53, in which the EV loads are also highlighted. While charging the EV loads, some lines may endure overloading (loading more than 90% of associated capacity), which is presented in Figure 54.

Figure 53. A typical LV network seen from a 1,000-kVA MV/LV transformer

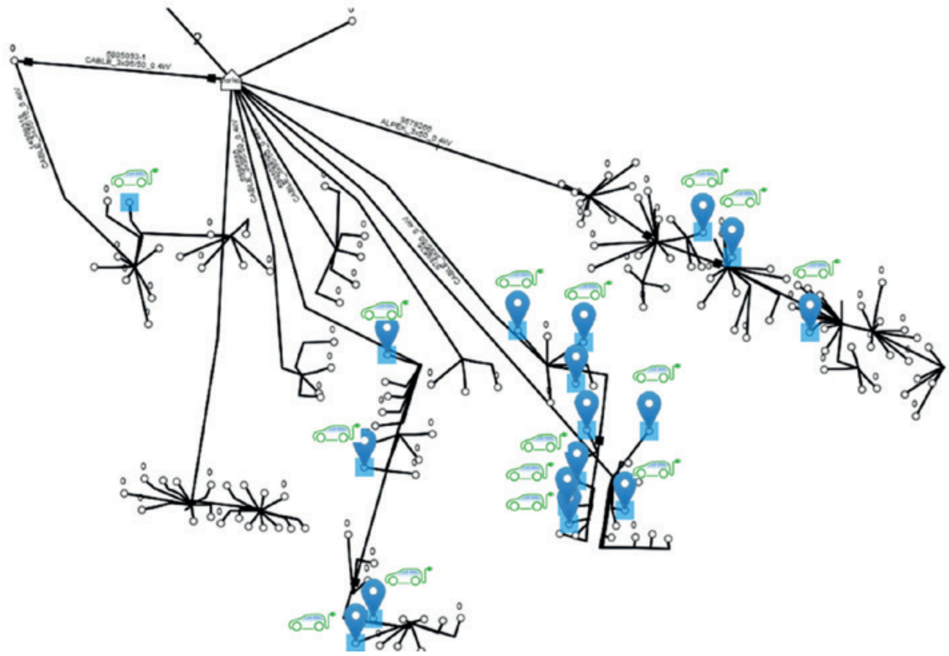
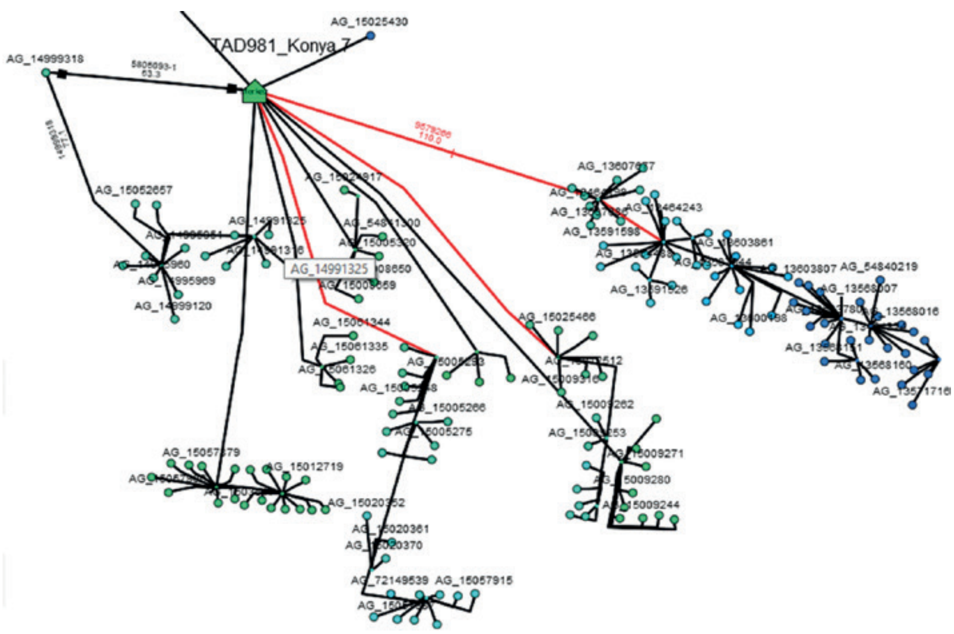
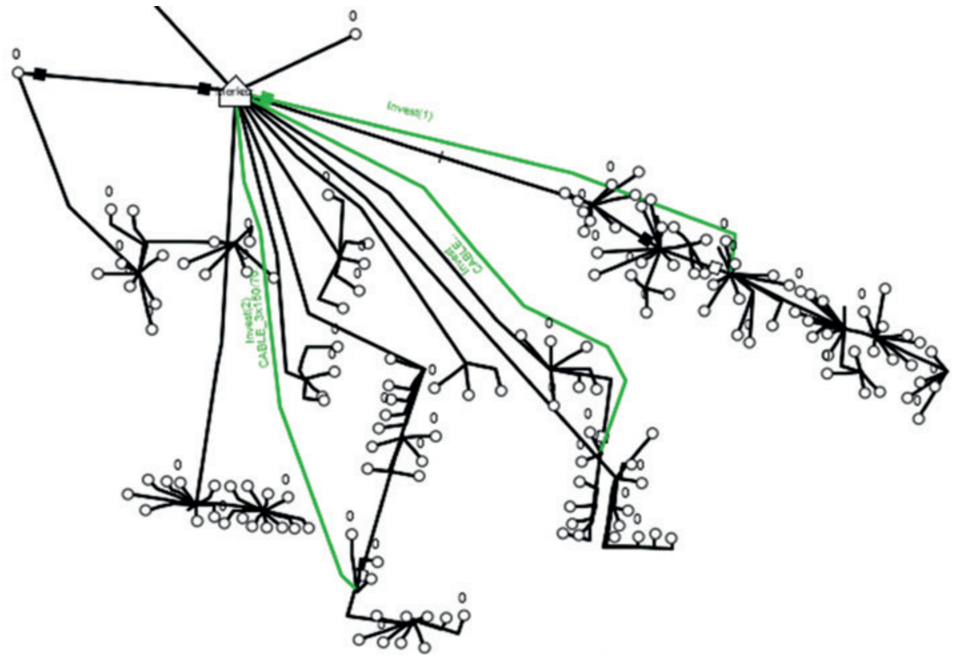


Figure 54. LV grid overloading due to the integration of the e-mobility load



Here, the investment-oriented solution is to add more LV feeders from the LV panel of the MV/LV transformer. Therefore, in case of port availability at the LV panel of the MV/LV transformer, the e-mobility-originated LV line investments can be realized. For instance, in Figure 55, three new LV feeders are added to compensate for the e-mobility load impact. However, in case of LV port unavailability at the LV panel of the MV/LV transformer, a cascade investment will be required from LV lines towards MV/LV transformers and MV lines, which will be discussed in the following section.

Figure 55. LV grid investments due to the e-mobility load (green lines are LV feeders receiving investments)



The second category is the investment requirements pertaining to MV/LV transformers. This type of investment should be calculated considering three factors, which will be discussed below.

- **Overloading factor:** The overloading of MV/LV transformers might be observed in both Home-EV and Public-EV transformers after the integration of EVs and LDVs. New investments should be made in the overloaded transformers to reduce the loading level after the uptick in EV and LDV usage. Here, if upgrading the transformer is possible, the overloaded transformer is upgraded (for instance replacing a 1.2-MVA transformer with a 1.6-MVA transformer). In the case that upgrading is not possible, a parallel transfer is considered.

- **Average loading level factor:** In line with common distribution system operating practices, distribution system operators (DSOs) typically aim to maintain transformer loading within certain thresholds to ensure system reliability. Take, for example, the average loading level of MV/LV transformers in the Akköprü region, as illustrated in Figure 47. Before the integration of EVs, this average loading sits at approximately 42%. However, it is crucial to understand that the remaining 58% should not be misconstrued as available capacity for additional loading. This 42%

loading level is determined based on factors such as load coincidence and reliability criteria, ensuring that the system operates reliably under normal conditions and withstands potential faults. Any increase in the average loading level beyond this threshold could lead to adverse effects on system reliability metrics like customer average interruption duration index (CAIDI) and System Average Interruption Frequency Index (SAIFI). In the event of a fault, a higher number of customers would be affected. To mitigate these risks and maintain system reliability, investments are necessary to restore the loading level of MV/LV transformers to pre-EV uptake conditions. This underscores the importance of proactive planning and infrastructure upgrades to accommodate the increasing demands of electric mobility while safeguarding the reliability of distribution grids.

- **LV system constraints factor:** Figure 56 provides a typical layout of a distribution system featuring both MV and LV networks. Within this diagram, a specific number of LV ports are designated at the outgoing end of the MV/LV transformer. These LV ports serve as connection points for distributing electricity to end-users. Table 14 outlines the guidelines for LV panels, as defined by the Turkish Electricity Distribution Corporation.[64] For instance, considering a 1,000-kVA MV/LV transformer as illustrated in Figure 56, ten LV ports are designated. Among these ports, two are typically reserved to accommodate future loads anticipated after the installation of the MV/LV transformer. However, in densely populated metropolitan areas like the pilot regions selected for this study, even these reserved ports may already be occupied due to rapid load growth. Consequently, if the demand for e-mobility charging facilities increases—for example, due to overloaded LV feeders from home EV charging or the establishment of EV parking lots in high-rise residences—it may be challenging to add new LV feeders, as all ports are already utilized. Under such circumstances, the only viable solution may be the addition of a new MV/LV transformer to provide additional LV ports for e-mobility loads in the area. This highlights a crucial point: even if the loading level of the associated MV/LV transformer remains within permissible limits, the saturation of LV ports may necessitate investment in additional MV/LV transformers. Moreover, following new MV/LV transformer installation, further investment in MV lines might be required, which will be discussed in the following section.

[64] TEDAŞ, 2015. ALÇAK GERİLİM DAĞITIM PANOLARI TEKNİK ŞARTNAMESİ. https://www.tedas.gov.tr/FileUpload/MediaFolder/cc6ffb86-7888-4606-a962-c706c7ef6722.pdf

Figure 56. Typical representation of MV and LV systems and their interference

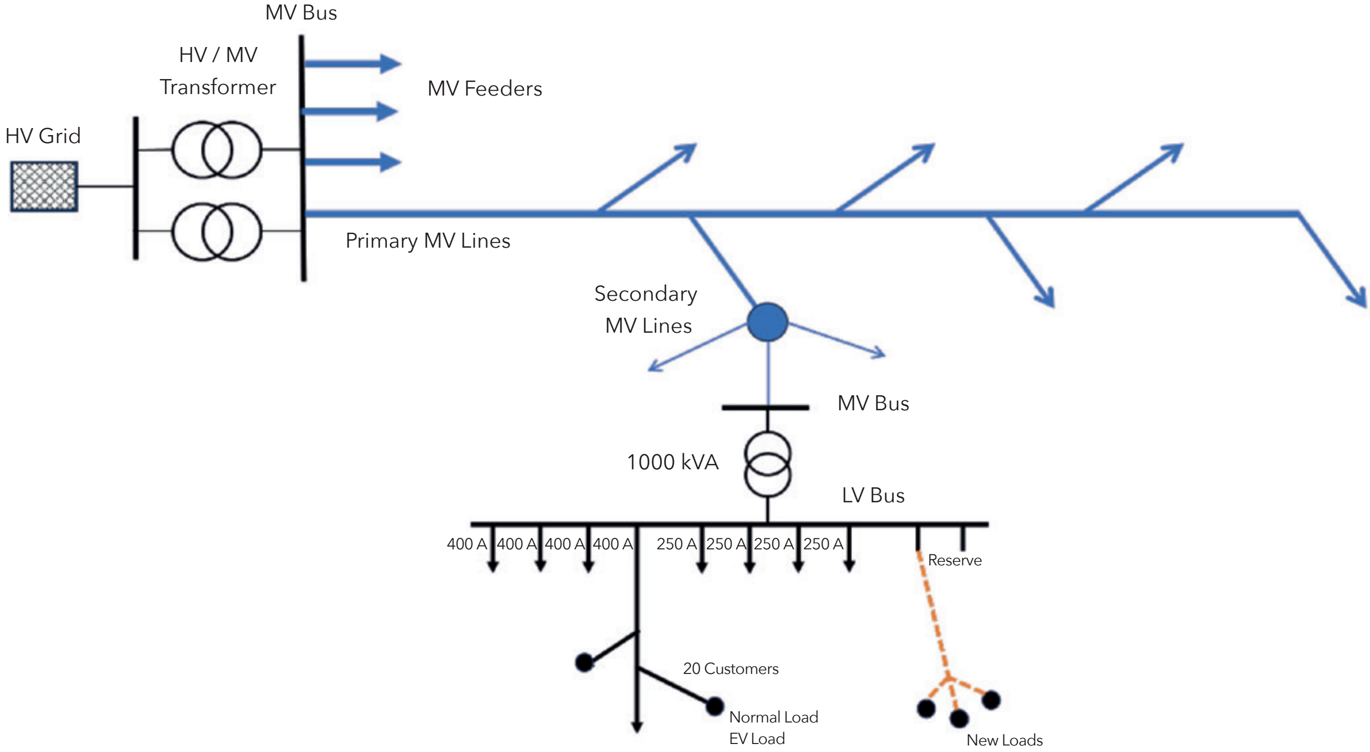


Table 14. LV panel equipment guidelines defined by the Turkish Electricity Distribution Corporation

LV Panel Equipment List														
Items			**400 kVA**		**630 kVA**		**800 kVA**		**1,000 kVA**		**1,250 kVA**		**1,600 kVA**	
Main Input	Main Bus and Cross-section		40x10 mm^2		60x10 mm^2		80x10 mm^2		100x10 mm^2		120x10 mm^2		2x(100x10mm^2)	
	Connection to the main bar		Unless otherwise specified, Direct Connection											
	Current Transformer		600/5		1,000/5		1,200/5		1,600/5		2,000/5		2,500/5	
Power supply outputs	Vertical fuse switch disconnector	Rated Current	160A	250 A	160A	250A	160A	250A	250A	400A	250A	400A	250A	400A
		Type of bushing	00 Size	1 Size	00 Size	1 Size	00 Size	1 Size	1 Size	2 Size	1 Size	2 Size	1 Size	2 Size
		VFLB type	The distance between main bar terminals will be 185 mm.											
		Number of Power Supply Outputs	2	3	4	4	4	4	4	4	5	5	5	5
			1(Backup)		2(Backup)		2(Backup)		2(Backup)		2(Backup)		2(Backup)	
Street Lighting Input	Vertical fuse switch disconnector	Rated Current	160A		160A		160A		160A		160A		160A	
		Type of bushing	00 Length		00 Length		00 Length		00 Length		00 Length		00 Length	
		Contactor	(AC-5a)											
Street Lighting Output	Cartridge fuse		Rated Current Number of Outputs						Will be specified in the Buyer's Order Form. ≤4					
Transformer Substation Internal Demand Circuit		Operating class: gG, Rated current: > 20 Amp.												
Internal Demand Circuit		Operating class: gG, Rated current:> 6 Amp.												
Measurement Circuit		Operating class: gG, Rated current:> 2 Amp.												

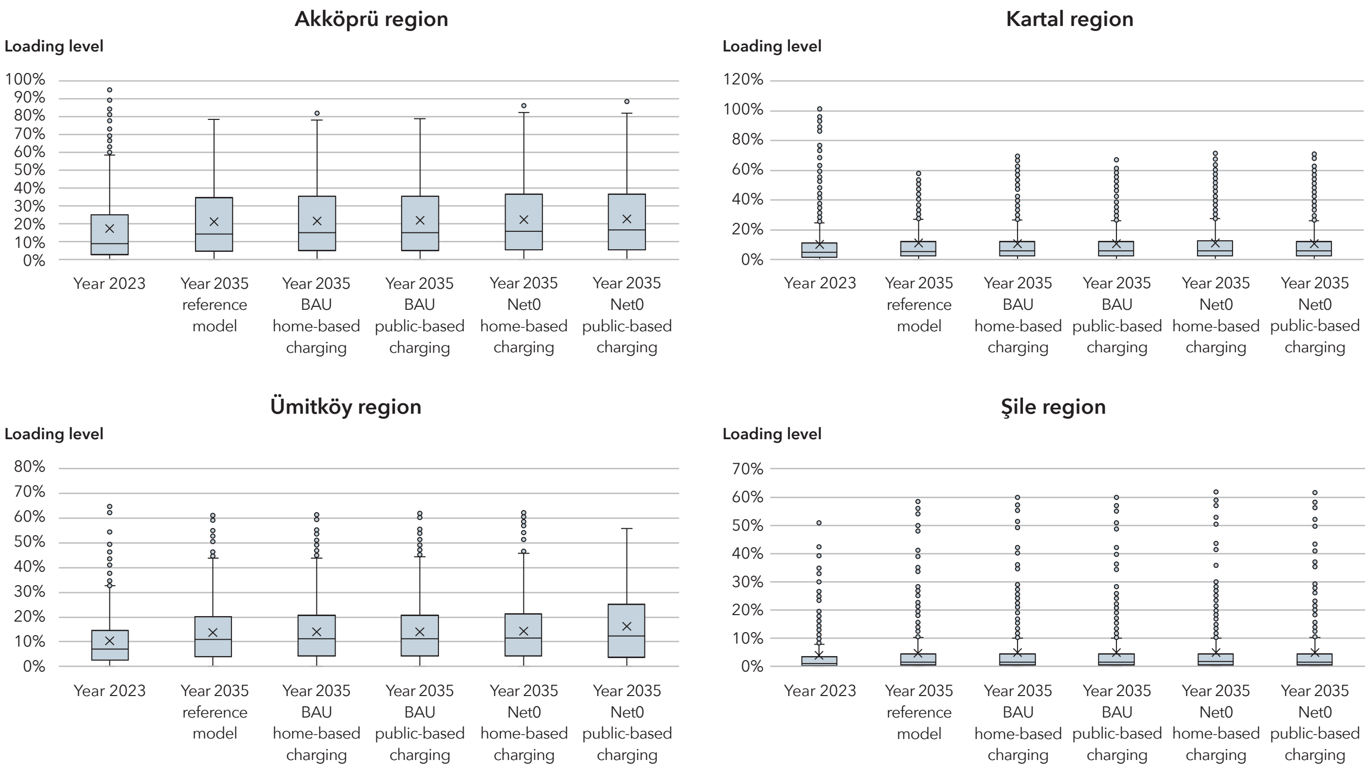
In addition to the aforementioned investment criteria pertaining to the MV/LV transformers, the e-mobility-originated MV/LV transformer investment requirement is depicted in Figure 57 for the home-based charging routine and the Net0 scenario. As shown in the figure, on top of the investments made to build the reference grid model, an additional 10% in investment on average is required in metropolitan areas to mitigate the impact of EVs on MV/LV transformers. In other words, the 10% more MV/LV transformer investment on top of the already have to be invested value is the impact of e-mobility load on the MV/LV transformer investment requirements.

Figure 57. Required investments in MV/LV transformers for e-mobility under Net0 Scenario

To calculate the required investments needed in MV lines for e-mobility, overloading, reliability, and voltage drop factor should be considered (see Figure 52).

- **Overloading factor:** The overloading factor assesses the MV lines in both the primary and secondary networks, wherein the associated loading levels exceed 90% following the integration of e-mobility loads. Such overloading scenarios may arise from both public and home-type e-mobility loads. However, while this factor indicates potential strain on the MV lines, it may not necessarily be the primary driver for MV line investment, as there could still be sufficient capacity available from a loading perspective in the existing MV lines. The loading profiles of MV lines under various e-mobility charging scenarios and routines are illustrated in Figure 58. Here, it is observed that the loading of MV lines will experience minor fluctuations following the e-mobility load integration. However, relying solely on loading levels can be misleading, as it might suggest that the existing MV lines are capable of accommodating e-mobility loads. Nevertheless, the key consideration for MV line investment lies in the reliability factor, which may necessitate MV line upgrades even if the available capacity of the MV lines appears to be adequate. This crucial point will be examined in detail in the following section.

Figure 58. The loading profiles of MV lines under various e-mobility charging scenarios and routines



- **Reliability factor:** The reliability factor of MV lines concerns the number of customers that might be impacted when a fault happens. DSOs typically consider reliability constraints based on the number of customers and feeding points on a MV lateral. While detailed reliability analyses, calculating indices like CAIDI, customer average interruption frequency index (CAIFI), and expected energy not supplied (EENS), are commonly conducted by DSOs, a rule of thumb is often applied. DSOs generally regard 16 units of 1.6 MVA MV/LV transformers (with a total capacity of around 25 MVA) on a lateral as the upper limit to maintain reliability constraints. As discussed in the MV/LV transformer investment section, the e-mobility load might necessitate around 10% more in MV/LV transformer investments. This might violate the reliability factor as the number of MV/LV transformers on a lateral would increase. Therefore, following e-mobility-originated MV/LV transformer investments, the required investments in MV lines in the secondary network (and in some cases, in the primary network) should be performed to ensure reliability. The e-mobility originated MV line investment due to reliability factor are depicted in Figure 59. Approximately 16% more on top of what is needed to build the reference grid model (the investments due to load growth and network expansion) is needed in MV line investments in order to alleviate the reliability concerns originating from e-mobility loads. In other words, this is the real requirement for MV line investments.

Figure 59. E-mobility-originated MV line investments to meet the reliability factor

- **Voltage drop factor:** Any new load integration, including the e-mobility load, might introduce a voltage drop in the distribution systems; therefore, the system voltage profile should be checked after the e-mobility load uptake. In case the voltage drop violates the minimum permissible level of voltage magnitude, that is 0.9 p.u., MV line investments should be performed. The voltage profile of the pilot regions after the EV uptake under the Net0 scenario is depicted in Figure 60. As can be seen, in the metropolitan pilot regions, the voltage profile is still in the associated permissible range even for the Net0 scenario, which integrates a greater number of EVs than that of the BAU scenario. However, in the rural Şile region, 5 km more MV is required to compensate for the voltage drop after the EV load uptake.

Figure 60. The voltage profiles of pilot regions after the EV load uptake under the Net0 scenario

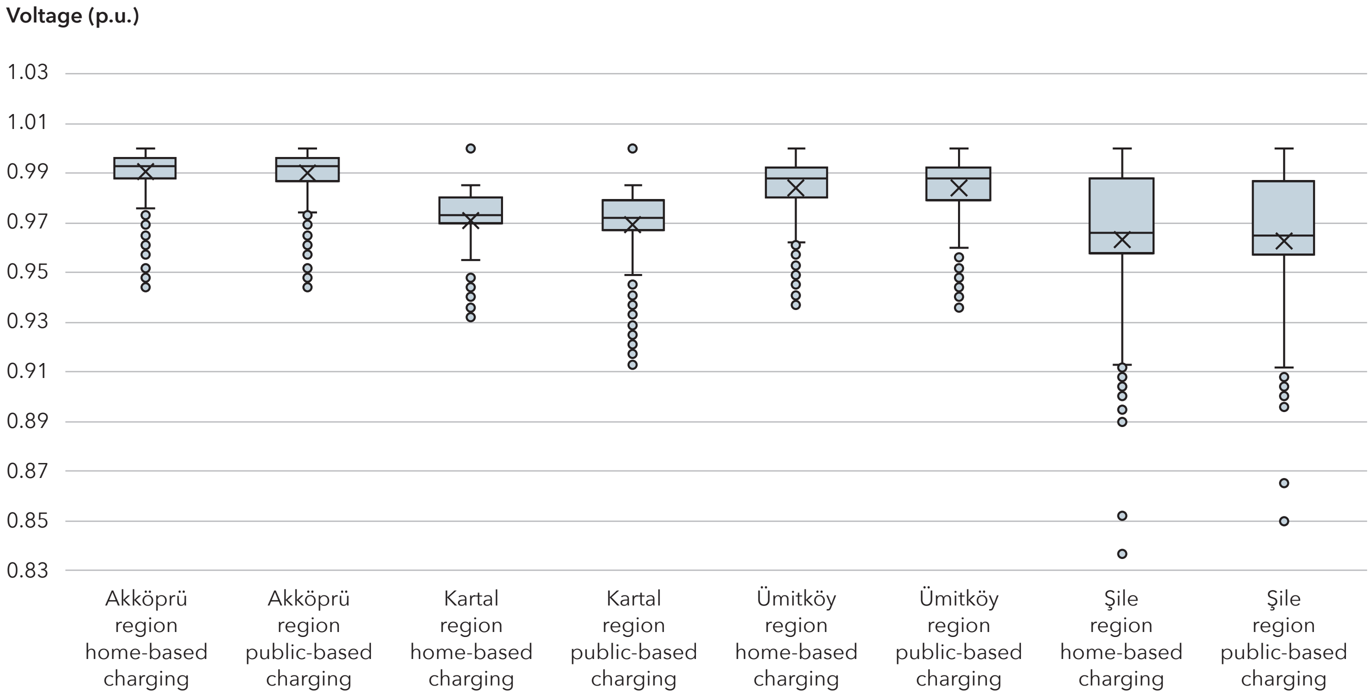


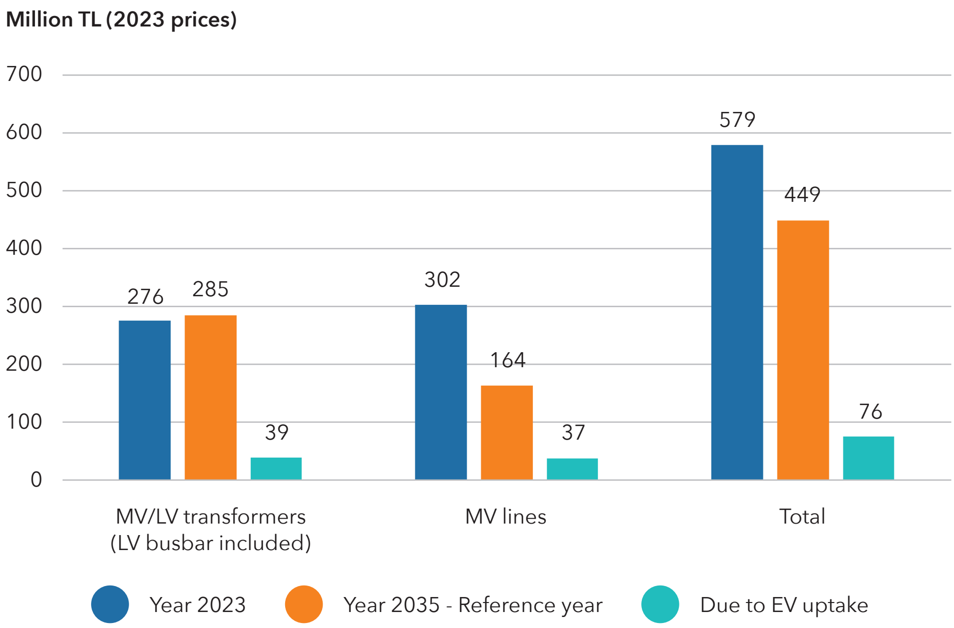
Table 14 shows the summary required investments in MV lines after the EV uptake. In metropolitan areas, on average an additional 12% should be built in MV lines on top of what has already been invested to build the 2035 grid reference model to neutralize the impact of e-mobility loads. In other words, an additional 12% should be invested.

Table 15. Summary of required investments in MV lines after the EV uptake

Pilot Region			Akköprü	Kartal	Ümitköy	Şile
MV/LV Transformer (LV busbar included)	Available at Year 2023	Capacity (MVA)	544	438	995	128
	Invested up to Year 2035 (Without EV)	Capacity (MVA)	561	410	939	71
		Cost (million TL, 2023)	285	209	550	63
	Additional Investment Due to EV Uptake	Capacity (MVA)	**63**	**54**	**46**	**31**
		Cost (million TL, 2023)	**39**	**34**	**29**	**14**
MV Lines	Available at Year 2023	Length (km)	210	307	688	462
	Invested up to Year 2035 (Without EV)	Length (km)	114	115	177	35
		Cost (million TL, 2023)	164	166	255	50
	Additional Investment Due to EV Uptake	**Length (km)**	**26**	**6**	**16**	**14**
		Cost (million TL, 2023)	**37**	**9**	**23**	**12**
Total Investment up to 2035 - Without EV (million TL, 2023)			**449**	**375**	**805**	**113**
Additional Investment Due to EV Uptake (million TL, 2023)			**76**	**43**	**52**	**26**
Ratio of Additional Investment Due to EV Uptake			**17%**	**11%**	**6%**	**23%**

Based on the grid analysis, the impact of the e-mobility load in the pilot metropolitan areas requires around 12% more investment on top of what should already be invested to meet the needs of the expanded network. The breakdown of the investments required for the Akköprü region is depicted in Figure 61. As can be seen in the figure, the share of MV/LV transformers is greater than that of MV lines. In total, for the metropolitan regions under study, 62% of the required investments are for MV/LV transformers, which is mostly due to overloading and LV system constraints. The other 38% goes to investments in MV lines, which is mostly due to the reliability factor.

Figure 61. The cost of investments in the Akköprü region to mitigate the impact of e-mobility loads



5.2 Sensitivity analysis

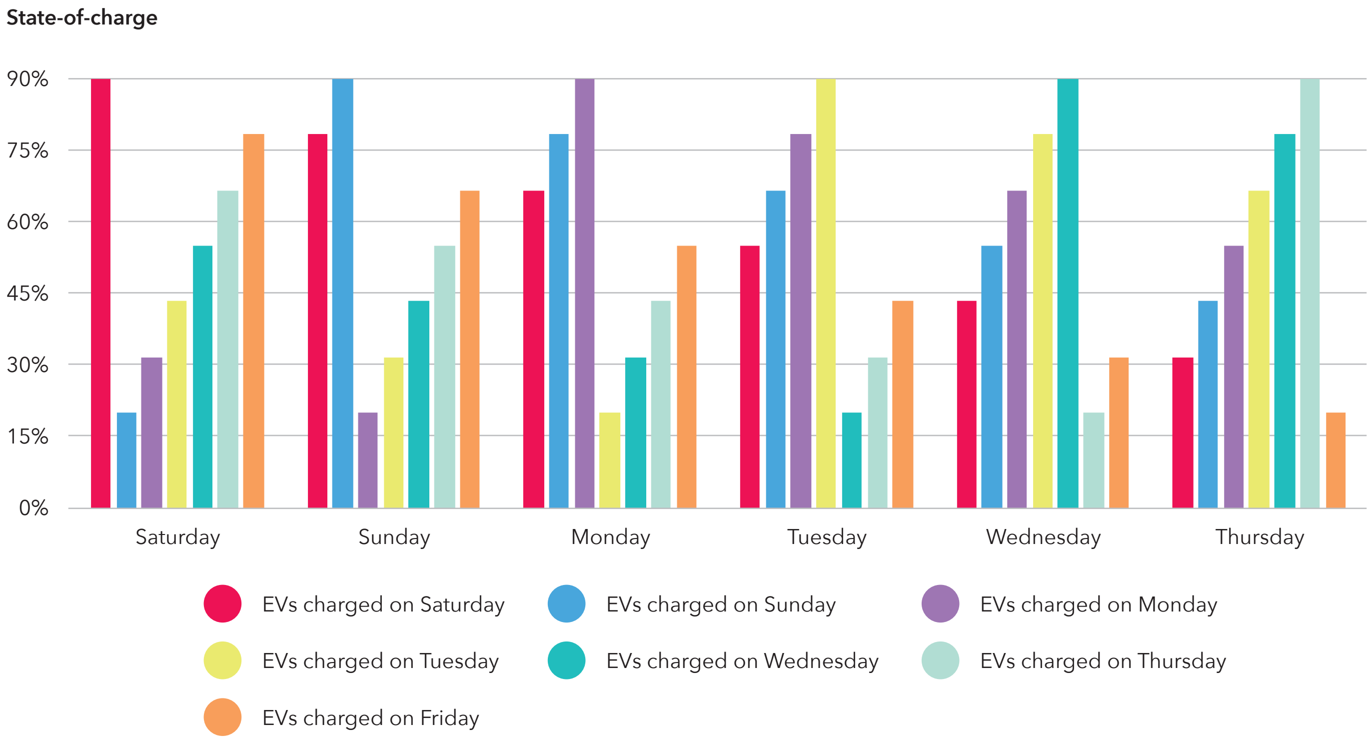
In this section, the sensitivity analysis is performed for other scenarios to evaluate the impact of EVs and LDVs in conditions other than those assumed for the main scenarios, BAU and Net0.

5.2.1 Case I: Excessive charging at holiday times

Thus far, the EV electrical load profiles that were developed in Section 4.3 are used to evaluate the impact of e-mobility loads on the distribution system. The mentioned profiles represent the normal charging behaviour of the e-mobility loads in the pilot regions for normal weekdays and normal weekends. However, around holiday periods, the grid may experience extensive charging that can negatively impact distribution systems and bring about considerable overloading. In this case, the extensive charging behaviour before a long holiday, such as a religious holiday in which many people will travel around Türkiye, is considered.

Charging behaviour for a normal week is presented in Figure 62. Based on the assumptions made for the average capacity of an EV battery and the permissible range of state-of-the-charge (see Section 4.3), it is assumed that the EVs in each pilot region are charged once per week up to 90% of their associated capacity, and on average, this charge lasts for the next six days. Therefore, as can be seen from Figure 62, EVs charged on Saturday, for example, attain a 90% state-of-charge condition, with charging levels diminishing progressively throughout the week. The same conditions are applied to EVs that are similarly charged during other days of the week, as well.

Figure 62. The charge status of vehicles charged on different days of the week – Normal week



Assuming that holidays begin on a Thursday, most of the EVs in the region will be charged on the day before so that drivers can take their EVs on a long trip. This charging behaviour is depicted in Figure 63. According to Figure 63, even though most EVs already have a considerable amount of charge, they are charged again to reach maximum charge on Wednesday. This charge will be then be used during the holiday period for traveling long distances. The EV load profile on Wednesdays for a normal day and the Wednesday before holidays begin is depicted in Figure 64 and Figure 65, respectively. By comparing Figure 64 and Figure 65, we see that the peak EV load on the day before a religious holiday is four times that of normal conditions (at least in the Akköprü Region). Note that the home-based charging routine is considered to represent the worst conditions (e.g., uncontrolled charging at home).

Figure 63. The charge status of vehicles charged on different days of the week – The Week before a public holiday

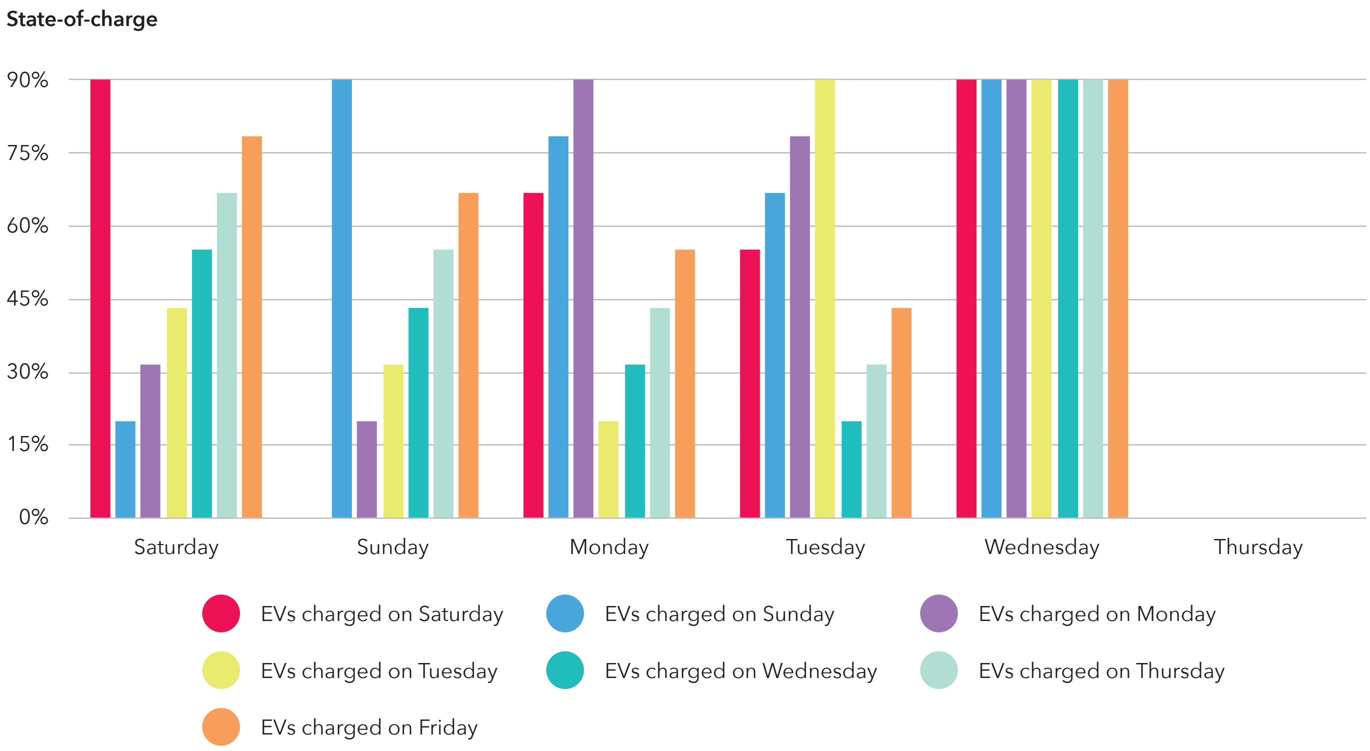


Figure 64. Charging load profile: Normal week – Akköprü region, home-based charging, Net0 Scenario

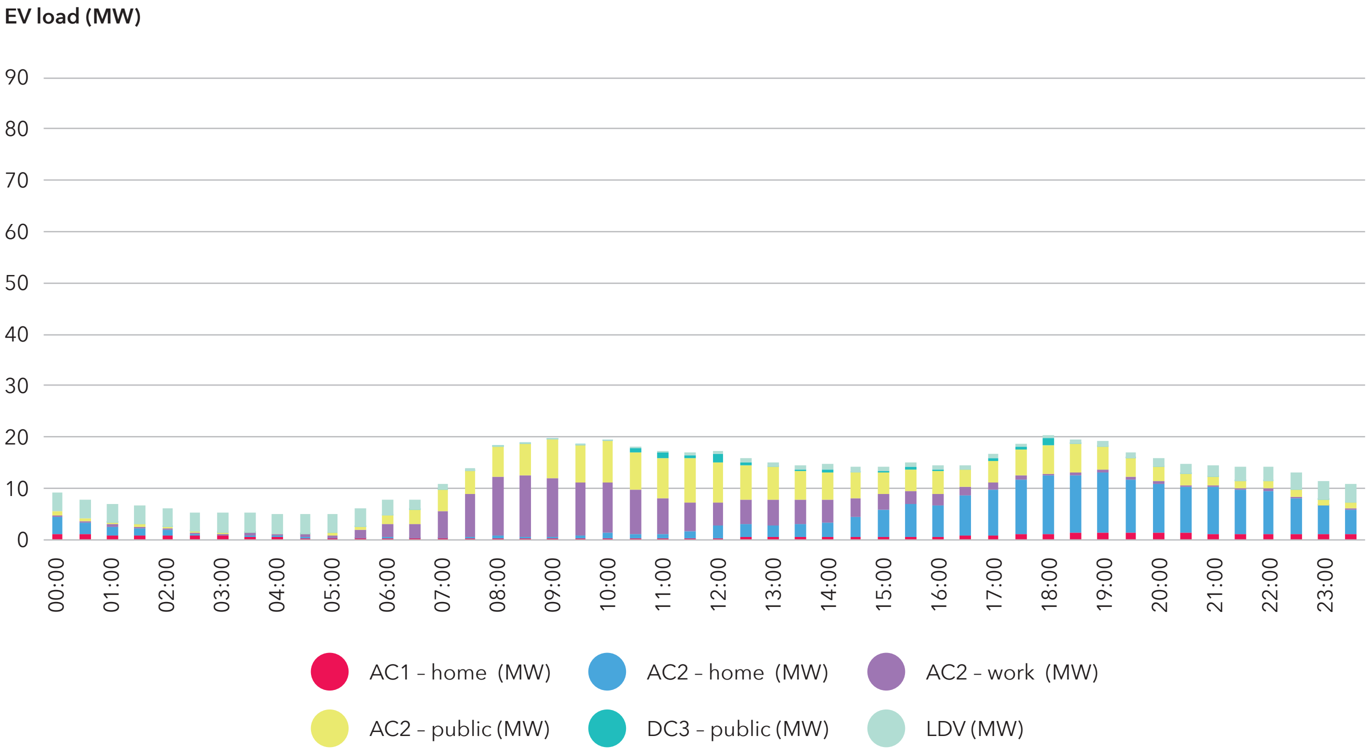
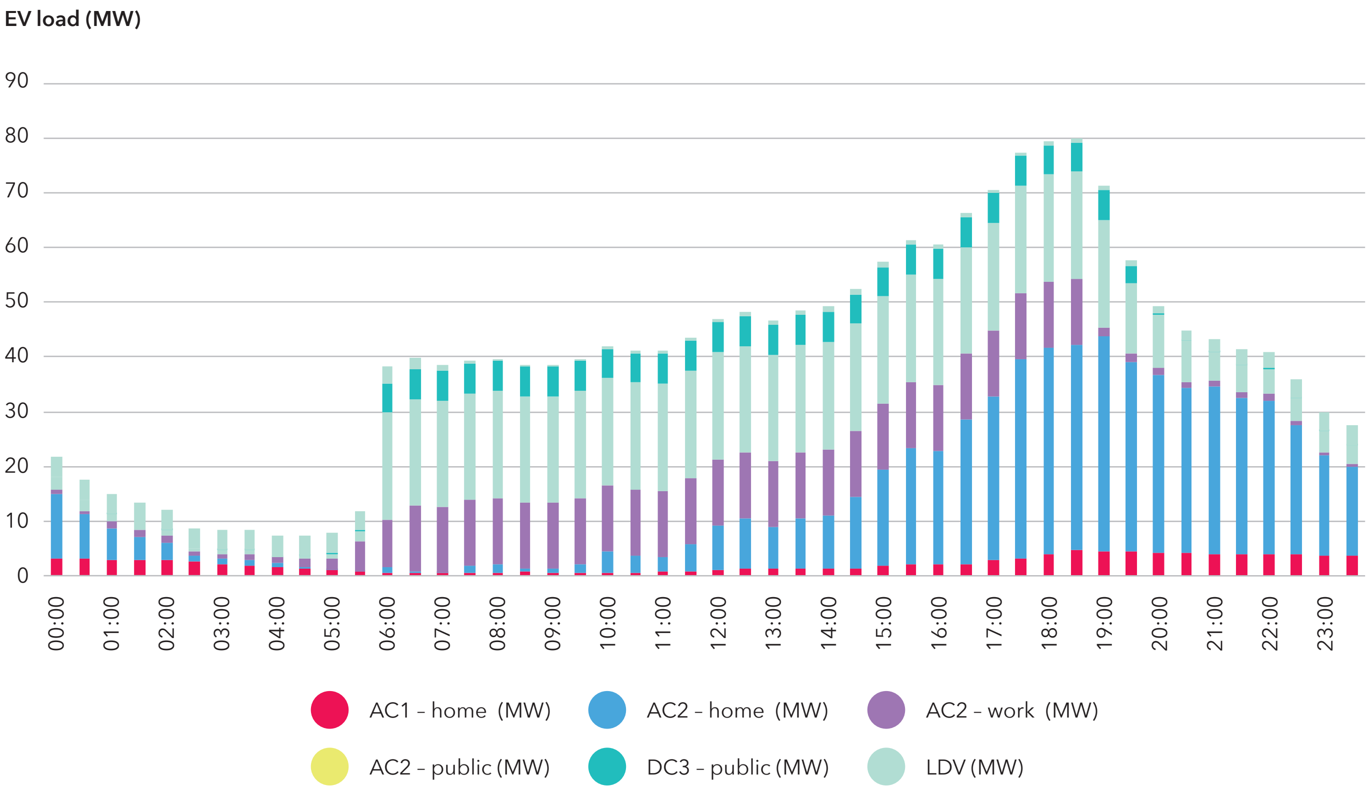


Figure 65. Charging load profile: Week before holidays start – Akköprü region, home-based charging, Net0 Scenario



The impact of excessive charging on the day before holidays is depicted in Figure 66. As can be seen from Figure 66, under normal conditions, the average load of transformers in residential areas is 47%, whereas this reaches 96% during holiday weeks. In addition, several MV/LV transformers will be exposed to this overloading. For MV/LV transformers, which feed the public charging station, the average load is increased from 36% to 78%. Overloading due to excessive charging at MV/LV transformers is represented in Figure 67. To cope with such overloading, additional investment is not deemed as a rational solution. This is because such a problem only occurs during a few hours a year. However, in the case that further investment is selected as the solution, the required investment would be very high as the system cannot endure very high peaks due to the coincidence of different charge incidents (for instance, up to four times normal conditions for the Akköprü Region). Therefore, controlled charging and smart charging mechanisms might be the most effective solutions to cope with such conditions, which will be discussed in the following sections.

Figure 66. The impact of excessive charging on the day before a holiday – Akköprü region

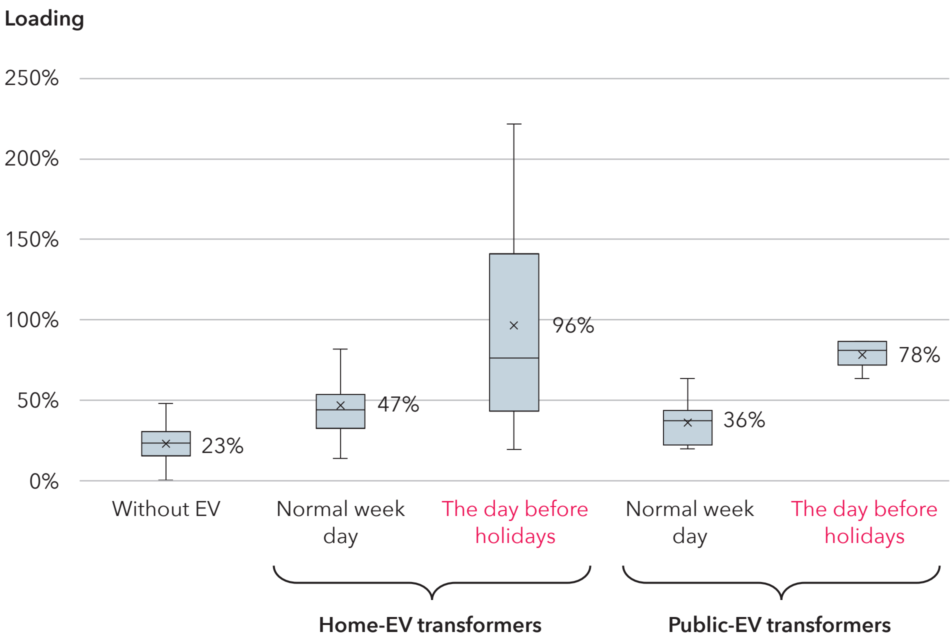
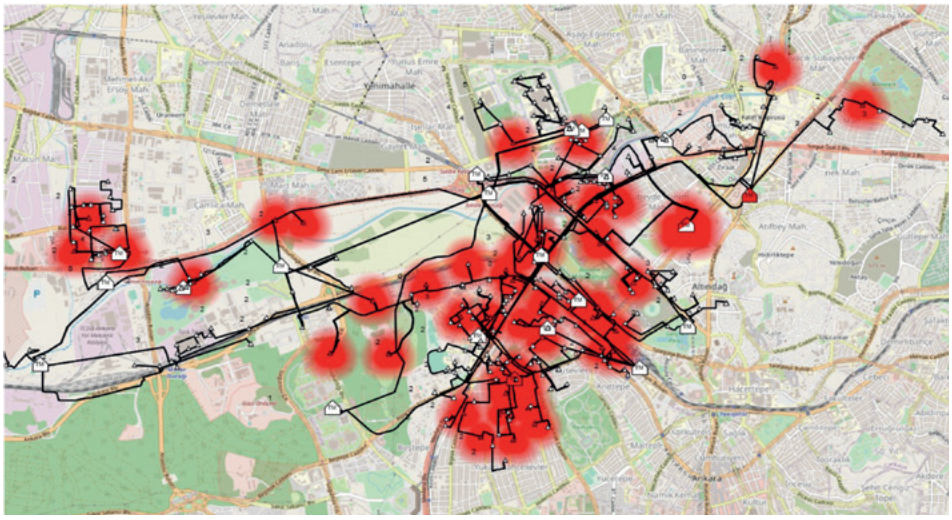


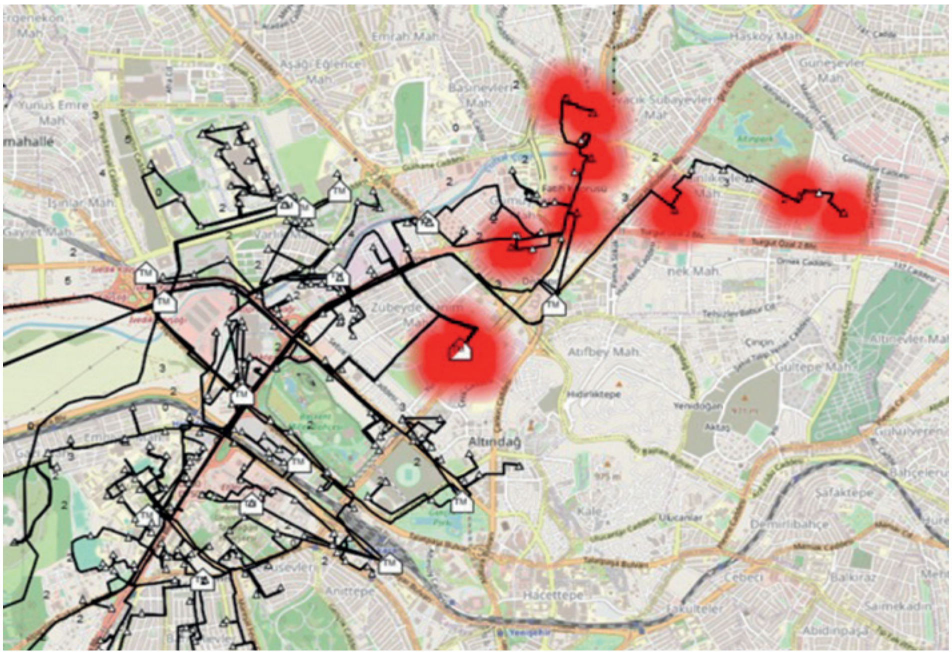
Figure 67. Overload from excessive charging on MV/LV transformers – Akköprü region



5.2.2 Case II: Smart charging

The e-mobility load profiles developed in Section 4.3 are associated with uncontrolled charging behaviours. These charging habits follow probability distribution functions. However, as discussed in Section 2.2.1, smart charging and controlled charging are integral components of optimizing the use of EVs within a sustainable energy ecosystem. These strategies aim to manage the charging process of EVs in a way that maximizes efficiency, minimizes strain on the grid, and potentially reduces costs for both consumers and utilities. In sensitivity case II, we investigate the impact on the grid of shifting e-mobility loads from congested hours to less congested hours. A portion of the distribution system in the Akköprü region is depicted in Figure 68. It depicts operation conditions on 19 January 2035, 9:30 AM under the Net0 scenario and the home-based charging routine.

Figure 68. MV/LV transformer overloading due to e-mobility loads – Akköprü region



In Figure 68, 11 MV/LV transformers are overloaded (loading more than 90%) due to the simultaneous charging of 385 EVs (AC type 2, 3.7 kW). The loading profile of a 63-kVA MV/LV transformer (one out of 11 overloaded transformers) is depicted in Figure 69. Here, the loading of the MV/LV transformer is split into normal loads and e-mobility loads to highlight the impact of e-mobility loads on the overloading of the transformers. According to Figure 69, if some portion of the e-mobility load from 8:00–10:00 is shifted to the 12:00–15:00 period, the overloading problem at that region due to simultaneous charging can be resolved. In Figure 69, the load of 219 EVs is shifted in the mentioned period. This value corresponds to the shifting of 56% of the EVs that are charging. In most of the cases studied, the EV loads can be shifted to the hours when renewable energies are more abundant, say midday for solar energy and high wind hours (night) for wind energy. Under these circumstances, renewable energy can be absorbed through EV charging, and renewable curtailment might be prevented. If flexibility mechanisms to enable controlled and smart charging are available (which will be discussed more in Sections 5.3 and 6), the impact of EV charging on the distribution systems can be limited, and grid investments can be deferred or even reduced.

Figure 69. Loading of a 630-kVA MV/LV transformer feeding e-mobility loads – Uncontrolled charging profile vs smart (controlled) charging

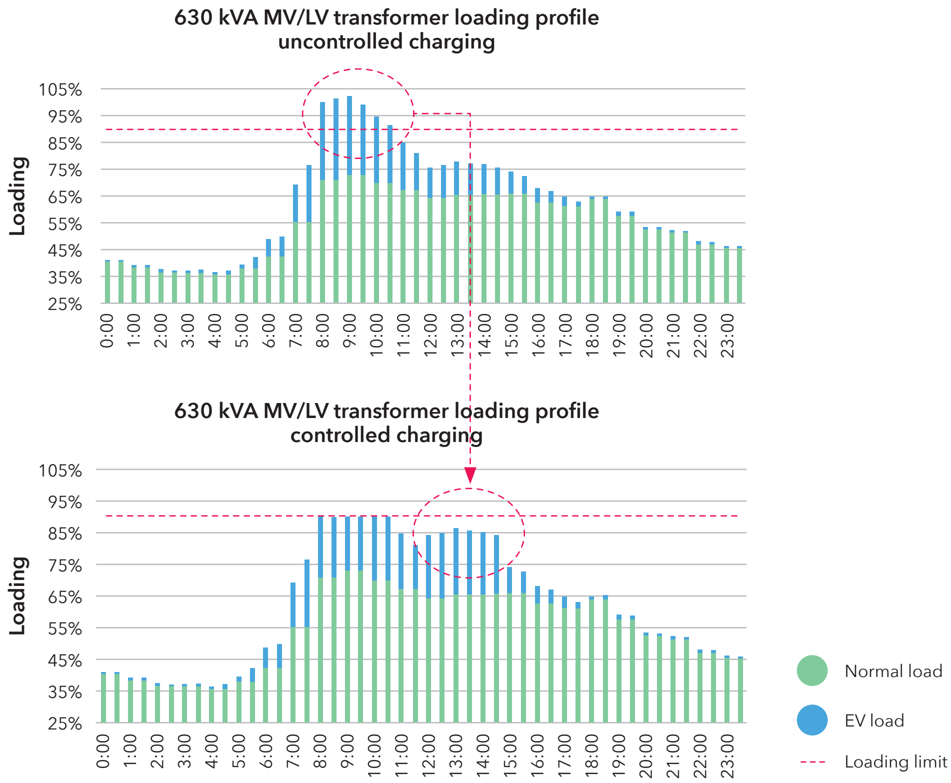
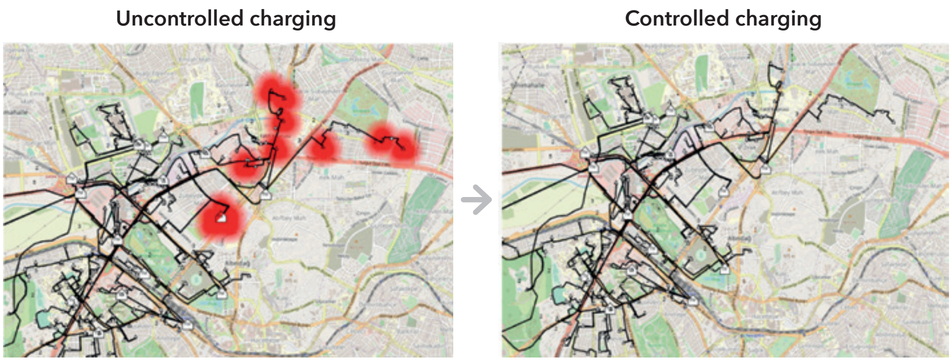


Figure 70. The impact of the e-mobility load on a portion of the distribution system in the Akköprü region: Smart (controlled) charging vs uncontrolled charging



5.2.3 Case III: Vehicle to grid

As an advanced form of smart charging, bidirectional charging or vehicle to grid (V2G) mechanisms can be used to optimize EV charging. Energy stored in EVs (which are connected to the plug but are not receiving charging services) is used to manage congestion in distribution systems. However, first, certain levels of technology and settlement mechanisms are required to realize V2G approaches. This section will examine the impact of these approaches on the distribution grid to understand their potential.

A typical representation of a LV grid is depicted in Figure 71, where the system hosts both bidirectional EVs, which are capable of V2G contribution, and the unidirectionally charging EVs, which are integrated into the grid as part of the load. Table 16 summarizes the state-of-charge for plug-connected EVs in a typical LV network as depicted in Figure 71.

Figure 71. Typical LV grid with V2G capable EVs

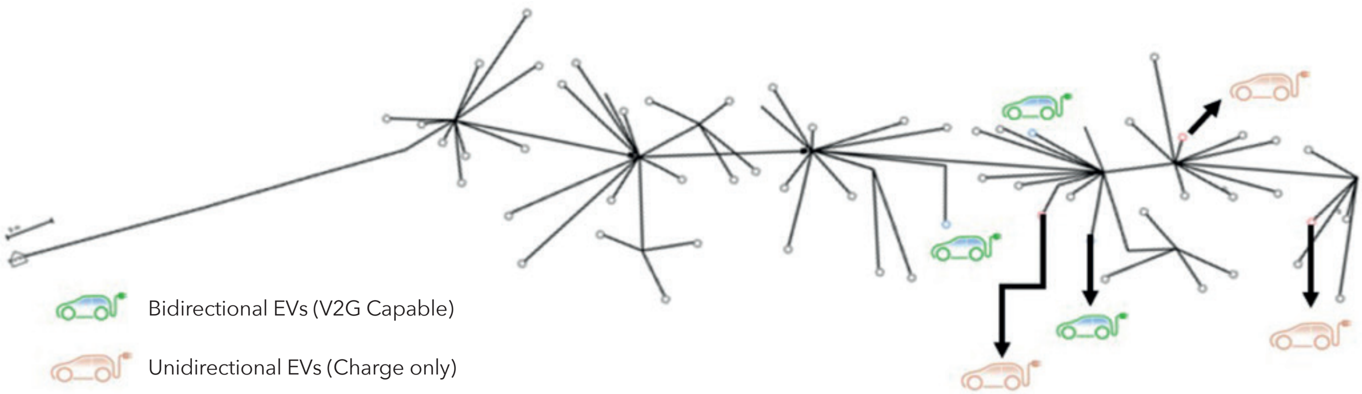


Table 16. The state-of-charge of EVs in a typical LV grid as depicted in Figure 71

Item	Value
EV charge load (only unidirectional EVs)	14 kW (around four AC2 connected cars)
Available charge in V2G capable EVs	20 kW (ten AC2 type 2 connected cars)

A theorical representation of unidirectionally charging EVs and discharging V2G-capable EVs are depicted in Figure 72. Here, the impacts of V2G on loading the LV main line and its voltage profile are presented in Figure 73 and Figure 74, respectively. As seen in the figure, V2G can reduce line loading and improve the voltage profile of the LV network under study.

Figure 72. A theorical representation of EVs capable of unidirectional charging and V2G discharging

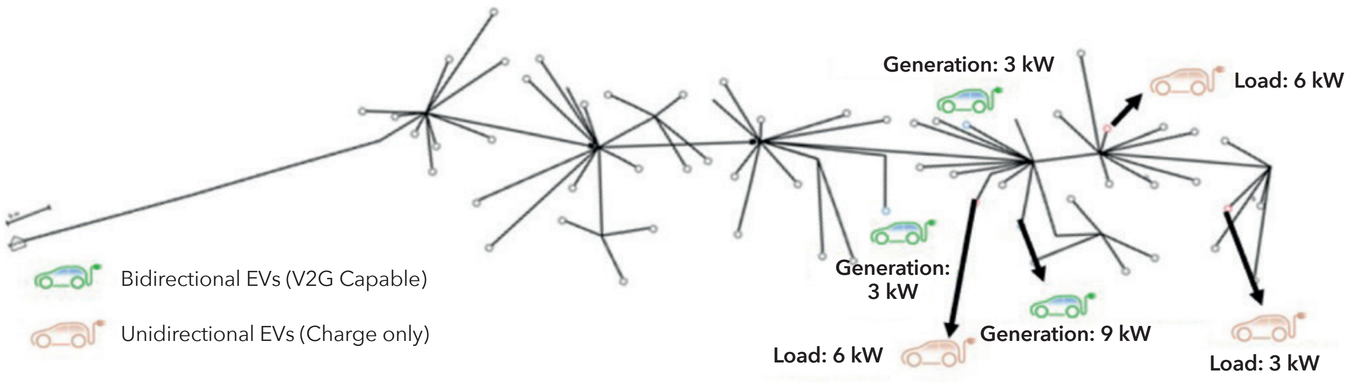


Figure 73. The impact of V2G on the main LV line loading of the grid depicted in Figure 71

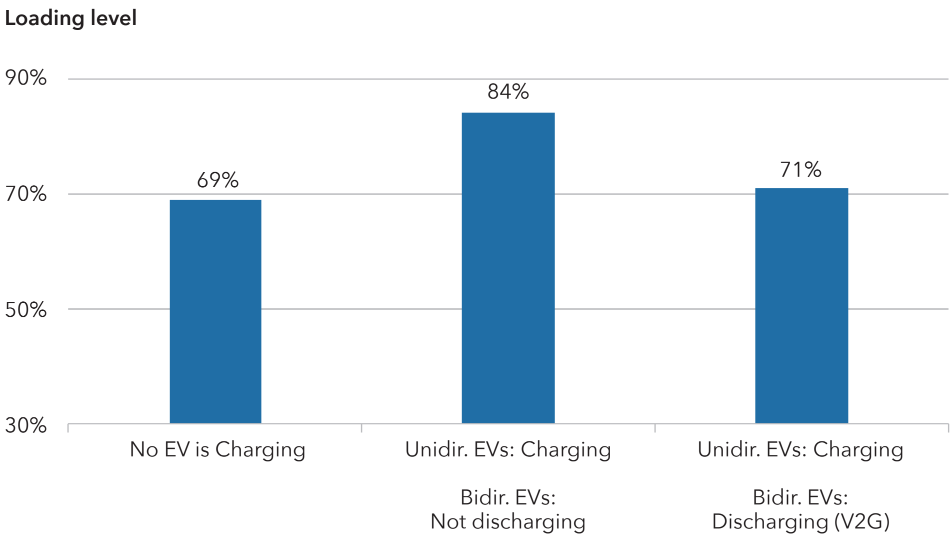
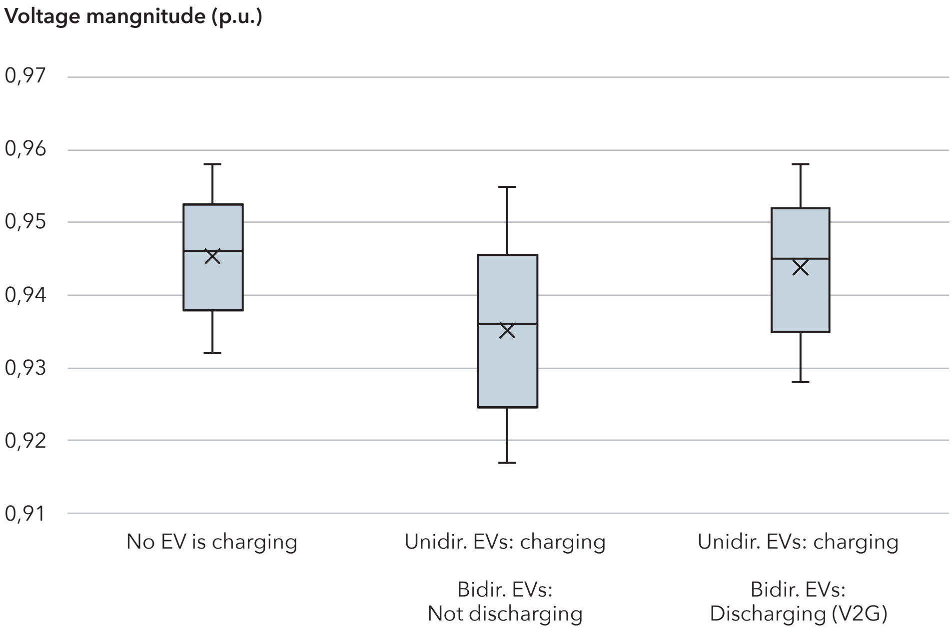


Figure 74. The impact of V2G on the voltage profile of the grid depicted in Figure 71



Based on this theorical example, we consider a real-world example on a portion of the Akköprü distribution grid as depicted in Figure 68 (the same case is used for the unidirectional smart charging case in the previous section). As mentioned in Section 5.2.2, 385 AC2 EVs are charging at the same time, which results in the overloading of 11 MV/LV transformers. Here, by discharging 94 V2G capable AC2 EVs, the overloading of 10 MV/LV transformers can be alleviated (see Figure 75). In this case, a discharge in the range of 25% of the e-mobility load is sufficient for handling overloading from e-mobility. Although a certain level of infrastructure and mechanisms are required for the realisation of V2G, it can be an effective approach to limit the impact of e-mobility loads on distribution systems and defer the required investments.

Figure 75. The impact of V2G on a portion of the Akköprü distribution grid

5.2.4 Case IV: Charging along highways

The impact of charging along highways and fuel stations, which are located along the roads in the pilot regions, on the grid is studied under this case. The main difference between the impact of e-mobility loads on the grid in metropolitan areas and highways are two-fold:

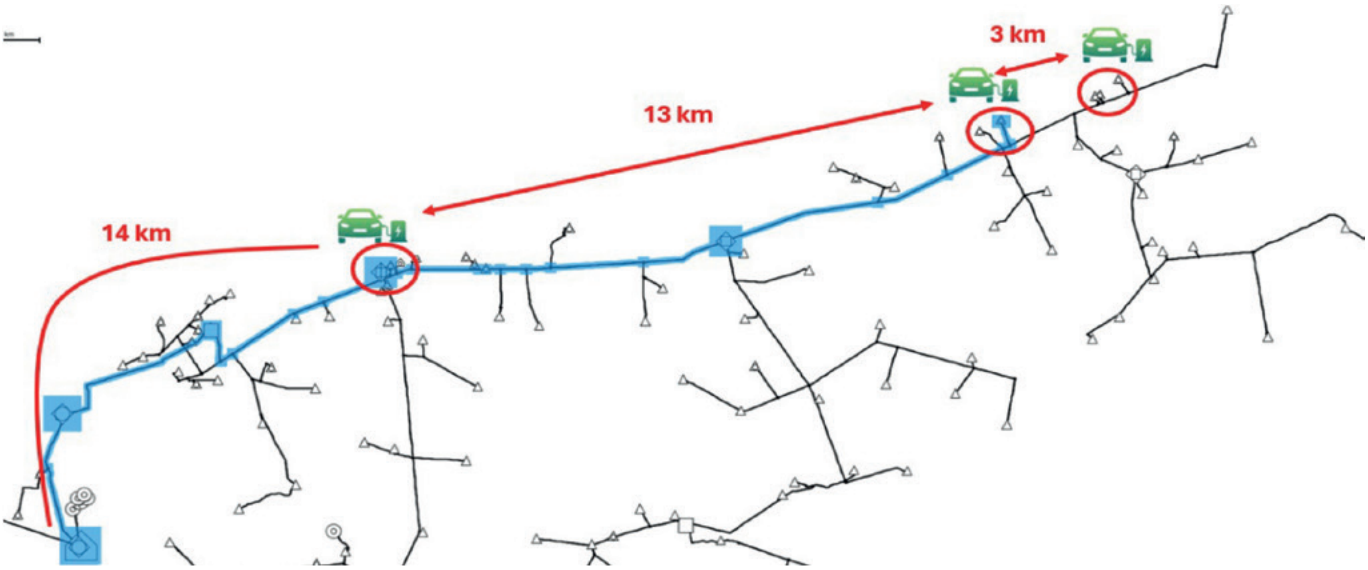
1. Distribution grids in metropolitan areas are normally well-invested grids designed to meet the load growth in the region. However, fuel stations along roads and highways are normally fed through weak distribution lines such as Swallow-type conductors over long distances, e.g., 20 kilometers (km). Such a weak connection may bring about voltage issues.

2. E-mobility loads in metropolitan regions are a mix of different charging technologies and home-based charging routines, which will be the backbone of this charging profile. However, when charging on a highway, the preference is fast direct current (DC) charging. Therefore, different charging occasions can coincide, and a high peak in the e-mobility load will be imposed on the distribution grid.

A typical representation of a charging station on the highway is presented in Figure 76: the network configuration is very close to common real-world applications. As can be seen in the figure, there are six charging points on a feeder. The distance between the source and first pair of charging stations is 14 km, and the distance between the source and the furthest pair of stations is 30 km. The assumptions are:

- The fuel stations are fed by Swallow-type conductor with a capacity of around 9 megawatt (MW);
- At each charging station, three charging rows are available;
- At each charging row, two charging points are available;
- At each charging pint, two charging plugs are available;
- In total, there are 12 plugs per charging station and 72 charging plugs per feeder;
- DC fast charging technology with a rating of 100 kW is used;
- The peak e-mobility load can reach 7,200 kW.

Figure 76. Typical charging along a highway



The voltage profile of the network depicted in Figure 76 is illustrated in Figure 77. As can be seen from Figure 77, if all the charging plugs on the fuel stations are loaded with e-mobility loads (100 kW DC), a voltage drop in the network would be inevitable. This can also happen during the holidays when people are traveling with their EVs and most of the charging points will be occupied. To maintain voltage at the permissible level of operation, feeding conductors can be reinforced through further investment. However, as such cases may only happen a few days in a year, operational measures such as controlled charging is also a viable solution. Figure 78 depicts the critical loading level for a 25-km Swallow-line feeding six charging stations. As seen in the figure, from a voltage standpoint, 1,200 kilowatt (kW) is the critical loading level that corresponds to 12 DC fast charging EV. In other words, either only 12 EVs will be charged simultaneously, or in case all 72 plugs are occupied, the charging power will reduce from 100 kW to 17 kW (1,200 kW divided by 72) to maintain the critical loading level. Under such circumstances, the charging duration can be increased from 30 minutes to three hours.

Figure 77. The voltage profile of the network depicted in Figure 76: Fast charging along a highway

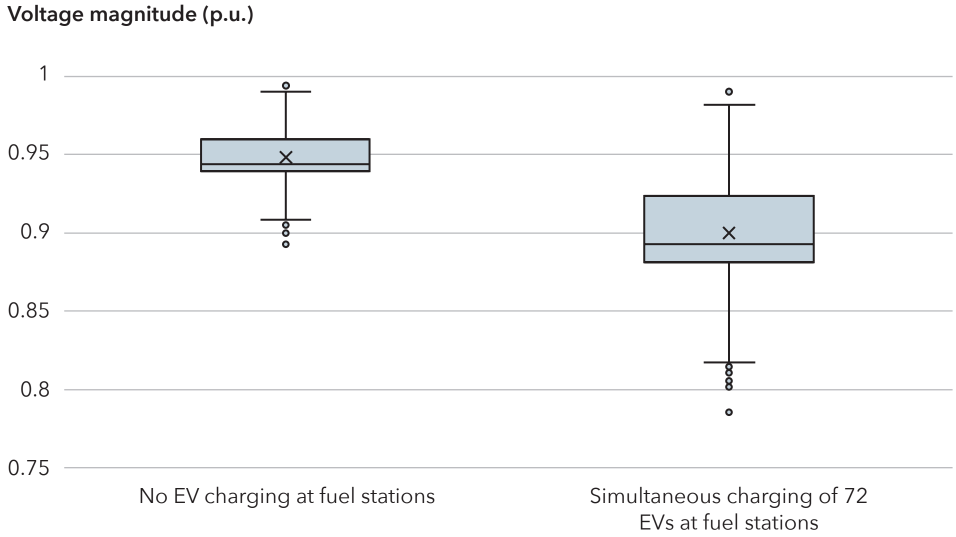
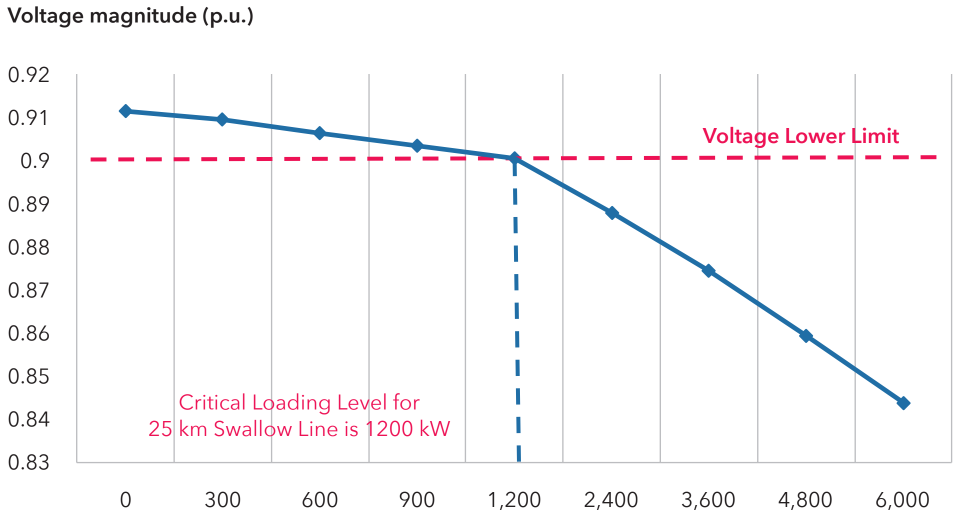


Figure 78. Critical loading level for a 25-km Swallow line feeding six charging stations



5.3 Discussion of findings

5.3.1 Distribution grid impact assessment and investment requirements

Based on the analysis of data from four grids that represent around 14% of Türkiye's total population and electricity demand along with areas of the two major cities in Türkiye (that is, Istanbul and Ankara), the results of the analysis show that 11 million EVs (including LDVs) can be integrated into Türkiye's distribution grid subject to increasing investments by 12% on top of what should be invested for meeting the non-EV load growth. For BAU scenario, which deals with integration of 5 million EVs (including LDVs) up to year 2035, e-mobility load asks for 3.5% more investment. The projection of an additional 11 million EVs is line with the required electrification of the transportation sector to meet Türkiye's climate target in 2053. The estimated investments in e-mobility, however, largely exclude the benefits and savings that can be gained from optimized EV charging.

The main driver of this investment requirement is the impact of LV systems on MV/LV transformers and MV line investment plans. As both an uncontrolled and, at the same time, economic way of charging, home-based charging routines require the use of new LV feeders and the utilisation of spare LV ports to serve e-mobility loads. However, in the case of LV port availability, which is common particularly in metropolitan areas, investment in new MV/LV transformers and MV lines is necessary.

The diagram in Figure 79 illustrates the incremental impact of e-mobility loads on the distribution grid infrastructure. It outlines a bottom-up approach where the initial investment is directed towards new LV lines. Subsequently, this investment cascades towards MV/LV transformers and MV lines, reflecting the evolving needs of accommodating EV adoption. Figure 80 provides a breakdown of investment factors specifically concerning MV/LV transformers. Notably, a significant portion of these investments can be attributed to LV system constraints and the average loading level increment. These factors primarily stem from reliability considerations, underlining the critical importance of ensuring grid stability and performance in the face of increasing e-mobility demands.

When examining MV line investments, it becomes apparent that virtually all investment requirements are driven by reliability concerns. This is elucidated by the relatively low average loading level of MV lines, typically ranging between 10% to 15%. This underscores the imperative for robust infrastructure capable of sustaining the added strain posed by e-mobility loads. In sum, the burden imposed by e-mobility loads on the distribution grid is predominantly from due to reliability factors. This necessitates proactive measures from both distribution system planners and CapEx providers, and policymakers and regulatory authorities such as Ministry of Energy and Natural Resources (MENR) and Energy Market Regulatory Authority (EMRA) in Türkiye.

Based on these findings, the investment prerequisites to accommodate the anticipated e-mobility load of 11 million EVs in Türkiye's metropolitan areas are as follows:

- 10% more MV/LV transformer investment on top of what should be invested up to year 2035;
- 16% more MV line investment on top of what should be invested up to year 2035;
- 12% more investment on top of what should be invested up to year 2035.

For 5 million EVs, which corresponds to BAU scenario, the investment requirements are as follows:

- 3% more MV/LV transformer investment on top of what should be invested up to year 2035;
- 5% more MV line investment on top of what should be invested up to year 2035;
- 3.5% more investment on top of what should be invested up to year 2035.

As the main drivers of the additional investment requirements due to e-mobility loads are reliability factors, policymakers and regulatory authorities such as MENR and EMRA should consider a trade-off between dedicating e-mobility-oriented CapEx to DSOs or relax the reliability criteria to the extent possible.

Figure 79. The bottom-up impact of e-mobility loads

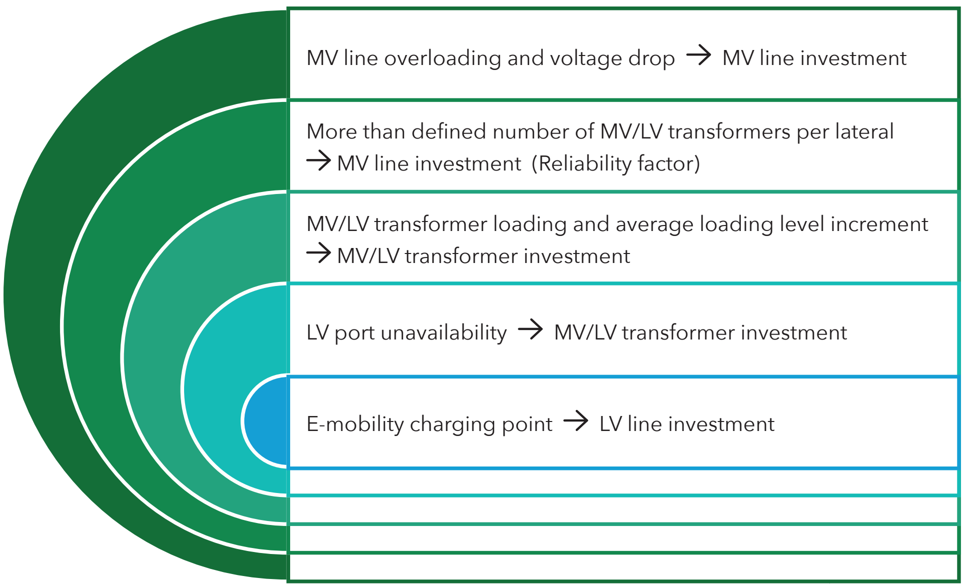
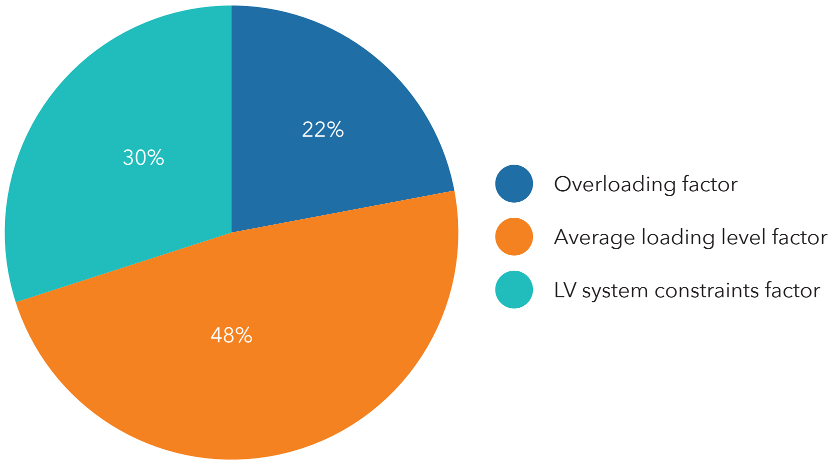


Figure 80. The share of different factors in MV/LV transformer investment



5.3.2 Controlled and smart EV charging solutions to reduce the impact on the grid

In addition to maintaining the rate of grid investments, the results point to the importance of using controlled and smart charging mechanisms that can enable optimisation of EV charging at public and residential charging points. These range from smart unidirectional charging to bidirectional charging (V2G) mechanisms based on price signals and can be simply controlled through charging assisted by local automation solutions.

Smart charging mechanisms are essential to saving system costs, in particular to save on grid investments when the investment to cover the maximum capacity needed seems unrealistic. For instance, during rare loading conditions such as extreme charging before the holidays (sensitivity analysis case I), the peak load of EVs in the Akköprü region increases up to four times that of normal charging patterns, which can have a serious impact on the distribution grid. This number can vary in different regions of Türkiye; however, an increase in the load from EV charging during holidays due to simultaneous charging is inevitable. This can be managed by either limiting the number of charging points spatially or by using on-site load management, e.g., by optimizing charging schedules, and helped by automation solutions.

EV charging and discharging can be made more efficient for the grid—and hence cost-efficient—based on certain signals. These signals can come from the grid, e.g., to indicate when there is grid capacity available, and from the energy market, e.g., when renewable energy is available. If this information is available to customers, more advanced solutions can be deployed to handle implicit flexibility measures such as dynamic and locational tariffs for charging, enabling demand response through EV-based grid services. For example, the charging tariff can be more reasonable during the days approaching the holidays, but for the day before holidays start, the charging prices can be extremely high. With the proper announcement of pricing policies, extreme simultaneous charging occasions can be prevented. Or through locational pricing approaches, charging prices in less congested areas can be governed to steer e-mobility loads towards less congested areas.

One smart charging case considered in this study (sensitivity case II) looks into shifting EV loads towards hours in which local renewable-based generation dominates the energy mix. Through these shifting mechanisms in place, e-mobility loads can be shifted to less congested hours. For instance, in sensitivity case II, overloading originates from the simultaneous charging of 385 EVs (AC type 2, 3.7 kW), which results in overloading 11 MV/LV transformers more than 90%. Here, by postponing 56% of the charging load, that is 219 EVs, the overloading on the MV/LV transformers is alleviated. In addition, the hours with low loads and high renewable generation can also be targeted to avoid renewable curtailment. Under both charging routines, home-based charging and public-based charging, the benefits that can be gained from the synergies between renewable energies and flexibility measures such as storage and EV charging are obvious. The benefits would be more prominent from a grid integration perspective during summertime, when additional loads from EVs increase already high loads due to the use of air conditioning. Distributed energy and battery storage can create significant benefits to meet the additional EV load, thereby reducing the operational and investment requirements on distribution grids. Note that the realisation of e-mobility load shifting requires proper settlement and technological readiness. For instance, time-of-use and dynamic pricing mechanisms are required at the initial stage, which can be then improve the flexibility aggregation mechanism through the aggregators to harvest the flexibility of the EVs at that specific hour. An additional step is the establishment of a local flexibility market so that the aggregated flexibility can be traded in the local flexibility market with DSO coordination.

V2G mechanisms can also be considered as controlled charging/discharging mechanisms where a certain level of EV charging demand is served by V2G EVs. For the conducted simulation (sensitivity case III), by serving only 25% of the e-mobility load through other available cars, the overloading of most of the MV/LV transformers in the Akköprü region can be alleviated. In addition to the availability of time-varying pricing to enable EV flexibility, for V2G applications, certain levels of technology and settlement mechanisms readiness are required. For instance, for the V2G flexibility provision from residential charging points, an aggregation mechanism will be required enabled by the aggregators through smart contracts. Here, both local flexibility market-based settlement and local peer-to-peer trading mechanisms can be used. In both cases, advanced registration infrastructure such as blockchain applications will be required. For V2G at public charging points, the parking lots of charging service providers or parking where the EVs will remain for relatively long periods, such as parking at airports, represent a viable option. Here, customers can request a desired state-of-charge level when departing plus the permissible number of charging and discharging sessions and compensated for with benefits, such as a reduction in their parking bill. Note that V2G mechanisms not only target the congestion alleviation originating from e-mobility loads but also can be beneficiary for congestion management for non-EV loads.

The final option when smart charging mechanisms are not available is to simply control charging through local automation solutions that can control part of the e-mobility load. For instance, in the case of charging along highways, coordinated charging on consecutive charging points on one weak feeder is a difficult task. Here, based on the loading level of the feeder or the voltage magnitude drop originating from the e-mobility load, the rate of simultaneous charging can be limited. In other words, if simulatious charging at consecutive charging points is inevitable (e.g., in instances of excessive charging along highways during holiday times), the delivered power can be limited in a way that total deliverable power will be less than the critical loading level of the feeding line. Obviously, under such circumstances, the charging duration would increase.

5.3.3 Considerations for the smooth uptake of e-mobility loads

Based on the conducted simulation studies, there are considerable differences in the investment requirements for each pilot region. As an outstanding example, although the number of EVs in both the Akköprü and Ümitköy regions are identical, the impact of e-mobility loads on associated distribution systems is not the same. This observation implies the need for grid-specific planning to determine the proper number and location of the charging infrastructure as well as the investment requirements to limit the impact of e-mobility loads.

Another important point is that most of the smart charging mechanisms, which ease the uptake of e-mobility loads, require advanced solutions and technology and settlement readiness levels. Here, one of the most important issues is the lack of data and monitoring pertaining to the use of public charging stations in Türkiye. This is often in the hands of investors, and therefore, it is challenging for planners to craft effective incentive mechanisms. For instance, the Şarj@TR platform in Türkiye, which provides the location of public charging stations, their availability, and charging tariffs, is devised by EMRA; therefore, the charging patterns are not accessible. The

Netherlands represents a best practice case for monitoring the utilisation of charging points and sharing the collected data publicly. Evidence from the Netherlands shows that the utilisation factors of charging infrastructure remain low even in dense markets and that monitoring data is needed to develop the charging services market. For example, Amsterdam's public charging points have an average utilisation of 35%, which is high compared to other Dutch cities and locations in Europe. The fact that EVs use only 20% of their parking time for actual charging implies further optimisation potential.[65] More generally, there is a lack of publicly available usage data for charging points that would allow a targeted policy design.

[65] Wolbertus, R., van den Hoed, R., and Maase, S., 2016. Benchmarking charging infrastructure utilization. World Electric Vehicle Journal 8(4), 748-765. Retrieved from https://www.researchgate.net/ publication/316561797_ Benchmarking_Charging_Infrastructure_ Utilization

6. Priority Areas for Transforming Türkiye's Transportation Sector

Based on the results of this analysis, this section proposes five priority areas for energy policymakers, the market regulator, distribution grid companies, the automotive industry, charging technology developers and investors, urban planners, and academia. The proposed areas for policy action are not ranked in order of priority or importance but are rather categorized depending on which stakeholder groups or part of the energy sector they impact.

1) Accelerate the market for electric vehicles (EVs) in parallel with charging services

Experiences from the pioneering EV markets in the European Union (EU), the United States (US), and China underscore the importance of a comprehensive policy framework led by the government to foster both EV adoption and the development of charging infrastructure. This approach is crucial to ensuring that EVs become cost-competitive compared to traditional combustion-based vehicles.

- **Purchase incentives:** Implementing purchase incentives such as price rebates or tax deductions can significantly stimulate EV sales. These incentives should be strategically combined with measures aimed at phasing out internal combustion vehicles, like the 'Bonus-Malus' Scheme in France. This scheme finances purchase reductions on low-emission vehicles through levies on higher-polluting vehicles. Norway, as another pioneer, has also paved a similar path. The overall signal from the majority of political parties in Norway is that it should always be economically beneficial to choose zero- and low-emission cars over high-emission cars. This is obtained through "the polluter pays principle" in the country's vehicle taxation system: high taxes for high emission cars and lower taxes for low and zero-emission cars. For a long time, taxes on polluting cars have partly financed incentives for zero-emission cars without any loss in revenues.[66] In Norway, the purchase tax for all new cars and their emissions is calculated through a combination of weight, carbon dioxide (CO_2), and NO_x emissions. The tax is progressive, making big cars with high emissions very expensive. For the last few years, the purchase tax has been adjusted gradually to put more emphasis on emissions and less on weight. Additionally, scrapping schemes can be introduced to encourage lower-income groups to opt for less polluting vehicles. In Türkiye, for the domestically manufactured EV, Türkiye's Automobile Joint Venture Group (TOGG), some facilities such as without interest loans are envisioned.

[66] Norsk elbilforening, n.d. Norwegian EV policy. https://elbil.no/english/norwegian-ev-policy/

- **Government leadership:** Governments should take a proactive role in expanding the EV market. This includes setting ambitious targets, providing regulatory support, and investing in research and development to advance EV technology. In the case of Norway, the Norwegian Parliament decided on a national goal that all new cars sold by 2025 should be zero-emission vehicles (electric or hydrogen). By the end of 2022, more than 20% of registered cars in Norway were battery electric vehicles (BEVs). BEVs held a 79.2% car market share in 2022. The speed of Norway's transition is closely related to policy instruments and a wide range of incentives. In October 2021, Türkiye ratified the Paris Agreement on climate and pledged to achieve net-zero emissions by 2053. Although two different pathways towards net zero were published at the time of ratification and the role of transportation sector electrification was highlighted,[67,68] there is no officially published long-term plan for the electrification of the transportation sector.[69]

- **Electrification of public and fleet vehicles:** Electrifying public transportation vehicles, such as buses, and commercial fleets, including delivery and taxi services, can significantly reduce emissions and promote EV adoption. Government subsidies or incentives can encourage fleet operators to transition to electric vehicles.

- **Charging infrastructure:** To alleviate anxiety and facilitate widespread EV adoption, a robust charging infrastructure network must be established. Governments should invest in the deployment of charging stations in strategic locations, such as urban centres, highways, and parking facilities. Additionally, public-private partnerships can incentivize businesses to install charging infrastructure on their premises.

- **Phased approach:** While critical in the early stages of market development, EV incentives should be gradually phased out to establish a sustainable and competitive market. This allows for a smooth transition and ensures long-term viability of the EV market.

By implementing these policies in conjunction with one another, governments can accelerate the transition to e-mobility while addressing key barriers to adaptation. This holistic approach lays the foundation for a sustainable and competitive EV market.

[67] SHURA, 2023. Net Zero 2053: A Roadmap for the Turkish Electricity Sector. https://shura.org.tr/wp-content/uploads/2023/05/Net-Zero-EN.pdf
[68] IPC, n.d. TURKEY'S DECARBONIZATION PATHWAY NET ZERO IN 2050 -EXECUTIVE SUMMARY. https://ipc.sabanciuniv.edu/Content/Images/CKeditorImages/20211103-20111678.pdf
[69] ekonomim, 2023. 'Türkiye'nin elektrikli araçlarda 2030 hedefi şarj sistemine bağlı'. https://www.ekonomim.com/ekonomi/turkiyenin-elektrikli-araclarda-2030-hedefi-sarj-sistemine-bagli-haberi-693362

2) Develop e-mobility-oriented distribution grid investment strategies

Based on the grid analysis conducted, which considers various EV integration scenarios and charging routines up to the year 2035, it is evident that accommodating 11 million EVs will require a significant increase in investment in the distribution grid. Specifically, it is estimated that at least a 12% increase in investment is necessary beyond what is already planned to compensate for non-EV load growth, which is projected at a 5% annual average growth rate. The primary driver behind the need for e-mobility-oriented investment lies in the constraints faced by the LV grid, directly impacting reliability criteria. The investment requirements originate from the LV system and subsequently affect MV and LV transformers, as well as MV lines in a cascading manner. To address this need, policymakers and regulatory authorities such as the Ministry of Energy and Natural Resources (MENR) and Energy Market Regulatory Authority (EMRA) should allocate e-mobility-related Capital Expenditure (CapEx) to distribution system operators (DSOs). This allocation would help alleviate DSO concerns regarding reliability standards. Alternatively, policymakers and regulatory authorities could reconsider reliability criteria to accommodate the influx of EVs. Specifically, given that most e-mobility-related investments are driven by reliability concerns rather than overloading factors, policymakers and regulatory authorities could slightly relax the reliability thresholds, such as customer average interruption duration index (CAIDI) and customer average interruption frequency index (CAIFI) limits, to facilitate the smoother integration of EVs into the grid. However, addressing this issue necessitates a careful balance between reliability and e-mobility-focused CapEx dedication. This balance should be optimized by policymakers, such as MENR and EMRA, in coordination with DSOs or their coordination association, such as the Electricity Distribution Services Association (ELDER). A complementary solution can be dedicating a specific capacity of each transformer to e-mobility loads so that DSOs can only allocate that capacity accordingly. In case of increasing capacity requirements for other load types, say commercial or residential, new transformers should be planned. Ultimately, a collaborative approach is essential to ensure the seamless integration of EVs into the grid while maintaining reliability standards.

3) Develop time-specific and region-specific charging measures

A. Development of time-varying charging price strategies to integrate higher shares of EVs into the grid: Lessons from mature EV markets in the US and Europe underscore the significance of electricity pricing in supporting and incentivizing smart charging practices. Smart charging refers to the ability to charge electric vehicles in a cost-effective and grid-friendly manner, particularly during periods of low grid load or high availability of renewable energy sources. Time-varying tariffs, aligning closely with the actual costs of electricity production and delivery, can steer charging activities towards off-peak hours, benefiting both EV owners and overall grid stability. In the medium to long term, further development of wholesale electricity markets, including day-ahead, intraday, and balancing markets, is essential to support more dynamic pricing structures. Shorter imbalance periods and pricing mechanisms driven by supply-demand dynamics can better capture the value of flexibility in the grid. These wholesale prices can then be reflected in consumer bills through time-varying pricing schemes. In the short term, as retail market liberalisation progresses, the introduction of dedicated time-of-use tariffs for EVs can capitalize on the inherent flexibility of EV charging. Türkiye already has time-of-use tariffs as part of its regulated pricing framework; however, for e-mobility loads only the upper and lower limits are regulated by regulating authorities, and the charging price itself should be a cost-reflective price determined by day-ahead and intraday markets in hourly resolution. EV-specific tariffs could extend this approach. With the increasing adoption of renewable energy and EVs, and as the market becomes more competitive, dynamic pricing models are likely to emerge naturally. However, if market dynamics do not lead to the emergence of dynamic pricing structures, regulators may intervene by implementing more dynamic EV tariffs in the future. These tariffs can incentivize energy suppliers to develop innovative pricing offers. Regardless, regulatory parties should closely monitor the effectiveness of EV tariffs in integrating EVs into the grid in a cost effective manner. Continued assessment and adjustment of tariff structures will be essential to ensure the successful integration of EVs into the energy market. Last but not the least, time-of-use tariffs can mitigate the effects of excessive charging, especially on days preceding religious holidays when the distribution grid may experience significant overloading. Pricing adjustments can be made in the days leading up to such occasions to encourage EV charging during off-peak periods and discourage it during peak times. By implementing higher charging prices on these specific days, EV charging can be shifted to periods with lower pricing, thereby reducing strain on the grid.

B. Introduction of time-of-use network pricing to direct EV charging

Volumetric time-of-use pricing of power networks in particular is an essential condition to ensure distributed energy resources, such as EVs, can use existing grid capacity most efficiently. Compared to other network tariff designs, where the cost of using power networks is based on the annual peak demand capacity (so-called demand charges), a predominantly volumetric design is more suitable to more flexible electrified end-uses such as EVs. Especially charging point operators (CPO) in the high-capacity charging business, e.g., operating public charging sites along highways, face easier market conditions with costs of using the networks limited based on the volume of electricity charged over the year, instead of paying for peaks that occur rarely (e.g., during national holidays, see section 5.2.). Adding a time-varying element to the network tariff depending on grid utilisation would incentivize all consumers to shift charging to optimal times for the grid and also be more suitable to a variety of other electrified end uses that are being added to the power system as the energy transition advances. Time-varying network tariffs help to accurately assess grid investment needs and avoid overinvestment (hence, costs that are shared among all users).

C. Development of region-specific charging price strategies to integrate higher shares of electric vehicles to the grid: The findings highlight that the adoption of e-mobility can introduce challenges to the distribution grid, including line/transformer overloading and voltage drops exceeding set limits. However, it is crucial to note that these issues are not uniform across all regions served by the DSOs. In fact, overloading due to e-mobility loads tends to be more pronounced in specific regions, presenting regional challenges that can be addressed by leveraging the inherent mobility of e-mobility. One potential solution involves directing e-mobility loads towards less congested feeders for charging purposes, utilizing various settlement mechanisms and region-specific pricing strategies. Such measures require the establishment of flexibility markets within distribution systems, which would enable the aggregation of flexibility, demand response options, vehicle to grid (V2G) and peer-to-peer possibilities, and thereby enhancing grid resilience and reliability. However, the implementation of these mechanisms necessitates the adoption of locational pricing strategies that accurately reflect the costs associated with alleviating local technical constraints. While locational marginal pricing (LMP) is common at the transmission level in the US, the concept of distribution locational marginal pricing (DLMP) is currently under consideration, particularly in states like California, where distributed generation levels are high. Embracing these strategies can effectively manage e-mobility-related grid challenges while promoting the efficient integration of electric vehicles into the energy ecosystem.

4) Plan, develop and implement smart charging mechanisms to limit the impact of the e-mobility load on distribution grids

A. Grid-integrated planning of EV charging infrastructure

Planning charging infrastructure should be based on detailed mappings of where charging demand is expected and matched with maps of available or planned grid capacity to enable grid- and cost-optimal build-out of charging infrastructure. For this, it is crucial that DSOs make information on grid capacity available, e.g., through hosting capacity maps. Country-wide planning processes that take into account regional specifics, as illustrated by the pilot regions in this study, should be developed. Coordinated stakeholder processes including both transportation and energy stakeholders can help to ensure information exchange and planning at early stages.

B. Deployment of intelligent technologies to support grid-friendly EV uptake: Several pricing trials around the world have demonstrated the effectiveness of integrating smart charging mechanisms to optimize the integration of EVs into the power system. This smart technology ranges from advanced metering systems,[70] which measure and transmit data on charging point consumption, to solutions like automated charging that can adjust in response to pricing signals or any signal that can control the charging pattern. Thus, it is imperative that the charging infrastructure deployed both presently and in the future incorporates smart functionality, even if not immediately utilized. Policymakers should mandate this minimum level of intelligence for all charging infrastructure, particularly in workplaces and public charging stations, where larger numbers of EVs are expected to charge for extended periods. This enables control over peak-hour usage and maximizes the potential of optimized charging.

C. Establishment of synergies between EV charging and renewable energy integration and energy storage: A comprehensive approach to energy and transportation planning is essential to ensure cost-efficient integration of EVs into the grid and fully realize their benefits. In the medium to long term, more nuanced pricing structures, such as efficient market mechanisms, are necessary to integrate renewables and effectively manage flexible loads like EVs. In essence, the improvement of currently available wholesale markets to more cost-reflective wholesale electricity markets, the establishment of locational prices at the wholesale level, improving retail markets to hourly resolution and providing end-users with hourly electricity prices, and finally, the establishment of DLMP are among the medium- to long-term structures for promoting the integration of renewables and effective management of electrified loads such as EVs. For instance, during peak solar generation periods, such as sunny summer days, incentivizing EV charging through price adjustments can optimize grid utilisation and alleviate technical constraints, such as voltage fluctuations caused by excess solar energy generation. This not only benefits EV owners but also enhances the stability of the distribution grid. Moreover, enhancing the implementation of time-varying network pricing and maximizing the efficiency of existing infrastructure are crucial for deferring costly grid investments. Smart EV charging tariffs, based on time-varying pricing schemes linked to wholesale market prices, can inform consumers of optimal charging times, either through manual notifications or automated load management technologies. By leveraging dynamic pricing mechanisms and encouraging smarter charging practices, policymakers can foster a more sustainable and resilient energy ecosystem while facilitating the seamless integration of EVs into the grid. Continued collaboration between

[70] In Türkiye, the MASS project targets domestic development of smart meters as the building block of its smart grid system and is widely use in all 21 DSOs. This project can pave the way towards smart charging mechanisms for e-mobility loads (https://www.mass.org.tr/).

stakeholders and ongoing evaluation of pricing strategies will be vital to maximize the benefits of EV grid integration while minimizing its impact on the distribution network.

D. Development of local automation schemes to manage the impact of simultaneous and excessive charging: In addition to smart charging mechanisms, it is essential for current and future charging infrastructure to integrate local automation capabilities. These automation features enable control over and limitation of simultaneous charging events, which significantly affect the reliable operation of distribution systems. For example, consider the scenario of charging stations located along highways connected to a medium voltage (MV) line. Charging multiple vehicles simultaneously in this setup can potentially lead to voltage issues, impacting the overall electricity quality within the DSO service area. By implementing local automation solutions, the occurrence of simultaneous charging incidents can be restricted to ensure they do not exceed the critical loading level of the feeder. This proactive management helps maintain the acceptable quality of delivered electricity, safeguarding the stability and reliability of the distribution system. Incorporating such automation options into charging infrastructure not only enhances the efficiency of EV charging but also contributes to the resilience of the grid, ultimately supporting the seamless integration of electric vehicles into the energy ecosystem.

5) Assess, develop, and implement new business models for EV charging

Despite the progress in EV charging infrastructure globally, creating a sustainable business case remains a significant challenge for many companies. Public support programs are crucial to facilitate the commercialisation of the EV charging market. Although utilisation rates vary, even in the best cases, they remain around 30% in Europe. While Norway has successfully implemented commercial operations, less mature markets often rely on partial support from the public sector. However, as the EV market matures, public sector support is expected to decrease, emphasizing the need for self-sustainability. In Türkiye, support policies for EV charging infrastructure should focus on transitioning to commercial operations and could be tied to the number of EVs in use, gradually reducing subsidies accordingly. Furthermore, separating installation cost subsidies from ongoing operational costs promotes commercial viability. It is imperative to monitor and publicly share utilisation data from charging points to inform decision-making and improve efficiency. To cope with the low-capacity factor locations, models of public-private co-funding should be explored, enabling the joint investment of resources from both sectors. Additionally, operating through electricity network companies could be considered, potentially through public tenders, to ensure efficient EV charging infrastructure across regions.

Alternative technology solutions, such as battery-assisted chargers, offer flexibility by allowing charging points to be relocated based on demand or to leverage stored energy during peak hours, enabling operators to adapt their business models more effectively to varying conditions. These innovative approaches can enhance the efficiency and sustainability of EV charging infrastructure deployment and operations.

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About Istanbul Policy Center at the Sabancı University

Istanbul Policy Center (IPC) is a global policy research institution that specializes in key social and political issues ranging from democratization to climate change, transatlantic relations to conflict resolution and mediation. IPC organizes and conducts its research under three main clusters: The Istanbul Policy Center–Sabancı University–Stiftung Mercator Initiative, Democratization and Institutional Reform, and Conflict Resolution and Mediation. Since 2001, IPC has provided decision makers, opinion leaders, and other major stakeholders with objective analyses and innovative policy recommendations.

About European Climate Foundation

The European Climate Foundation (ECF) was established as a major philanthropic initiative to help Europe foster the development of a low-carbon society and play an even stronger international leadership role to mitigate climate change. The ECF seeks to address the "how" of the low-carbon transition in a non-ideological manner. In collaboration with its partners, the ECF contributes to the debate by highlighting key path dependencies and the implications of different options in this transition.

About Agora Energiewende

Agora Energiewende develops evidence-based and politically viable strategies for ensuring the success of the clean energy transition in Germany, Europe and the rest of the world. As a think tank and policy laboratory, Agora aims to share knowledge with stakeholders in the worlds of politics, business and academia while enabling a productive exchange of ideas. As a non-profit foundation primarily financed through philanthropic donations, Agora is not beholden to narrow corporate or political interests, but rather to its commitment to confronting climate change.

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