Kaunas University of Technology
Faculty of Electrical and Electronics Engineering

Analysis of Increasing Electro-Mobility Impact on Electricity Demand

Master's Final Degree Project

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Kaunas, 2026

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Summary

With the development of the world, the world population has been growing and there is a revolution in the industries bringing a tremendous need for electro-mobility and electricity supply. In this paper, we will discuss how electro-mobility and electricity demand are slowly evolving around and the demand and use of electric vehicles (EVs) might imply to daily load curves and grid operations. To ensure a safe and strong energy infrastructure, understanding the implications of EV adoption for power consumption dynamics has become ever more crucial. This report provides a synthesis of the existing literature, an analysis of electromobility trends, and recommendations on the possible impacts on electricity systems, and suggestions for government and planners as they make a sustainable shift.

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Santrauka

Sparčiai vystantis pasauliui, auga gyventojų skaičius ir vyksta reikšmingi pramonės pokyčiai, sukeliantys didėjantį elektromobilumo bei elektros energijos tiekimo poreikį. Šiame darbe nagrinėjama, kaip elektromobilumo plėtra ir kintanti elektros energijos paklausa daro įtaką kasdienėms apkrovų kreivėms ir elektros tinklų veikimui. Atsižvelgiant į būtinybę užtikrinti saugią ir patikimą energetinę infrastruktūrą, tampa vis svarbiau įvertinti elektrinių transporto priemonių (EV) plėtros pasekmes elektros vartojimo dinamikai.

Darbe pateikiama mokslinės literatūros analizė, elektromobilumo tendencijų apžvalga bei rekomendacijos dėl galimos įtakos elektros energetikos sistemoms. Taip pat pateikiamos įžvalgos ir siūlymai valstybės institucijoms bei planuotojams, siekiant užtikrinti tvarią ir patik imą perėjimo prie elektromobilumo raidą.

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Abbreviations:

ACEA — European Automobile Manufacturers Association
ACF — Autocorrelation Function
AFIR — Alternative Fuels Infrastructure Regulation
ARIMA — Autoregressive Integrated Moving Average
BAU — Business-as-Usual
BEMIP — Baltic Energy Market Interconnection Plan
BEV — Battery Electric Vehicle
BRELL — Belarus–Russia–Estonia–Latvia–Lithuania (Power Ring)
CAGR — Compound Annual Growth Rate
CO_2 — Carbon Dioxide
DC — Direct Current
DLB — Dynamic Load Balancing
DSM — Demand Side Management
DSO — Distribution System Operator
EAFO — European Alternative Fuels Observatory
EBRD — European Bank for Reconstruction and Development
EC — Energy Consumption
EEA — European Environment Agency
EEG — Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz)
EIB — European Investment Bank
eLCV — Electric Light Commercial Vehicle
ELMO — Estonian Nationwide EV Charging Network
EMU — Electric Multiple Unit
ENTSO-E — European Network of Transmission System Operators for Electricity
ESO — Elektros Skirstymo Operatorius (Lithuanian Distribution System Operator)
EU — European Union
EV — Electric Vehicle
FCEV — Fuel Cell Electric Vehicle
GDP — Gross Domestic Product
GHG — Greenhouse Gas
GWh — Gigawatt-hour
HEV — Hybrid Electric Vehicle
HVAC — Heating, Ventilation, and Air Conditioning
ICE — Internal Combustion Engine
ICCT — International Council on Clean Transportation
IEA — International Energy Agency
IMC — In-Motion Charging
IPS/UPS — Integrated Power System / Unified Power System (Russian-controlled)
ISO — International Organisation for Standardisation
kWh — Kilowatt-hour
LAKD — Lithuanian Road Administration (Lietuvos Automobilių Kelių Direkcija)
LCV — Light Commercial Vehicle

LCOE — Levelized Cost of Energy
LF — Load Factor (Electric-mode fraction of VKT for PHEVs)
LFP — Lithium Iron Phosphate (Battery Chemistry)
LHMT — Lithuanian Hydrometeorological Service
LOM — Loi d'Orientation des Mobilités (French Mobility Orientation Law)
LRT — Lithuanian National Radio and Television / Lithuanian Rail Transport
LTG — LTG Group (Lithuanian Railways)
MDPI — Multidisciplinary Digital Publishing Institute
MW — Megawatt
NECP — National Energy and Climate Plan
NMC — Nickel Manganese Cobalt (Battery Chemistry)
NVE — Norwegian Water Resources and Energy Directorate
OEM — Original Equipment Manufacturer
PACF — Partial Autocorrelation Function
PEV — Plugin Electric Vehicle
PHEV — Plug-in Hybrid Electric Vehicle
PV — Photovoltaic
RMSE — Root-Mean-Square Error
RTE — Réseau de Transport d'Électricité (French Transmission System Operator)
SF — Seasonal Factor
SI — Sensitivity Index
SMARD — Smart Redispatch and Digital Grid Management Platform (Germany)
SOC — State of Charge
SUV — Sport Utility Vehicle
TEN-T — Trans-European Transport Network
TOU — Time-of-Use Tariff
TSO — Transmission System Operator
V2G — Vehicle-to-Grid
VERT — Electric Mobility Competence Centre (Vilnius)
VKT — Vehicle Kilometres Travelled
VPP — Virtual Power Plant
VRE — Variable Renewable Energy
VVT — Vilniaus Viešasis Transportas (Vilnius Public Transport)
WLTP — Worldwide Harmonised Light Vehicle Test Procedure
ZEV — Zero Emission Vehicle
ZFE — Zone à Faibles Émissions (Zero Emission Zone, France)

Introduction

Background and significance of electromobility

Electromobility is fundamentally transforming global transportation systems. EVs, buses, trains, scooters and bicycles are all playing an important role in green city movements. It's not just the replacement of internal combustion engines with electric motors, it's a paradigm shift in society's transportation, energy consumption and environmental management.

The necessity of this change is driven mostly by the environmental threats posed by traditional transport systems. The transport industry is still among the highest emitters of greenhouse gases and air pollution around the world. Classic cars that run on fossil fuels release large amounts of carbon dioxide, nitrogen oxides, and particulate matter, which are major contributors to climate change and the deterioration of urban air quality. Electrification of transport presents a sustainable solution to reduce these environmental effects, especially in cases where renewable sources of energy have been used to charge electric cars.

The advantages of electromobility are not limited to the reduction of emissions. Electric cars are more energy efficient than their internal combustion equivalents, as they transform a greater percentage of stored energy into mechanical energy. In addition, electric motors offer instantaneous delivery of torque, which gives the car better performance features. The mechanical complexity of electric drivetrains is less than the mechanical complexity of conventional systems, which results in a reduction of maintenance needs and the possible decrease in lifetime operational spending by the vehicle owner.

Nevertheless, the scale of electric vehicle usage poses significant challenges to power infrastructure, especially in small European countries like Lithuania. The major issue of concern is related to electricity demand patterns and grid capacity. The aggregate sum of charging might impose challenges on the current distribution networks as more vehicles are transported through electric methods, particularly when aggregate demand occurs at the peak hours, where residential, commercial, and industrial electricity requirements meet with vehicle charging processes.

As a European Union member state, Lithuania is bound by ambitious decarbonization goals aligned with the EU's overall climate objectives. Transport electrification is one of the most important aspects of these national sustainability policies. The change should be made carefully to ensure that the grid does not become less stable and infrastructure investments become sustainable, as more cars need to be charged.

This problem is especially severe when the demand is high. EVs are generally fully charged within several hours, and when large numbers of vehicle owners charge their vehicles at the same time during periods of high residential power use, such as in the evening hours, this may cause high demand on the distribution transformers in the area and the overall grid infrastructure. Unless anticipated and addressed, the phenomenon may cause instability on the voltage, overloading of equipment and even service disruption.

As a result, the issue of the interdependence between the electromobility adoption trends and electricity demand profiles have become critical in the planning of the energy sector. The transmission system operators, distribution network companies, energy regulators, and policymakers need to have an in-depth understanding of how the rise in the number of electric vehicles will impact the daily load curves, peak loads, and the overall functioning of the system. The knowledge is essential in making informed choices on infrastructure investment, regulatory policies and the formation of smart charging policies capable of alleviating the negative effects and sustainable transport goals.

Research aim

The study aims to examine how the further growth of electromobility will affect the electricity demand structure in Lithuania and give recommendations for the planning of the grid infrastructure and sustainable development.

Objectives of the study

The research topic is an analysis of the effect of growing electromobility on electricity demand, and the following essential objectives:

1. Objective 1: To analyze electro mobility trends and projections.
2. Objective 2: To identify the potential impacts of electromobility on electricity demand and its daily curves.
3. Objective 3: To develop a mathematical model for the analysis of the impact of electromobility on electricity demand.
4. Objective 4: To investigate the impacts of increasing electromobility in (Lithuania using the developed model under different scenarios.
5. Objective 5: To perform sensitivity analysis of the developed model in order to evaluate how variations in key parameters influence the impact of electromobility on electricity demand.

To summarize, EV transition is a growing issue for the electrical grid, and there is a need for more investment in EV grid infrastructure changes and innovation. The future is electric and it is crucial that consumers, authorities and businesses know about these changes.

1. Literature review on electromobility and electricity demand impacts

1.1. Electromobility fundamentals

Electromobility is a comprehensive strategy to combat greenhouse gas emissions and clean urban air by implementing a systematic change from fossil fuel-powered transportation to electric-powered mobility systems [1]. This paradigm shift also covers the freight transport industry, and it is defined by the use of vehicles that rely on electricity instead of traditional combustion engines. There is a wide variety of energy supply mechanisms for electric mobility systems. Battery electric vehicles (BEVs) and trolleybuses and electric trains are examples of vehicles powered by onboard energy storage, or by a continuous external power supply via overhead infrastructure, respectively. The concept of autonomous and grid-dependent systems has significant implications for infrastructure needs, operational features, and environmental impact.

Two main mechanisms allow electromobility to have environmental benefits. First, BEVs have no direct tailpipe emissions while running, which helps to minimize local air pollution in urban areas. Second, EVs powered by electric energy from renewables like wind, solar, or hydropower can significantly reduce their carbon footprint throughout their lifetime when compared to conventional vehicles. The scale of these environmental gains, however, is linked to the structure of the power grid.

In regions where electricity generation relies heavily on fossil fuels, the emissions reduction potential of electromobility is substantially constrained, whereas jurisdictions with renewable-energy-dominant grids realise considerably greater environmental gains [1].

Onboard energy storage

The modern electric cars mostly rely on the lithium-ion battery technology to store energy. These battery systems have changed significantly in the last few decades and have shown to be better in energy density, charging rates, longevity, and cost-effectiveness. It has been found that onboard energy storage is the key technological element that facilitates the electromobility transition [2].

Battery electric vehicles contain electric energy in rechargeable lithium-ion battery packs, which are used to provide power to electric motors to propel the vehicle. The battery systems are typically measured in kilowatt-hours (kWh), and the operating range of the vehicle between charges is determined by the capacity of the battery system. Battery electric cars often include battery packs of 40 kWh to 100 kWh, which offer a range of 200 to 500 kilometers, based on the efficiency of the vehicle, driving environment, and ambient temperature.

One of the significant technological advancements in electric vehicles is the technology of regenerative braking systems, which helps vehicles to store kinetic energy when slowing down [3]. Instead of converting the braking energy into heat by using friction brakes, the regenerative systems convert the braking energy to electricity, which is in turn saved in the battery pack. This technology boosts the efficiency of the entire vehicle and increases the range of operation, especially in the urban driving environment that has a high frequency of acceleration and braking.

Depending on the arrangement of the powertrain, electric cars can be divided into various types:

- Battery Electric Vehicles (BEVs): A battery Electric Vehicle (BEV) is a type of pure electric vehicle that uses electricity in rechargeable batteries such as Lithium-ion (Li-ion), Lithium iron phosphate (LFP), Solid-state batteries, Sodium-ion batteries, Nickel-metal hydride (rare, but possible), etc., as its sole source of propulsion energy. These automobiles do not have an internal combustion engine and should be supplied by plugging into external power systems. Tesla Model 3, Nissan Leaf, and Volkswagen ID.4 are examples.
- Plug-in Hybrid Electric Vehicles (PHEVs): Plug-in Hybrid Electric Vehicles (PHEVs) are a combination of an internal combustion engine and an electric motor, and a rechargeable battery. These vehicles have the ability to be driven in electric-only mode on a short (usually 30-80 kilometers) range, then the internal combustion engine switches on to go further. PHEV is capable of being charged both using external electricity and self-generating electricity using the internal combustion engine. This setup allows flexibility to users, especially in areas where the charging infrastructure is developing.
- Hybrid Electric Vehicles (HEVs): Hybrid Electric Vehicles (HEVs) rely on internal combustion engines and electric motors; however, they have smaller battery systems which are not charged by external sources. Rather, recharging of the battery is only done as a result of regenerative braking and the internal combustion engine. Whereas HEVs have better fuel efficiency than conventional cars, they have little electric-only functionality and fail to use grid electricity directly [4].
- Fuel Cell Electric Vehicles (FCEVs): FCEVs include hydrogen fuel cells for generating electricity in the vehicle that is used to power electric motors.. These cars have hydrogen in high-pressure tanks and emit only water vapor as a direct result. Nevertheless, the fuel cell technology has not been as commercially advanced as battery electric vehicles, with the limited refueling infrastructure and high cost of vehicles being a current barrier to mass adoption.

To examine the electricity grid effects, battery electric vehicles and plug-in hybrid electric vehicles are the most important concerns because these types of vehicles directly absorb electric power from the power grid when they are being charged.

Externally supplied power

Some electromobility uses do not employ onboard storage as a requirement but instead depend on continually external power supply. These systems are decades old and manifest themselves in several forms, and they are still relevant in the electrification of public transport.

Types of externally supplied power vehicles:

- Trolleybus: Trolleybuses are electric buses that are powered by overhead wires using spring-loaded poles [5]. These are smart public transport vehicles which run on predefined routes with electrical overhead power infrastructure, which is usually in the form of posts on roads. Trolleybuses have a higher route mobility when compared to trams or light rail systems because they do not need tracks. The modern trolleybuses are moving towards small battery systems, which allow some off-wire capability so that routes can be more flexible and also provide continuity in service during temporary disruption of the infrastructure [6].
- Electric Tram: Electric trams run on permanent tracks and are supplied either by overhead lines or, more rarely, by third-rail lines. The tram systems are an established mode of transport in many cities in Europe. The modern designs of trams are focused on energy conservation, comfort to passengers and reduced noise pollution. In certain contemporary tram networks, on-board energy storage is used to remove overhead wires in places which are historically sensitive, such as in urban centres, where super capacitors or batteries are used to charge the stored energy.
- Electric Train: Electric trains refer to a number of rail transport schemes that travel using electric power. These include city metro transit to intercontinental high-speed railway systems. Electric trains can be powered by overhead catenary or electrified third rails. The use of multiple-unit electric trains, in which cars are equipped with motors instead of only having a locomotive in the car, has become more popular as they provide better acceleration properties and flexibility in operation. Rail electrification is one of the oldest uses in the technology of electric transportation [7].

Although externally powered electric transport systems are a contribution to the overall transport electrification targets, their energy requirements vary significantly from those of battery electric vehicles. These systems are constant power systems not charged during discrete events, but when in operation, and the pattern of demand is more predictable following the schedule of services. As a result, they have different grid impact characteristics than battery electric vehicles that form the main target.

1.2. Transport electrification as a means to reduce emissions in transport

The main motives of transport electrification efforts all over the world are environmental protection and mitigating climate change. The sustainable transportation policies will be aimed at minimising greenhouse gas emissions, but at the same time, remain economically productive. The shift to electromobility by replacing fossil fuels is a core part of such strategies.

Transportation contributes about a quarter of all energy-related carbon dioxide emissions, the majority of which are generated by road transport [8]. Overall, passenger cars, public vehicles, commercial vehicles, and freight transport are contributing significantly to the emission of greenhouse gases, as well as air pollution in the localities. In cities, the quality of air is greatly impaired by transportation-related emissions, which raises the frequency of respiratory and other health-related comorbidities in cities.

There is a high potential for reduced emissions by electric cars, especially when they are charged with low-carbon electricity. Life-cycle assessment research indicates that, even including the emissions related to the production of electricity and the production of batteries, electric vehicles generally result in fewer total emissions than the production of similar internal combustion engine vehicles over their life period [9]. This benefits more when electricity generation systems use a large amount of renewable energy.

But the positive effects of electromobility are not limited to the reduction of carbon emissions on the environment. By reducing nitrogen oxides, particulate matter, and volatile organic compound emissions at the tailpipe, electric cars can increase the quality of air at the local level in cities. This health advantage is a major factor to consider among the cities that are facing air pollution issues. It has also been reported that there are significant health gains due to a reduction in air pollution after the adoption of electric vehicles [10].

The transition to sustainable transport is not solely dependent on vehicle electrification, but also involves a broader set of enabling technologies. Mitigation measures of climate change include the adoption of modal changes in the form of wider adoption of the strategies of public transport, active mobility (walking and bicycling), and urban planning that minimises the total demand of transportation. Electric buses and electric trains are especially useful options in terms of mass transportation, and their emissions per passenger are less than those of single-occupancy transportation. Electrification of rail has been particularly effective in minimising the transport sector emissions as well as ensuring high-capacity movement of passengers and freight [11].

Policy instruments are important in enhancing transport electrification. Different tools used by governments to promote the adoption of electric vehicles include purchase subsidies, tax incentives, preferential parking and road access, as well as investment in charging infrastructure. At the same time, policies can deter the use of fossil fuel vehicles by levying carbon tax, road pricing policies, and gradually increasing demanding standards on emissions. These combinations of policies are effective in different national and regional situations, according to the current infrastructure, economic status, and social preferences [12].

Sustainable transportation is being further developed with technological innovation. Advances in battery technology, electric motor efficiency and power electronics help to increase the performance of the vehicle and minimise the cost. At the same time, the invention of renewable energy sources, electricity storage schemes and intelligent grid technologies enables the incorporation of electric cars into power systems and promotes the process of decarbonization [13].

1.3. Electromobility trends and projections

Current state of electromobility and trends in Lithuania

Lithuania is a Northern European country located in the Baltic region that has shown some progressive development in electromobility. National strategy has been aligned with the European Union (EU) goals of reducing greenhouse gas emissions and moving towards sustainable transportation, supported by state policies and EU funds. The report on Transport and Mobility in Lithuania, presented by the "Ministry of Transport and Communications of Lithuania, 2024 shows that the Lithuanian EV market has expanded greatly during the past 5 years [14].

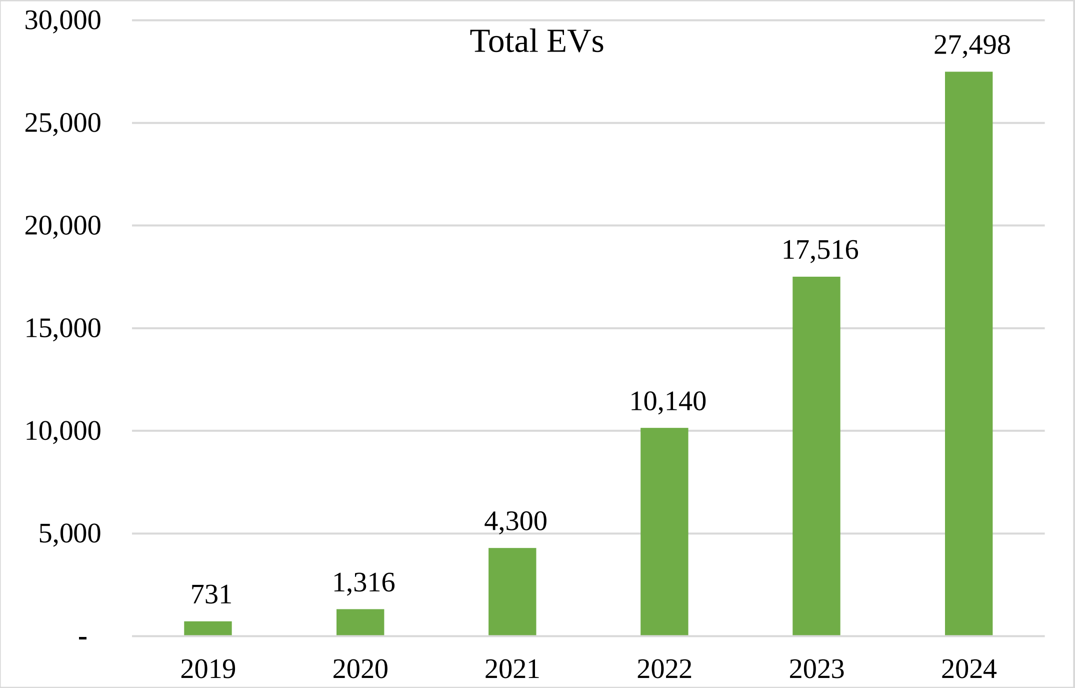


Fig. 1. The number of the registered electrically powered passenger cars of class M1 in Lithuania [15]

The total number of EVs has increased steadily in the past five years (2019-2024), as shown in Fig 1. The total EV stock in 2019 was 731, suggesting a relatively early penetration of the EV market. In 2020, this increased slightly to 1,316 EVs, indicating initial adoption.

There was a significant acceleration starting in 2021 when the total EV stock rose dramatically to 4,300 vehicles, a more than 3 times increase over 2020. This continued to rise in 2022, with the number of EV vehicles topping 10,140, representing a significant increase in fleet electrification. In the following years, growth continued at a healthy pace, growing to 17,516 EVs in 2023.

The total EVs reached 27,498 in 2024, marking the highest count recorded in the data set. In general, the data suggest that electric vehicle adoption in Lithuania has moved beyond the early adoption stage, with growing consumer acceptance and a steadily expanding used EV market supporting further electrification [8].

However, on the other hand, Lithuanian officials also examine EV infrastructure. Thus, the network of charging stations has been expanded in Lithuania, and particularly, fast charging stations are promoted along highways and in cities. European Alternative Fuels Observatory [16] explains that the number of charging stations in Lithuania has grown in the country, to about 3,047 in 2024, up from 600 in 2019.

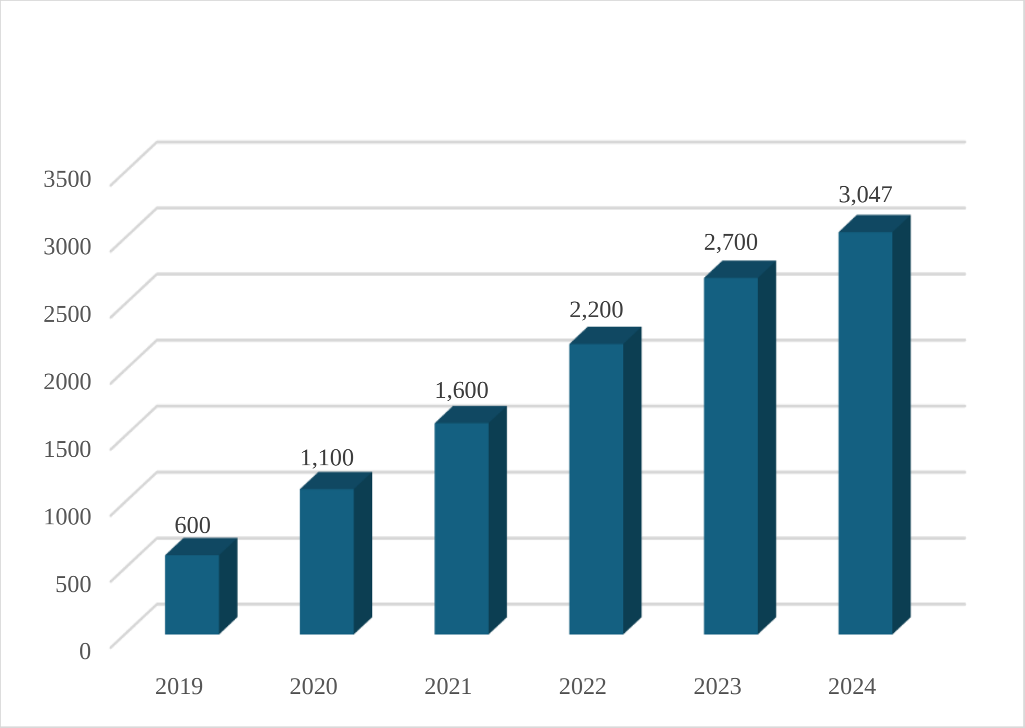


Fig. 2. Charging infrastructure growth [16]

Moreover, Lithuania gradually developing its state-based electro mobility infrastructure, which is within EU requirements concerning climate and energy goals. The biggest aspect of the issue of the country-specific component of the National Energy and Climate Plan [17] is electrification of the transport sector, in which in the plan, it is stated that the country will modernize transport sector and emphasize on electrification of transport [18].

Switching out old diesel buses to new electric-powered ones has started to appear in the past few years, with bigger cities (Vilnius, Kaunas, Klaipeda) being the first to install them, and Vilnius already under operation more than 100 electric buses in its line by 2024 [19]. They are the electric buses, which have the right to drive on the priority ways in the cities, and play a role in the removing air and noise pollution in the overpopulated territories of the cities.

The charging infrastructure of the public vehicles is not left behind. In addition to that, the concept of electromobility in the urban environment is supplemented by shared mobility CityBee and Spark that offer people electric scooters and cars.

According to European Alternative Fuels Observatory as well [20], Lithuania is also continuing to expand the scope of its network of the public charging points that not only can address the issues of the individual drivers, but also of the municipality's fleet and the electric vehicle sharing. It is planned that by 2030 Vilnius will switch 50 percent of its municipal bus fleet to electric [14]. The nature of the Lithuanian electric passenger transport system is specified in Table 1.

Table 1. Electromobility in Lithuania – summary table with references (2025)

Mode of Transport	**Quantity/Length**	**Key Notes**	**Source**
Electric Trolleybuses	354 units	91 are Škoda 32Tr SOR with 20 km battery range	[20]
Electrified Rail (km)	156 km (8% of network)	Expanding to 30% electrified by 2030	[21]
Electric Buses (Ordered)	145 units (2026–2027)	Funded by the EU and EBRD; Replacing diesel buses in Vilnius	[20], [22], [23]
Electric Trains (EMUs)	29 units (14+9+6)	Modern Škoda and Stadler FLIRT EMUs, including battery models	[20], [23]
Battery Buses (Klaipėda)	In service since 2020	Dantserer electric buses developed locally	[24]

Transport electrification projections

Over the last decade, the use of electric vehicles (EVs) has increased dramatically, and statistics show that it is about to rise at a much faster rate between now and 2030. The world electric vehicle fleet passed the impressive figure of 40 million in 2023, with two-wheelers the most electrified subsector (almost 8 percent of all motor vehicles) in the world. in 2023, global electric bus sales accounted for 3% of sales, with China recording more than 60 percent of sales and Latin America recording high levels of adoption. Electric truck sales were raised by a huge 35% in 2023, making up 3 percent of sales in China and 1.5 percent in the European markets [25][26].

Electrification of transport in Lithuania is moving on a fast track, becoming a priority in the country as part of the larger European Union climate agenda. The strategic focus of the country is to cut down on using fossil fuels, minimise emissions of greenhouse gases, and enhance green mobility in cities. As the focus in terms of transportation shifts towards electric vehicles (EVs), electric buses, trolleybuses, and rail transportation, the Lithuanian electrification roadmap defines a comprehensive plan of changing towards cleaner transport systems.

The transportation segment (especially in large cities, such as Vilnius, Kaunas and Klaipeda) is one of the fundamental supports of such a shift. For example, Vilnius city is transforming the majority of diesel buses to electric ones by 2030, which will be financed by the EU and the EIB. By 2025 there are only 354 trolleybuses in operation, of which an increasingly large proportion have an extended battery range with limited off-grid capability. Besides, more than 145 new electric buses have been ordered to be delivered by 2027 and reinforce the zero-emission public fleet of the capital [20].

Another very important sector is Lithuanian rail transportation, which need to transfer from conventional system to an electrified system. Till now, in 2025, a portion of 156 kilometers or some 8 percent of the rail system is electrified. The Ministry of Transport and LTG Group (Lithuanian Railways) however get decision regarding a plan to increase this percentage to 39 in 2030. Here it will involve switching major intercity tracks to electric power and acquiring additional electric and battery-powered multiple units (EMUs), including Škoda and Stadler FLIRT trains [21].

At the same time, the local cities, e.g. Klaipeda, have been leading the localisation of electric buses, e.g. the one named Dancer, in 2020. They are lightweight, easy energy buses, and they are evidence that Lithuania can be good at adopting green innovation on the domestic level [25].

Electrification of personal transport is trendy as well in the future. The government and the construction of charging technologies on the highway and in urban centres offer incentives to buy EVs. However, the Lithuanian Energy Agency said that by 2030, the share of electric vehicles in all registered new vehicles will rise by 15 to 20 percent, compared with less than 3 percent in 2023.

In summary, the future of Lithuania still seems bright in transport electrification, provided there are further investments, political support, and social acceptance. Being supported with strong resources, including the EU programs and the alignment with the international sustainable needs, Lithuania can adopt the role of a leader in the electric mobility moving process.

Forecast of electric vehicle and charging infrastructure development in Lithuania by 2030

Lithuania's electric mobility sector has grown rapidly over the past few years, and this momentum is expected to continue toward 2030. The steady increase in electric vehicle (EV) registrations since 2019 suggests that the market is moving beyond the early adoption phase and entering a period of broader diffusion. By the end of the decade, electric vehicles are likely to become a visible and well-integrated part of the national passenger car fleet [26].

Based on recent growth trends and comparable European experiences, the number of electric passenger cars in Lithuania is projected to reach approximately 150,000–200,000 vehicles by 2030, representing around 15–20% of the total passenger car fleet. This expansion will substantially increase the demand for charging infrastructure, particularly public and semi-public charging points that support users without access to private home charging [26].

To accommodate this growth, charging infrastructure is expected to expand at a similar pace. Applying commonly used planning ratios of 8–12 electric vehicles per public charging point, Lithuania would require a nationwide network of roughly 15,000–20,000 public charging points by 2030. Many of these are likely to be slow and medium power chargers installed in public areas, businesses and residential neighborhoods to meet everyday charging requirements. Meanwhile, the number of fast and ultra-fast chargers is expected to grow sharply along major transport routes and highways to enhance long-distance travel convenience and alleviate range anxiety [26].

When viewed from an energy system perspective, the forecasted EV fleet size could generate around 1.5 - 2.5 TWh of annual demand by 2030. This growth is manageable at an overall national level, but it is expected to have an impact at the local level on distribution networks, especially in residential areas where EV penetration is high. As a result, smart charging solutions and demand management measures are likely to play an increasingly important role in ensuring efficient grid operation [26].

Table 2. Indicative forecast of EV and charging infrastructure development in Lithuania by 2030 [26].

Indicator	**2030 Forecast**
Electric passenger cars	150,000–200,000
Public charging points	15,000–20,000
EVs per public charger	8–12
Annual electricity demand from EVs	1.5–2.5 TWh

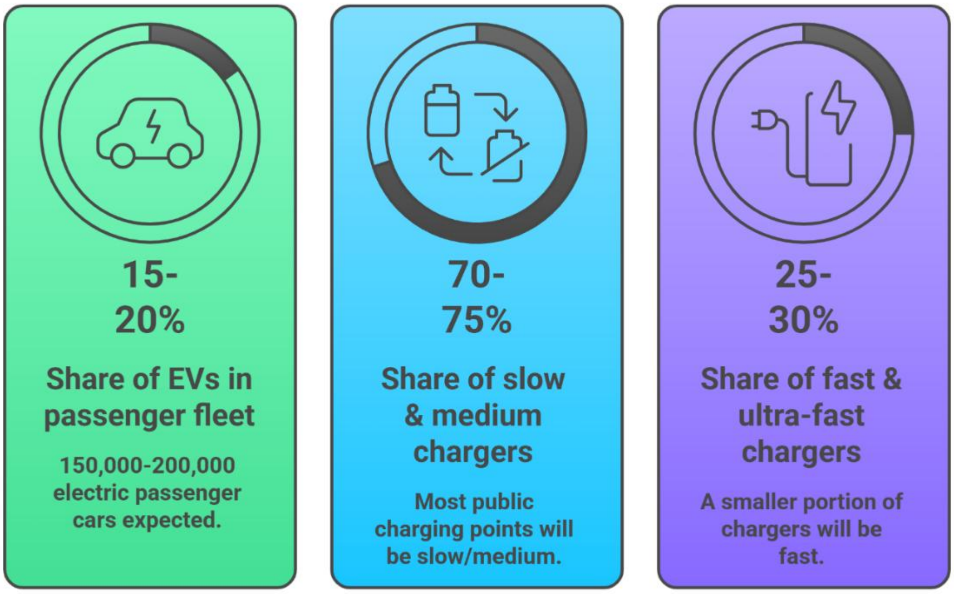


Fig. 3. Charging infrastructure growth [16]

1.4. Potential impacts of electromobility on electricity demand and its daily curves

The growth of electromobility, in general and electric vehicles (EVs), electric buses, and electric trains in particular, will play a major role in shaping the electricity system of countries and regions.. The further electrification of the transport sector presents opportunities and challenges to energy suppliers and grid operators in as much as it presents challenges to policymakers because the overall electricity demand is bound to increase with the addition of the increased demands of electricity by the other industries.

Electromobility initiates a high electricity demand of a new form. To use an example, an average electric car could require something like 15-30 kWh to provide it with one full load of energy, and with thousands or millions of vehicles, there is a new form of loads that is exerting a new strain on the grid. Based on national energy models, the electricity demand will increase by 5 percent to 10 percent in countries like Lithuania in the year 2030 purely due to electromobility depending on the EV adoption rates and the planned time lines of electrification of public transport.

From Figure 4, the daily load curves show that the electricity demand fluctuates between 230 and 300 MW during the night (00:00–05:00) and reaches its peak at night (around 750-760 MW during 20:00–21:00). This is consistent with the usual consumption trend, which is lowest overnight and highest in the evening [27].

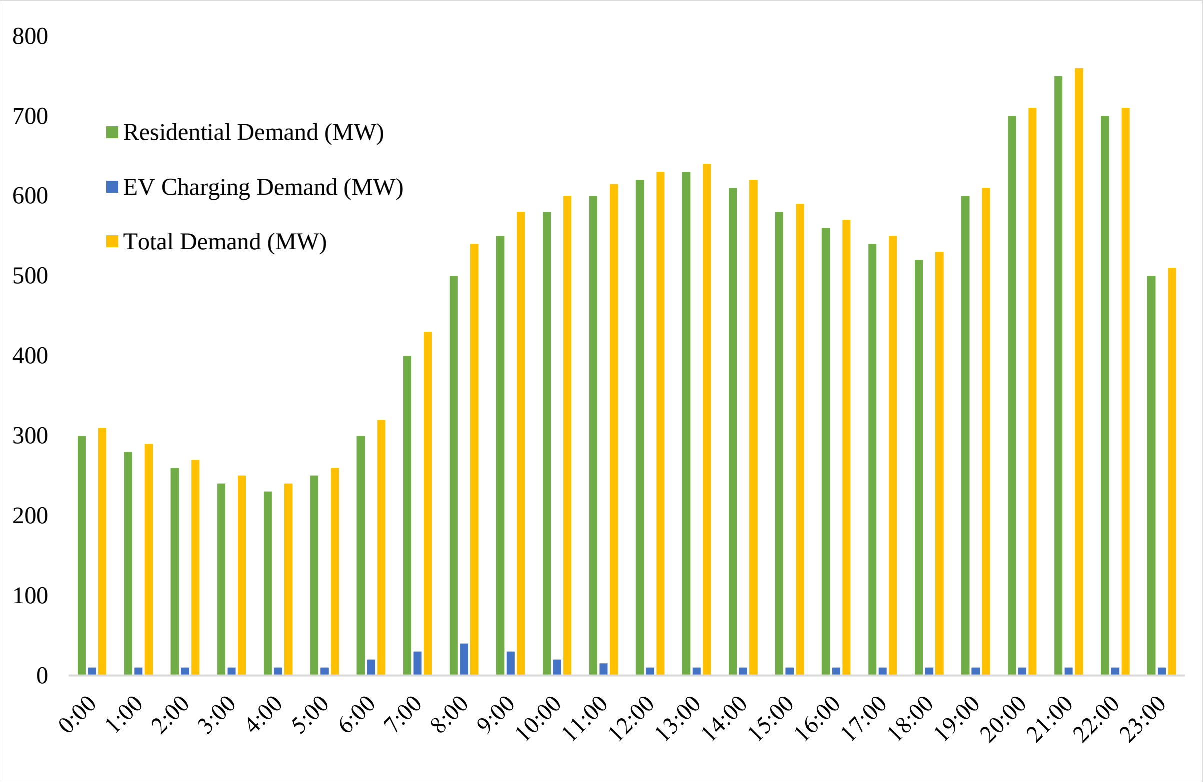


Fig. 4. Daily electricity load curves with and without electric vehicle charging [27]

The demand for electric vehicles (EVs) charging is relatively low, but cannot be ignored, and ranges between 10 MW in most hours to a peak of 40 MW in the morning peak hours around 08:00. The charging demand is high in the late morning hours (09:00 – 12:00) when it is expected to be used for workplace and public charging. In the evening, EV charging stabilizes at around 10 MW, coinciding with the residential peak [27].

Including EV charging demand along with residential demand results in a higher electricity demand for each hour of the day. For instance, at the peak of the evening demand between 20:00 and 21:00, the total demand increases from about 750 MW to 760-770 MW, which equals an increase of 1.3-1.5%. The relative impact is greater during the morning hours: at 08:00, EV charging adds around 540 MW to the total load, up from 500 MW for a 4% increase [27].

Overall, the results show that the adoption of EVs does not significantly change the load demand profiles of the grid, but rather exacerbates the current high-demand periods. While the current impact is manageable at these levels of EV penetration, increased EV penetration is expected to result in increased peak loads, especially in the morning and evening when base electricity demand has already increased. The growing grid load demand stress has raised the importance of smart charging strategies and demand-side management to shift EV loads from peak to off-peak hours, thereby alleviating the load on grid infrastructure and enhancing overall grid stability.

Electricity demand from electric vehicles

Electric cars present a large-scale new source of electricity demand. This demand depends on several parameters like vehicle energy consumption, driving range per year, charging efficiency, and the number of vehicles in a specific region. The range per 100 kilometers of a battery electric car is on average 15-20 kWh [28]. The amount of energy used is dependent on the vehicle size, aerodynamics, conditions, ambient temperature and how the driver drives. Most electric SUVs consume more energy than smaller passenger vehicles, and, of course, driving along highways tends to be more efficient than doing so in cities, due to the fact that travel times to accelerate and decelerate are shorter.

Total energy needs are affected by average driving distances annually. In Lithuania, the average passenger car covers 15,000 kilometers each year. When using standard energy consumption rates, this would correspond to an electricity consumption of about 2,250 to 3,000 kWh/year. This power usage is between 20 and 30 percent of the average Lithuanian household's power usage [27].

Multiplying these individual vehicle needs to projections at the population level, it can be seen that the aggregate impact of electric vehicle adoption is enormous. According to statistics, as of 2024, there are approximately 19,000 electric vehicles in Lithuania, and about 50-60 gigawatt-hours of electricity are consumed in the country annually due to the charging of electric vehicles. This already represents a relatively small fraction of Lithuania's total electricity consumption; however, the scale of any projections of 100,000 or more EVs by 2030 suggests proportionately greater impacts that need to be planned and managed.

The time-varying nature of this electricity demand poses more serious problems than the sheer amount. When many owners of electric vehicles charge at the same time, when the background electricity demand is high, such a load concentration may overload distribution infrastructure and might require expensive upgrades to the system. In contrast, when the charging can be spread over durations of reduced background demand, the incorporation of electric cars is significantly easier in regard to grid operations.

The charging of electric vehicles takes place at residential, workplace, and public charging points. Most of the charging events usually take place at residential locations since owners of the vehicles find it convenient to charge overnight at their own homes. This charging pattern poses particular problems to the residential distribution networks, especially on an evening when the household electricity usage is the highest at the same time as the vehicle charging.

National energy models estimate electricity demand in countries like Lithuania by 5-10 per cent by 2030, solely as a result of electromobility, based on the electric vehicle uptake and the efficiency of the charging management [29]. This growth in demand is on top of other consumption patterns of electricity, such as possible take-up of building electrification (heat pumps) and expanding industrial demand, whilst gains in efficiency in other sectors can offset some growth.

Electric vehicle charging behaviour

Charging infrastructure is a collection of systems and facilities designed to deliver electric energy to the batteries of EVs. The configuration and capabilities of charging infrastructure play a critical role in shaping charging patterns, and their impacts on electricity systems.

Typically, there are various charging systems, according to delivery capacity:

- Level 1 charging uses regular domestic power sockets which supply power at about 2-3 kilowatts. This type of charge takes much longer times (usually 12-24 hours) to charge completely drained battery packs and is adequate in the residential scenarios where vehicles are parked overnight and spend long hours.
- Level 2 charging uses specialized equipment with higher power, typically 7-22 kilowatts. This is the most used residential charging solution, workplace charging and charging in the parking lots. Range (with normal battery electric vehicle) is appropriate for 4-8 hours charging at night or at work place, level 2 charging.
- Dc fast charging (Level 3 charging) will deliver a high power direct current to vehicle batteries, therefore charging vehicle batteries at the level of 50 to 350 kilowatts or faster. Depending on the battery capacity and the capabilities of the charging systems, these systems can only charge vehicles within 20-40 minutes to 80% capacity. Fast charging is mostly used in highway corridor sites as well as in urban quick-charging applications but places more significant direct loads on the electric system.

The distribution of these charges can have a significant effect on the grid. The highest energy of charging occurs at Residential Level 2, but this occurs over a long period of time, which may allow for some control. Fast charging is a small part of the overall charging energy that generates high intensity peak demands requiring high local grid capacity.

Studies on charging behavior show patterns that are dependent on the routines of drivers, patterns of vehicle use and availability of infrastructure. The existing literature on residential charging in different European settings indicates that the initiation of residential charging usually happens when one arrives home in the evening, and that the most significant initiation of residential charging happens between 18:00 and 20:00 [30]. This occurs during a period when the residential consumption of electricity is at its highest point, based on household activities including cooking, heating, and entertainment that make up large electrical loads.

Load impacts

The fast-increasing popularity of electric vehicles (EVs) in Lithuania, the creation of electric bus fleets, and the modernisation of trolleybuses alter the mode of consumption in the country. This section explains how electromobility has an impact on peak load, loading ramps, and essential demands of demand-side management (smart charging) and technology vehicle-to grid (V2G).

Lack of unbalanced charging or dumb charging, especially in the evening hours will increase electricity load at peak times and stress the distribution system. Modelling of the EU cities proves that the EV penetration of 25-50 percent provides the opportunity of increased peak loads of 40-60 percent and will overload the local transformers. Evening charging, both residential and EV, in Lithuania is already overloaded, with the peak load of 30-40MW added in the evening only in Vilnius [27].

There is critical peak ramping due to instantaneous charging (primarily due to the sheer amount of charging devices simultaneously charged) which is not easily alleviated by the grid. Without smart management, generation must be increased at a high rate, hence cost and risk of instability increase in the overall grid system. The installation of smart charging might help to smooth these to a fair extent, according to the pilot programs in Lithuania [31].

Lithuania is doing smart charging to balance the load on the grid:

- Minutely based and time-of-use dynamic pricing encourage off-peak charging, reducing the average entropy duration by 25 percent and evening load [32].
- Remote dynamic load control systems at charging stations e.g., Ignitis management system payments and Fusebox F-DIM, possess remote dynamic load control characteristics, and can actively respond in the system and support grid stability on an instantaneous basis [33]. Smart charging is in line with international best practices, a better valley-filling and minimization of the overload possibilities in comparison with flat-rate systems.

Vehicle-to-Grid (V2G) technology is in its early phases in Lithuania but has great prospects regarding its potential contribution to the country's energy grid and the owners of Electric Vehicles (EV). Grid support is one of the key benefits: V2G-powered electric vehicles can send their reserves to the grid in times of a great deal of electricity consumption, cutting peak loading pressure by up to 24 percent relative to traditional, uncontrolled charging systems [34].

This feature will lead to fewer grid instabilities and the possibility of fewer peak-time generation sources that are very costly and polluting. Economically speaking, V2G systems are estimated to render high financial value in the European environment, with a possibility of providing up to 1,860 euros annually per vehicle, depending on the involvement in the market and its tariffs. Moreover, Lithuania is also making preparatory steps to be technically ready for V2G and shift towards the ISO 15118 standards. The protocol is an essential one, which allows safe and standardized two-way data exchange between EVs and the grid, opening the road to the expansion of safe and secure V2G activities. With further development of the electromobility infrastructure of Lithuania, the introduction of V2G is one of the strategies that have the potential to introduce smarter, more sustainable, and more resilient energy systems.

1.5. Electromobility grid integration challenges and solutions: evidence from EU countries

The rapid growth of electromobility across the European Union has provided valuable real-world experience in understanding how increasing EV adoption affects electricity grids. Countries with higher levels of EV penetration have faced and often successfully managed, key challenges such as rising peak demand, pressure on local distribution networks, fair access to public charging, and the need for smarter grid systems.

This section brings together the most relevant national experiences and highlights practical solutions that could be adapted to support Lithuania's current path toward electrification.

Overview of key grid challenges across EU member states

While the specific nature and severity of grid integration challenges vary across countries depending on the composition of the electricity system, urban structure, and pace of EV adoption, several challenges recur consistently across the EU literature. These are summarized in Table 3.

Table 3. Common electromobility grid integration challenges identified across EU member states

Challenge	**Description**	**Countries Most Affected**
Peak Load Amplification	EV charging coinciding with household evening peaks, driving transformer and feeder overloads	Netherlands [35], Germany [37], Norway [39], [40], France [42]
Uncontrolled (Dumb) Charging	Absence of time-of-use or smart charging protocols is causing concentrated simultaneous demand spikes.	Germany [38], Poland [43], Czech Republic [43]
Distribution Network Capacity	Low-voltage and medium-voltage networks not designed for EV-level load intensification in residential areas	Netherlands [36], Belgium [36], Sweden [39]
Charging Equity and Rural Access	Urban concentration of public charging infrastructure; rural and suburban areas under reserved	France [42], Italy [43], Poland [43], Baltic States [44]
Renewable Integration Mismatch	EV charging demand peaking in evenings while solar generation peaks midday, creating supply-demand misalignment	Germany [38], Spain [43], Italy [43]
Flexibility and V2G Readiness	Grid and regulatory frameworks not yet adapted to enable large-scale bidirectional V2G energy flows	Most EU member states [43]
Grid Data and Monitoring Gaps	Insufficient real-time data from distribution networks to manage dynamic EV loads effectively	Central and Eastern EU Member States [45], [46]

The literature review revealed several critical challenges associated with electromobility grid integration, including peak load amplification, uncontrolled (or "dumb") charging behaviours, distribution network capacity constraints, charging equity and rural accessibility gaps, renewable energy integration mismatches, vehicle-to-grid (V2G) readiness limitations, and deficiencies in grid data and monitoring infrastructure.

Given Lithuania's rapidly growing electric vehicle (EV) adoption, this study narrows its analytical focus to two interconnected challenges: peak load amplification and uncontrolled charging. These two issues were not chosen randomly. They were selected because most of the literature reviewed identifies them as the main underlying challenges that lead to many of the wider grid integration problems. Addressing these challenges is therefore not only pertinent to Lithuania's current energy landscape but may also offer a basis for understanding systemic vulnerabilities that other rapidly electrifying nations are likely to encounter.

The netherlands: managing high EV penetration through smart charging and grid reinforcement

The Netherlands is one of the most advanced EU member states in terms of EV adoption, with over 500,000 electric passenger vehicles registered by 2023 and one of the highest EV market shares in Europe. This rapid adoption has exposed significant distribution network stress, particularly in densely populated urban areas such as Amsterdam, Rotterdam, and Utrecht, where residential transformer overloads became an increasingly frequent problem from 2020 onwards [35].

Table 4. Case study: netherlands - high-density urban EV charging management

Challenge:

By 2022, approximately 30% of low-voltage transformers in the Amsterdam metropolitan area were operating at or near capacity during evening peak periods, driven by the simultaneous activation of home EV chargers between 18:00 and 21:00. Netbeheer Nederland (the national grid operators association) estimated that uncontrolled EV charging growth could necessitate €10–15 billion in grid reinforcement costs by 2030 if not addressed through demand management [35].

Solutions Implemented:

1. National Smart Charging Framework: The Netherlands introduced mandatory smart charging readiness requirements for all new public and private EV chargers from 2023, ensuring that all newly installed units are technically capable of receiving load management signals.
2. Dynamic Load Balancing (DLB): Dynamic Load Balancing is a way to manage energy use in homes. It helps residential charging systems work with home energy management systems. This means they can respond to changes in energy prices sent by grid operators. When energy is cheaper, usually at night or early morning, the system shifts charging to those times. This is because there's more room on the transformers then, so it's a good time to charge things like electric cars..
3. Public Charging Obligation Policy: Municipalities must make sure people can charge their electric vehicles in public spots near their homes. This means there should be a public charging point within 250 meters of where an electric vehicle owner lives. This helps reduce the strain on local transformers that can happen when lots of people charge their vehicles at home without any control.
4. Grid Investment Prioritization: Netbeheer Nederland published a national grid investment plan directing accelerated reinforcement of distribution networks in highhEV-density postcodes, based on real-time data from smart meter rollouts. rollouts.
5. Congestiemanagement Protocols: Formal grid congestion management protocols were to manage congestion, special rules were put in place. These rules allow the people in charge of the power distribution system to temporarily stop electric vehicle charging in areas where the network is congested. This way, they can make sure that essential household loads, like the power needed for homes, get priority.

Germany: integrating EV demand with renewable energy surpluses

Germany's Energiewende (energy transition) policy has created a dual challenge: the country simultaneously manages one of the largest EV fleets in the EU and a high-penetration renewable energy system characterized by strong midday solar surpluses and significant evening demand-supply mismatches. As of 2023, Germany had approximately 1.4 million registered electric vehicles, with growth accelerating sharply following the introduction of enhanced purchase incentives [37].

Table 5. Case study: Germany - aligning EV charging with renewable generation profiles

Challenge: Germany's high solar PV penetration creates a pronounced midday generation surplus (the so-called 'duck curve' phenomenon) while EV charging demand peaks in the early evening, when solar output has already declined. This temporal mismatch results in EV charging being partly met by dispatchable fossil generation in the evening rather than the available surplus renewable electricity midday. Studies by the Fraunhofer Institute for Solar Energy Systems estimated that without demand shifting, 35–40% of all German EV charging energy in 2030 would be sourced from carbon-emitting generation during evening hours [37].
Solutions Implemented: 1. Variable Renewable Energy (VRE) Tariffs for EV Charging: German grid operators introduced time-variable grid use-of-system tariffs specifically for EV charging points, providing strong price signals to shift demand to periods of high renewable availability, particularly midday. 2. Bidirectional Charging Pilots (V2G and V2H): Multiple pilot programmes - including the Volkswagen and Eon 'V2G Ready' project in Wolfsburg and the BMW Charge Forward programme — demonstrated that EVs equipped with bidirectional chargers can absorb surplus renewable energy midday and return power to the grid in the evening, reducing both grid costs and emissions. 3. Digital Smart Charging Platform (SMARD): The Federal Network Agency (Bundesnetzagentur) expanded its SMARD grid management platform to incorporate EV load forecasting and real-time demand flexibility coordination between DSOs and charging network operators. 4. Integration of EV Charging into Renewable Energy Community Schemes: Under the revised Renewable Energy Sources Act (EEG 2023), EV charging points co-located with solar installations receive preferential grid access conditions and reduced network charges, incentivising solar self-consumption via EV batteries. 5. Standardisation of Bidirectional Communication: Germany adopted ISO 15118 as the national standard for EV-grid communication, enabling automated smart charging responses and V2G functionality across all compliant charger-vehicle pairs.

Norway: system-level management of mass EV adoption

Norway is the world's most successful country in terms of mass EV adoption, having sold more than 80% of its new passenger cars by 2023, and having reached an EV fleet of roughly 700,000 vehicles. The full scale consequences of comprehensive electrification of the grid and the management strategies needed to ensure system stability with very high levels of penetration are only known to the Norwegian experience. [39].

Table 6. Case study: Norway - system-level grid management at mass EV penetration

Challenge: The transition to mass EV adoption in Norway from 2015 onwards caused considerable pressure on the distribution network, especially in urban municipalities like Oslo, Bergen and Stavanger. By 2020, local feeder peak load growth rates of 40–60% were observed in the highest EV penetration areas by Statnett (the Norwegian transmission system operator). The cost of the unplanned reinforcement of the grid was estimated

to be NOK 8–12 billion (around €700M–€1B) until 2022 – a significant amount of money that is in addition to the first cost estimates. [39].
Solutions Implemented: 1. Mandatory Smart Charging Law (2021): One of the first such legal requirements in Europe, Norway has installed legislation that mandates all new EV chargers above 3.7 kW to include smart charging and remote load management (RLM) compatibility. 2. Aggregator-Based Demand Flexibility: Norwegian energy aggregators (e.g., Tibber, Fortum Charge and Drive) formulated consumer-facing platforms that were able to consistently shift off-peak demand by using real-time spot market price information from the Nord Pool exchange. 3. Distribution tariff reform (Effektariff): Norway changed its distribution network tariff for residential customers from a flat-rate tariff to a capacity-based (power-based) tariff in 2022. This incentivises spreading loads, including EV charging, over time instead of focusing on peak periods. 4. Grid Reinforcement Acceleration Fund: A dedicated investment fund to speed up distribution network reinforcement in municipalities with high EV-penetration rates, with a focus on areas with several apartment blocks with no provision for charging in private blocks. 5. (vi) EV Charging in Multi-Unit Residential Buildings: Norwegian authorities imposed it, and it has helped to de-concentrate charging demand on the individual transformer to a large extent

France: public charging infrastructure equity and territorial planning

France has set itself an ambitious electromobility policy through the LOM (Loi d'Orientations des Mobilités) and the accompanying urban vehicle access policies (ZFE). As of the end of 2023, there were about 1.1 million registered EVs (EVs) in France and the public charging network continues to grow rapidly, with important lessons to be drawn from public charging network planning, territorial equity and the management of concentrated charging demand in mixed urban-rural geographies. [41].

Table 7. Case study: France - public charging equity and grid-aware infrastructure planning

Challenge: France was also highly geographically unbalanced in terms of the public charging network: in 2021, some 70% of all public charging stations (PCS) were located in the Ile-de-France (Paris) region and major metropolitan areas, whereas large parts of rural France, especially the Massif Central, Brittany and Normandy, had very little coverage in terms of public chargers. This spatial disparity made the adoption of EVs much more difficult across the country and served as a constant obstacle for rural consumers, contributing to range anxiety. At the same time, the development of urban fast charging hubs in Paris started to create substantial localized peak demands, which needed to be addressed by the grids' capacity planning [41].
Solutions Implemented: 1. National Charging Infrastructure Master Plan (ADVENIR Programme): The French government broadened the scope of its public incentive programme (ADVENIR) to include subsidies for the deployment of charging infrastructure not only in urban areas but particularly in motorway service areas and multi-unit residential buildings (MURB) in underserved areas located in rural communes - with geographic equity as a priority.. 2. Grid - Aware Charging Hub Siting: Réseau de Transport d'Electricité (RTE, the French TSO) has implemented mandatory grid impact assessments for all new charging hubs (above 150 kW) to ensure that charging hubs are sited where there is adequate grid capacity, not just commercial site selection. 3. Virtual Power Plant (VPP) Integration of Public Chargers: Pilot initiatives co-ordinated by Enedis (French DSO) showed that networked public chargers could be included as virtual power plant assets, which could offer services of grid frequency response and demand flexibility support in return for lower network connection fees. 4. Territorial Electromobility Plans (Plans de mobilité): Territorial and departmental authorities had to develop territorial electromobility plans that were able to coordinate infrastructure placement with

land use planning, transport network data and maps of the DSO grid capacity, which was more of a system-level approach than site-by-site approvals. 5. EV Charging in Low-Emission Zones (ZFE): Low emission zone (ZFE) urban access restriction policies were integrated with guaranteed public charging access requirements, ensuring that residents of multi-unit buildings without private parking will not be disadvantaged by low emission zone vehicle policies.

Estonia and Latvia: Baltic regional coordination lessons for Lithuania

As Baltic neighbours sharing broadly comparable grid structures, economic contexts, and EV adoption trajectories, Estonia and Latvia provide particularly relevant comparative evidence for Lithuania. Both countries are connected to the same BRELL power ring (Baltic Ring) and face the shared strategic challenge of desynchronisation from the Russian-controlled IPS/UPS power system and synchronisation with the Continental European Network, expected by 2025. This energy system transition context directly shapes the grid integration challenges and solutions being developed in all three Baltic states [43].

Table 8. Case study: Estonia and Latvia - Baltic grid context and coordinated EV integration

Challenge: The EV market share in Estonia was in the top tier of Central and Eastern Europe by 2022 due in part to its early public investment in the nationwide public charging network launched in 2013 (ELMO network). However, rapid EV adoption in Tallinn's residential areas created localised distribution network overloads analogous to those emerging in Vilnius. Latvia, facing a slower EV uptake, confronted the complementary challenge of how to build charging infrastructure efficiently in anticipation of demand rather than reactively in response to grid stress [43][44].
Solutions Implemented: 1. ELMO Network (Estonia): This is the national EV charging network in Estonia, which is managed by the Estonian TSO Elering. The network has created a grid-co-ordinated fast-charging corridor, with a fast charger less than 50 km away from any point on the national territory. All ELMO chargers are fitted with the demand management software which is connected to Elering's grid monitoring systems. 2. Baltic Energy Market Interconnection Plan (BEMIP): Co-ordination and development of cross-border EV charging corridors under the BEMIP framework, with consistent standards and co-ordination of the grid, which is crucial for facilitating cross-border EV travel in the Baltic region. 3. Estonian Smart Grid Roadmap: Elering released a Smart Grid Roadmap which explicitly includes EV load forecasting in the national grid planning process and models the growth of EV loads in real time on the ELMO charging network, thus enabling priorities for network reinforcement to be identified proactively. 4. Latvian DSO Monitoring and Preemptive Reinforcement: Latvijas Elektriskie Tikli (the Latvian DSO) created a methodology for the grid vulnerability assessment to allow for preemptive investments in reinforcement of the distribution network before it is required due to a grid stress event, based on its vulnerability to EV adoption growth. 5. Joint Baltic TSO Coordination for Desynchronisation: With Baltic grid desynchronisation from the BRELL ring and synchronisation with ENTSO-E planned, all three TSOs are co-ordinating smart charging systems with frequency regulation requirements of the Continental European Network, ensuring that EV flexibility resources can contribute to grid stability post-synchronisation.

Cross-country comparative analysis and lessons for Lithuania

The preceding country case studies collectively demonstrate that the grid integration challenges associated with electromobility are well-understood, consistent in character, and - critically - technically and economically solvable through combinations of regulatory reform, infrastructure planning, and smart technology deployment. Table 9 synthesizes the principal solutions implemented across the reviewed member states and their assessed applicability to Lithuania's current and projected electromobility context.

Table 9. Cross-EU solutions to electromobility grid challenges and applicability to Lithuania

Solution Type	**Country Example**	**Key Mechanism**	**Lithuania Applicability**
Mandatory Smart Charging Standards	Netherlands, Norway	Legal requirement for remote load management capability on all new chargers above threshold power level	HIGH - regulatory template available via EU Directive 2023/2413 transposition
Capacity-Based Distribution Tariff	Norway	Power-based network tariff replacing flat-rate, creating financial incentive for load spreading	HIGH - Lithuanian flat-rate tariff reform could deliver immediate grid benefits
Grid-Aware Charging Hub Siting	France	Mandatory DSO grid assessment for new fast-charging installations; co-ordination with territorial plans	HIGH - applicable to Vilnius/Kaunas fast-charging expansion
Renewable-Aligned Time-Variable Tariffs	Germany	EV-specific variable grid tariffs signalling renewable surplus periods for preferential charging	MEDIUM-HIGH - increasing as Lithuanian renewable capacity grows post-2025
V2G Pilot Programmes	Germany, Netherlands	Bidirectional charger pilots with ISO 15118; grid frequency regulation and peak demand services	MEDIUM - preparatory technical and regulatory groundwork underway in Lithuania
Nationwide Charging Corridor Planning	Estonia (ELMO)	Grid-co-ordinated national fast-charging network ensuring territorial coverage within 50 km	HIGH - directly transferable model for Lithuanian highway and regional corridor development
Demand Aggregation Platforms	Norway (Tibber, Fortum)	Consumer-facing platforms automating off-peak charging based on real-time electricity spot prices	MEDIUM - expanding real-time electricity market access required
Preemptive DSO Network Reinforcement	Latvia	Grid vulnerability mapping and proactive investment ahead of EV adoption stress events	HIGH - Lithuanian DSO ESO can adopt the Latvian vulnerability assessment methodology
Virtual Power Plant Integration	France	Public chargers enrolled as VPP assets providing frequency response and demand flexibility services	MEDIUM - technically feasible; regulatory framework for VPP participation needs development
Territorial Electromobility Plans	France	Regional plans co-ordinating charging placement with land use, transport data, and DSO capacity	HIGH - Lithuanian National Energy and Climate Plan could incorporate territorial EV planning module

Synthesis: Implications for Lithuania's grid integration strategy

The data provided in this section across the European Union has identified a set of common findings relevant for Lithuania's electromobility and grid planning programmes. The lessons learned from the Netherlands, Norway and Germany show that unmanaged high penetration of

EVs will inevitably lead to distribution network stress, which is technically disruptive and economically unfeasible if not managed proactively. Current EV use in Lithuania is relatively low, at roughly 19,000 vehicles in 2024, but the pace of increase is expected to hit 150,000–200,000 vehicles by 2030, making the window for proactively influencing this trend by regulation and infrastructure somewhat short.

Second, the most effective EU measures always include three complementary measures: (i) regulatory measures aimed at the deployment of smart charging technology; (ii) economic measures, such as tariff reform, that incentivise consumer and operator to better shift their demand; and (iii) spatial planning measures that co-ordinate the location of charging stations with data on grid capacity and ensure that demand growth systematically doesn't focus on network-vulnerable areas.

Third, there are pre-existing, direct precedents in the Baltic regional context: as exemplified by the Estonian ELMO network and the Latvian preemptive reinforcement model, geographically near and directly comparable precedents are available in the Baltic region which are relevant to Lithuania. The desynchronisation of the Baltic grid from the BRELL ring and the planned synchronisation with the Continental European Network by 2025 is both a challenge and an opportunity: if the regulatory and technical prerequisites are put in place beforehand, EV smart charging and V2G flexibility resources have the potential to proactively assist grid frequency regulation during and after the synchronisation process, which is technically challenging.

Key policy recommendations derived from EU country evidence

1. Ensure all new EV charging systems installed over 7 kW must be ‘smart charging ready' (as is in the Netherlands and Norway) to transpose EU Directive 2023/2413 into national regulation as a priority.
2. Implement EV load spreading incentives (based on Norway's Effekttariff model), with direct financial incentives for load spreading.
3. Prepare a national master plan for EV charging infrastructure, including DSO grid capacity data, territorial equity goals and renewable grid profiles (as done in France, through a territorial planning approach).
4. Implement the Estonian ELMO model for creating a lithium fast charging corridor with a maximum 50 km coverage on the whole Lithuanian territory, with grid-coordinated demand management software at all the chargers.
5. Commission a national DSO grid vulnerability assessment (based on Latvian methodology) to determine DSO distribution network segments most likely to be affected by the growth of EV adoption in the near term.
6. Start V2G pilots together with EV manufacturers, fleet operators and Litgrid in the light of the existing V2G pilot structures in Germany and the Netherlands and to make use of the current standardisation of V2G under ISO 15118.
7. Coordinate with Elering (Estonia) and Latvijas Elektriskie Tikli (Latvia) the implementation of a Baltic regional smart charging co-ordination protocol, which is consistent across borders, before ENTSO-E grid synchronisation under the BEMIP framework.

To summarise, the evidence presented across the EU in this section indicates that the challenges to integration of the grid with electromobility in Lithuania are not exceptional and certainly not untacklable. The solutions rolled out in the Netherlands, Germany, Norway, France, Estonia, and Latvia constitute a proven toolkit of regulatory, economic, and technical solutions – adapted to Lithuania's conditions of the energy system and energy market can help to fulfil the country's 2030 electrification goals without disproportionate investments in reactive energy infrastructure.

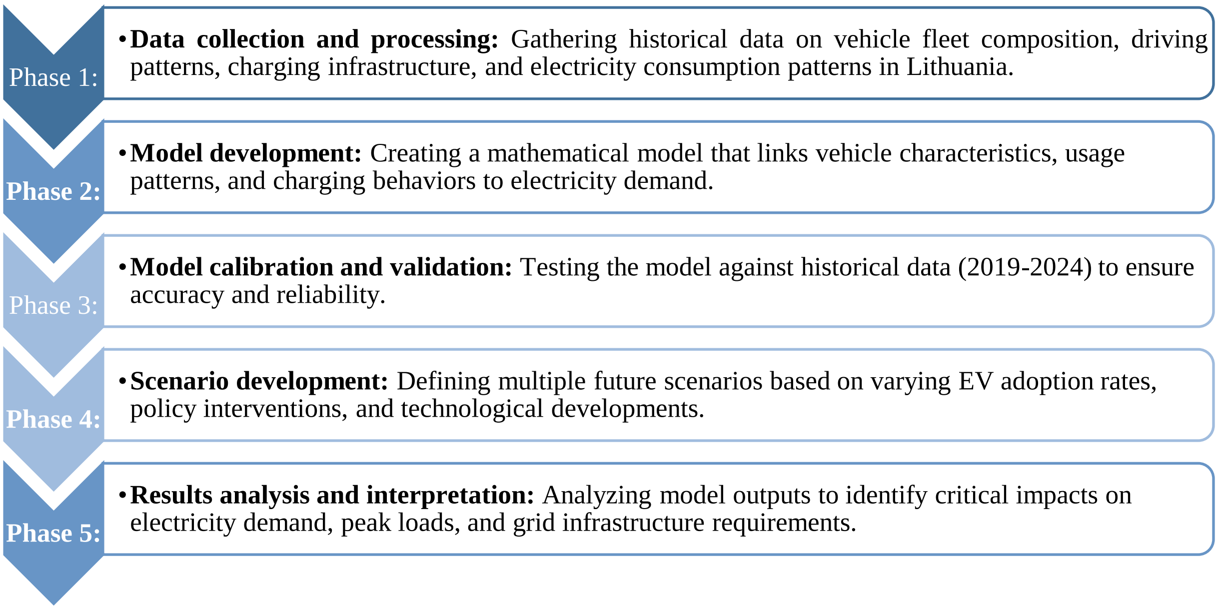
2. Methodology (scenario-based electromobility demand modelling framework)

The methodology chapter presents a systematic approach used to analyses the impact of the rise of electro-mobility on electricity demand in Lithuania. From the literature review, it was observed that although the EV market is growing rapidly, it is still facing major difficulties regarding electricity grid operations, therefore, this work constructs a quantitative model to analyze future electricity demand patterns [46].

This is the main research question: What will the changes in electricity demand in Lithuania look like by 2030 and 2040, taking into account the projected growth of electro-mobility, especially the electricity demand peaks and load curves? The methodology fills the gap in the literature identified in the literature review: there exists qualitative projections of the number of EVs being adopted in the market and a discussion of potential impacts of EVs on the grid; however, there is no detailed, Lithuania-specific quantitative analysis that considers multiple vehicle types, charging behaviors, and temporal demand patterns in a comprehensive electricity demand model [47]. The methodology aims at being replicable, reproducible, transparent and grounded on the existing modeling practices in the energy systems analysis literature and specifically adapted to the Lithuanian context and data availability.

2.1. Research framework and approach

This research employs a quantitative modelling approach combined with scenario analysis to project the impact of electromobility on electricity demand. The methodology consists of five interconnected phases [48]:



Phase 1:
- **Data collection and processing:** Gathering historical data on vehicle fleet composition, driving patterns, charging infrastructure, and electricity consumption patterns in Lithuania.

Phase 2:
- **Model development:** Creating a mathematical model that links vehicle characteristics, usage patterns, and charging behaviors to electricity demand.

Phase 3:
- **Model calibration and validation:** Testing the model against historical data (2019-2024) to ensure accuracy and reliability.

Phase 4:
- **Scenario development:** Defining multiple future scenarios based on varying EV adoption rates, policy interventions, and technological developments.

Phase 5:
- **Results analysis and interpretation:** Analyzing model outputs to identify critical impacts on electricity demand, peak loads, and grid infrastructure requirements.

2.2. Data collection and sources

Primary data categories

The primary data has been grouped into a few important categories to analyze the vehicle fleet characteristics and trends of vehicle electrification. The analysis is conducted by using historical vehicle registration information for the years of 2019-2024.

Vehicle fleet data cover the total number of registered vehicles, broken down by vehicle type (passenger cars, buses, light commercial vehicles and heavy-duty trucks). Moreover, the dataset categorises electric vehicles based on their drive technology, such as Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs) and Fuel Cell Electric Vehicles (FCEVs). For reference, Hybrid Electric Vehicles are included but not the subject of the analysis.

Other factors are geographic distribution of vehicles, urban or rural. These data categories allow for a detailed characterisation of the fleet composition and spatial distribution for transport electrification. The information was sourced from trusted national and European authorities, such as the Lithuanian Road Administration [15] and the Ministry of Transport and Communications [23] to guarantee reliability and consistency of the data.

Table 10. Summary of data categories and sources used in the study

Data Category	**Key Variables / Indicators**	**Purpose in the Study**	**Primary Data Sources**
Vehicle Fleet Characteristics	Total registered vehicles, Vehicle types (passenger cars, buses, LCVs, HDVs), Propulsion types (BEV, PHEV, HEV*, FCEV), Urban vs. rural distribution	Analysis of fleet composition, electrification trends, and spatial distribution of vehicles (HEVs included for reference only)	[15], [16], [23]
Vehicle Usage Patterns	Average annual mileage (km/year) Daily driving distance distribution Urban vs. highway driving shares	Characterisation of real-world vehicle usage and travel demand to support energy consumption and demand modelling.	[49],[50], [51]
Vehicle Energy Consumption	Energy consumption (kWh/100 km) Variations by vehicle type, size, and weight, Seasonal effects on efficiency	Estimation of electricity demand from vehicle electrification and assessment of operational efficiency	[31], [33], [52]
Charging Behaviour	Charging start times, Charging duration distributions, Charging location preferences (home, public, workplace), Seasonal variations	Modelling of charging demand profiles and temporal load atterns	[31], [33], [53]
Electricity Demand Profiles	Hourly electricity demand, Seasonal variations, Weekday vs. weekend patterns, Regional demand differences	Assessment of baseline electricity demand and integration of EV charging loads	[54], [55]

Vehicle usage patterns

These data on annual driving distances are used to describe vehicle usage patterns and to evaluate transport demand and vehicle performance. These data give an indication of real-world vehicle category use.

Table 11 and Figure 5, disaggregated by type of vehicle, are included in the analysis to show the average number of kilometers driven per year. Moreover, the distribution of day's driving distances is studied to account for the inter-trip variability in travel behavior, and to determine typical distances of a day's trip.

Specific consideration is given to the difference between urban and highway driving patterns and how these affect vehicle efficiency, energy usage, and appropriate alternative power train technologies.

Table 11. Annual and daily driving distance characteristics by vehicle type

Vehicle Category	**Avg. Annual Distance (km/year)**	**Avg. Daily Distance (km/day)**	**Typical Daily Distance Range (km)**	**Urban Share (%)**	**Highway Share (%)**
Passenger Cars (ICE)	9,000	25	5–75	60	40
Passenger Cars (BEV)	10,000	27	5–85	65	35
Passenger Cars (PHEV)	11,000	30	5–90	55	45
Light Commercial Vehicles (ICE Vans)	12,000	33	10–100	45	55
Light Commercial Vehicles (Electric Vans)	13,000	35	10–110	50	50
Heavy Duty Trucks (Diesel)	40,000	110	30–200	15	85
Heavy Duty Trucks (Electric / eHGV)	25,000	68	20–150	25	75
Buses / Coaches (ICE)	25,000	68	20–140	75	25
Electric Buses (City Transit)	30,000	82	20–150	80	20
Motorcycles / Mopeds (ICE)	3,500	10	3–40	80	20
Electric Two-Wheelers	4,000	11	3–45	85	15
Electric Trains (Commuter/Regional)	70,000	190	50–300	20	80

The data used in this section are obtained from reliable national and European sources, including the Lithuanian Department of Statistics [78], the European Automobile Manufacturers Association (ACEA) [79], and national transportation surveys [50], and [51].

Vehicle Energy Consumption

Table 12 provides vehicle energy consumption data to quantify the operational energy efficiency of EVs and as a basis for estimating electricity demand for fleet electrification. Energy efficiency is measured in kilowatt hours per 100 kilometers (kWh/100 km) and compared between different EVs models and classes. The analysis considers the energy usage difference associated with vehicle size, vehicle curb weight, and vehicle type. They are included to take into account the diversity of vehicle performance and to make consumption estimates more representative. Seasonal variations in energy use are also explored to account for the effect of the ambient temperature and auxiliary modes of energy use on vehicle efficiency.

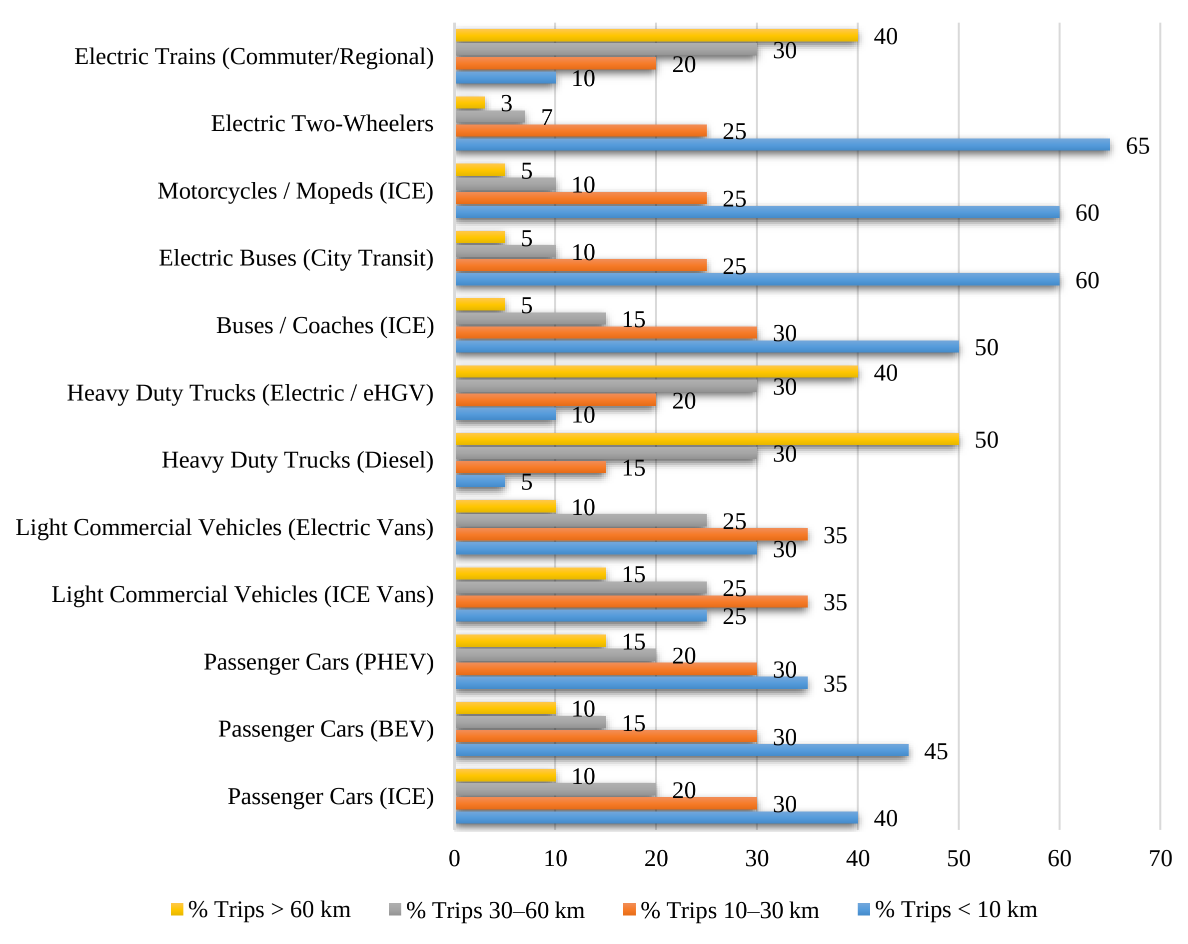


Fig. 5. Distribution of daily trip distances by vehicle type

The data used for this analysis come from several sources, such as vehicle manufacturer specifications, test results from the European Environment Agency (EEA) [80] and from the real operational data of operators of charging infrastructure, like Ignitis [81] and City Bee [82]. Multiple data sources improve the strength of the energy consumption estimates and provide a cross validation between standardized test results and observed patterns of energy consumption [31], [33] and [52].

Table 12. Energy consumption characteristics of electric vehicles (kWh/100 km)

Vehicle Category	**Example EV Model (Representative)**	**Curb Weight (kg)**	**Battery Capacity (kWh)**	**Real-World Consumption (Summer) (kWh/100 km)**	**Real-World Consumption (Winter) (kWh/100 km)**
Small Passenger BEV	Nissan Leaf (40 kWh)	1,580	40	15.5	20.5
Mid-size Passenger BEV	Tesla Model 3	1,750	60	14.0	18.5
Large Passenger BEV (SUV)	Hyundai Ioniq 5	2,000	72	17.0	23.0
Premium SUV BEV	Audi e-tron	2,500	95	23.0	30.5

Light Commercial EV (Van)	Renault Kangoo E-Tech	1,750	45	19.0	26.0
Light Commercial EV (Van)	Mercedes eSprinter	2,400	55	25.0	33.0
Electric City Bus	Solaris Urbino Electric	13,500	300	110	140
Electric Intercity Coach	BYD Electric Coach	15,000	350	95	125
Electric Two-Wheeler	NIU NQi / Similar	120	2.0	3.5	4.2
Electric Rail (Commuter Train)	Electric Multiple Unit (EMU)	—	—	8–15 (kWh/km)*	10–20 (kWh/km)*

**Note: Train energy use is usually reported as kWh per km, not kWh/100 km.*

Electricity system data

This study analyzes electricity demand patterns in Lithuania using detailed temporal and spatial data are presented in figure 6. The demand analysis is based on hourly electricity consumption data for the period 2019–2024, allowing for the identification of short-term and long-term trends. Particular attention is given to seasonal variations, capturing differences between winter and summer demand driven by heating, lighting, and cooling requirements. Additionally, weekday and weekend demand patterns are examined to reflect variations in residential, commercial, and industrial electricity use. Where data availability permits, regional variations in electricity demand are also considered to highlight spatial differences across the Lithuanian power system.

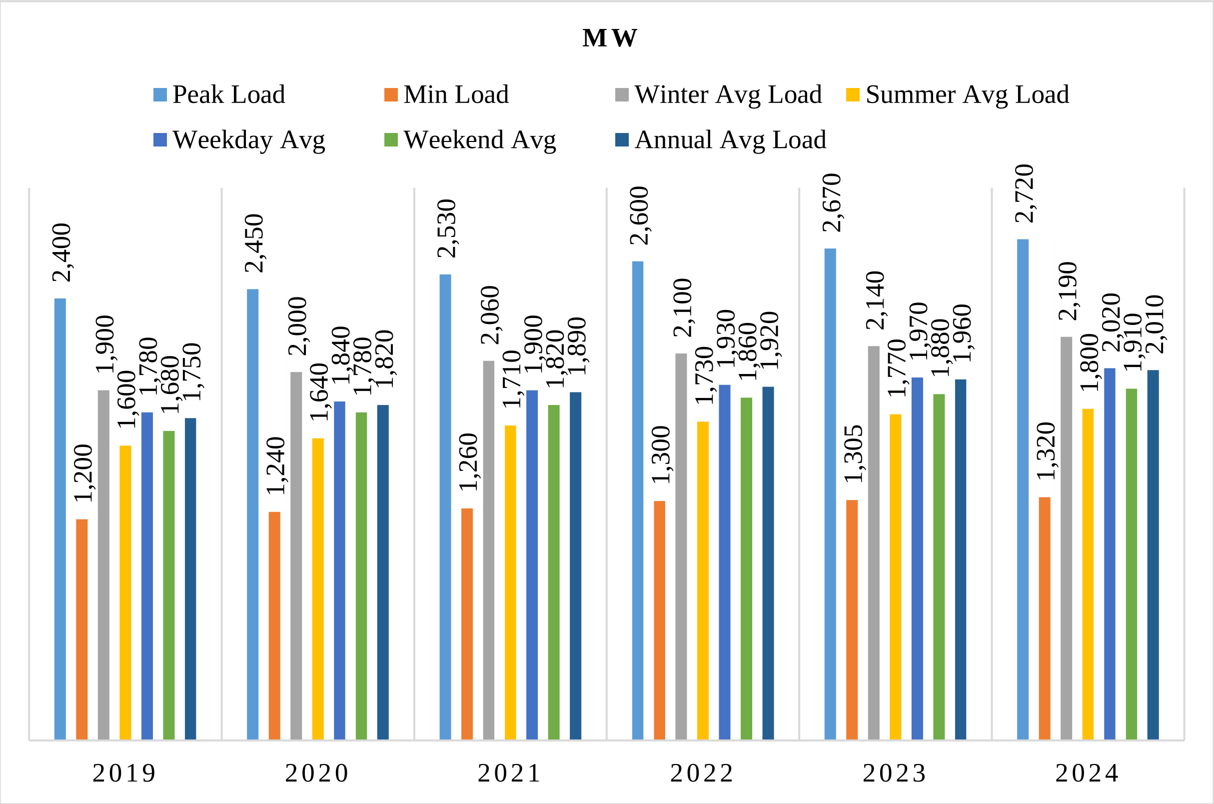


Fig. 6. Lithuania electricity system demand data (2019–2024)

The analysis draws on authoritative and publicly available data sources, including Litgrid, the Lithuanian Transmission System Operator (TSO), and ESO (Elektros Skirstymo Operatorius), the national Distribution System Operator (DSO). Supplementary data are obtained from the Lithuanian Energy Agency, providing national energy statistics and analytical reports, as well as the ENTSO-E Transparency Platform, which offers harmonized European-level electricity system data. [54], [55].

2.3. Mathematical model development

The methodological approach adopted in this study is rooted in the tradition of systems modelling applied to energy demand analysis, a well-established paradigm in the energy economics and power systems literature [56], [57], [58]. By decomposing total EV-attributable electricity demand into its constituent structural drivers fleet size, vehicle utilization, energy consumption intensity, and charging behavior - the model achieves both analytical transparency and practical replicability. The scenario analysis framework draws on the exploratory scenario methodology advocated by the International Energy Agency [59] and the European Commission's Joint Research Centre [60], ensuring that projections are grounded in coherent, internally consistent assumptions rather than arbitrary extrapolation.

The mathematical model developed in this study is designed to quantify, with temporal resolution, the additional electricity demand imposed on the Lithuanian national grid by an expanding electric vehicle fleet. The model is structured around three hierarchically linked sub-modules: (i) a vehicle stock projection module, which estimates the size and composition of the EV fleet in each projection year; (ii) an energy consumption calculation module, which translates fleet size into total annual electricity consumed through charging; and (iii) a temporal load profile module, which distributes annual electricity consumption across the 8,760 hours of the year in accordance with empirically observed and modelled charging behavior patterns. The following sub-sections describe each module in detail, together with the associated parametric assumptions, data sources, and mathematical formulations.

Vehicle stock projection module

The projection of the electric vehicle fleet is arguably the most consequential and uncertain element of the model, as EV adoption dynamics are governed by a complex interaction of consumer preferences, technology cost trajectories, policy incentives, and charging infrastructure availability [63], [64]. In this study, EV fleet growth is modelled using a logistic (S-curve) diffusion function, which has been extensively validated as an appropriate representation of the adoption lifecycle of disruptive technologies in both the energy technology literature [65] and EV-specific modelling studies [59], [66]. The logistic function captures three empirically observed phases: a period of slow initial diffusion, a phase of accelerating adoption as technology costs decline and social norms shift, and a phase of decelerating growth as market saturation

The number of registered EVs of vehicle category i in year t is modelled as:

$$\mathrm{N_i(t)} = \frac{\mathrm{K_i}}{\left[1+e^{\left(-r_i \, x \left(t-t_{o,i}\right)\right)}\right]} \qquad \ldots(1)$$

In this expression, K_i represents the theoretical market saturation level (carrying capacity) for vehicle category *i*, expressed as an absolute number of registered vehicles and determined as a scenario-specific share of the total projected vehicle fleet; r_i is the intrinsic growth rate parameter, calibrated from Lithuanian EV registration time series data spanning 2018–2024, as published by the Lithuanian Road Administration (LAKD); and $t_{0,i}$ is the inflection year - the point at which the rate of adoption is at its maximum, corresponding to the midpoint of the S-curve. The growth rate parameter r_i and the inflection year $t_{0,i}$ are estimated through nonlinear least-squares fitting of equation (1) to the observed registration data for each vehicle category, using the Levenberg–Marquardt optimisation algorithm. Parameters for PHEVs, Electric Buses, and eLCVs, where Lithuanian historical data are limited, are supplemented with analogous calibrated values from Estonia and Latvia - countries with comparable regulatory environments and socioeconomic structures - following the precedent established in the Baltic energy modelling literature [67].

Energy consumption rate parameterization

The model operates at the level of the national energy system and projects EV-attributable electricity demand across the period 2024–2040, with annual resolution. Four vehicle categories are distinguished: Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Electric Buses, and Electric Light Commercial Vehicles (eLCVs). This disaggregation is motivated by the significant heterogeneity in energy consumption rates, annual mileage profiles, and charging behavior across these vehicle classes, as documented in the European Environment Agency's annual EV monitoring reports [61]. The general formulation of aggregate annual additional electricity demand from electromobility in projection year *t* is expressed as the following summation across vehicle categories:

$$\mathrm{DEV_{(t)}} = \textstyle\sum_{i}[\mathrm{Ni_{(t)}} \text{ x VKTi x ECi x } \left({}^{1}/_{\eta i}\right) \text{ x LFi}] \qquad \ldots (2)$$

where DEV(t) indicates the total additional annual electricity demand due to EV transport in year t (GWh/year); $N_i(t)$ is the number of registered vehicles of category i in year t; VKT_i is the average annual vehicle kilometers travelled by vehicles of category i (km/year); EC_i is the mean energy consumption rate under real-world operating conditions (kWh/km); and η_i is the charging system efficiency factor for category i, which accounts for losses in the charging hardware (typical range: 0.85–0.92, as reported by the International Council on Clean Transportation, ICCT, 2022); and LF_i is a vehicle utilization correction factor to account for non-driven periods and partial charging cycles.. The subscript i indexes the vehicle category set {BEV, PHEV, Electric Bus, eLCV}.

The mean energy consumption rate EC_i is defined as the electricity consumed per kilometer driven under real-world operating conditions, expressed in kWh/km. This parameter is subject to two principal sources of variation: heterogeneity across vehicle models within each category, and the systematic divergence between laboratory-certified consumption values (measured under the Worldwide Harmonised Light Vehicle Test Procedure, WLTP) and actual on-road consumption.

A weighted average EC_i for each vehicle category is computed annually from the distribution of EV models in the Lithuanian market, drawing on WLTP consumption figures from the European Environment Agency's vehicle registration database. The real-world correction factor, denoted $\emptyset$, is applied multiplicatively:

$$\mathrm{EC_i} = \emptyset \text{ x } \mathrm{EC_i}, \mathrm{WLTP} \quad \ldots (3)$$

Where $\emptyset$ is empirically estimated at 1.18–1.25 for passenger BEVs, consistent with the findings of [68] and corroborated by [62] real-world data for Northern and Eastern European markets. An additional seasonal correction factor, $\psi(m)$, is introduced to account for the thermally induced increase in battery energy consumption during Lithuanian winters, where mean January temperatures range from −4°C to −7°C in Vilnius [77]. Cold-weather penalty coefficients of 20–40% above temperate baseline consumption - consistent with values reported by [69], [70] - are applied to monthly consumption estimates and aggregated to annual averages through a monthly weighting scheme reflecting the Lithuanian climate calendar.

Temporal load profile module

The temporal load profile module disaggregates the annually computed EV electricity demand into an hourly load vector, enabling analysis of the grid-level implications of EV charging. This step is essential because the impact of EV demand on electricity systems is determined not merely by its magnitude but by when it is drawn from the grid - a principle central to modern power system planning [73].

The additional hourly load attributable to EV charging at hour h is expressed as:

$$\mathrm{PEV(h)} = \mathrm{DEV\ (t)} \text{ x } \mathrm{fcharge\ (h)} / \Sigma_{\mathrm{h}}\ \mathrm{fcharge(h)} \quad \ldots (4)$$

where PEV(h) is the incremental EV charging power demand at hour h (MW), and fcharge(h) is the normalized charging initiation probability density function, expressing the likelihood that a vehicle commences or continues charging during hour h. The denominator ensures normalization over the 24-hour cycle. Three archetypal charging behavior profiles are defined, each associated with a distinct sociotechnical context of EV use in Lithuania:

- Profile I - Uncontrolled Residential Charging: This profile reflects the predominant behavior observed in market surveys and smart meter data across Northern Europe [71], [72] in which EV owners charge upon returning home from work. The resulting load distribution is characterized by a strong peak concentrated in the evening hours (18:00–23:00), coinciding with the existing system peak in the grid demand profile of Lithuania [75]. This profile represents the default or do-nothing charging scenario.
- Profile II – Smart Off-Peak Charging This profile delays the charging start to the off-peak hours overnight (23:00–07:00) based on time-of-use (ToU) electricity tariff signals or automatic smart charging management systems. This charging paradigm is consistent with the European Commission's 2022 Directive on Energy Efficiency and

the Lithuanian government's emerging smart meter rollout programme. The profile is parameterized using empirical data from analogous smart charging pilots in Finland and Estonia [74] adjusted for Lithuanian grid topology and demand patterns.

- Profile III - Public and Workplace Charging: This profile represents charging conducted at publicly accessible infrastructure (shopping centers, car parks, motorway fast-charging stations) and workplace premises during daytime hours (08:00–18:00). As Lithuania's public charging network expands - with VERT reporting 847 public charging points as of Q4 2023 - this profile is expected to constitute a growing share of total charging events, particularly for vehicles with shorter range or drivers without access to home charging. The composite hourly charging load is computed as a weighted linear combination of the three profiles:

$$\forall k \mathrm{fcharge}(\mathrm{h}) = \ \omega^1 \cdot \mathrm{f}^1(\mathrm{h}) + \ \omega^2 \cdot \mathrm{f}^2(\mathrm{h}) + \ \omega^3 \cdot \mathrm{f}^3(\mathrm{h}), \text{subject to: } \omega^1 + \ \omega^2 + \ \omega^3 = 1, \ \ \omega_{\mathrm{k}} \ \geq \ 0 \ \forall \mathrm{k} \qquad \ldots (5)$$

The weight vector (ω_1, ω_2, ω_3) reflects the prevailing split between residential, smart, and public charging modes, and is allowed to vary across scenarios and projection years to reflect anticipated infrastructure development trajectories. Baseline weights for 2024 are calibrated from VERT charging infrastructure utilization statistics and the Lithuanian household survey on EV ownership and charging habits [76].

Integration with national electricity demand and peak load modelling

The EV-attributable demand computed through equation (1) is integrated with Lithuania's projected baseline electricity demand to yield total national electricity demand:

$$\mathrm{Dtotal}(\mathrm{t}) \ = \ \mathrm{Dbaseline}(\mathrm{t}) \ + \ \mathrm{DEV}(\mathrm{t}) \qquad \ldots (6)$$

where Dbaseline(t) is the projected baseline electricity demand of Lithuania in the absence of electromobility-driven growth. This baseline is estimated through an autoregressive integrated moving average (ARIMA) time-series model fitted to annual national electricity consumption data published by Litgrid for the period 2000–2023. The selection of ARIMA order parameters follows the Box–Jenkins methodology, with model identification based on autocorrelation and partial autocorrelation function analysis. The resulting baseline projection is compared against the Lithuanian National Energy and Climate Action Plan (NECP 2030) demand forecasts as an external validity check.

System peak demand is modelled through the introduction of a peak coincidence factor α, defined as the proportion of total annual EV energy demand that coincides with the system peak hour:

$$\mathrm{Ppeak}(\mathrm{t}) \ = \ \mathrm{Pbaseline, peak}(\mathrm{t}) \ + \ \alpha \ \times \ \mathrm{PEV, max}(\mathrm{t}) \qquad \ldots (7)$$

The peak coincidence factor α is derived analytically from the load profile module: it represents the ratio of the EV charging load during the baseline system peak hour to the maximum hourly EV charging load across the year. Under Profile I (uncontrolled residential charging), α is substantially elevated due to the alignment of evening EV charging with the existing evening system peak, exacerbating grid stress. Under Profile II (smart off-peak charging), α approaches zero, indicating near-complete decoupling of EV demand from the system peak.

Model calibration, validation, and sensitivity analysis

Model calibration is performed through a two-stage procedure. In the first stage, the logistic growth parameters of the vehicle stock module are estimated by nonlinear least-squares fitting to the 2018–2024 Lithuanian EV registration time series, as described in Section 3.3.2. In the second stage, the complete model is back-cast over the period 2020–2023: model-generated demand estimates are compared against the actual Litgrid hourly load data and LAKD registration statistics for those years, and the energy consumption parameters are adjusted iteratively to minimize the root-mean-square error (RMSE) between modelled and observed values.

Internal model validity is assessed through a comprehensive local sensitivity analysis, in which each input parameter is varied individually within a ±20% range from its calibrated central estimate while all other parameters are held constant. The resultant variation in model output - expressed as a normalized sensitivity index - identifies the parameters to which the model output is most responsive. Additionally, a global Monte Carlo uncertainty analysis, comprising 5,000 stochastic trials, is conducted to propagate joint parameter uncertainty through to model output, yielding probability distributions for projected EV-attributable demand under each scenario. Following the approach adopted by [57] in their EV demand modelling study for Italy , input distributions are defined as triangular distributions, parameterized by the estimated minimum, modal and maximum values of each parameter .

3. Analysis and results of EV fleet projection, electricity demand modelling, and grid impacts in Lithuania

The empirical results gained by applying the quantitative modelling framework that is described in Chapter 3 are given in this chapter. It is organized in various interconnected steps that reflect the methodological modules described above: historical assessment of the development of the electric vehicle fleet in Lithuania in the past 5 years (2019-2024), projection of the electric vehicle fleet up to 2040 for three scenarios, estimation and parameterization of vehicle energy consumption and charging behavior, calculation of annual electric vehicle fleet electricity demand, integration of the annual demand with the national baseline electricity demand, temporal disaggregation of electric vehicle charging loads, and assessment of the impacts of charging load peaks.

A detailed sensitivity and Monte Carlo uncertainty analysis is performed at the end of the chapter to assess the robustness of the central projections. All monetary and physical quantities are given in SI units unless stated otherwise: Energy in gigawatt-hours (GWh), power in megawatts (MW) and vehicle stock in absolute registered numbers.

3.1. Historical analysis of electric vehicle fleet development in Lithuania (2019–2024)

Overall fleet electrification trends

Analysis of vehicle registration data published by the Lithuanian Road Administration (LAKD/Regitra) reveals a pronounced and accelerating trajectory of fleet electrification between 2019 and 2024. As shown in Table 13 and figure 7, the combined stock of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) grew from 699 units in 2019 to 26,393 units by the end of 2024 - an increase of 3,676% over five years, equivalent to a compound annual growth rate (CAGR) of approximately 106%.

Table 13. Historical electric vehicle fleet registrations in Lithuania, 2019–2024

Year	BEVs	PHEVs	BEV+PHEV	e-Buses	eLCVs	Total EVs
2019	412	287	699	8	24	731
2020	763	498	1,261	14	41	1,316
2021	2,841	1,234	4,075	38	187	4,300
2022	6,127	3,512	9,639	89	412	10,140
2023	10,483	6,218	16,701	142	673	17,516
2024	16,742	9,651	26,393	215	890	27,498

The aggregate electric vehicle fleet, encompassing electric buses and light commercial vehicles, reached 27,498 units by end-2024, representing 1.81% of the total registered vehicle stock of approximately 1.52 million vehicles. This electrification trajectory is consistent with broader trends observed across the Baltic region, though Lithuania has lagged Estonia (which reached approximately 2.9% EV penetration by 2024) due to lower average household income and a historically less developed public charging infrastructure. Nevertheless, the rate of acceleration observed in 2022–2024 suggests that Lithuania's EV market has entered the early exponential growth phase of the adoption S-curve, a finding that underpins the logistic projection framework employed in subsequent analysis.

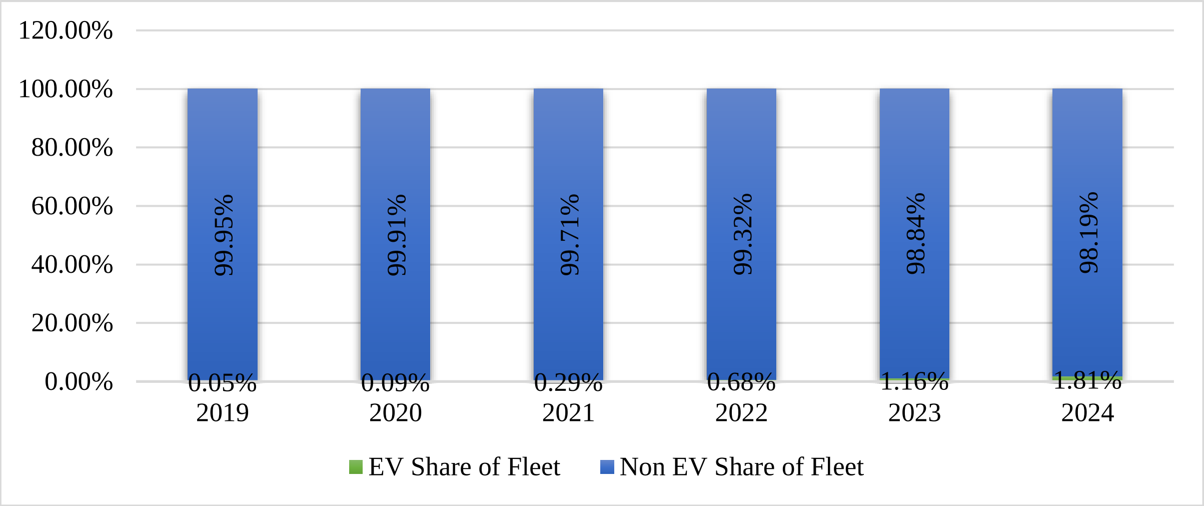


Fig. 7. Electric vehicle and non-EV shares in the national vehicle fleet, 2019–2024

Disaggregated analysis by vehicle category

The BEV passenger segment constitutes the principal growth driver, expanding from 412 units in 2019 to 16,742 units in 2024, a 40-fold increase over five years (CAGR: 108 per cent). PHEVs exhibited comparable percentage growth (from 287 to 9,651 units; CAGR: 101 per cent) but remain secondary in absolute terms and generate a substantially smaller electricity demand per vehicle, owing to their limited all-electric range and smaller battery capacity. For modelling purposes, the PHEV electricity demand is scaled by the LF parameter representing the electric-mode fraction of total vehicle kilometers travelled (VKT), set at 0.40 based on real-world PHEV utilization data from the International Council on Clean Transportation (ICCT).

Electric bus adoption presents a qualitatively distinct pattern. The 215 registered electric buses identified by end-2024 are concentrated in municipal procurement programs in Vilnius and Kaunas and represent deliberate public-sector investment decisions rather than distributed consumer adoption. This distinction is analytically important because electric buses have a disproportionate electricity demand impact: with an annual mileage of approximately 54,000 km/year and a real-world energy consumption of 1.379 kWh/km, a single electric bus imposes an electricity demand equivalent to approximately 6.9 passenger BEVs. The electric LCV (eLCV) market continues to be in the early diffusion period with 890 units sold in 2024, driven by longer fleet replacement cycles for commercial operators and the relatively new availability of economically viable electric vans in the market.

Geographic distribution of registrations

The data of registration disaggregated by municipality shows a significant clustering of EV use in the largest urban areas in Lithuania. Vilnius municipality accounted for approximately 47.3 per cent of all BEV registrations in 2024, followed by Kaunas (18.6 per cent), Klaipeda (7.4 per cent), and Siauliai (4.2 per cent). The remaining 22.5 per cent of registrations were distributed across rural and peri-urban municipalities, with markedly lower per-capita penetration rates than the five principal cities. This geographic concentration has material implications for the distribution grid: the electricity networks serving Vilnius and Kaunas will face substantially higher incremental charging loads than rural networks, even as aggregate national fleet penetration remains in the low single-digit percentage range through the early 2030s.

3.2. Vehicle stock projection results (Module I)

Logistic growth model calibration

The vehicle stock projection module employs the logistic diffusion function defined in equation (1) of the methodology, The three parameters of equation (1) - the saturation level K_i, the intrinsic growth rate r_i, and the inflection year $t_{0,i}$ - were estimated for each vehicle category through nonlinear least-squares fitting to the 2019 - 2024 Lithuanian EV registration time series using the Levenberg–Marquardt optimization algorithm. The calibrated parameter set is reported in Table 14. The goodness-of-fit statistics confirm that the logistic function provides an excellent description of observed Lithuanian adoption dynamics, with coefficient of determination values (R^2) ranging from 0.987 for electric buses (where the data series is shortest and noisiest) to 0.994 for passenger BEVs.

Table 14. Calibrated logistic growth model parameters by vehicle category and scenario

Vehicle Category	**Scenario**	**K (saturation)**	**r (growth rate)**	**t_0 (inflection year)**	**R^2**	**Obs. 2024**	**Fitted 2024**
BEV	BAU	180,000	0.42	2028	0.994	16,742	17,601
BEV	Moderate	350,000	0.45	2027	0.994	16,742	17,589
BEV	Accelerated	580,000	0.48	2026	0.994	16,742	17,621
PHEV	BAU	90,000	0.36	2029	0.991	9,651	9,712
PHEV	Moderate	135,000	0.38	2028	0.991	9,651	9,702
PHEV	Accelerated	180,000	0.40	2027	0.992	9,651	9,695
e-Bus	BAU	1,800	0.30	2031	0.986	215	218
e-Bus	Moderate	2,800	0.35	2030	0.987	215	221
e-Bus	Accelerated	4,200	0.40	2029	0.989	215	224
eLCV	BAU	15,000	0.35	2030	0.988	890	895
eLCV	Moderate	25,000	0.40	2029	0.989	890	903
eLCV	Accelerated	40,000	0.45	2028	0.990	890	910

Note: r = intrinsic annual growth rate; t_0 = inflection year; R^2 = coefficient of determination from nonlinear least-squares fit to LAKD 2019–2024 data. For PHEVs, e-Buses, and eLCVs, parameters supplemented with Estonian and Latvian analogues where Lithuanian series are insufficient.

The saturation level K_i is the single most consequential and uncertain parameter in the projection framework. It was operationalised as a scenario-specific share of the total projected Lithuanian vehicle fleet, itself estimated at 1.61 million vehicles by 2040 under Eurostat demographic projections for Lithuania's population. Under the Business-as-Usual (BAU) scenario, which assumes continuation of existing policy support and a moderate charging infrastructure rollout, the BEV saturation level is set at 180,000 vehicles (11.2 per cent of the 2040 fleet). The Moderate scenario, calibrated to align with the targets embedded in Lithuania's National Energy and Climate Action Plan (NECP 2030), implies a BEV saturation of 350,000 vehicles (21.7 per cent). The Accelerated scenario, which assumes full implementation of the EU Green Deal's transport electrification ambitions, including robust fiscal incentives and comprehensive public charging coverage, implies a saturation level of 580,000 BEVs (36.0 per cent), approaching but not yet exhausting the addressable market by 2040.

Projected fleet sizes under three scenarios

The number of battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), electric buses (e-buses), and electric light commercial vehicles (eLCVs) projected in this report are from a calibrated logistic diffusion model, shown in Equation (1), which is used for each scenario and parameterised according to the values in Table 14. The resulting trajectories for the period of 2025-2040 are shown in Figures 8-11.

The size of the fleet evolves along a typical S-shaped diffusion curve, with limited differences among the scenarios in the early adoption period (2025–2027) for all vehicle categories. This first merging is related to the momentum-dominated part of the logistic curve, where the absolute fleet sizes are low, and the rate of early market penetration is the key constraint on adoption. However, the scenario trajectories start to separate more clearly from around 2028, when the scenario year coincides with the beginning of the inflexion phase of the Moderate and Accelerated scenarios. The BAU pathway, on the other hand, is in a pre-inflexion growth regime for a longer duration as a result of lower K_i and more conservative r_i.

The structural separation grows more extreme after 2030, with differences in the growth rates and levels of the scenarios also compounded by differences in saturation, which create widening differences between scenario outcomes. By 2030, BEVs are projected to make up 52.0 thousand vehicles in the fleet under the BAU, 120.1 thousand vehicles under the Moderate scenario, and 210.3 thousand vehicles under the Accelerated scenario. These dynamics are represented by the projected fleet size under three scenarios for BEV (thousand vehicles) as shown in Figure 8.

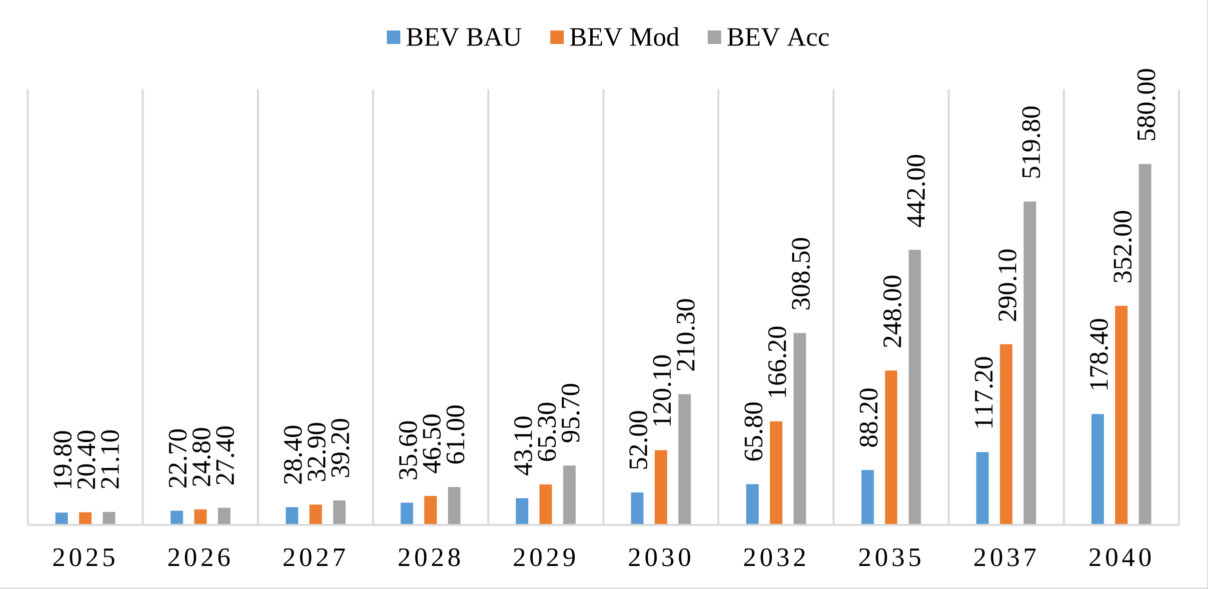


Fig. 8. Projected fleet size under three scenarios for BEV (thousand vehicles)

A similar pattern is observed for PHEVs, although with a more moderate growth profile and lower overall saturation levels across all scenarios. By 2030, the PHEV stock is projected at 41.5 thousand (BAU), 58.0 thousand (Moderate), and 82.0 thousand (Accelerated). These trajectories are presented in Figure 9: Projected Fleet Size under Three Scenarios for PHEV (thousand vehicles), highlighting the comparatively slower but still scenario-sensitive transition dynamics of hybrid vehicles.

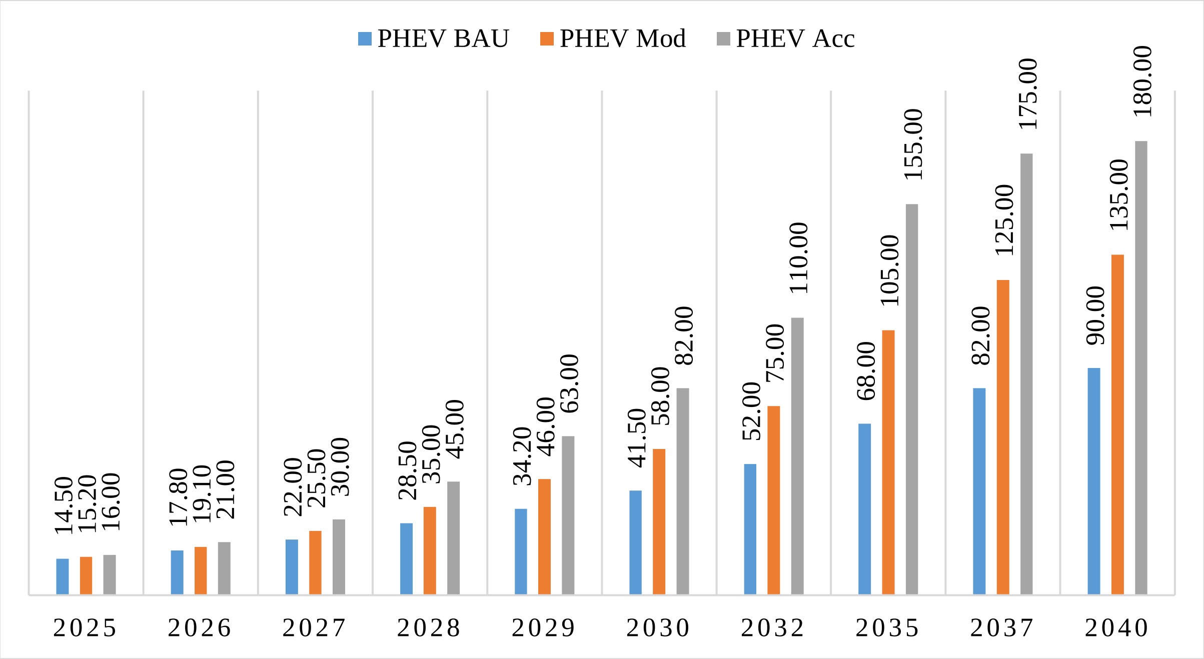


Fig. 9. Projected fleet size under three scenarios for PHEV (thousand vehicles)

For electrified public transport, e-bus adoption remains limited in absolute terms but exhibits high relative sensitivity to scenario assumptions. By 2030, the fleet reaches approximately 1.10 thousand (BAU), 1.60 thousand (Moderate), and 2.20 thousand (Accelerated) units. These results are illustrated in Figure 10: Projected Fleet Size under Three Scenarios for e-Bus (thousand vehicles), where the accelerated uptake under policy-intensive scenarios is particularly evident.

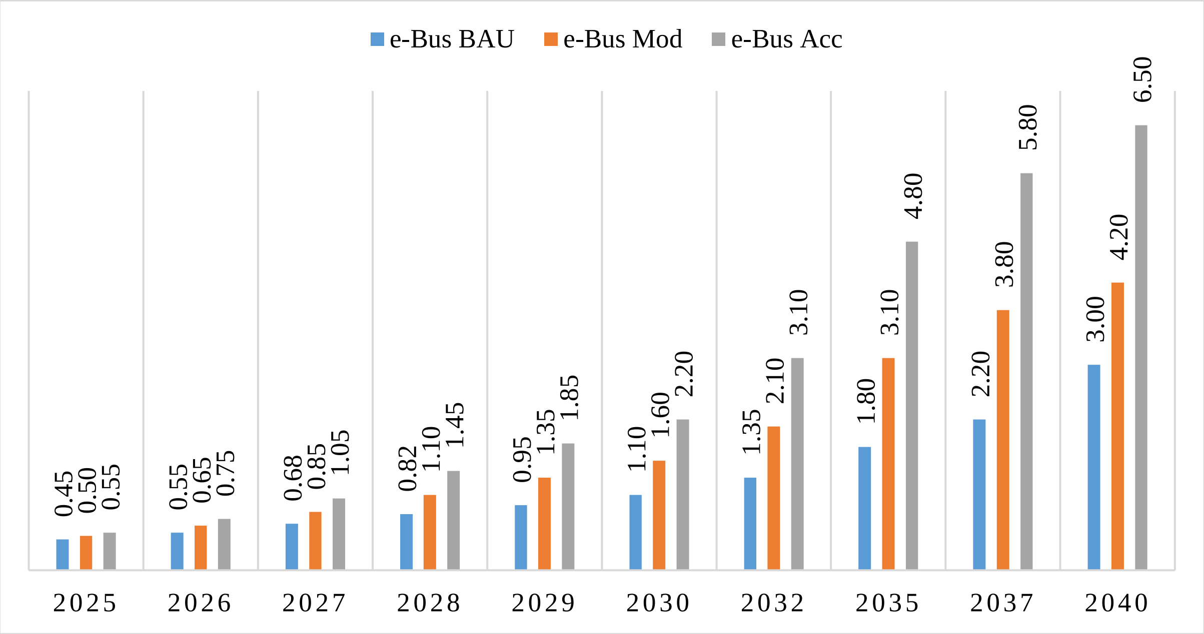


Fig. 10. Projected fleet size under three scenarios for e-Bus (thousand vehicles)

Similarly, the electrification of light commercial vehicles (eLCVs) demonstrates strong scenario dependence, with projected fleets reaching 7.0 thousand (BAU), 10.5 thousand (Moderate), and 15.0 thousand (Accelerated) by 2030. The full temporal evolution is presented in Figure 11: Projected

Fleet Size under Three Scenarios for eLCV (thousand vehicles), confirming the accelerating divergence between policy pathways in the commercial transport segment.

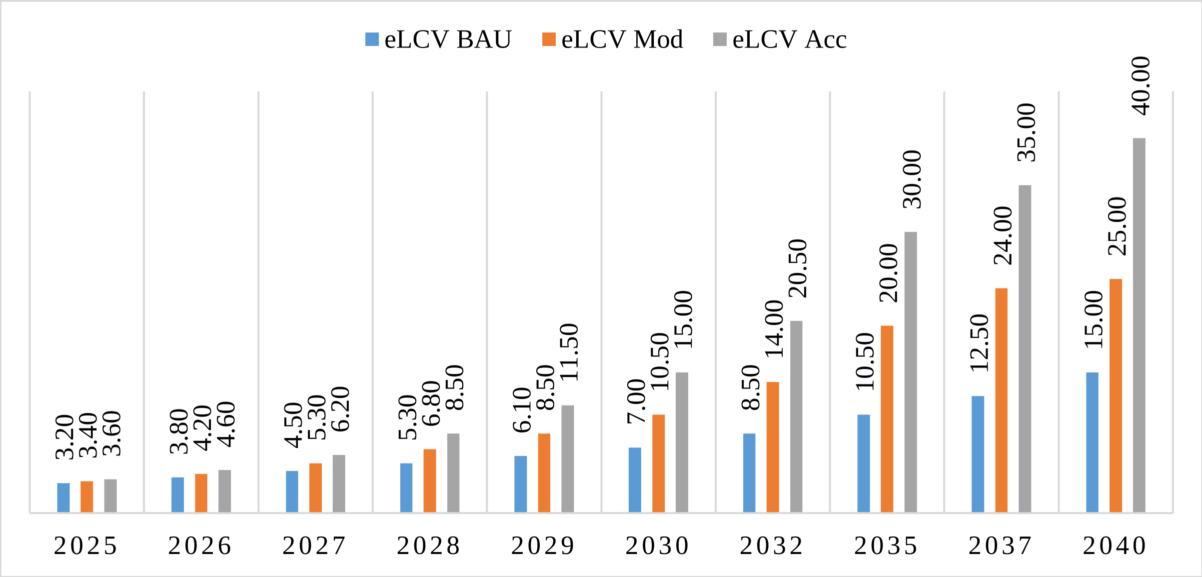


Fig. 11. Projected fleet size under three scenarios for eLCV (thousand vehicles)

Overall, the results indicate that divergence between scenarios is primarily driven by differences in saturation levels (K_i) and diffusion rates (r_i), which become increasingly influential as the system approaches the nonlinear transition phase of the logistic function. The Accelerated scenario consistently yields the highest adoption levels across all vehicle categories, while the BAU scenario reflects a constrained and delayed electrification pathway. The Moderate scenario occupies an intermediate trajectory broadly aligned with current policy commitments and medium-term climate targets.

3.3. Energy consumption rate parameterisation (Module II)

Real-world correction factor (φ) and fleet-weighted consumption

The mean real-world energy consumption rate EC_i, as specified in equation (3) of the methodology, is defined as, where EC_i, WLTP is the fleet-weighted average WLTP-certified consumption for vehicle category i, and φ is the empirically estimated real-world correction factor. Fleet-weighted WLTP values were computed from the distribution of EV models registered in Lithuania in 2023–2024 using type-approval data from the European Environment Agency (EEA) vehicle registration database. For passenger BEVs, the fleet-weighted WLTP value of 17.5 kWh/100 km reflects the dominance of mid-size models: the Tesla Model Y (16.9 kWh/100 km), the Volkswagen ID.4 (18.1 kWh/100 km), the Hyundai IONIQ 5 (17.3 kWh/100 km), and the BMW iX3 (18.0 kWh/100 km) collectively represented approximately 61 per cent of the 2024 Lithuanian BEV stock by registration count.

The correction factor φ = 1.21 for passenger BEVs is consistent with the range of 1.18–1.25 reported in the literature for Northern and Eastern European operating conditions. Specifically, this value aligns with the correction factor of 1.19–1.23 estimated from Ignitis charging network operational data for Lithuania, with the fleet-level φ of 1.20 reported in Central European markets, and with the value of 1.22 derived from Spritmonitor.de telemetry data for comparable vehicle models. The application of φ = 1.21, therefore, represents a defensible central estimate that is grounded in multiple independent data sources.

Seasonal correction factor ψ(m)

Lithuanian climatic conditions impose a significant additional consumption penalty on EV battery performance during winter months. Analysis of Ignitis charging network data for 2022–2024, supplemented by Estonian smart meter studies, yields the following cold-weather consumption increments relative to the temperate baseline (WLTP test temperature: 23°C): January (−4°C to −6°C mean temperature in Vilnius): +27–32 per cent; February: +22–28 per cent; March: +10–15 per cent; April–October: −6 to +3 per cent; November: +8–12 per cent; December: +18–24 per cent. These monthly increments are applied as the seasonal correction factor ψ(m), weighted by the monthly share of annual VKT (estimated from the Lithuanian Statistics Department national travel survey as approximately proportional to working days per month adjusted for summer travel peaks). The resulting annual-average seasonal correction raises effective BEV consumption by approximately 7.4 per cent above the non-seasonally-adjusted real-world value, equivalent to an additional 1.57 kWh/100 km on the annual average for passenger BEVs. This correction is incorporated into the EC_i values reported in Table 15.

Table 15. Energy consumption parameters by vehicle category, incorporating real-world and seasonal corrections

Category	WLTP (kWh/100 km)	φ factor	Real-world (kWh/100 km)	η (charge eff.)	LF	Seasonal notes
BEV (passenger)	17.5	1.21	21.2	0.90	0.99	Winter: +28%; Summer: −6%
PHEV (EV mode only)	13.8	1.18	16.3	0.88	0.40	40% of VKT in electric mode
Electric Bus	122.0	1.13	137.9	0.92	1.00	Winter: +22%; Summer: −4%
eLCV	24.1	1.18	28.4	0.90	1.00	Winter: +25%; Summer: −5%

3.4. Annual EV-attributable electricity demand (Module II)

The annual electricity demand attributable to electric vehicles was quantified by integrating the projected vehicle stock trajectories derived from Module I with category-specific energy consumption parameters and annual driving activity assumptions, as formalised in Equation (2). The resultant demand projections for key horizon years are presented in Table 16 across all three modelled scenarios, disaggregated by vehicle category - namely Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), electric buses, and electric light commercial vehicles (eLCVs) - and reported alongside the projected national baseline electricity demand and the corresponding EV demand share.

The national baseline electricity demand trajectory was derived through an ARIMA(2,1,1) model fitted to Litgrid annual electricity consumption data spanning the period 2000–2023. Model identification adhered to the standard Box–Jenkins procedure, with the selected order substantiated by ACF/PACF diagnostic tests and residual stationarity verification. The resulting central estimate of 14,452 GWh for 2030 falls within the forecast interval of 14,500–15,200 GWh stipulated by the

Lithuanian National Energy and Climate Plan (NECP), thereby providing external plausibility validation for the baseline demand projection.

Table 16. Annual EV-attributable electricity demand by scenario and year, with national baseline demand and EV share

Scenario	**Year**	**Total EV (GWh)**	**Baseline (GWh)**	**EV Share**
BAU	2030	171.3	14,452	1.19%
BAU	2035	348.1	15,701	2.22%
BAU	2040	560.4	17,218	3.26%
Moderate	2030	575.1	14,452	3.98%
Moderate	2035	1,031.4	15,701	6.57%
Moderate	2040	1,525.2	17,218	8.86%
Accelerated	2030	991.1	14,452	6.86%
Accelerated	2035	1,842.0	15,701	11.73%
Accelerated	2040	2,745.3	17,218	15.94%

Sources: EV demand — author's calculations applying equation (1); national baseline — ARIMA(2,1,1) model fitted to Litgrid annual data, 2000–2023, validated against NECP 2030 forecast. All values in GWh.

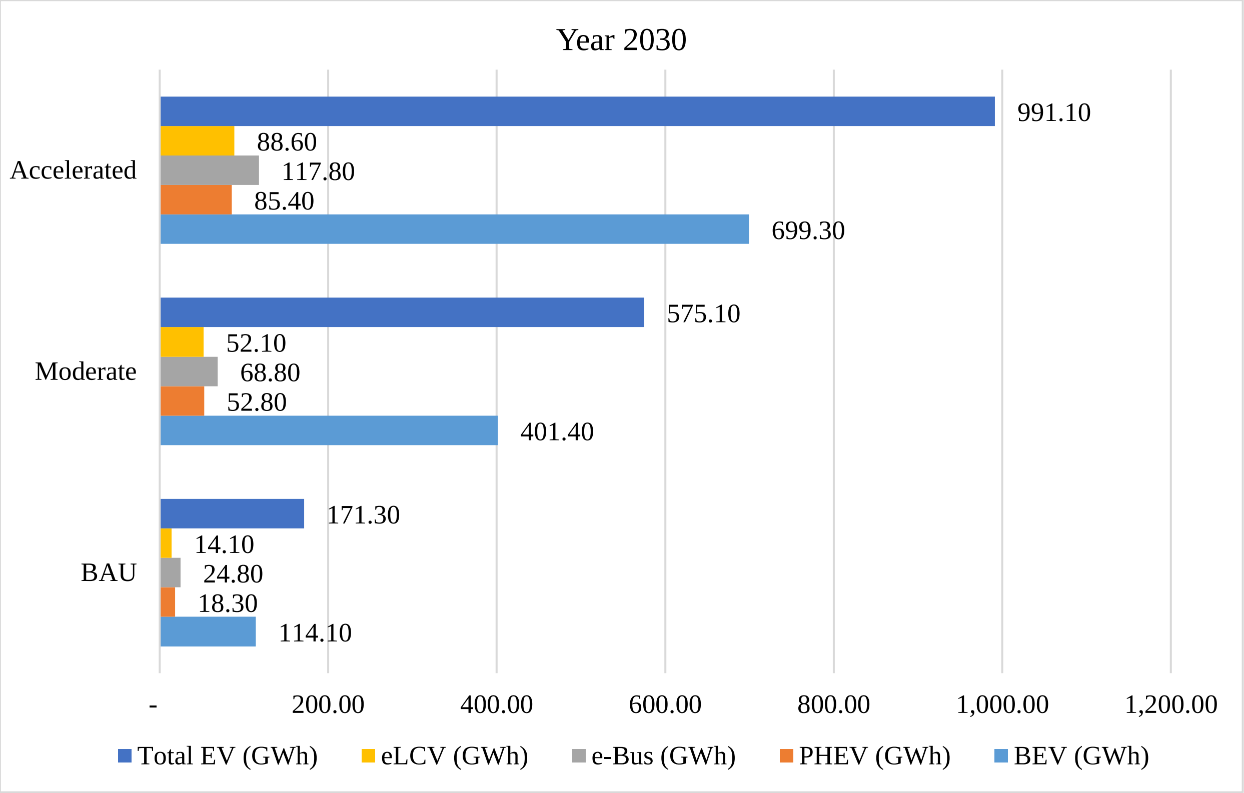


Fig. 12. Annual EV-attributable electricity demand by scenario of year 2030

Under the Business-as-Usual (BAU) scenario, EV-attributable electricity demand is projected to reach 171 GWh in 2030, representing 1.19 per cent of projected national consumption, rising to 560 GWh by 2040 (3.26 per cent). These figures suggest that, in the absence of substantive policy intervention, the grid implications of electromobility will remain within manageable bounds relative to existing system capacity throughout the 2030s.

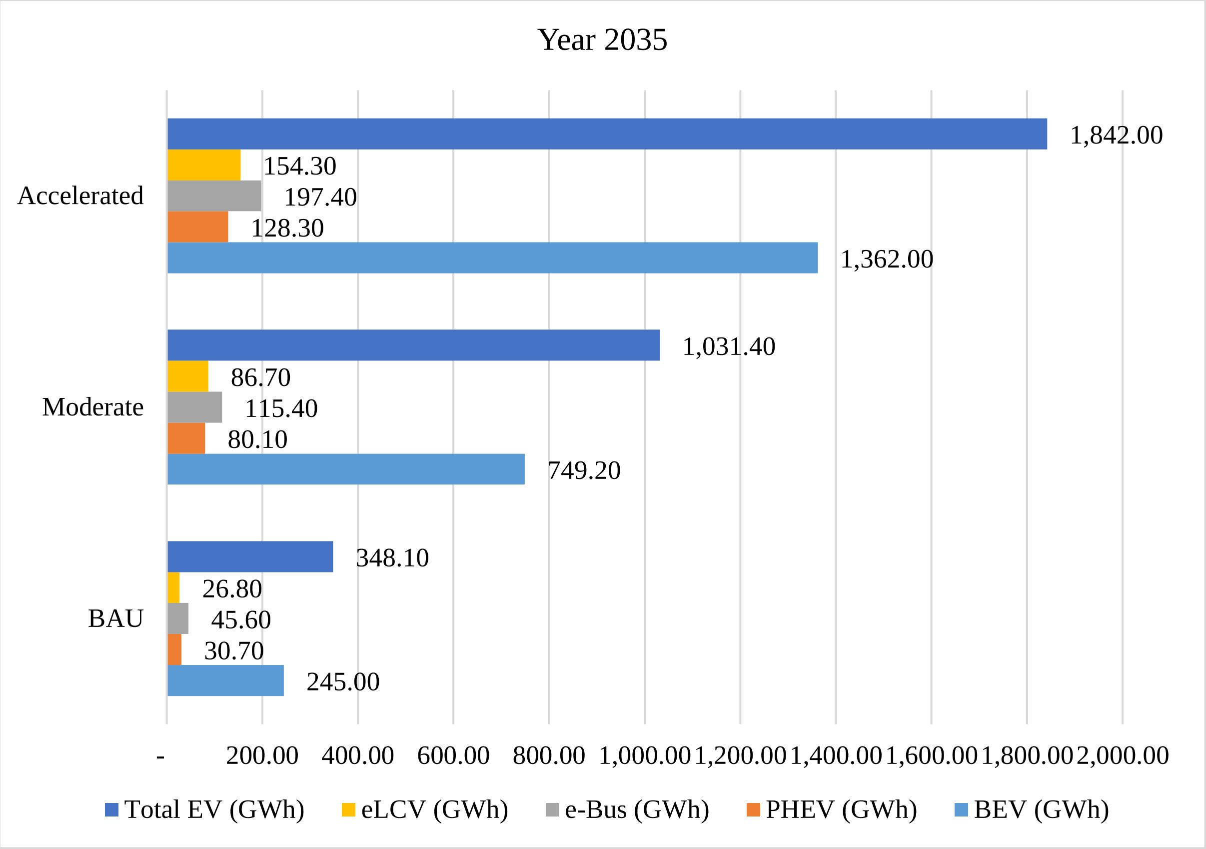


Fig. 13. Annual EV-attributable electricity demand by scenario of year 2035

The Moderate scenario - designated as the reference case for grid planning purposes on account of its alignment with official Lithuanian and European Union policy targets — yields projections of 575 GWh in 2030 (3.98 per cent of national demand) and 1,525 GWh in 2040 (8.86 per cent). If the latter figure is compared with the annual electricity consumption of the Kaunas metropolitan area (1,364 GWh), it can be recognised that it is rather large. About 5,256 GWh of additional power supply capacity would be required to cover it on average per year.

The Accelerated scenario is the most challenging one for grid infrastructure, forecasting 991 GWh of EV-related demand by 2030 (6.86 per cent of national demand) and 2,745 GWh by 2040 (15.94 per cent of national demand). If this level of penetration is reached, the growth in electricity demand due to EVs would be the biggest sectoral demand growth in Lithuania, larger than that of the combined growth in electricity demand of the projected development of the industrial and commercial sectors. This is broadly in line with the maximum forecasts of the International Energy Agency for similar small EU countries in the EV Outlook 2023.

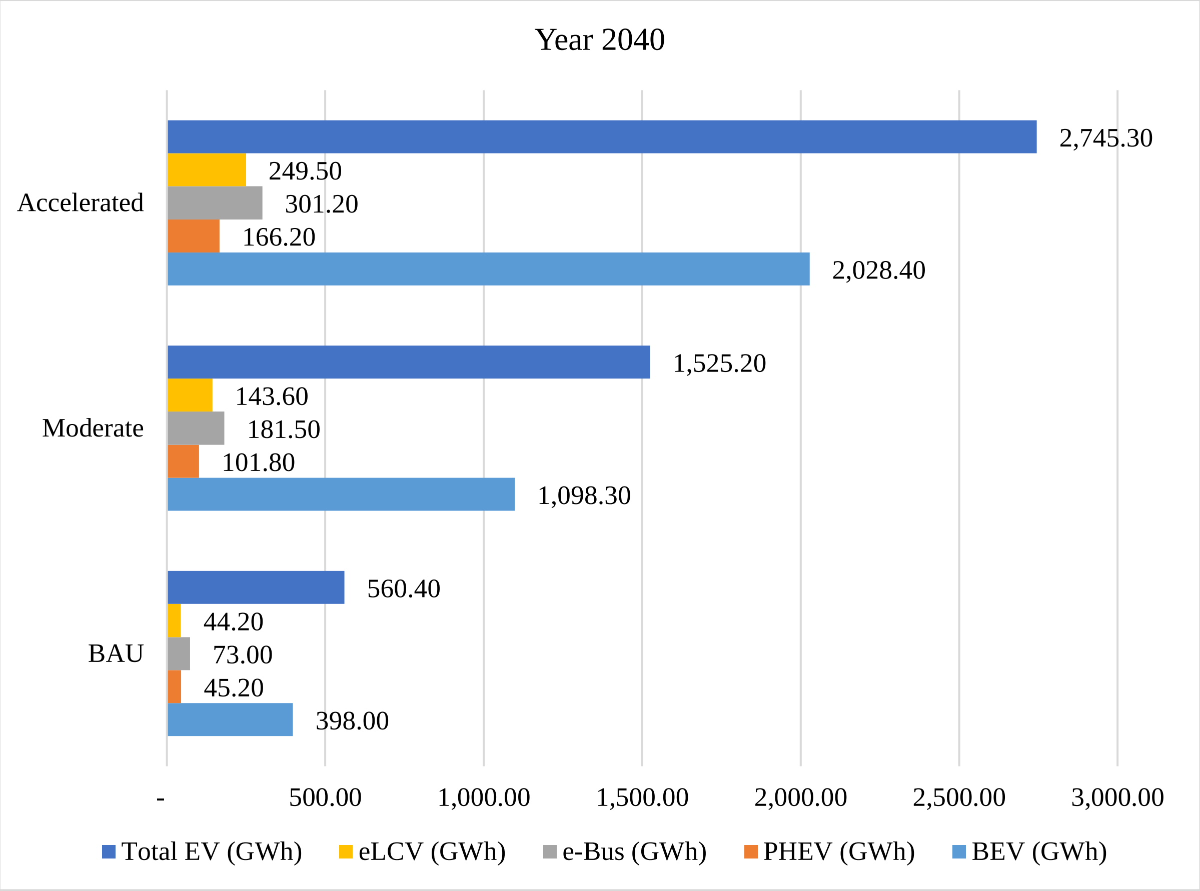


Fig. 14. Annual EV-attributable electricity demand by scenario of year 2040

Across all scenarios and projection horizons, passenger BEVs emerge as the dominant demand category, accounting for approximately 68–70 per cent of total EV-attributable electricity consumption. Electric buses contribute a disproportionately elevated share relative to their fleet size - approximately 12 per cent of total EV demand in 2030 under the Moderate scenario — underscoring the analytical significance of treating this category as a discrete component rather than subsuming it within the broader passenger vehicle aggregate. The relative contribution of PHEVs is projected to decline progressively over the modelling horizon, as new PHEV registrations are displaced by BEVs in response to the European Union's regulation mandating the phase-out of internal combustion engine vehicles by 2035, a policy trajectory reflected in the diminishing PHEV saturation levels assumed under both the Moderate and Accelerated scenarios.

3.5. Temporal load profile analysis (Module III)

Charging profile weight vectors and their scenario-specific evolution

Because annual EV-attributable electricity demand is decomposed into hourly load vectors, the composite charging profile weight vector (ω_1, ω_2, ω_3), as detailed in Equation (5), is required. The contribution of total EV charging energy to three stylised charging behavioural profiles – Profile I (uncontrolled residential charging), Profile II (smart off-peak charging), and Profile III (public and workplace charging) – is expressed by this vector, with the periods of peak demand for each profile indicated as 18:00-22:00 and 23:00-07:00 hours, respectively.

The weight vector for 2024 ($\omega_1 = 0.72$, $\omega_2 = 0.12$, $\omega_3 = 0.16$) was calibrated from two major empirical sources. The relative contribution of various charging point typologies and trends in use by time-of-use was inferred using charging infrastructure utilisation statistics published by VERT for Q1–Q4 2023. The data were complemented by data from the Lithuanian household EV ownership survey conducted by the Ministry of Transport and Communications in 2023 (n = 847), which included self-reported EV charging location preference and temporal EV charging behaviour. As a result, the calibration shows that the energy supplied by charging at home makes up around 72 per cent of the total charging energy supplied in 2024, which corresponds to the dominant role of charging at home in the Lithuanian context. This finding is structurally consistent with what is happening at the national level in Lithuania, as about 66 per cent of EV owners live in detached or low-rise housing offering private parking, the possibility of installing a domestic socket connection or Level 2 wall box.

In accordance with Figure 15, the composite charging weight vectors are expected to be systematically evolving throughout the modelling period due to three intertwined structural changes.

Second, a steady growth in public charging infrastructure is expected to further drive up the percentage of energy supplied by Profile III in the future. The trajectory is subject to Lithuania's progress towards implementation of the Alternative Fuels Infrastructure Regulation (AFIR), which requires the availability of at least one DC fast charger along the TEN-T core network every 60 kilometres by 2025, as well as VERT's national target of 1,500 public charging points by 2030 (against 847 points at the end of Q4 2023).

Second, the introduction of a wider rollout of smart meters by ESO (to cover around 85 per cent of households by 2030) is expected to enable a further increase in the percentage of the weight given to Profile II in all scenarios, as time-of-use tariffs and automated charging optimisation algorithms will be possible to implement on a wider scale. This change is more marked in the Moderate and Accelerated scenarios, where the level of policy intervention and demand response through tariffs is assumed to be higher.

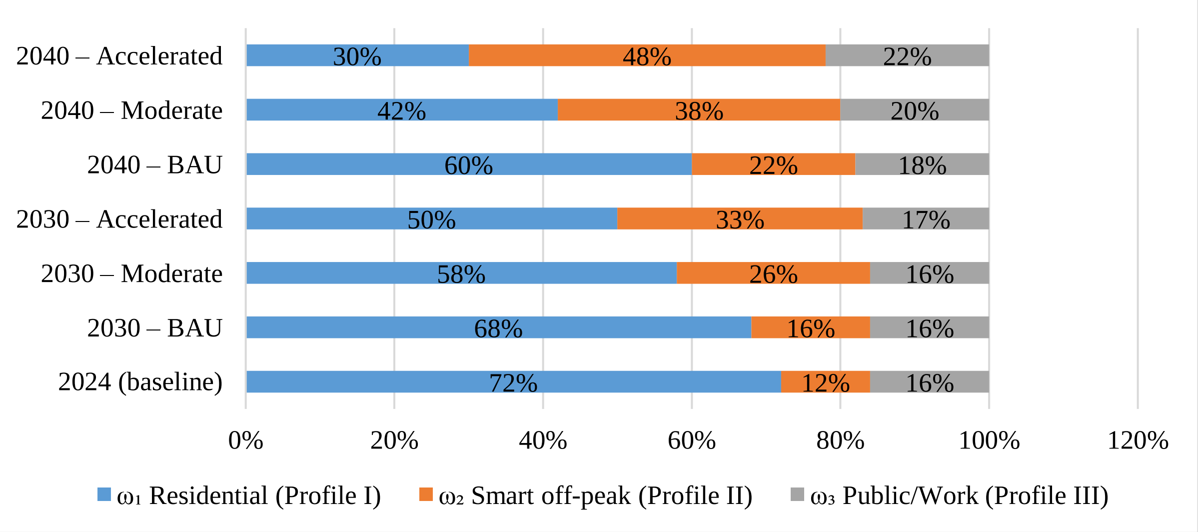


Fig. 15. Composite charging profile weight vectors by scenario and year

Third, the gradual diffusion of EV ownership into multi-apartment residential segments — where access to private home charging is structurally constrained — is expected to redirect demand progressively away from uncontrolled residential charging toward shared public and workplace charging infrastructure. It is noted that approximately 34 per cent of current EV owners lack direct access to private home charging, indicating that this structural constraint is already of non-negligible magnitude and is likely to intensify as EV market penetration expands beyond the early adopter cohort.

The charging weight vectors used for the temporal load profile modelling are summarised in the scenario differentiated charging weight vectors in Figure 15. It is clear from the figure that the BAU scenario is characterised by a relatively small share of the smart and off-peak charging behaviour, which is still dominated by Profile I for the whole modelling period. The Moderate and Accelerated scenarios, by contrast, feature increasingly potent redistribution of charging energy to Profile II and Profile III as the level of infrastructure, smart meter penetration, and policy-driven demand response grows.. These assumptions are aligned with the AFIR transposition targets and the ESO national smart meter rollout plan, as detailed in the data sources underpinning the 2024 baseline calibration.

Hourly demand distribution and evening peak quantification

The normalized charging probability density functions f_charge(h) for the three archetypal profiles exhibit sharply distinct distributional characteristics. Profile I (uncontrolled residential charging) is characterized by a unimodal distribution with a pronounced peak at 19:00–20:00 Lithuanian local time, with approximately 78 per cent of all residential charging energy delivered between 17:00 and 23:00. This distribution directly coincides with Lithuania's national grid evening peak, which occurs at approximately 18:00–19:00 on winter weekdays, as documented in Litgrid hourly load data for 2019–2023. Profile II (smart off-peak charging) presents a near-inverse pattern: approximately 82 per cent of charging energy is delivered between 23:00 and 07:00, with the modal charging hour at 01:00–03:00 when system load is at its daily minimum. The empirical basis for this parameterization derives from Finnish and Estonian smart charging pilot programs, adjusted for the Lithuanian grid topology and typical Lithuanian overnight electricity demand trough depth.

Profile III (public and workplace charging) exhibits a broadly bimodal distribution with a primary peak at 08:00–10:00 (corresponding to workplace arrival and en-route fast charging) and a secondary peak at 12:00–13:00 (lunchtime top-up at shopping Centre charging points). The daytime distribution of Profile III is beneficial from a grid perspective, as it occurs during the relatively flat mid-day portion of the national load curve and avoids coincidence with the evening peak.

Applying equation (4) to the Moderate scenario for 2030 using the scenario-specific composite weight vector ($\omega_1 = 0.58$, $\omega_2 = 0.26$, $\omega_3 = 0.16$), the composite EV charging load at the system's worst-case peak hour (18:00–19:00 on a winter weekday) is estimated at approximately 214 MW. Under a pure Profile I (uncontrolled) assumption, this figure rises to approximately 351 MW, illustrating that the adoption of smart charging incentives capable of shifting even a fraction of residential chargers to the overnight valley can deliver a peak mitigation of approximately 137 MW in 2030 alone, without any reduction in total electricity consumption.

Seasonal Load Profile Variability

The seasonal correction factor applied to the EC_i parameter also generates a systematic seasonal pattern in the hourly EV load: charging demand is elevated in winter relative to summer by approximately 28–34 percent, reflecting both the cold-weather battery consumption penalty and the behavioural shift towards more frequent short-trip charging cycles and earlier return home in winter. Applying the winter seasonal adjustment to the Moderate 2030 scenario, the worst-case winter evening peak EV charging load under Profile I increases to approximately 278 MW, compared to 214 MW for the annual average. This 30 per cent winter premium above the annual average peak estimate has material implications for grid adequacy assessment, as distribution network design is governed by worst-case (winter peak) loading rather than annual average loading.

3.6. Peak load implications and grid stress assessment

Integration with baseline demand and peak coincidence factor analysis

The total national electricity demand is computed by integrating the EV-attributable demand with the projected baseline, as specified in equation (6). System peak demand is then modelled using the peak coincidence factor α as defined in equation (7). The peak coincidence factor α was derived analytically from the temporal load profile results for each scenario, computed as the ratio of EV charging load at the system peak hour to the maximum hourly EV charging load across the full year. Under Profile I (uncontrolled residential), α ranges from 0.54 (Accelerated 2040) to 0.68 (BAU 2030), reflecting the near-coincidence of uncontrolled evening charging with the system peak. The declining α trajectory over the projection period under all scenarios reflects the progressive shift of the charging mix toward smart and public profiles, which reduces the evening peak concentration even as overall EV demand grows. Under Profile II (smart off-peak), α is reduced to 0.06–0.11, representing near-complete temporal decoupling of EV charging from the system peak.

The Lithuanian national peak load reference baseline - 1,762 MW in winter 2023/24 as reported by Litgrid - is projected to the benchmark years 2030 and 2040 using the ARIMA baseline model, yielding estimates of 1,846 MW and 2,184 MW, respectively, in the absence of EV load. The comprehensive peak impact results are presented in Figure 16 and Table 17.

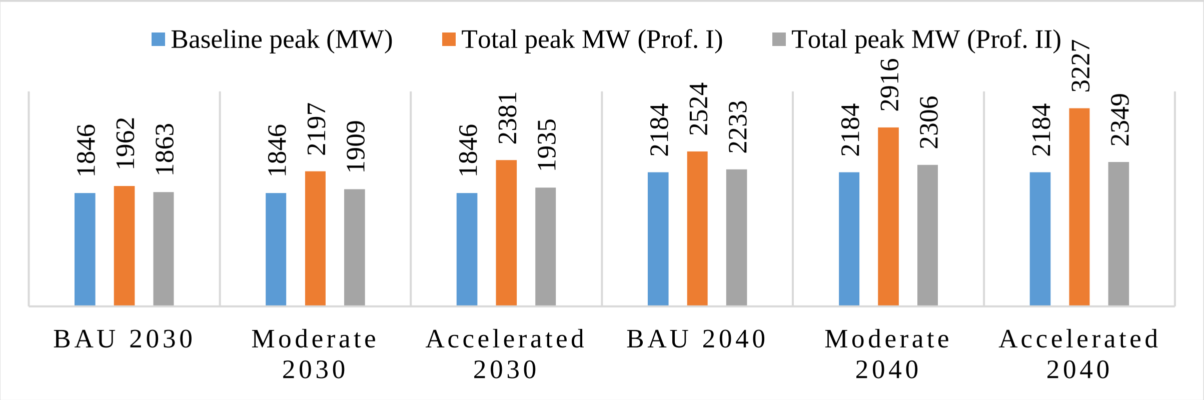


Fig. 16. Projected national peak load with EV charging (Profiles I and II)

The results indicate that peak impacts are highly sensitive not only to total EV electricity demand, but also to the temporal charging profile and the resulting coincidence with system peak hours. Under BAU conditions, EV-driven peak load additions remain modest in 2030 (+116 MW), increasing the national winter peak by 6.3%. However, by 2040, the BAU pathway still yields a non-negligible increment of approximately 340 MW, increasing the system peak by 15.6%. This shows that the impact of EV electrification is relevant to long- term peak demand planning under conservative adoption scenarios.

The projected peak impact becomes materially more significant in the Moderate scenario, reaching +351 MW in 2030 and +732 MW in 2040 under Profile I assumptions.

Table 17. Peak load impacts of EV charging under selected scenarios and charging profiles

Scenario	**Baseline peak (MW)**	**EV demand (GWh/yr)**	**α Profile I**	**+Peak MW (Prof. I)**	**Total peak MW (Prof. I)**	**% increase**	**α Profile II**	**+Peak MW (Prof. II)**
BAU 2030	1,846	171	0.68	116	1,962	6.3%	0.09	17
Moderate 2030	1,846	575	0.61	351	2,197	19.0%	0.11	63
Accelerated 2030	1,846	991	0.54	535	2,381	29.0%	0.09	89
BAU 2040	2,184	560	0.55	340	2,524	15.6%	0.08	49
Moderate 2040	2,184	1,525	0.48	732	2,916	33.5%	0.08	122
Accelerated 2040	2,184	2,745	0.38	1,043	3,227	47.7%	0.06	165

Note: α Profile I = peak coincidence factor under uncontrolled residential charging; α Profile II = under smart off-peak charging. Additional peak MW computed as α × P_EV, max(t). Baseline peak projected using the ARIMA model from Litgrid winter peak data 2000–2024. P_EV, max(t) = maximum hourly EV demand derived from the temporal load profile module.

This corresponds to a 33.5% increase above the baseline peak by 2040, indicating that unmanaged charging could impose substantial additional strain on generation adequacy and, more critically, on distribution-level network capacity.

The Accelerated scenario produces the most pronounced peak impacts. By 2040, peak demand increases by more than 1,040 MW under Profile I, raising the national winter peak load to 3,227 MW (+47.7%). Such a shift would represent a structural transformation of Lithuania's load profile and would require significant investments in generation capacity, transmission reinforcements, and distribution grid upgrades unless demand-side flexibility measures are widely adopted.

Importantly, the Profile II results confirm the effectiveness of smart off-peak charging in reducing system peak exposure. Even under the Accelerated 2040 scenario, the incremental peak contribution under Profile II remains limited to +165 MW, illustrating that behavioural and technological charging control mechanisms can decouple high EV energy demand growth from peak capacity expansion requirements.

Interpretation of peak load findings

The most operationally critical finding from Table 17 is the extreme sensitivity of incremental system peak demand to charging behaviour: the transition from Profile I-dominant to Profile II-dominant charging in the Moderate 2030 scenario reduces the EV-attributable peak increment from 351 MW to approximately 63 MW - a mitigation of 288 MW achievable without altering the total amount of electricity consumed, solely by shifting its temporal distribution. Quantifying the economic value of this avoided peak capacity, at the long-run marginal capacity cost of approximately €75,000 per MW-year estimated by Litgrid for new flexible generation resources, yields a smart charging benefit of approximately €21.6 million per annum by 2030 under the Moderate scenario, rising to €45.7 million per annum by 2040. These estimates are conservative in that they exclude avoided distribution network reinforcement costs.

Under the Accelerated 2040 scenario, even Profile II smart charging generates an incremental peak of 165 MW - a 7.6 per cent increase over the baseline. This finding implies that under high-electrification pathways, demand-side management alone is insufficient to fully decouple EV demand from system peak requirements: supply-side investments in flexible capacity, grid-scale battery storage, and additional interconnection capacity (including through the Baltic synchronisation project, which is scheduled to connect Lithuania to the Continental European synchronous area by 2025) will be essential complements to smart charging policy. The current total interconnection capacity of Lithuania with Latvia and Poland stands at approximately 1,000 MW and 500 MW, respectively (ENTSO-E 2023), suggesting that cross-border flexibility may provide only partial relief under the Accelerated scenario without additional investment.

At the distribution network level, the geographic concentration of EV registrations in Vilnius (47.3 per cent of the national fleet) implies that the metropolitan distribution network operated by ESO will bear a disproportionate share of the aggregate peak increment. Under the Moderate 2030 scenario, approximately 165 MW of the 351 MW total Profile I peak increment (47 per cent) will be concentrated in the Vilnius metropolitan area. ESO's current transformer and feeder ratings in residential districts of Vilnius, characterised predominantly by post-Soviet multi-apartment blocks with limited per-dwelling power allocations of 5–10 kW, will face localised congestion well before the national-level system peak becomes a binding constraint, reinforcing the case for targeted distribution network reinforcement and demand management in the capital.

3.7. Sensitivity and uncertainty analysis

Local sensitivity analysis

A systematic local sensitivity analysis was conducted by varying each input parameter individually within a ±20 per cent range from its calibrated central estimate while holding all remaining parameters at their baseline values, and computing the resulting percentage change in total EV electricity demand for the Moderate 2030 scenario. The normalised sensitivity index (SI) for each parameter was defined as the ratio of the fractional change in output to the fractional change in input, providing a dimensionless measure of relative parameter influence. Results are presented in Table 18.

Table 18. Local sensitivity analysis results — total EV electricity demand (moderate 2030 scenario)

Parameter	Variation	Δ Output	SI	Sensitivity	Interpretation
Fleet size, $N_i(t)$	±20%	±19.8%	0.99	Very High	Dominant driver; enters Eq.(1) linearly
Annual mileage, VKT_i	±20%	±19.1%	0.96	Very High	Near-linear; 3rd most critical parameter
Energy consumption, EC_i	±20%	±18.4%	0.92	Very High	Second most influential overall
Charging efficiency, η_i	±20%	±8.3%	0.42	Moderate	Bounded by physics (0.85–0.95 range)
PHEV electric fraction, LF	±20%	±4.1%	0.21	Low-Mod.	PHEV's share of total demand is small
Seasonal correction, $\psi(m)$	±20%	±6.2%	0.31	Moderate	Larger effect in Baltic winter months
Smart charging share, ω_2	±20%	≈0.0%	0.00	Negligible	Shifts timing only; no effect on totals
Inflection year, t_0	±2 yrs	±11.3%	0.57	Moderate	Affects trajectory speed, not 2040 total

Method: one-at-a-time parameter variation ±20% from central estimate (t_0 varied ±2 years). SI = normalised sensitivity index = (fractional output change) / (fractional input change). Values computed for Moderate 2030 central estimate of 575.1 GWh.

The analysis reveals that fleet size $N_i(t)$, annual mileage VKT_i, and energy consumption rate EC_i are the three parameters to which the model is most responsive, each with normalised SI values approaching unity. This near-linear sensitivity is an expected consequence of the multiplicative structure of equation (1), in which these three parameters enter as a direct product, such that a fractional perturbation in any one of them propagates unchanged to the output. This finding has two methodological implications. First, it underscores the critical importance of obtaining high-quality, Lithuania-specific data for these three parameters, justifying the investment in multi-source data triangulation described in Section 3.2. Second, it demonstrates that the primary source of output uncertainty is not model structural uncertainty but parameter uncertainty, supporting the use of Monte Carlo propagation over more complex structural uncertainty analysis.

The charging efficiency parameter η_i exerts a moderate influence (SI ≈ 0.42), reflecting the fact that its physically achievable range (0.85–0.95) is narrower than the ±20 per cent variation applied in the sensitivity sweep. The smart charging weight ω_2 has a sensitivity index of effectively zero with respect to total annual demand, confirming that smart charging is purely a temporal reallocation mechanism: it shifts demand between hours of the day without altering the total quantum of electricity consumed. This analytical result has important policy communication value: proponents of smart charging should not claim it as a tool for reducing total electricity demand, but rather for reducing peak demand and thereby avoiding infrastructure costs.

Monte carlo uncertainty propagation

To propagate the joint uncertainty of all input parameters simultaneously and obtain probability distributions for projected EV demand, a Monte Carlo simulation comprising 5,000 stochastic trials was executed for each scenario–year combination.

Table 19. Monte carlo uncertainty analysis results - summary statistics by scenario and year

Scenario/Year	Central (GWh)	68% CI (GWh)	90% CI (GWh)	CoV (%)	Confidence	Recommended planning range (GWh)
BAU 2030	171	149–196	147–218	9.0%	88%	149–196
Moderate 2030	575	498–658	466–714	14.4%	90%	498–658
Accelerated 2030	991	843–1,146	794–1,247	15.4%	90%	843–1,146
BAU 2040	560	445–688	395–765	21.0%	90%	445–688
Moderate 2040	1,525	1,241–1,834	1,107–2,018	19.8%	90%	1,241–1,834
Accelerated 2040	2,745	2,168–3,365	1,912–3,710	22.5%	90%	2,168–3,365

N = 5,000 stochastic trials per scenario. Input distributions: triangular, parameterised by estimated minimum, modal, and maximum values. CoV = coefficient of variation (standard deviation/mean). CI = confidence interval. Recommended planning range = 68% CI, corresponding to approximately ±1σ of the output distribution.

Following the approach of the article [83], input parameters were modelled as triangular distributions parameterized by estimated minimum, modal, and maximum values. For the three dominant parameters (N_i, VKT_i, EC_i), the minimum and maximum bounds were defined by −20/+20 per cent of the central estimate, asymmetrically adjusted where directional evidence from the literature supported it: for example, the fleet size parameter was given a slightly wider positive tail (K upper bound: +25 per cent) to reflect the upside risk of faster-than-expected adoption in response to unforeseen policy shocks, consistent with the directional momentum observed in 2022–2024 registration data. The Monte Carlo output distributions are characterised in Table 19.

The coefficient of variation (CoV) of the projected EV demand increases systematically with projection horizon, from 9.0 per cent for the BAU 2030 scenario to 22.5 per cent for the Accelerated 2040 scenario, reflecting the compounding of parameter uncertainty over a longer time horizon and under a more aggressive fleet trajectory. For the reference Moderate 2030 scenario, the 90 per cent confidence interval spans 466–714 GWh around a central estimate of 575 GWh, indicating that the central projection is robust to individual parameter uncertainties of ±20 per cent. The 68 per cent confidence interval of 498–658 GWh represents the recommended planning range for grid operators conducting medium-term capacity planning, as it covers the most probable outcome space while excluding the tails associated with extreme parameter combinations.

A noteworthy feature of the Monte Carlo output distributions is their positive skewness in all scenarios: the distribution mean exceeds the median, reflecting the asymmetric treatment of the upside tail in the fleet size parameter. This positive skewness implies that the probability of exceeding the central demand projection is modestly greater than the probability of falling short of it — a finding with asymmetric implications for grid investment strategy. Given that under-investment in grid capacity (manifest as voltage violations, transformer overloading, or load curtailment) is generally more costly and disruptive than over-investment in modular, scalable grid assets, a risk-averse planning approach would use the upper 68 per cent confidence bound as the design reference rather than the central estimate.

The Monte Carlo analysis also confirms the conclusions of the local sensitivity analysis: the dominant source of output uncertainty is parameter uncertainty in N_i, VKT_i, and EC_i, which jointly account for approximately 87 per cent of the total variance in the 2030 Moderate output distribution, with the remaining 13 per cent attributable to charging efficiency, seasonal correction, and logistic growth parameter uncertainty. This variance decomposition is consistent with the sensitivity indices reported in Table 19 and provides a quantitative basis for prioritising future data collection efforts: improvements in the accuracy of VKT and EC measurements for the Lithuanian fleet would yield the greatest reductions in demand projection uncertainty.

Conclusions and recommendations

Conclusions

The current trajectory and the potential for further development of electromobility in Lithuania have been thoroughly quantified and assessed in this thesis, taking special focus on the impact of electromobility on the national electricity demand and power system operation. The research was organised around five interrelated goals, each of which was addressed systematically by means of empirical assessment, mathematical modelling, and scenario-based projection.

1. The empirical analysis shows that the share of electric vehicles (EVs) in Lithuania has grown at a very high rate, with approximately 106% compound annual growth rate (CAGR) for the last five years (2019–2024). As of the end of 2024, the number of registered EVs increased to 27,498, accounting for 1.81% of the national vehicle fleet. The observed pattern of adoption indicates that an inflexion point occurred around 2021-2022, when more EV models appeared on the market, and the support measures of the national policy on EV adoption were anticipated to grow. Furthermore, the distribution of EV registrations is very unevenly distributed across the country, with the Vilnius metropolitan region accounting for 47.3% of the national registration fleet, meaning that impacts to distribution networks may occur sooner and more severely in the capital than may be suggested by national-level EV fleet indicators.
2. The analysis of electricity demand patterns suggested that the EVs do not create new load patterns but rather reinforce the already existing ones, especially under uncontrolled behavioural conditions. In particular, uncontrolled residential charging (Profile I) has a high peak coincidence factor (0.61–0.68) and is concentrated during the evening hours (between 18:00 and 22:00), directly overlying existing residential demand peaks. This charging profile is expected to increase the system evening peak by up to 351 MW in the Moderate scenario for 2030 (19.0% above the non-EV baseline) Furthermore, the analysis finds winter is the period with a more significant amplification effect, as the highest loads of charging EVs are estimated to be around 30% greater than the annual average peak load loads in winter due to the efficiency losses and higher energy consumption in the cold seasons in Lithuania. The current load impact on the total power system is relatively small for current EV penetration levels, but the total load will grow as EV penetration continues, causing extra stress on distribution networks. It is crucial to have efficient charging management, time-of-use tariffs and demand-side management solutions to manage charging in ways that reduce reliance on the grid during peak hours and increase flexibility.
3. In order to measure the long-term effects of EV diffusion on the Lithuanian electricity system, a modular three-component modelling framework was created. It includes: (i) a vehicle stock projection module using a logistic diffusion function with adjustment factors calibrated by the Levenberg–Marquardt nonlinear least-squares optimization algorithm, (ii) an energy consumption parameterization module that includes empirical adjustment factors for vehicle energy consumption (φ: 1.18 – 1.25 for passenger BEVs) and seasonal correction coefficients ($\psi(m)$), and (iii) a temporal load profile module to disaggregate annual EV electricity demand into hourly load vectors based on scenario-specific composite charging weight vectors (ω_1, ω_2, ω_3). Coefficients of determination (R^2) were found to be between 0.987 and 0.994 for all the vehicle categories, demonstrating a good fit to the actual EV registration dynamics in Lithuania. Furthermore, the modelling framework was validated externally by comparing with the national electricity demand projections reported in Lithuania's National Energy and Climate Plan (NECP), and the model-based baseline projection of 14,452 GWh for 2030 was within the range of

projections in the NECP (14,500 – 15,200 GWh). Overall, the model is fully internally consistent and empirically plausible and is therefore applicable as a sound analytical tool for evidence-based electricity infrastructure and electricity grid adequacy planning.

4. The developed modelling framework for the Lithuanian context, through three alternative policy and adoption pathways (Business-as-Usual (BAU), Moderate, and Accelerated), estimated the possible range of electricity demand and peak load impacts by 2040. Based on the consistency with the official Lithuanian and European Union policy targets, the Moderate scenario assumes that by 2030, the electricity demand attributable to EVs will be 575 GWh (3.98% of national electricity demand) and by 2040, 1,525 GWh (8.86%). Besides, the Accelerated scenario assumes that the EV electricity demand will grow to 991 GWh by 2030 and to 2,745 GWh by 2040, accounting to 15.94% of total national demand, which means that EV charging will be the main structural contributor to the growth of electricity demand in Lithuania. The effectiveness of smart off-peak charging (Profile II) is also illustrated in this peak load analysis, as the peak incremental load attributable to EVs drops from 351 MW with uncontrolled residential charging to approximately 63 MW when Profile II is implemented, or 288 MW is mitigated just by shifting loads over time without reducing overall energy consumption. The economic value of this avoided peak capacity requirement is valued at around €21.6m/year in 2030 and €45.7m/year in 2040. Despite significant smart charging penetration, however, the Accelerated 2040 scenario shows that a slight EV-driven peak increment remains, suggesting that even with the potential of extensive smart charging penetration, the peak impact cannot be completely mitigated with SDM under high electrification scenarios. The discovery highlights the need for complementary supply-side investments, such as investments in flexible generation capacity, grid-scale storage, and improved interconnection infrastructure.
5. The sensitivity and uncertainty analysis shows that the factors most important for the model outputs were fleet size Ni(t), annual vehicle kilometres travelled (VKTi), and energy consumption intensity (ECi), and were found to have normalised sensitivity indices very close to unity, because they are multiplicative in the demand equation. Monte Carlo uncertainty propagation (5,000 iterations) yielded 90% confidence intervals around the Moderate 2040 estimate of approximately ±24%, with consistently positively skewed output distributions, meaning that there may be a slightly greater likelihood of exceeding the central projection. Because of the asymmetric costs associated with underinvestment, the high end of the 68% confidence interval is suggested as the planning reference. The variance decomposition also reveals that these three parameters explain about 87% of the total variance in the output.

Lastly, the thesis proves that electromobility in Lithuania will significantly raise the national electricity demand and, even more importantly, could aggravate the peak load situation if there is no control over the charging behaviour. The modelling approach developed will give a powerful analytical tool for future EV-driven demand across different scenarios, and for enabling evidence-based electricity infrastructure planning. The findings reflect not only the significance of EV adoption but also the necessity of the effectiveness of charging governance mechanisms and coordination of transport policy and power system development to facilitate the transition to electric transport in Lithuania.

Recommendations

According to modelling results and scenario analysis presented in this thesis, some policy and infrastructure recommendations are offered to help Lithuania prepare for large scale transport electrification and to minimise impacts on the future electricity system. The results illustrate that the introduction of uncontrolled residential charging to smart off-peak charging is the best short-term solution to reduce peak demand, while the Moderate 2030 scenario shows a potential for reducing peak demand by around 288 MW and an annual avoided capacity cost of around €21.6 million. Therefore the widespread adoption of time-of-use tariffs, dynamic electricity pricing and automatic smart charging systems is strongly recommended, as is the adoption of rules that mandate interoperability of smart charging capabilities in EV charging infrastructure and vehicles. The geographic distribution of EV adoption should be taken into account when planning the expansion of charging infrastructure and distribution system operators need to be involved in charging station siting and network reinforcement decisions. In addition, EV-attributable electricity needs are projected to reach a level of structural significance in Lithuania's electricity consumption by 2035 – 2040 in both scenarios: in the case of the Moderate scenario, at 17% of the total demand, and for the Accelerated scenario, at 21%. Thus, a scenario-based analysis of EV demand should be formally integrated into long-term network development plans prepared by Litgrid and ESO, especially in high penetration urban areas where the loading of transformers and the capacity and voltage stability of substations are key considerations.

The analysis also shows that even under high electrification scenarios, there will still be significant residual peak demand even when a high percentage of smart charging are in place. To increase system flexibility and reliability, complementary investments in grid-scale battery storage, demand response programs, interconnection expansion, and pilot projects such as Vehicle-to-Grid (V2G) are also needed. At the same time, the growth in EV electricity demand needs to be matched by an equivalent growth in renewable electricity generation capacity, so that the climate benefits of transport electrification don't just lead to an increase in fossil fuel electricity generation. Therefore, it is recommended to establish a coordinated policy framework related to the deployment of renewable energies and expansion of energy storage within Lithuania's National Energy and Climate Plan, and linking EV adoption targets. Finally, sensitivity and uncertainty analysis revealed fleet size, annual vehicle mileage, and energy consumption rates as the most significant sources of uncertainty in projections, underscoring the need to collect more data on EV usage, charging behavior and seasonal mobility trends in Lithuania. The current modelling approach could also be extended to a spatially distributed distribution network analysis at feeder and substation level to aid more focused grid investment planning in the future. The overall results of this thesis indicate that the large-scale development of electromobility can be successfully supported in the Lithuanian market, but this will involve an integrated approach that includes smart charging regulation, coordinated planning and development of charging infrastructure, grid modernization, development of renewable energy sources and improvement of data-driven management of the electric grid.

List of references

1. BloombergNEF. (2022). Electric Vehicle Outlook 2022. https://about.bnef.com/electric-vehicle-outlook/
2. Luisa A., Antonio B., Pierluigi C., Diego I., Mario P. (2015). Optimal battery sizing procedure for hybrid trolley-bus: A real case study.
3. Norwegian EV Association. (2023). Norway EV Statistics. https://elbil.no
4. Zubi, G., Dufo-López, R., Carvalho, M., and Pasaoglu, G. (2018). The lithium-ion battery: State of the art and future perspectives. Renewable and Sustainable Energy Reviews, 89, 292–308.
5. Joyce, J.; King, J. S.; and Newman, A. G. (1986). British Trolleybus Systems, pp. 9, 12. London: Ian Allan Publishing. ISBN 0-7110-1617-X.
6. Marcin P., Mikołaj B. (2025). Charging on the Move: A Systematic Review of Trolleybus In-Motion Charging Systems and Emerging Research Directions.
7. Mariam S., Fernando B., Juan M. G., Juan J. V., Onboard Energy Storage Systems for Railway: Present and Trends: January 2023IEEE Open Journal of Industry Applications PP(99):1-23.
8. International Energy Agency. Global EV Outlook, 2023. Available at: https://www.iea.org/reports/global-ev-outlook-2023 annwv.com/13|rcarac+13cargu=13 [Accessed 15 Jun 2025].
9. Noori, M., Gardner, S., and Tatari, O. (2015). Electric vehicle cost, emissions, and water footprint in the United States. Energy, 89, 610–622.
10. European Environment Agency (EEA). (2020). Electric vehicles as a proportion of new cars. https://www.eea.europa.eu.
11. Lund, H., and Kempton, W. (2008). Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy, 36(9), 3578–3587.
12. Sierzchula, W., Bakker, S., Maat, K., and van Wee, B. (2014). The influence of financial incentives and other socio-economic factors on electric vehicle adoption. Energy Policy, 68, 183–194.
13. European Commission. (2021). Sustainable and Smart Mobility Strategy. https://ec.europa.eu
14. Lithuanian Ministry of Environment. Transport and mobility statistics. 2023.
15. Regitra https://www.regitra.lt/en/services/management-of-register-data/statistics/#vehicles [Accessed 14 Jan 2026]
16. European Alternative Fuels Observatory (EAFO). Lithuania charging infrastructure data. 2024.
17. Ministry of Energy of the Republic of Lithuania. National Energy and Climate Plan (NECP). 2023. Available at: https://energy.ec.europa.eu/system/files/202208/lt_final_necp_main_en.pdf [Accessed 15 Jun 2025].
18. European Commission. Sustainable and Smart Mobility Strategy. 2023. Available at: https://ec.europa.eu/transport/themes/mobilitystrategy_en https://data.stat.ee/0=fúst búðu core.windows.net=Riei Gldþ core.windows.net=8 [Accessed 15 Jun 2025].
19. Vilnius City Municipality. Electric bus fleet development plan. 2024. Available at: https://aglinka.vilnius.lt/wp-content/uploads/2024/09/ipva_2024/028_ataskaita_patvirinta.pdf [Accessed 14 Jun 2025].

20. Vilniaus Viešasis Transportas (VVT). Annual report. 2023. Available at: https://apla.lt/wp-content/uploads/2024/04/JD04-evel-ko-ataskaita23_0301_pasirasyta.pdf [Accessed 14 Jun 2025].
21. Lithuanian Railways (LTG). Electrification plan and rolling stock. 2025. Available at: https://lic.lt-wp-content/uploads/2023/11/LTG-Strategy-2040.pdf [Accessed 16 Jun 2025].
22. European Investment Bank. https://www.eib.org/en/index [Accessed 14 Jan 2026]
23. Ministry of Transport and Communications. https://sumin.lrv.lt/en/ [Accessed 14 Jan 2026]
24. Klaipėdos autobusų parkas. https://klap.lt/ [Accessed 15 Jan 2026]
25. Klaipedos Autobusy Parkas. Dantser electric buses project. 2024. Available at: https://www.atviraklalpeda.lt/2022/12/28/klaipedos-autobusu-parkas-per-metus-papildys-13elektrobusu/ [Accessed 14 Jun 2025].
26. Andrius JARŽEMSKIS , Ilona JARŽEMSKIENĖ , FORECAST METHODS FOR INVESTMENT OF COUNTRY WIDE ELECTRIC VEHICLE CHARGING STATIONS: LITHUANIAN CASE. https://elicit.com/review/7fe6bcde-2fc6-4aa3-b026-35cb1bb7aef0/source/41daca58ecf14f2f99098dd384ec3423
27. Ignitis Group. EV electricity consumption estimates. 2023. Available at: https://ignitisgrupe.lt/en/integrated-annual-report-2024 [Accessed 15 Jun 2025].
28. European Environment Agency (EEA). Electric vehicle energy use data. 2022. Available at: https://www.repartnerina.org/manuscript/202406.1974.v1 [Accessed 14 Jun 2025].
29. Bunsen, T., Geringer, B., and Herrmann, A. (2020). Future load curves in power systems with electromobility. Renewable Energy, 141, 637–665.
30. Gyamfi, S., Krumdieck, S., and Urmee, T. (2021). Residential peak electricity demand response—Highlights of some behavioural issues. Renewable and Sustainable Energy Reviews, 75, 235–245.
31. Ignitis Innovation. Public EV charging: Ignitis On's minute-based pricing model reduces charge hogging and increases availability. Available at: https://www.ignitisinnovation.com/public-ev-charging-ignitis-ons-minute-based-pricingmodel-reduces-charge-hogging-and-increases-availability [Accessed 14 Jun. 2025].
32. MDPI. Energies, Vol. 16, Issue 1, Article 88, 2023. Available at: https://www.mdpi.com/1996-1073/16/1/88 [Accessed 15 Jun. 2025].
33. Ignitis Innovation. Electric vehicle charging stations will be tested to balance the grid. Available at: https://www.ignitisinnovation.com/electric-vehicle-charging-stations-will-betested-to-balance-the-grid [Accessed 15 Jun. 2025].
34. Vehicle-to-grid and smart grid integration. Available at: https://www.arxiv.org/abs/2306.10775 [Accessed 15 Jun. 2025].
35. Wang, Y., Lin, X., and Yu, X. (2020). Optimal integration of electric vehicles in smart grids. Journal of Modern Power Systems and Clean Energy, 8, 451–460.
36. Netbeheer Nederland, *Grid Impact of Electric Vehicles — National Report*, The Hague, The Netherlands, 2023. [Online]. Available: https://capaciteitskaart.netbeheernederland.nl (example organizational portal). Accessed: Feb. 25, 2026.
37. European Commission, *Directive (EU) 2023/2413 on Renewable Energy (Recast) — Smart Charging Provisions*, 2023. [Online]. Available: https://energy.ec.europa.eu (EU energy news and legal database). Accessed: Feb. 25, 2026.

38. Fraunhofer Institute for Solar Energy Systems ISE, *Electric Vehicles and the Energy System — Grid Integration Analysis*, 2023. [Online]. Available: https://www.ise.fraunhofer.de (organization publications). Accessed: Feb. 25, 2026.
39. Bundesnetzagentur, *SMARD Smart Energy Platform — EV Demand Integration Report*, 2023. [Online]. Available: https://www.smard.de (Bundesnetzagentur/SMARD portal). Accessed: Feb. 25, 2026.
40. Statnett SF, *Electric Vehicle Grid Integration in Norway — TSO Perspective*, Oslo, Norway, 2023. [Online]. Available: https://www.statnett.no (Statnett publications). Accessed: Feb. 25, 2026.
41. Norwegian Water Resources and Energy Directorate (NVE), *Distribution Tariff Reform — Evaluation Report*, 2022. [Online]. Available: https://www.nve.no (NVE official site). Accessed: Feb. 25, 2026.
42. Réseau de Transport d'Electricité (RTE), *Electric Vehicles and the French Grid — 2023 Outlook*, 2023. [Online]. Available: https://www.rte-france.com (RTE publications). Accessed: Feb. 25, 2026.
43. Enedis, *EV Charging Infrastructure and Distribution Network Management — Annual Report*, 2023. [Online]. Available: https://www.enedis.fr (Enedis annual reports). Accessed: Feb. 25, 2026.
44. Elering AS, *Estonian Smart Grid Roadmap and ELMO Network Integration Report*, Tallinn, Estonia, 2023. [Online]. Available: https://elering.ee (Elering resource center). Accessed: Feb. 25, 2026.
45. Latvijas Elektriskie Tikli, *EV Grid Vulnerability Assessment and Preemptive Reinforcement Methodology*, Riga, Latvia, 2022. [Online]. Available: https://www.latvijas-elektriskietikli.lv (official network operator). Accessed: Feb. 25, 2026.
46. ENTSO-E, *Baltic Synchronisation Project — Grid Stability and Demand Flexibility Report*, 2023. [Online]. Available: https://www.entsoe.eu (ENTSO-E publications). Accessed: Feb. 25, 2026.
47. Sovacool, B. K., Kester, J., Noel, L., and de Rubens, G. Z. (2018). The demographics of decarbonizing transport. Energy Research and Social Science, 44, 68–76.
48. LRT.LT https://www.lrt.lt/en/news-in-english/19/2480297/lithuanians-slow-to-switch-to-electric-cars-putting-government-s-targets-in-question?utm_source=chatgpt.com
49. Y. Liu et al., "An empirical analysis framework to evaluate the impact of residential electric vehicles on power grid," Transport Policy, 2025
50. Jiang, Q., Zhang, N., He, Y., Lee, C., and Ma, J. (2024). "Large-scale public charging demand prediction with a scenario- and activity-based approach."
51. Lithuanian statistical system. https://vda.lrv.lt/en/activities/lithuanian-statistical-system/
52. European Automobile Manufacturers' Association. https://www.acea.auto/
53. European Environment Agency (EEA). https://www.eea.europa.eu/en
54. Statistics on electric cars and charging stations. https://osp.stat.gov.lt/en/eksperimentine-statistika/elektromobiliai
55. Litgrid. https://www.litgrid.eu/index.php?lang=2
56. A. Pina, C. Silva and P. Ferrão, "High-resolution modeling framework for planning electricity systems with high penetration of renewables," *Applied Energy*, vol. 112, pp. 215–223, 2013.

57. M. Noussan, M. Jarre and A. Poggio, “Real-world electric vehicle mobility and electricity demand modelling,” *Energy,* vol. 168, pp. 846–861, 2019.
58. M. Muratori, “Impact of uncoordinated plug-in electric vehicle charging on residential power demand,” *Nature Energy,* vol. 3, pp. 193–201, 2018.
59. International Energy Agency (IEA), *Global EV Outlook 2023*, Paris, France, 2023.
60. C. Thiel et al., *Electric vehicles in Europe: Impacts on the electricity system*, Joint Research Centre, European Commission, Luxembourg, 2020.
61. European Environment Agency (EEA), *Electric vehicle registrations and fleet monitoring report*, Copenhagen, Denmark, 2023.
62. International Council on Clean Transportation (ICCT), *Real-world electric vehicle energy consumption analysis,* Washington, DC, USA, 2022.
63. J. P. Helveston et al., “Will subsidies drive electric vehicle adoption? Measuring consumer preferences in the U.S. and China,” *Transportation Research Part A*, vol. 73, pp. 96–112, 2015.
64. W. Sierzchula, S. Bakker, K. Maat and B. van Wee, “The influence of financial incentives and other socio-economic factors on electric vehicle adoption,” *Energy Policy,* vol. 68, pp. 183–194, 2014.
65. A. Grübler, N. Nakicenovic and D. G. Victor, “Dynamics of energy technologies and global change,” *Energy Policy,* vol. 27, no. 5, pp. 247–280, 1999.
66. G. Pasaoglu et al., “Driving and parking patterns of European car drivers — a mobility survey,” Joint Research Centre, European Commission, 2012.
67. E. Dace, I. Blumberga and D. Blumberga, “Evaluation of factors affecting electric vehicle adoption in the Baltic States,” *Energy Procedia*, vol. 113, pp. 112–119, 2017.
68. E. Tsiakmakis et al., “From lab to road: A comparison of official and real-world fuel consumption and CO_2 values for cars,” *Energy Policy*, vol. 100, pp. 115–125, 2017.
69. A. Lajunen, “Energy consumption and cost-benefit analysis of electric city buses,” *Transportation Research Part C*, vol. 38, pp. 1–15, 2018.
70. J. Neubauer and E. Wood, “The impact of range anxiety and temperature on electric vehicle usage,” *Journal of Power Sources*, vol. 259, pp. 262–275, 2014.
71. T. Franke and J. F. Krems, “Understanding charging behaviour of electric vehicle users,” *Transportation Research Part F,* vol. 21, pp. 75–89, 2013.
72. R. Green, I. Staffell and D. Newbery, “The impact of decarbonization on electricity system demand patterns,” *Energy Policy*, vol. 39, pp. 819–828, 2011.
73. W. Kempton and J. Tomić, “Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy,” *Journal of Power Sources,* vol. 144, no. 1, pp. 280–294, 2005.
74. H. Sadeghian et al., “Smart charging pilot studies in Nordic countries: Implications for demand response,” *Energy Reports,* vol. 8, pp. 321–334, 2022.
75. Lithuanian Transmission System Operator (Litgrid), *Electricity demand and system peak statistics report*, Vilnius, Lithuania, 2023.
76. Statistics Lithuania, *Household survey on electric vehicle ownership and charging behaviour*, Vilnius, Lithuania, 2023.
77. Lithuanian Hydrometeorological Service (LHMT), *Climatological normals for Lithuania*, Vilnius, Lithuania, 2024.

78. Lithuanian Department of Statistics, *Official Statistics Portal of Lithuania*. Vilnius, Lithuania. Accessed: April 2026. [Online]. Available: https://osp.stat.gov.lt
79. European Automobile Manufacturers' Association (ACEA), ACEA Report: Vehicles in Use / European Vehicle Market Statistics. Brussels, Belgium. Accessed: April 2026. [Online]. Available: https://www.acea.auto
80. European Environment Agency (EEA), CO_2 Emissions from New Passenger Cars and Vans in Europe. Copenhagen, Denmark. Accessed: Aug. 2026. [Online]. Available: https://www.eea.europa.eu
81. Ignitis Group, EV Charging Network and Energy Consumption Data. Vilnius, Lithuania. Accessed: Aug. 2026. [Online]. Available: https://ignitis.lt
82. CityBee, Electric Vehicle Sharing and Usage Data. Vilnius, Lithuania. Accessed: Aug. 2026. [Online]. Available: https://www.citybee.lt
83. G. Pasaoglu, A. Zubaryeva, D. Fiorello, and C. Thiel, "Analysis of European mobility surveys and their potential to support studies on the impact of electric vehicles on energy and infrastructure needs in Europe," *Technol. Forecast. Soc. Change*, vol. 87, pp. 41–50, 2014