RIGA TECHNICAL UNIVERSITY
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IMPACT OF ELECTRIC VEHICLES AND CHARGING STATIONS ON THE DEVELOPMENT OF THE LATVIAN ENERGY SYSTEM AND ENVIRONMENTAL QUALITY

Doctoral Thesis

Scientific supervisor
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LATENERGI

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ANNOTATION

The main objectives of the state policy of Latvia are to create conditions for the sustainable development of the energy sector, fuel and electricity markets and reduce the consumption of fossil energy resources in order to improve the environmental situation. The Climate and Energy Policies of the European Union provide a reference point from which to view the progress achieved and the new targets for reducing energy consumption and greenhouse gas emissions progressively up to 2030 in Latvia. To meet these objectives, Latvia has adopted the Latvian National Development Plan for 2014 – 2020, which is associated with the Latvian Sustainable Development Strategy 2030 and the implementation of the National Reform Programme Strategy "EU 2020" aimed at improving the energy efficiency of apartment buildings, public and industrial buildings, infrastructure and municipal public spaces, heat and electric energy, and the use of alternative fuels in the transport sector.

In this regard, special attention should be devoted to the sustainable development of the transport sector, in particular road transport, which annually shows the largest increase in energy consumption and greenhouse gas emissions.

Within the framework of the Doctoral Thesis, the author has analysed the existing mathematical models, tools and methods for distribution network planning operation and management with electric vehicle charging infrastructure development, and come to the conclusion that despite the increased attention to the development of charging infrastructure, a number of theoretical and practical issues remain unresolved in Latvia.

The Thesis proposes an algorithm for examining and evaluating a local distribution network of a residential area and obtaining the optimal solution for creating electric vehicle charging infrastructure in active distribution networks. The algorithm allows modelling, setting targets and constraints, analysing behaviour and decision making. The proposed algorithm incorporates the analysis of large amount of real data and is based on mathematical methods. For completeness and accuracy studies, the algorithm is presented together with a test case.

In addition, based on the development of the road transport fleet, a scenario has been proposed for a long-term optimal distribution of energy resources in Latvia until 2030 and for a possible reduction in greenhouse gas emissions. Analysis of the scenario allows concluding that the goal set for 2030 can be achieved owing to the use of battery electric vehicles and plug-in hybrid electric vehicles, despite the expected increase of transport vehicle fleet.

The Doctoral Thesis has been written in English; it has been illustrated by 56 figures and 22 tables. The bibliography comprises 132 reference sources. The volume of the present Thesis is 138 pages.

ANOTĀCIJA

Latvijas valdības politikas galvenais uzdevums ir radīt apstākļus ilgtspējīgai enerģētikas sektora, degvielas un elektroenerģijas tirgus attīstībai un samazināt fosilās enerģijas patēriņu, lai uzlabotu vides stāvokli. Eiropas Savienības Klimata un enerģētikas politika ir orientieris, kā sasniegt progresu un minētos mērķus, lai Latvijā pakāpeniski samazinātu enerģijas patēriņu un siltumnīcu efekta gāzu emisijas līdz 2030. gadam. Lai sasniegtus šos mērķus ir pieņemts Latvijas Nacionālās attīstības plāns 2014. - 2020. gadam, kas saistīts ar Latvijas ilgtspējīgas attīstības stratēģiju 2030. gadam un Nacionālo reformu stratēģiju “ES 2020”. īstenošanu, kuras mērķis ir uzlabot daudzdzīvokļu, sabiedrisko un rūpniecības ēku energoefektivitāti un pašvaldību sabiedrisko ēku infrastruktūru, siltumenerģiju un elektroenerģiju, kā arī alternatīvā kurināmā izmantošanu transporta nozarē.

Šajā sakarā īpaša uzmanība jāpievērš ilgtspējīgai attīstībai transporta sektorā, īpaši autotransporta, kas ik gadu parāda lielāko pieaugumu enerģijas patēriņā un siltumnīcefekta gāzu emisijā.

Promocijas darba ietvaros autore ir analizējusi esošos matemātiskos modeļus, rīkus un metodes sadales tīkla plānošanas darbībai un vadībai ar elektrisko transportlīdzekļu uzlādes infrastruktūras attīstību un secina, ka, neskatoties uz lielāku uzmanību lādēšanas infrastruktūras attīstībai, teorētiskie un praktiskie jautājumi Latvijā joprojām nav atrisināti

Promocijas darbā piedāvāts algoritms dzīvojamo rajonu lokālo sadales tīklu izpētei un novērtējumam un optimālā risinājuma iegūšanai elektromobiļu uzlādes infrastruktūras izveidošanai aktīvos sadales tīklos. Algoritms ļauj modelēt, noteikt mērķus un ierobežojumus, analizēt un pieņemt lēmumus. Piedāvātais algoritms ietver lielu skaitu reālo datu analīzi un balstās uz matemātiskām metodēm. Pētījuma pilnīgumam un precizitātei algoritms tiek parādīts kopā ar testa gadījumu.

Turklāt, pamatojoties uz autotransporta flotes attīstību, tika piedāvāts scenārijs ilgtspējīgai energoresursu optimālai sadalei Latvijā līdz 2030. gadam un iespējamai siltumnīcefekta gāzu emisiju samazināšanai. Scenārija analīze, ļauj secināt, ka mērķi, kas noteikts 2030. gadam, var sasniegt, izmantojot akumulatoru elektromobiļus un hibrīds elektromobiļus, neskatoties uz sagaidāmo transportlīdzekļu parka pieaugumu.

Promocijas darbs ir uzrakstīts angļu valodā; to ilustrē 56 attēli un 22 tabulas. Bibliogrāfija satur 132 atsauces avotus. Promocijas darba apjoms ir 138 lapas.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my supervisor Prof., Dr.sc.ing. Irina Oleinikova for the patient guidance, valuable assistance, advice and invaluable support she has provided throughout all this time. I have been extremely lucky to have a supervisor who cared so much about my work.

I would also like to thank Leading Researcher, Dr.sc.ing. Gaidis Klavs and Dr.sc.ing. Janis Rekis for the suggestions and consultations really helpful for my research they made in reference to Chapter 4 of the Doctoral Thesis. Furthermore, I thank Gaidis Klavs for the great opportunity he has given me to conduct the research and not only for providing the funding which allowed me to undertake the research, but also for giving me the opportunity to attend conferences and meet interesting people. Moreover, I would like to thank all staff members of the Institute of Physical Energetics who helped me in my supervisor's absence.

Finally, I would like to thank the staff members of the Institute of Power Engineering for the support their provided throughout my Doctoral studies at Riga Technical University.

In particular, I would like to thank Prof., Dr.habil.sc.ing. Antans Sauhats for motivation he gave to me to accomplish my PhD project.

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Nomenclature

Active distribution networks	"Active distribution networks (ADNs) have systems in place to control a combination of distributed energy resources (DERs), defined as generators, loads and storage. Distribution system operators (DSOs) have the possibility of managing the electricity flows using a flexible network topology. DERs take some degree of responsibility for system support, which will depend on a suitable regulatory environment and connection agreement." (Ref.:www.etsi.org/WebSite/document/aboutETSI/EC_Mandates/m453%20EN.pdf)
British Petroleum (BP)	A British multinational oil and gas company headquartered in London. (Ref.:www.bp.com)
Central Statistical Bureau (CSB)	According to the laws of the Republic of Latvia, Cabinet Regulations and the By-Laws of the Central Statistical Bureau, the CSB is a direct administration body subordinated to the Ministry of Economics1 and acting as the main performer and coordinator of the official statistical work in the country. The CSB is responsible for organization of the statistical work and authenticity of the data it has produced by summarizing the information obtained from respondents. (Ref.:www.csb.gov.lv/en/about-us)
Consumer / End-user	Buyer of electric energy that does not resell. Often divided into groups (i.e. household, farming, industry, trade and services, public entities and holiday homes) (Ref.: www.lovdata.no/for/sf/oe/xe-19990311-0301.html)
Energy balance	A balance showing in a consistent accounting framework the production, transformation and final consumption of all forms of energy for a given geographic zone and a given period of time, with the quantities expressed in terms of a single accounting unit for purposes of comparison and aggregation. (Ref.: Energy dictionary.World energy council. 1992; 652 p; JOUVE SI; Paris (France); ISBN 2-909832-00-7)
Household	Consumer of electric energy in a house or apartment. Holiday homes and cottages are not included in this category. (Ref.: www.lovdata.no/for/sf/oe/xe-19990311-0301.html)
Primary energy	Primary energy that is has not undergone any transformation or conversion other than separation and cleaning resources (coal, crude oil, natural gas, solar power, nuclear power, etc.). (Ref.: www.iea.org/publications/freepublications/publication/energy-statistics-manual.html)

Power factor	The power factor is the phase angle between voltage and current (cosφ). (Ref.:www.grundfos.com/service-support/encyclopedia-search/power-factor.html)
Prosumer	A prosumer produces and consumes electricity, often through rooftop solar panels, and sells it back to the grid. (Ref.: www.wri.org/blog/2016/05/rise-urban-energy-prosumer)
Quality of supply	Quality of the delivery of electricity according to specific criteria. Quality of supply is often divided into: Reliability (interruption conditions); Voltage quality; Customer service / information to customers. (Ref.: www.lovdata.no/for/sf/oe/xe-20041130-1557.html)
Renewable energy	Energy from renewable energy resources (RES) including i.a. wind, solar, geothermal, ocean, hydro, gas from landfills, gas from sewage plants and biomass. (Ref.: www.lovdata.no/for/sf/oe/xe-20071214-1652.html)
Sensitivity analysis	Analysis performed to see the effect of changes in the underlying data. Testing the robustness of the results of a model in the presence of uncertainty in its inputs. Gives increased understanding of the relationships between input and output variables in a system or model. (Ref.: Wikipedia)
Secondary energy	Secondary energy that is obtained from a primary energy source employing a transformation or refining (oil products or electricity). Both electricity and heat can be obtained as primary and secondary energies. (Ref.:www.iea.org/publications/freepublications/publication/energy-statistics-manual.html)
Use case	A methodology used in system analysis to identify, clarify and organize system requirements. The use case is made up of a set of possible sequences of interactions between systems and users in a particular environment and related to a particular goal. (Ref.: www.searchsoftwarequality.techtarget.com/definition/use-case)

Abbreviations

ADS	Active distribution systems
CENELEC	European Committee for Electro technical Standardization
EU	European Union
EV	electric vehicle
GHG	greenhouse gases
MV	Medium Voltage, 1-35 kV, Distribution grid (Ref.: IEC 60038:2009)
LV	Low Voltage, 1-35 kV, Distribution grid (Ref.: IEC 60038:2009)
RES	Renewable Energy Sources
SGAM	Smart Grid Architecture Model
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle to Grid
V2H	Vehicle to Home
CO_2	Carbon dioxide
SOC	State-Of-Charge
PHEVs	Plug-in Hybrid Electric Vehicles
BEV	Battery Electric Vehicle
TSO	Transmission System Operator
V	Voltage
pu	per-unit
DSO	Distribution System Operator
c	The price of electricity in a particular hour
n	The number of EVs
m	The number of charging hour

INTRODUCTION

Energy development is the field of science and industry, which focuses on primary and secondary energy sources meeting the needs of society, including energy generation, transmission, distribution, energy transformation and rational use of energy.

The development of the energy sector determines the state of the economy, industry, agriculture and transport sectors in every country in the world. Under the conditions of the scientific and technological growth, the problem of providing consumers with energy, improving the quality of population's life and protecting our environment has become one of the most important issues of the second half of the 20th century and the early 21st century.

The investigation and analysis of energy problems have attracted attention worldwide. The annual production, import, export, consumption of energy resources and their distribution to sectors are reflected in the energy balance. The most important components of the energy balance are the following indicators of national economy: the gross domestic product (GDP), population, level of production of industry, agriculture, transport, services and labour productivity. The format of the energy balance assumed allows identifying the contribution of the primary and secondary energy sources to the national economy and is also the starting point for the analysis of energy efficiency and integrated planning of the long-term energy strategy. To assess strategic and integrated planning when adopting a short-term, medium or long-term energy strategy, the following indictors are used: the cost of energy resources and production of energy resources, energy distribution and provision of services and macroeconomic variables (foreign trade, inflation, the consumer price index (CPI), interest rates of available investment, etc.). A holistic picture of the economic concept of the energy industry related to the use of energy, regulation and management was detailed in the book "Energy Economics. Concepts, Issues, Markets and Governance" by Dr. Subhes C. Bhattacharyya [1].

It is also important to acquire an overall understanding of the situation in the energy sector in Latvia. For example, the analysis of the energy balance of Latvia shows that economic and social development has been of ambiguous nature since 1990 [2].

The largest decrease in the consumption of energy resources, more than twice, occurred from 1990 to 2000, during an economic decline. During the next 16 years, economic growth was observed, consumption of energy resources increased at an annual rate of close to 1.3 % from 2000 to 2016. The largest growth in consumption of energy resources was observed in the transport sector, where the indicators increased from 18 % in 1990 to 30 % in 2016. Crude oil and petroleum liquids that result from natural gas processing, including gasoline, diesel fuel are the main energy resources for the transport sector. The transport sector consists of road (passenger cars, trucks, buses and motorcycles), rail, water and air transport.

Policies of the European Union at the turn of the Millennium provide a reference point from which to view the progress achieved and the new targets for reducing greenhouse gas emissions progressively up to 2050. Key climate and energy targets that are set include: 2020 Climate and Energy Package and 2030 Climate and Energy Framework [3], [4].

These targets are defined to put the EU on the way to achieve the transformation towards a low-carbon economy. The longer-term perspective of transport strategy set out in the Energy Roadmap 2050 and the Transport White Paper for moving to a competitive low carbon economy in 2050 is also the main policy instrument to meet these objectives [5], [6].

Directives of the European Union are a flexible instrument mainly used as a means to harmonise national laws and requirements to achieve a certain result for EU countries.

The following documents have been adopted in Latvia: Latvian National Development Plan for 2014–2020, which is associated with the sustainable development strategy of the Latvian Sustainable Development Strategy 2030 and the implementation of the National Reform Programme Strategy "EU 2020" aimed at improving the energy efficiency of apartment buildings, public and industrial buildings, infrastructure and municipal public spaces, heat and electric energy, and the use of alternative fuels in the transport sector [7]–[9].

The plan for development of the road transport sector both worldwide and in Latvia, in particular, the expected growth in the number of electric vehicles not only will increase the demand for electricity, but also will prompt the profiles of peak daily load curve to change, which does not always have a positive effect on the work of local distribution networks. Subsequently, a need arises to either solve more network modernisation problems or to create the optimal planning of electricity supply for the all consumers. There are factors that should be considered when addressing this issue, such as:

- Electric vehicles will lead to an increase in energy demand, consequently requiring additional generation power.
- Simultaneous charging of electric vehicles at the same location will lead to overload of the distribution network.
- The existing model for energy distribution that depends on certain consumer's categories has to be analysed while installing new fast charging stations.
- Electricity tariffs have to be differentiated by respective times of the day.
- The possible applications of smart grid technology (SGT) for energy generation, distribution and management of electricity demand.

The mathematical, theoretical and practical foundations required for solving the tasks of electrical networks and systems, analysis and planning of long-term development of the national economy and environmental protection are widely described in books, scientific articles and research results of the Latvian and foreign scientists, such as: J.Barkans, J.Rozenkrons, A.Sauhats, V.Cuvicins, Z.Krihans, I.Oleinikova, A.Mutule, A.Mahnitko, S.Guseva, V.Zebergs, G.Klavs, J.Rekis, I. Kudrenickis and others.

The main objectives of the energy sector of the Latvian economic policy are to develop legislation in order to encourage the development of the energy sector and the implementation of energy saving policies and to improve the environmental situation in the country. The transport sector, in particular road transport, deserves special attention, which annually shows the largest increase in energy consumption and greenhouse gas emissions.

Thus, the subject of the Doctoral Thesis is topical; it aims at investigating the issues mentioned above and proposes smart solutions to evaluating and investigating the energy system in the case of integrating the potential fleet of electric vehicles into the electric power system of the country.

Topicality of the Doctoral Thesis

The quality of life, work and leisure of people are completely dependent on primary energy sources in all countries of the world. Modern technical possibilities of heat and power processing are not only aimed at creating favourable living conditions, but also at applying high technological equipment in all areas of human activity.

According to the BP Statistical Review of World Energy, primary energy consumption in the period from 1965 to 2016 increased by more than 3.5 times, which had a positive impact on economic development in several sectors of the economy, but exerted a negative impact on the environment, as a result of exposure to burning fossil fuels [10].

Moreover, the consumption by the transport sector is about 20 % of the total final consumption for a long time period. The same situation takes place in Latvia, where a large part of energy resources are consumed by the transport sector, accounting for 20 %–30 % of the annual final consumption of the country. In the transport sector it was 27.8 % of the total consumption in 2014, it was 29.7 % in 2015, and it was 30.3 % in 2016[1].

Greenhouse gas emissions in the transport sector increased by 6.1 % in 2015 compared to 2014 and decreased by 0.5 % in 2016 compared to 2015 mainly due to road transport, since 90 % of energy resources (petrol and diesel) are consumed by the road transport [11].

Adopting documents on financing of national economy sectors, the Ministry of Economics and the Ministry of Environmental Protection and Regional Development adhere to the "European Strategy for Clean and Energy Efficient Vehicles". The main priorities of the energy strategy are implemented: to ensure the economic efficiency by the reduced primary energy resources and the increased use of the renewable energy sources, as well as a quantitative increase of alternative fuels/technologies in road transport fleet, reducing the dependence of the transport sector on conventional fuels and climate change mitigation efforts. Electricity, hydrogen and compressed natural gas are the most commonly used alternative fuels in passenger cars, buses and light-duty vehicles (LDVs) [12].

All these aspects have determined the choice of the theme, objectives and content of the Doctoral Thesis.

The Hypothesis, Goal and Objectives of the Thesis

The number of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs) in Latvia will increase rapidly. The development of new EV models and better batteries happens fast. Electrical trucks and buses will also be more common within next years. All these developments will affect the planning and operation of the distribution network. The goal of the Doctoral Thesis is to contribute to the planning of the distribution system in order to

[1] Energobilance 2016. https://www.csb.gov.lv/lv/statistika/statistikas-temas/vide-energetika/energetika/meklet-tema/151-energobilance-2016-gada

support the transformation of today’s passive distribution network into the expected future active distribution network with a high number of EVs and PHEVs.

The objectives of the Thesis are to develop an algorithm for investigating the local distribution network in accordance with the technical requirements of electric transport, of the charging infrastructure and services; to evaluate and investigate the Latvian power system consumption up to 2030, which deals with the integration of electric vehicles into electric power systems by interaction of technical, ecological and economic aspects.

Methods and Tools of the Research

The methods and tools of the research include, but are not limited to:

- The database of the Central Statistical Bureau of Latvia.
- Eurostat database and publications.
- Statistical Review of World Energy.
- Standardization Mandate for Road Vehicles and Associated Infrastructure of World.
- Standardization Roadmap for Electric Vehicles.
- Processing, analysis and graphical representation of the results with MS Excel (the mathematical statistics methods, probability theory and the simplex mathematical optimisation method for linear programming task) and MATLAB (SimPowerSystems).
- Calculation of fossil fuel consumption, GHG emissions of road transport sector by COPERT 5 software.
- Energy and environmental analysis of historical and prediction indicators, the development of scenarios and comparison taking into account future uncertainties by using MARKAL model.

Scientific Novelty of the Thesis

- Latvian and world energy balances have been evaluated and classified by sectors of production and consumption over the period from 1990 to 2016[2].
- Electrical charging station technologies in the world and in Latvia have been researched and analysed.
- Algorithms have been developed to simulate and evaluate the impact of users of electric vehicles on the distribution network infrastructure and power supply system as a whole, in cities or districts.
- The development trends of the electric transport park in Latvia and its development potential until 2030 have been examined, taking into account the state energy policy guidelines.

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[2] Total Global Energy Balance data for 2017 will be public in 2019.
Summary of available Latvia Energy Balance data at the end of July 2018

- Energy balance has been developed by sectors and emissions in Latvia until 2030, with particular attention being paid to the road transport sector.

Practical Significance of the Thesis

The Doctoral Thesis addresses both fundamental science and practical issues. Its implementation will significantly contribute to the integration process of Latvia into a united European research area. The methodologies and algorithms proposed in the Thesis can be used as follows:

- by companies and organisations involved in the implementation of state policies in the road transport sector and the assessment of environment and natural resources;
- for conducting theoretical and scientific research related to the rational construction of power supply systems in cities or in districts, optimisation of parameters and development planning, taking into account the rapid development of smart grids, the introduction of new network elements and the active role of the end consumer;
- by energy companies and organisations involved in the technical assessment and development of power supply schemes in the city or its districts, design and modernisation of 0.4 kV networks and 20-10/0.4 kV transformer substations in accordance with the requirements of electric vehicle users (customers);
- for assessing the end-user’s participation in both the electricity market and the balancing market.

The Scope of the Thesis

To achieve the goals set, the following objectives have been formulated:

- to develop a new algorithm in order to investigate the local distribution network of a residential area and obtain the optimal solution for creating charging infrastructure on its territory of district, in accordance with the requirements of residents (owners of electric vehicles) at the same time ensuring the reliability of the power supply network in the urban or rural area;
- to evaluate and investigate the increase of electricity consumption and the reduction of fossil fuel consumption in Latvia until 2030, due to the integration of electric vehicles in the road transport sub-sector, as well as estimate the decrease of greenhouse gas emissions within the framework of the accepted national targets.

The results of the research have been partly presented in the projects:

1. National Research Programme (NRP) project “Energy Efficient and Low-Carbon Solutions for a Secure, Sustainable and Climate Variability-Reducing Energy Supply” (LATENERGI) 2015–2017. Project Manager: Dr.sc.ing. Gaidis Klāvs, Institute of Physical Energetics (IPE).

2. National Research Programme (NRP) project "The Value and Dynamic of Latvia's Ecosystems under Changing Climate" (EVIDEnT) 2014–2017. Project Manager: Dr.sc.ing. Gaidis Klāvs, Institute of Physical Energetics (IPE).
3. Riga City Sustainable Energy Action Plan for the Smart City 2014–2020. Riga Municipality Agency "Rīgas enerģētikas aģentūra" (REA). Approved by Decision No.1358 of Riga City Council, 8 July 2014.
4. National Research Programme (NRP) project "Development of Energy Electronics Technologies for Reduction of Electricity Consumption and Promotion of the Use of Renewable Energy Sources in Latvia" (EVIDEnT) for 2010–2013. Project Manager: Dr.sc.ing. Gaidis Klāvs, Institute of Physical Energetics (IPE).

Contracts:

1. Latvia's National Inventory Report. Submission under UNFCCC and the Kyoto Protocol. Common Reporting Formats (CRF). 1990 – 2016. 2018. 492 p.
2. Latvia's National Inventory Report. Submission under UNFCCC and the Kyoto Protocol. Common Reporting Formats (CRF). 1990–2015. 2017. 845 p.
3. National Research Programme (NRP) project "Energy Efficient and Low-Carbon Solutions for a Secure, Sustainable and Climate Variability-Reducing Energy Supply" (LATENERGI) 2015–2017. Project Manager: Dr.sc.ing. Gaidis Klāvs, Institute of Physical Energetics (IPE).
4. National Research Programme (NRP) project "The Value and Dynamic of Latvia's Ecosystems under Changing Climate" (EVIDEnT) 2014–2017. Project Manager: Dr.sc.ing. Gaidis Klāvs, Institute of Physical Energetics (IPE).
5. Upgrading the National Environmental Monitoring System (NEMS) of Azerbaijan on the basis of the EU best practices. Activity 4.2. Applying the Modernised Emission Inventory System for EMEP reporting. TWINNING MISSION REPORT No: 37/2018. November 2016 – January 2019. https://agora.fmi.fi/display/AZTWIN.
6. Latvia's National Inventory Report. Submission under UNFCCC and the Kyoto Protocol. Common Reporting Formats (CRF). 1990–2014. 2016. 782 p.
7. Calculation of direct and indirect greenhouse gas emissions from the transport sector by the COPERT IV model for 2014. IPE, the contracting authority: the Latvian Environment, Geology and Meteorology Centre, 2015.
8. Ministry of Environmental Protection and Regional Development of Latvia. "Calculation of Direct and Non-direct GHG Emissions in Transport Sector in Latvia by COPERT IV model (1990–2013)", description corresponding to IPCC Guidelines, IPE, 2014.
9. A study on the identification of effective measures to reduce greenhouse gas (GHG) emissions and the assessment of their costs. IPE, the contracting authority:

Ltd. Liepājas RAS and the Ministry of Environmental Protection and Regional Development of Latvia, 2014.

10. Riga City Action Plan for Smart City Calculation of GHG Emissions for 2012–2014, GHG forecast for 2020 and methodology development. IPE, the contracting authority: Riga Municipality Agency "Rīgas enerģētikas aģentūra", 2014.
11. Calculation of direct and indirect greenhouse gas emissions from the transport sector by the COPERT IV model for 2012. IPE, the contracting authority: the Latvian Environment, Geology and Meteorology Centre, 2014.
12. National Research Programmes (NRP). NRP "Innovative Technologies of Extraction and Utilisation of Energy Resources and Ensuring Low Carbon Emissions by Renewable Sources, Support Activities to Limit Degradation of Environment and Climate Change", project "Integrated Planning of Latvia's Energy Supply and Demand Systems by Taking into Account Environmental and Economical Factors", IPE. 2010–2014.
13. Ministry of Environmental Protection and Regional Development of Latvia. "Preparation of Projections of Latvian Direct and Indirect GHG Emissions up to 2020 and 2030 according to the Requirements Defined by the UN FCCC Kyoto Protocol and EU's Legal Documents"; IPE. 2013.
14. Ministry of Environmental Protection and Regional Development of Latvia. "Calculation of Direct and Non-direct GHG Emissions in Transport Sector in Latvia by COPERT IV model (1990–2012)", description corresponding to IPCC Guidelines, IPE, 2013.
15. Ministry of Environmental Protection and Regional Development of Latvia. "Calculation of Direct and Non-direct GHG Emissions in Transport Sector in Latvia by COPERT IV model (1990–2011)", description corresponding to IPCC Guidelines, IPE, 2012.
16. National Research Programme (NRP) project "Development of Energy Electronics Technologies for Reduction of Electricity Consumption and Promotion of the Use of Renewable Energy Sources in Latvia" (EVIDEnT) for 2010–2013. Project Manager: Dr.sc.ing. Gaidis Klāvs, Institute of Physical Energetics (IPE).
17. EEZ and Norway Financial Instrument. "Climate Policy Assessment and Integration Methodology Development for the New EU GHG Emission Commitment in Latvia" within the Environmental Policy Integration Programme in Latvia 2009–2011.
18. Ministry of Environmental Protection and Regional Development of Latvia. "Calculation of Direct and Non-direct GHG Emissions in transport sector in Latvia by COPERT IV model (1990 – 2010)", description corresponding to IPCC Guidelines, IPE, 2011.

Approbation of the Doctoral Thesis

The results of the research have been presented and discussed in 17 scientific conferences and published in 16 international journals and proceedings.

Conferences

1. 17th International Multi-Conference on Reliability and Statistics in Transportation and Communication (RelStat'17). Transport and Telecommunication Institute. 18–21 October 2017, Riga, Latvia.
2. 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 12–13 October 2017, Riga & Mezotne, Latvia.
3. 8th International Scientific Symposium on Electrical Power Engineering ELEKTROENERGETIKA 2017, 12–14 September 2017, Stara Lesna, Slovak Republic.
4. 57th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 13–14 October 2016, Riga & Cesis, Latvia.
5. 13th International Conference on the European Energy Market (EEM) FEUP, 6–9 June 2016, Porto, Portugal.
6. 15th International Multi-Conference on Reliability and Statistics in Transportation and Communication (RelStat'15). Transport and Telecommunication Institute. 21–24 October 2015, Riga, Latvia.
7. 8th International Scientific Symposium on Electrical Power Engineering ELEKTROENERGETIKA 2015, 16–18 September 2015, Stara Lesna, Slovak Republic.
8. 5th International Conference on Power Engineering, Energy and Electrical Drives. POWERENG 2015, 11–13 May 2015, Riga, Latvia.
9. 11th International Conference on the European Energy Market (EEM), 28–30 May 2014, Krakow, Poland.
10. 11th International Conference of Young Scientists on Energy Issues (CYSENI), 29–30 2014, May, Kaunas, Lithuania.
11. 3rd International Doctoral School of Electrical Engineering and Power Electronics, 23–24 May 2014, Ronishi, Latvia.
12. 71st Conference of the University of Latvia on Environmental Management. 7 February 2013, Riga, Latvia.
13. 5th Scientific and Practical Seminar "The Economic Security of the State and the Scientific and Technological Aspects of its Provision", 21–22 October 2013, Kiev, Ukraine.
14. 2nd International Doctoral School of Electrical Engineering and Power Electronics, 24–25 May 2013, Ronishi, Latvia.

15. 54th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 14–16 October 2013, Riga, Latvia.
16. 4th Scientific and Practical Seminar "The Economic Security of the State and the Scientific and Technological Aspects of its Provision", 23–26 October 2012, Dnepropetrovsk, Ukraine.
17. 70th Conference of the University of Latvia on Environmental Management. 9 February 2012, Riga, Latvia.

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1. ENERGY BALANCE, ENERGY SYSTEM AND GREENHOUSE GAS EMISSIONS

The electric power industry is one of the most important energy industries of any country and the world community as a whole, which covers the generation, transmission, distribution and sale of electric power to the industry, transport and households. The increase in electricity consumption and resource depletion require careful monitoring of the world energy situation, as fossil fuels are limited resources.

In order to get a clear picture of the situation of energy resources, an overall energy balance (referred to as "energy balance" in Chapter 1) is used. This format is an accounting framework for the compilation and reconciliation of data on import, export and consumption of all energy resources within the territory of a country during a reference period. It gives information about the fuel conversion and energy demand efficiency, including energy dependence, safety and efficiency.

Energy balance format is used for the analysis of the existing energy system potential of the country, and it assesses the preparation of short, medium and long-term forecasts that are essential aspects of the economic planning process and environmental problem solving in a country. The data of the energy statistics and methodology are given in the book "Energy Statistics Manual" [13]. The international recommendations on energy statistics are presented in the United Nations documents, with the time interval of 5 years, taking into account that the reference year is 2015 [14]. The main provisions of these documents are included in national methodologies and guidelines, when drawing up the energy balance of Latvia.

1.1. Energy balance as an integrated energy system worldwide

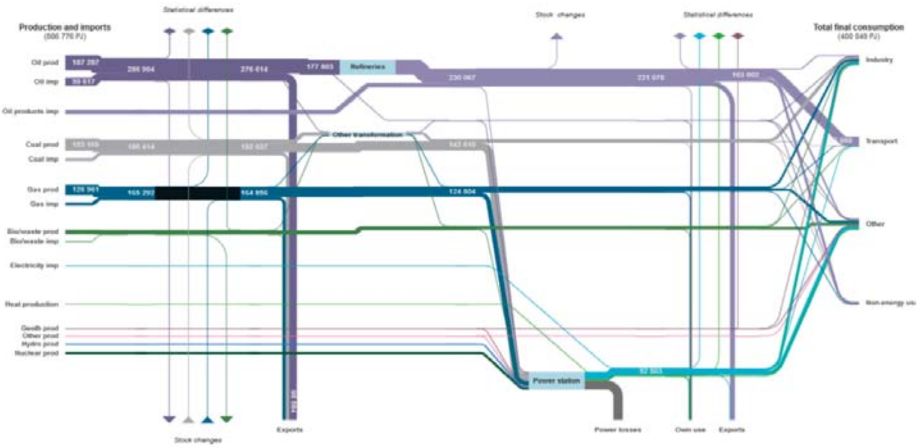
Since 1973, the International Energy Agency (IEA) has been issuing the Annual World Balance Overview for over 150 countries and regions. To better understand the entire process from Production and Imports to Total Final Consumption, the World Energy Balance Chart is compiled. Figure 1.1 shows the Global Energy Balance 2016 [15].

For data collection, the information base of the energy sector of each country is used. It can be subdivided into three main levels: Global and National Energy Level, Consumption and Distribution Level, Energy Resource Level. Transformation of the three main levels into the world energy balance is schematically illustrated in Fig. 1.2.

Global and National Energy Level: the current policy and institutions of global energy management (The Politics and Institutions of Global Energy Governance) covering all countries of the world.

Consumption and Distribution Level: the current policy and institutional changes to support energy management in the sectors of national economy of all the states.

Energy Resource Level: statistical data on extraction, production, transportation of primary and secondary energy resources and implementation of all co-operative trade and legal contracts.



Source: https://www.iea.org/Sankey/#?c=World&s=Balance)

Fig. 1.1. Flow diagram of the World Energy Balance 2016.

The starting points for the energy balance are the indicators of all the types of the used energy resources shown in natural units. To calculate energy balance in a single unit of measurement, for example, in terajoules (TJ) or thousand tonnes of oil equivalent (ktoe), the appropriate conversion factors for each individual type of fuel and energy are used.

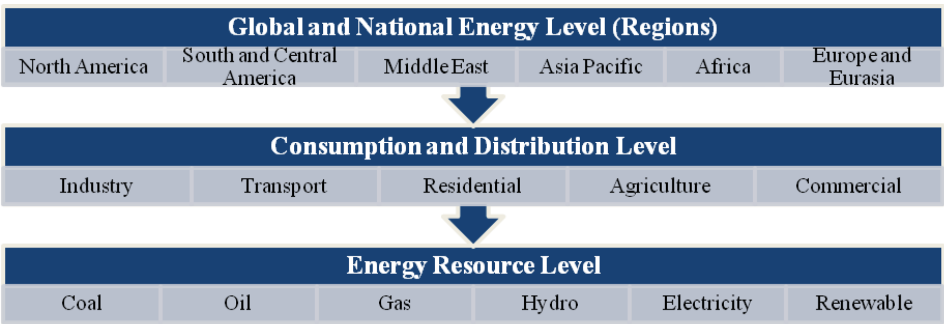


Fig. 1.2. Block scheme of multi-level interaction of the global energy balance.

To evaluate the data collected and the final consumption figures in a certain country or in the entire world, the information on supply, transformation and demand is required, which is shown in Table 1.1.

Information on supply includes a system of indicators characterising the structure of the production process and all types of energy resources (primary energy and secondary energy), including their imports, exports, etc. However, it must be noted that the amounts and types of primary and secondary energy sources used differ in each country and depend on availability of the domestic energy sources (including renewable energy sources) and on imports of energy resources.

Table 1.1

Information on the Energy Balance

Supply	Transformation	Demand
Production (+) Recycled products (+) Imports (+) Exports (-) Bunkers (-) Stock change (+ /-)	Consumed in the transformation sector Produced in the transformation sector Transmission and distribution Losses (-)	Final energy consumption
Energy resources: Primary energy Secondary energy	Electricity plants, public CHP plants, auto-producer CHP plants, public heat plants, auto-producer heat plants, utilised heat, production of peat briquettes, charcoal production etc.	Agriculture Industry Transport Residential Commercial Non-energy uses (lubricants, white spirit, bitumen, etc.)

Information on transformation reflects the structure of energy producers (public plants, public CHP plants, etc.) and their own needs and losses in the process of transmission and distribution of energy.

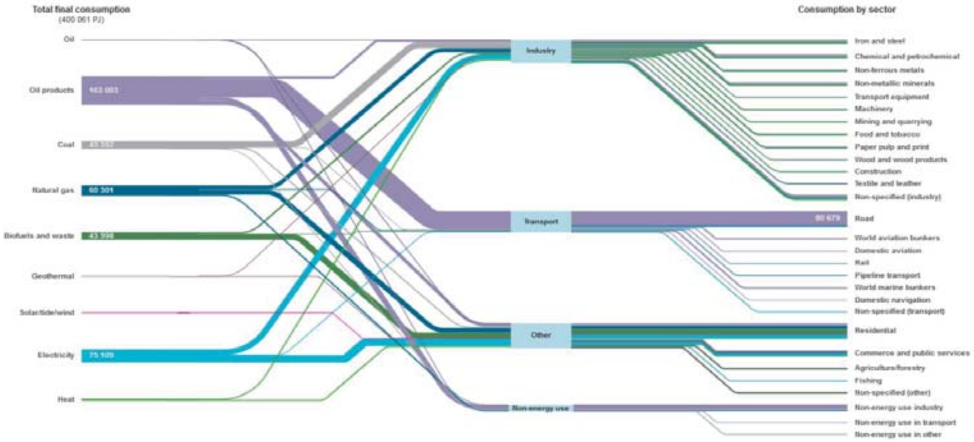
Information on demand reflects the energy flows available to end users. The final figures on the energy consumption in the all by-sectors of the economy are necessary for understanding the existing rates of development.

As an example, the 2016 World Final Energy Consumption is shown in Fig. 1.3, where the width of the flows is proportional to the amount of energy consumption by the sectors.

According to the BP Statistical Review of the World Energy Consumption, global consumption of energy resources has increased more than 3.5 times over the past fifty years. Up to the year 2000, the world energy resources had been consumed as follows: more than 60 % – by North America, Europe and Eurasia regions, less than 30 % by Asia Pacific and about 10 % by South and Central America, Middle East and Africa, as indicated in Fig. 1.4 [16].

Since 2002, there have been significant quantitative changes, putting the Asia-Pacific region on par with North America, Europe and Eurasia regions. In 2015, 42 % of the total final consumption of Asia Pacific became commensurable with 41.9 % and with 42.1 % in 2016 of the total final consumption of North America, Europe & Eurasia regions. The Asian region has shown an increase in demand for energy in all sectors of the national economies, mainly owing to the high consumption figures of India and China. In South and Central

America, Middle East and Africa consumption has also been increasing, but at a lower rate and in smaller amounts.



Source: http://www.iea.org/Sankey/#?c=World&s=Final%20consumption

Fig. 1.3. World final energy consumption 2016 in the flow diagram.

The quantitative changes in the regions depend on the presence or absence of local sources of energy, their geographical proximity to the countries importing hydrocarbons, the level of development of industry and transport, the specifics of consumption and other factors determining the trends and the pace of development in each region as a whole.

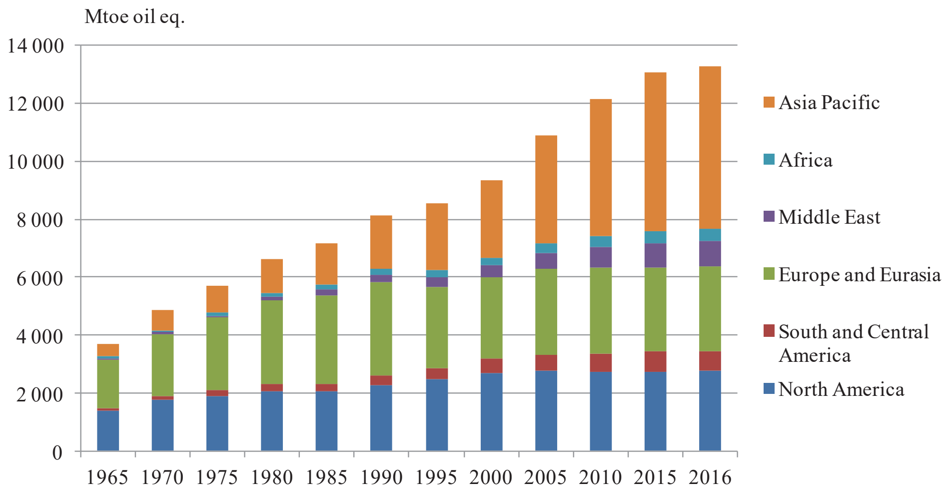


Fig. 1.4. World energy consumption by the region, 1965–2016.

Oil, gas and coal were the primary energy carriers of global demand over the considered period of time (see Fig.1.5). In the graph, the dynamics of consumption of energy resources is shown by the type of energy.

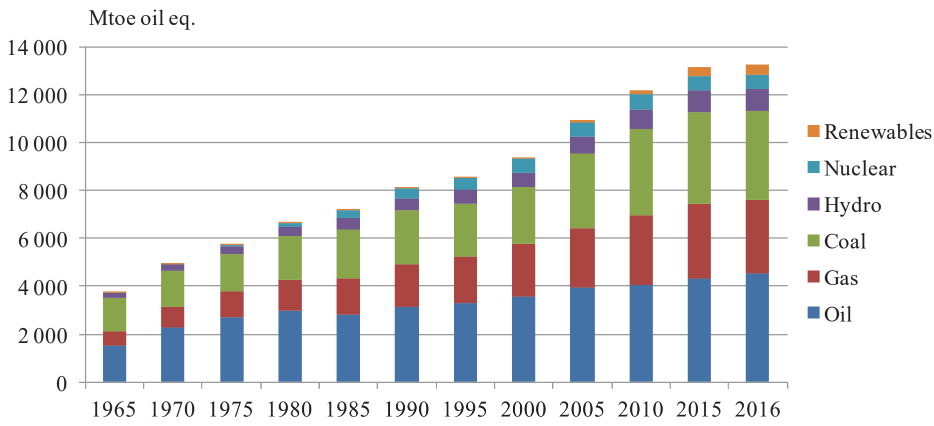


Fig. 1.5. World primary energy consumption by the type of resources.

It shows a slow shift towards a decrease in the consumption of hydrocarbons and looks as follows:

- **1965:** 40.9 % oil, 37.6 % coal, 15.7 % gas, 5.6 % hydro, 0.2 % nuclear and 0 % renewable energy sources.
- **2000:** 38.2 % oil, 25.3 % coal, 23.3 % gas, 6.4 % hydro, 6.2 % nuclear and 0.6 % renewable energy sources.
- **2015:** 32.9 % oil, 29.2 % coal, 23.9 % gas, 6.8 % hydro, 4.4 % nuclear and 2.8 % renewable energy sources.
- **2016:** 34.4% oil, 28.0% coal, 23.2% gas, 6.9% hydro, 4.5% nuclear and 3.1% renewable energy sources.

BP Statistical Review of World Energy (BC SRWE) also shows the structure of an average annual growth rate in 1965–2016. As for the type of energy resources, there is a great difference in the average annual growth figures in the periods from 1965 to 1999 and from 2000 to 2016. In the BC SRWE Report on the Average Annual Growth, they are distributed as follows: between 1965 and 1999, 2.58 % of oil is consumed, 3.85 % of gas, 1.48 % of coal, 3.14 % of hydro, 15.06 % of nuclear sources and 12.07 % of renewable energy sources (wind, solar, geothermal and biomass); between 2000 and 2016, 1.25 % of oil is consumed, 2.56 % of gas, 3.30 % of coal, 2.63 % of hydro, 0.17 % of nuclear sources and 13.74 % of renewable energy sources.

However, it should be noted that over the past sixteen years, significant changes in the field of hydrocarbons have been mainly associated with financial crises that have worsened economic performance in almost all countries of the world. At the same time, oil is still the dominant energy source (it accounts for more than one third of the primary energy resources), although gas and renewables are slowly and gradually replacing oil. Gas and coal also remain stable energy resources; their competitiveness has increased owing to the low production costs. Worldwide development in the field of hydroelectric power is slow. Production and consumption of nuclear energy has declined after the accident at Fukushima plant in Japan (2011), and nuclear power development programmes have been closed in several European countries since 2012. Globally, the share of power production using renewable energy sources remains less than 3 %, although in some geographic areas a certain progress is observed.

Thus, it may be concluded that many world regions are dependent on imports of fossil fuels as their domestic resources are depleted or extraction is too costly. Some countries have also started investing in renewable energy sources that generate electricity from such alternative sources of energy as wind, solar power, waves; a new trend is to use animal manure, household and plant waste for the same purpose. However, the investments in these new ways of energy production are insignificant.

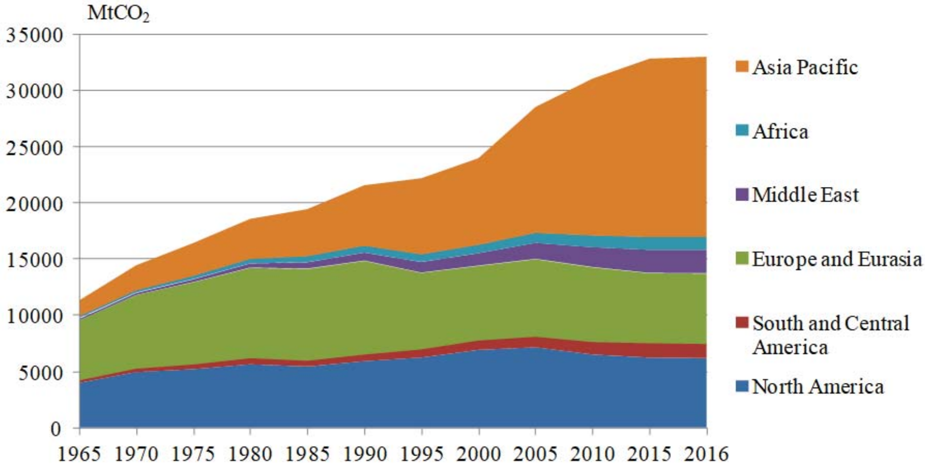
1.2. Worldwide Greenhouse Gas Emissions

Production of energy and consumption of energy resources are closely interrelated with the problems of pollution and quality of the environment. Carbon dioxide (CO_2), methane (CH_4), and nitric oxide (N_2O) are the greenhouse gases (GHGs), emissions of which have the major effect on the climate, with CO2 by far the most significant effect. Therefore, the Global Greenhouse Gas Emissions data (kt of CO_2 equivalent) are of greatest importance in making assessment of the world economy. Annual total greenhouse gas emissions are presented in the reports of the European Environment Agency, British Petroleum and PBL Netherlands Environmental [16], [17]. The report “CO_2 and Other Greenhouse Gas Emissions” provides an extensive analysis of the historical and modern perspectives of the global and regional trends in CO_2 emissions between 1900 and 2017 [18].

These historical data suggest that over the last fifty years, from 1965 to 2016, global CO_2 emissions almost tripled, from 11357.79 Mt to 33017.6 Mt, as it is shown in Fig. 1.6.

Between the years 2000 and 2016, a significant growth by 8,301.8 Mt or 107.6% was recorded in Asia Pacific. Other facts of growth by more than 400 Mt were registered in the Middle East (966.3 million tonnes, 88.5%), South and Central America (411.3 million tonnes, 44.9%) and Africa (412.3 million tonnes, 53.4%). Decline in CO_2 emissions was registered as follows: in North America – by 723.7 million tonnes, or 10.5 %; in Europe and Eurasia – by 353.8 million tonnes, or 5.3 %.

Comparison of indicators for the years 2000 and 2016 shows an increase of 37.6 %, but from 2014 to 2015 there was a decline of 0.12 %, which suggests that the tendency for decrease in global annual emissions of CO_2 can either continue or stabilize. It proves that even under the conditions of steady growth of energy consumption there is a possibility to slow down and harness the growth of emissions.



Source: BP Statistical Review of World Energy 2018://www.bp.com

Fig. 1.6. World CO_2 emissions in the world regions, 1965–2016.

In addition, the main sources of greenhouse gas emissions are divided into the following economic sectors: energy (electricity and heat production, transport, industry, residential); industrial processes and product use (IPPU), agriculture, land use, land use change and forestry (LUCF), waste and other energy. Over the period under review, the energy sector has been the leader in GHG emissions (nearly 60 %); the second largest emitter has been the land use change and forestry sector (nearly 24 %).

1.3. Analysis of Segments of the Latvian Energy Sector

1.3.1 Overview of the Energy System of Latvia

In Latvia, the entire energy production is concentrated at hydropower plants and combined heat and power plants where renewable energy sources (water, wood and wind) and fossil fuels (natural gas and diesel) are primary fuels. The main electricity and heat producers are the Daugava hydropower plants (Keguma HPP, Plavinu HPP, and Riga HPP), Aiviekste HES, Ainazi WPP, Kegums boiler house and two Riga Combined Heat and Power (CHP) plants, namely: Riga TEC-1 and Riga TEC-2.

According to the information on sustainability and Annual Report 2015 by Latvenergo Group, the installed capacity of the Daugava HPPs is as follows: 264.1 MW is the capacity of Kegums HPP, 868.5 MW of Plavinas HPP and 402 MW of Riga HPP. Their work schedules are designed for peak, half-peak and emergency modes of operation as generation of electricity depends on the water inflow in the Daugava River. In 2015, electricity generation at the Daugava HPPs was 1.805 GWh, which is 6.2 % less than in the previous year and 50 % less than in 2012 (Fig. 1.7). The decrease in generation can be explained by the ongoing reconstruction, which is to be completed in 2022 [19].

Both CHPPs have total installed electrical capacity of 1025 MWel and thermal energy capacity of 1617 MWth, and they work in the co-generation mode. In 2015, they produced 2175 GWh of thermal energy, which is 6 % less than in 2014 or 18.6 % less than in 2010 and 2025 GWh of electricity generated is 23 % more compared to 2014 or 15.7 % less compared to 2010.

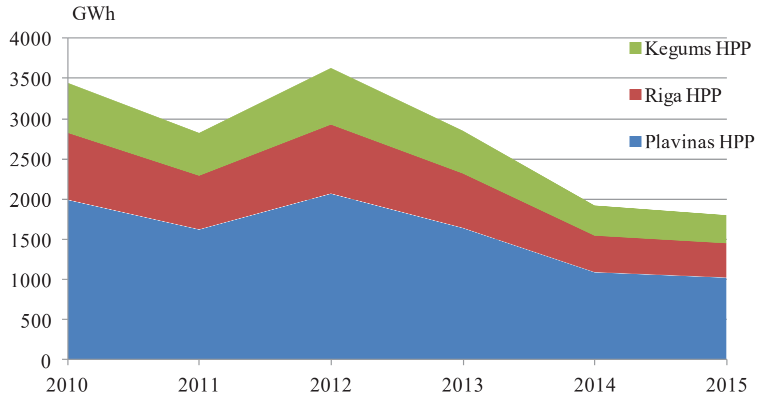


Fig. 1.7. Electricity generation at the Daugava HPP, 2010–2015.

As shown below in Fig. 1.8, the trends in energy generation at Riga CHPPs depend on the thermal energy and electricity demands determined by duration of the heating season and operational modes under market conditions.

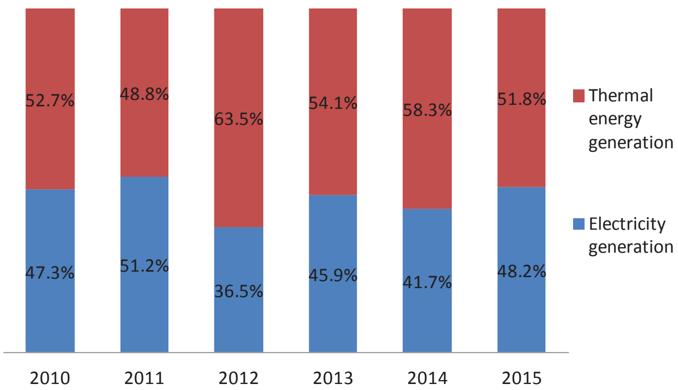


Fig. 1.8. Generation at Riga CHPPs, 2010–2015.

The power system of Latvia also includes Liepaja CHP, Ainazi wind power plant, Aiviekste HPP, Kegums boiler house and smaller boiler houses and power plants.

In 2015, the total electricity output at the small boiler houses and power plants was approximately 0.1 % of the total output. Theoretically, according to the information provided by Latvenergo Group, about 146 small power plants are capable of producing about 300 GWh of electricity per year. However, the reported (practically implemented) figures are 20 % to

30 % lower than the theoretical ones as the production capacity of the smaller power plants has the limitations on the use of hydro resources imposed by the law in force on protection of the environment as well as by the weather and landscape conditions.

1.3.2 Energy Balance of Latvia

First of all, the energy balance data for Latvia between 1990 and 2016 show the state of economic development of the country over this time period (see Fig. 1.9). By 2000, the main indicators of the gross inland energy consumption and the final energy consumption of the country had fallen by half. Then, over the following sixteen years, a gradual increase in production and consumption was observed. In 2016, gross inland energy consumption rose by 12.7 % and final energy consumption rose by 17.7 % compared to 2000 [20].

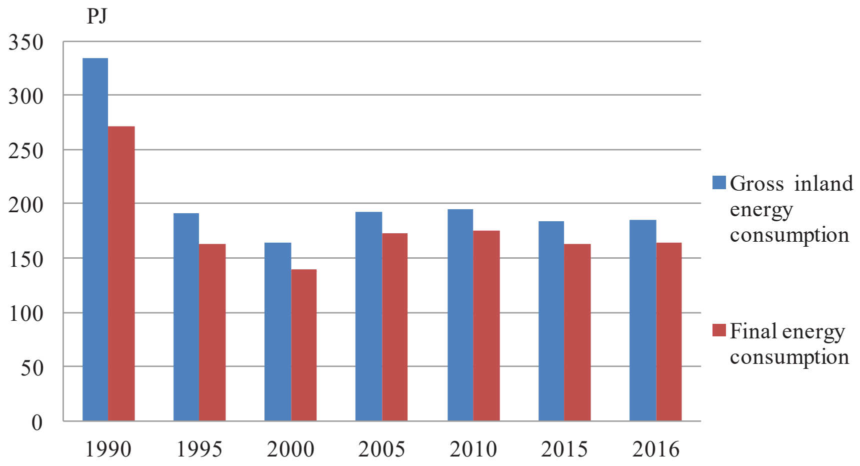
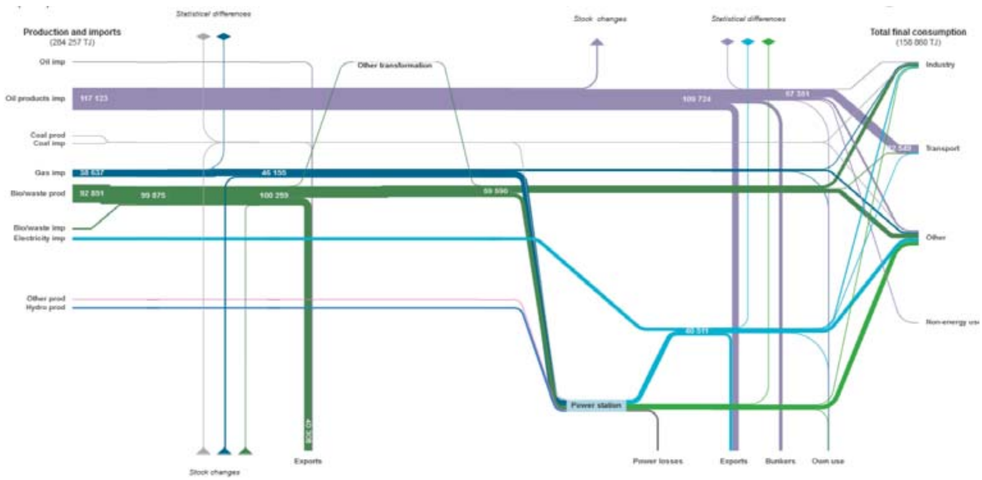


Fig. 1.9. Energy balance of Latvia: Gross inland energy consumption and final energy consumption, 1990–2016.

Energy balance is generally presented as a table, but the same information looks much more illustrative when presented as a Sankey diagram. To make a diagram of the energy balance of Latvia 2016, an interactive tool of Eurostat (Sankey diagram) was used to visualise the results. Figure 1.10 [21] shows the entire process from production and imports to final consumption.

It should be noted that the final energy consumption figures include the amounts of energy consumed in different sectors of the country's economy, which are agriculture, residential, transport, industry, commercial and others. Over the last eleven years, the final energy consumption figures did not change notably. In 2010, the final energy consumption figure was 1.9 % higher than in 2005 (3.32 PJ), while in 2016, the final energy consumption (11.5 PJ) dropped by 6.6 % as compared to 2010.



Source: http://ec.europa.eu/eurostat/cache/sankey/sankey.html

Fig. 1.10. Energy balance flow, Latvia 2016.

Figure 1.11 shows the share of economic sectors in the final energy consumption figures in Latvia from 1990 to 2016. By 2005, significant changes had come about in different sectors of the national economy. In 2005, 2010, 2015 and 2016, the percentage of the sectors in the final consumption was as follows:

- **In 2005**, the share of agriculture sector was 3.1 %, industry sector –18.7 %, residential sector – 36.5 %, transport sector – 26.6 %, the share of the commercial and other sectors was 15.1 %.
- **In 2010**, the share of agriculture was 3.5 %, industry – 19.9 %, residential sector – 33.1 %, transport – 29 %, commercial and others sectors – 14.6 %.
- **In 2015**, the share of agriculture sector was 4.0 %, industry sector – 21.8 %, residential sector – 29.9 %, transport sector – 29.7 %, the share of the commercial and others sectors was 14.6 %.
- **In 2016**, the share of agriculture sector was 4.3 %, industry sector – 20.7 %, residential sector – 29.2 %, transport sector – 30.3 %, the share of the commercial and others sectors was 15.4 %.

Analysis of the structure of energy consumption by the sector reveals that the transport and residential sectors account for more than 60 % of total consumption. Although such percentage of energy consumption in these sectors remains rather stable, it must be pointed out that the figure for the residential sector has an average annual decline of 2.1 %, in the transport sector it has increased by approximately 1.2 %.

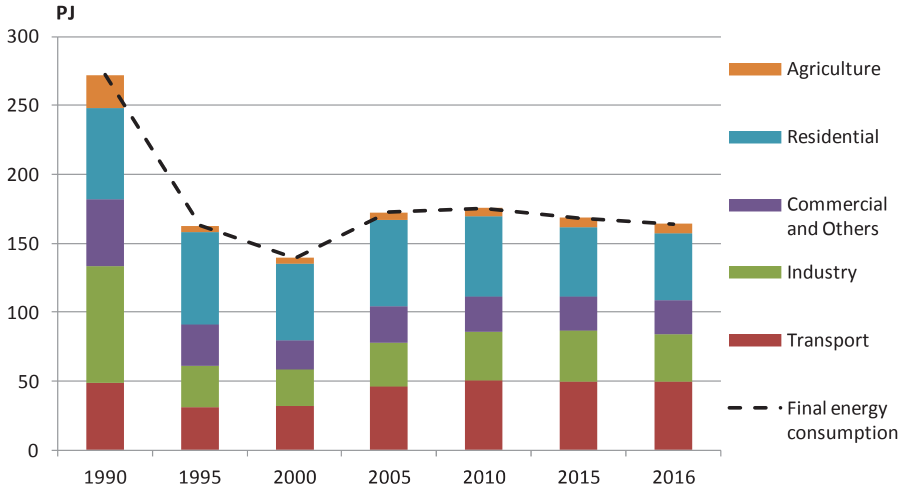


Fig. 1.11. Share of economic sectors in the final energy consumption data, 1990– 2016.

The transport sector includes the following sub-sectors: road transport, railway, civil aviation and domestic navigation. The main energy resource prevailing in the transport sector is oil products, which is shown in detail in the Annual Report of the Central Statistical Bureau (CSB) [20]. The highest energy consumption is observed in the road transport; it amounts to as much as 85 %.

The high consumption figures in this sector are mainly the result of the growth in the number of vehicles. Second, the range of engine types and capacity has extended. The list of vehicles registered in Latvia includes vehicles with petrol, diesel, gas engines, petrol and gas engines, gas and diesel engines, as well as ones with electric engines (electric vehicles) and electric and petrol engines (plug-in hybrid electric vehicles). Detailed information on the statistics of the registered vehicles by the type of engine is available at the website of the Road Traffic Safety Directorate of the Republic of Latvia [22]. Road transport includes all types of vehicles on the roads: passenger cars, light duty vehicles (< 3.5 tonnes), buses, heavy-duty vehicles (> 3.5 tonnes), motorcycles and mopeds.

1.3.3 Greenhouse Gas Emission Inventory, Latvia

The impact of human activities on the climate has been recognised as a global environmental challenge in the second half of the 20th century. Therefore, for mitigation of the effects of this problem, a number of important normative guidance documents have been adopted and signed aimed at promotion of environmental protection and sustainable development in the entire world and its regions.

The United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol and Regulation (EC) No 525/2013 of the European Parliament and of the Council (May 21, 2013) have worked out a mechanism for monitoring and reporting on greenhouse gas emissions at the national level in all European countries including Latvia, and they annually monitor and report on greenhouse gas emissions.

According to Decision 24/CP.19, the main sources of greenhouse gas emissions include the following sectors: energy, industrial processes and product use (IPPU), agriculture, land use, land use change and forestry (LULUCF) and waste [16]. Annual inventories of GHG emissions by the sector between 1990 and 2016 are shown in Fig. 1.12.

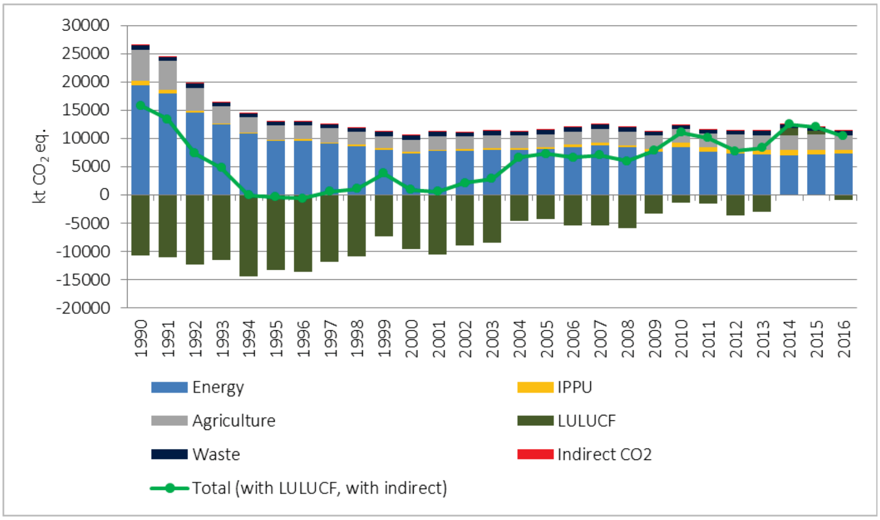


Fig. 1.12. GHG emissions by the sectors in Latvia, 1990–2016.

In 2016, total GHG emissions were reduced by 57.3 % compared to 1990 (base year). Consequently, the following trends can be observed in the sectors: a decrease of 62.7 % in the energy sector; an increase of 8.3 % in the IPPU sector and LULUCF sector; a decrease of 52.5% in the agricultural sector; an increase of 3.8 % in the waste sector.

It is worth emphasising that the energy sector is the most significant source of GHG emissions, with 60 %–80 % share of the total emissions between 1990 and 2016. Relative contribution of the activity sectors in total GHG emissions by the sector in 2016 is presented in Fig. 1.13.

A break-down for the year 2016 shows that the contribution in the total GHG emissions made by the sectors in 2016 is as follows: the share of the energy sector is 64 %, where a larger part comes from the transport sub-sector; the share of IPPU (excluding LULUCF sector) is only 5.8 %; the share of the agricultural sector is 23.6 %; the share of the waste sector is 6.4 %, and the rest (indirect) comprises 0.1 %.

As Fig. 1.13 shows, in 2016 the greatest share of the GHG emissions with 44.2 % of emissions in the energy sector comes from the transport sub-sector, where 90 % of emissions are generated by road transport. Civil aviation, road transport, railways and domestic navigation are included in the transport sub-sector.

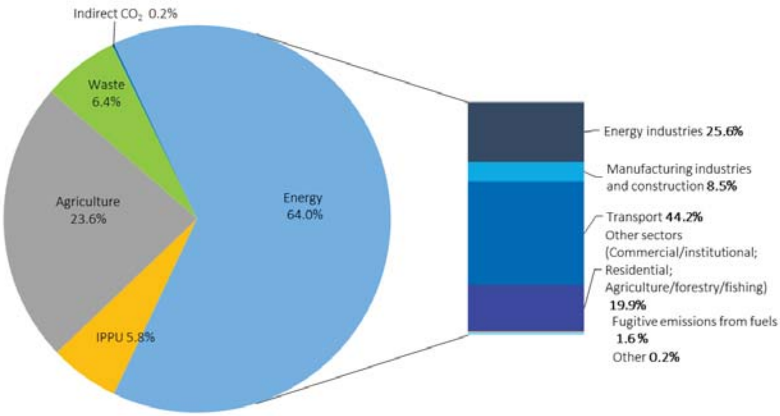


Fig. 1.13. Relative contribution of the activity sectors in total GHG emissions by the sector, 2016.

As shown in Fig. 1.14, between 1990 and 2016 there was an annual increase of emissions, which came from road transport, the contribution of which was more than 90 % of the total emissions of the sector. In 2016, total GHG emissions from the transport sub-sector increased by approximately 5.1 % compared to 1990, whereas in 2007 the increase was as high as 27.4 %.

GHG emissions from road transport of the country are the result of the following parameters: a decrease or an increase in the number of vehicles; an average age of the vehicles; progress in technology of the vehicle engines, fluctuation in the price of fuels and CO_2 tax on fuels.

Furthermore, the share of domestic navigation in the emissions of the transport sector is lower than 0.5 % over the whole period, with only 0.3 % in 2016.

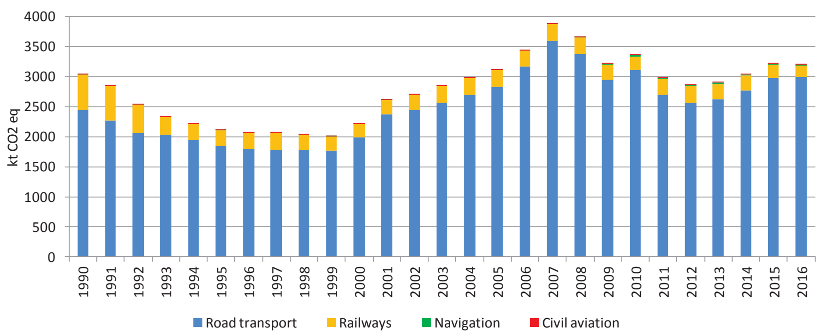


Fig. 1.14. GHG emission trends in the transport sector in 1990–2016, kt CO_2 eq.

The contribution of civil aviation in the total figure was lower than 0.5 % in 2016, while the contribution of the railway dropped from 19.7 % in 1990 to 6.1 % in 2016.

1.4. Energy and Climate Policy of the European Union

The early 21st century is the starting point of significant and qualitative changes in the principles of energy policy of the European Union, which is focused on the problems of energy supply and environment. In 2009, the European Union adopted the climate and energy package, which is a set of binding legislation and instruments aimed at reducing greenhouse gas emissions progressively up to 2050. The key climate and energy targets are set in the:

– 2020 Climate and Energy Package [3].
– 2030 Climate and Energy Framework [4].

These objectives are to be achieved in order to put the EU on the way of transformation towards a low-carbon economy. The 2020 package sets three targets for 2020, namely:

– 20 % reduction in greenhouse gas emissions (as compared to 1990 levels);
– 20 % of the EU energy to be obtained from the renewables;
– 20 % improvement in energy efficiency.

The 2030 Climate and Energy Framework is the guidelines for achieving the results envisioned in the 2020 package as the first step and, consequently, for establishing the new three key targets for the 2030 Framework, recognised and accepted by all member countries of the European Union in October 2014:

– At least 40 % reduction in greenhouse gas emissions (compared to 1990 levels);
– At least 27 % share for renewable energy sources;
– At least 27 % improvement in energy efficiency.

To achieve the goals, comprehensive strategies “Transport 2050” and “White Paper on Transport COM (2011)” were also accepted. They contain proposals for reducing dependence of the European countries on imported oil and cutting carbon emissions in transport by 60 % by 2050 [5], [6]. One of the most important goals of this strategy is related to inevitable changes in road transport that uses fossil fuels. The suggestion is to reduce the number of road vehicles that use fossil fuels by 50 % and to replace them with more efficient cars that work on clean fuels, for example, electric vehicles (EV). This will reduce GHG emissions in urban and rural areas with high density of population.

All these strategies also establish one general principle of liability of each country in achieving collective goals, which stipulates that the government of each EU country is to make their own decisions concerning economic and environmental constructive solutions in line with the principles of the Energy Policy of the European Union [23].

In the context of these principles, the government of Latvia has adopted specific documents: “Latvian National Development Plan for 2014–2020”, “Latvian Sustainable Development Strategy 2030” and “National Reform Programme Strategy “EU 2020””, which are aimed at improving energy efficiency of apartment buildings, public and industrial buildings, infrastructure and municipal public premises, heat- and power-saving measures and use of alternative fuels in the transport sector [7]–[9].

Models and Tools of Energy Systems Analysis

Computer supported modelling forms the core of the approach to energy system analysis and planning in many countries all over the world, to date. Analysts and planners at the Ministry of Energy, the Ministry of Environmental Protection and Regional Development, the Ministry of Economics and research institutions are the main users of the energy systems analysis and climate change models and tools.

The analytical models and tools of energy systems analysis, such as BALMOREL, EMPS, MESSAGE, MiniCAM, PERSEUS, RAMSES, WILMAR Planning Tool, MARKAL (TIMES), EnergyPlan, Mesap and others, offer solutions for the design of least-cost pathways of sustainable energy systems, compilation of long-term energy scenarios and the preparation of low-emission development strategies. More information on these tools and training in their use is available at the following websites: www.iaea.org; www.energyplan.eu; www.iiasa.ac.at; www.eifer.kit.edu [24].

In Latvia, some models and tools have been used for academic programmes and research projects, namely: MESAP, MARKAL (TIMES), MESSAGE, and EFOM. In particular, such tool as MARKAL (TIMES) is being implemented since 1995 in Latvia. It is practically used for the analysis of the energy potential in the country's energy system from different aspects, and it assesses the possible impacts of energy decisions under different scenarios and conditions. That is particularly relevant for energy strategy policy makers; therefore, research projects are funded by the State Energy Research Programme, Ministry of Economics of the Republic of Latvia and the Ministry of Environmental Protection and Regional Development [25].

1.5. Summary of Chapter 1

Electric and heat energy production in Latvia is based both on renewable energy sources such as water, wood and wind and combined electric and thermal power plants working on fossil fuels. Availability of energy resources is crucial for modernization of production capacities, which has been implemented over the past decade. The existing production facilities provide consumers with heat and partly with electricity (in the base and peak modes at present) all year round. However, full provision of electricity is possible owing to the import/export trade turnover, which allows responding flexibly to the processes occurring in the electricity market. Although dependence of the country on energy imports remains high, yet it has fallen from 86 % to 60 % over the past 26 years.

The energy system of modern Latvia is a dynamically developing system that operates in a coordinated mode and consensual management, with balanced continuous processes of production, transmission and distribution of electricity and heat. Therefore, the priority tasks of the state policy for development of the energy sector are the adoption of laws aimed at creating conditions for safe, efficient and sustainable operation of the energy sector and implementation of energy-saving strategies in order to improve the environmental situation in the country.

To implement the national development plans, a special attention is also paid to the transport sector, particularly to the road transport sub-sector which shows the largest annual increase in energy consumption and greenhouse gas emissions. Thus, it is evident that investigation of the potential for development of a fleet of vehicles with engines working on alternative fuels (cars with hybrid engines, clean electric motors, hydrogen fuel, etc.) is essential for Latvia. It is of critical importance in the fight for reduction of consumption of fossil fuels and in retaining the growth of GHG emissions.

2. CONDITIONS FOR OPERATING THE DISTRIBUTION NETWORKS AND PLANNING OF ELECTRIC VEHICLE CHARGING STATIONS

2.1. Conditions for Operating the Distribution Grids

In modern society, secure and reliable access of consumers to electricity is dependent on a well-functioning power system with uninterrupted supply of electricity. The important feature of the operating of the power system is the maintenance of a balance between total generation and total consumption of power requested by consumers at all times.

Latvia has an extensive electricity grid, where two companies ensure transmission and distribution of electricity from producers to consumers:

- JSC Augstsprieguma tikls (transmission system operator in Latvia), responsible for the operation of 330 kV and 110 kV networks, system reliability and balancing, ensures the physical flow of electricity and electricity trading (wholesale and retail market) in the form of commercial transactions. JSC Augstsprieguma tikls also includes interconnectors that provide links to other countries' networks (Baltic and Nordic countries) and make it physically possible to export and import power trough Nord Pool [26].
- JSC Sadales tikls, the biggest distribution system operator in Latvia, services 0.4 kV and 6–20 kV distribution lines to the end users such as industry, households and services [27].

Both companies are responsible for reliable operation of power transmission and distribution to the consumers according to technical and economic requirements.

By modernising equipment, existing distribution networks and designing new connections, these companies are gradually introducing the smart grid technology (SGT), which allows for monitoring, analysis, control and communication within the supply to help improve efficiency, reduce energy consumption and costs, as well as maximise the transparency and reliability of the energy supply [28]. The SGT is also used for planning processes of emergency, energy independence scenarios and inventory of emissions in the energy sector.

In compliance with the Latvian legislation, the electricity market liberalisation in the country was completed on 1 January 2015. In this regard, the process of introducing smart meters for all categories of consumers has become available. Advantage for users of the smart electricity meter is an opportunity to monitor their own hourly consumption that allows reducing the bill by modifying one's electricity use habits and making the first step to become prosumer.

In Latvia, the payment for electricity for industry, household, services objects is based on tariffs, which are differentiated by the time of the day. According to the local energy traders, for legal entities the payment is based on 3 time zone tariffs and for private entities on 2 time zone tariffs[3].

2.1.1 Planning of Load

Planning for the operation of all components of the power system is based on technical and statistical information on generation and loads connected to distribution networks. The size of the power, location and type of electric receivers determine the structure of the circuit and the parameters of the power supply elements of all consumer groups. Important and necessary (mandatory) information is the following:

- Existing load and generation during the year and day.
- Peak load and peak generation during the year and day (active power and reactive power with hourly resolution).
- Forecast of load changes (depending on customer groups) and generation for the next period of time.

The quality of this information is important for technical and economic analysis of the entire system, as well as for changing its structure in the future. When planning the operating conditions of electrical equipment, demand for electricity by existing consumers, as well as drawing up information and analytical reports, daily load schedules are estimated using two methods – statistical and settlement.

The statistical method is the most reliable method for studying the loads, since it is based on real measurements: indications of individual and general consumers' counters, as well as counters at network transformer points. The calculation method is used to design the power supply system to select all its elements or in the absence of real measurements for individual objects. This method estimates the maximum loads on the basis of mathematical statistics and probability theory [29], [30].

Demand for electricity by consumers varies by the hour of the day and by the seasons, it is not constant. For example, the load of street lighting has a maximum value in the evening and night hours. But in the winter period the duration is longer than in summer. The load during the work days and weekends also varies depending on the group of consumers. Thus, under the condition of working one, two or three shifts used in the production sector, the load can have both a maximum value for the entire week (in case of 3 shifts) and a minimum load on the weekend (in the case of 1 shift work). In turn, the load character of the transformer substation is determined by the total load of all consumers connected to it.

[3] Tariffs came into effect on 1 August 2016.electricity distribution differential tariffs starting from 1 August 2016. https://www.sadalestikls.lv/uploads/2018/01/ST_tarifi_ENG.pdf

2.1.2 Standard Load Variation Curves

In all countries, there are standard load variation curves for different consumer categories, which are based on historic measurement and used to estimate the load for each consumer at any time of the year. Usually, the load variation curves express the load as monthly variation, load in % of the peak load for each month of the year or daily variation, load in % of the peak load for each hour of the day. The standard curves of typical load variation during a day for more than 40 consumer categories are presented at the website of the transmission system operator in Latvia [31].

For the present study, the analysis has been made to evaluate the average daily electricity consumption profile from 2010 to 2013. The average variation curve of total factual consumption for each month of the year in Latvia shows that the maximum power consumption occurs during the winter season, whereas minimum consumption is observed in the summer season, it is by 20 % less than in the winter months (refer to Fig. 2.1). The curve is based on average variation for the total load in the grid, approximately 6.5 TWh/year.

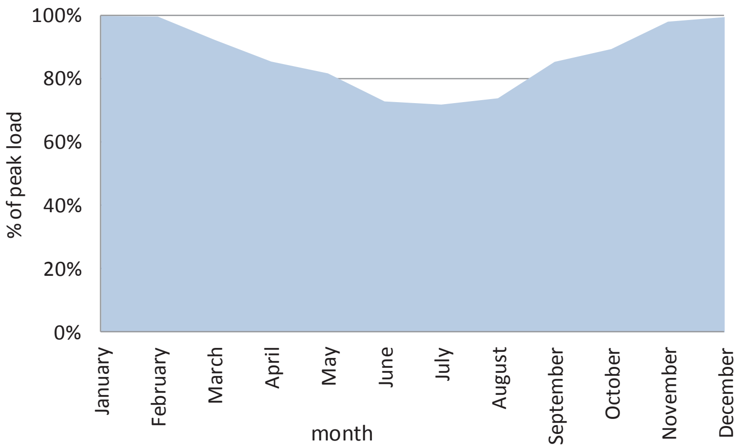


Fig. 2.1. Standard yearly variation curve (Latvia).

Analysing the weekly electricity consumption profile, the following conclusions can be drawn (Figs. 2.2 and 2.3):

- In the winter season: from Wednesday to Friday power consumption is maximum, on Saturday and Sunday power consumption is minimum.
- In the summer season (and also in autumn and spring seasons): from Monday to Thursday power consumption is maximum, on Saturday and Sunday it is minimum.
- Peak load is observed in the daytime.

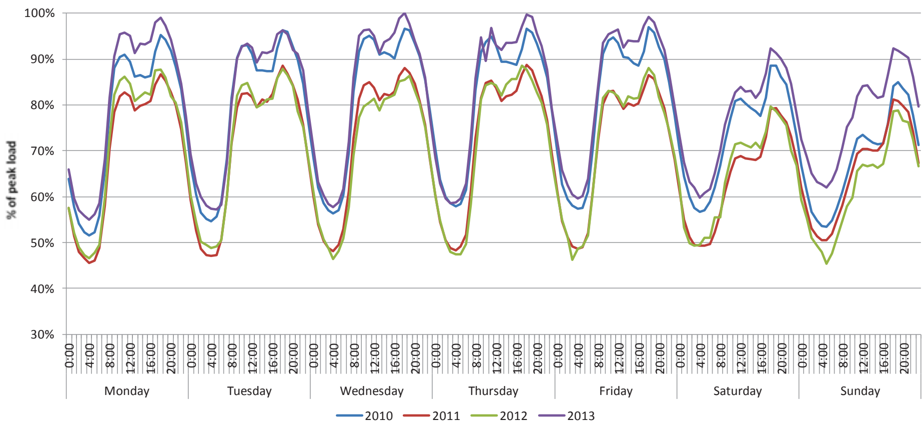


Fig. 2.2. Consumption profile of seasonal electricity (winter), 2010-2013.

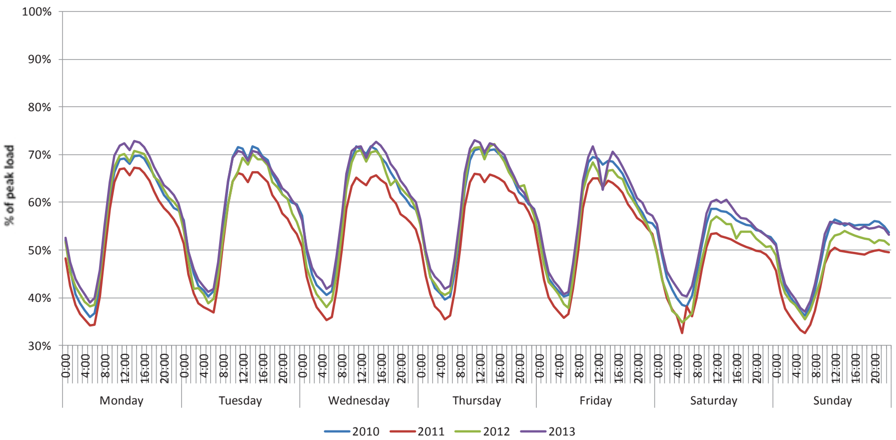


Fig. 2.3. Consumption profile of seasonal electricity (summer), 2010–2013.

Thus, we can conclude that throughout the whole year, maximum power consumption load can be observed from Mondays to Thursdays, whereas minimum load would be during weekends.

The load and generation simulation on low-voltage (LV) networks should ideally be carried out on the data received from smart meters (taking into account active and reactive power). At present, most Latvian customers report energy consumption (active power, kWh) manually only twelve times a year, which means that the distribution system operators (DSO) have limited information on the actual change in the load flow in the network. Therefore, in many cases, the necessary calculations are based on the standard curves of the load variation during the day. It should be noted that in the country there is already a process of equipping objects with smart meters regardless of the load of consumers and generation capacity. Figures 2.2, 2.3, 2.4 and 2.5 show examples of standard load variation curves during a day for separate consumer categories in a working day. They are chosen as they directly represent a large number of customers.

Fig. 2.2. Daily variation curves of household sector (consumers of private and dwelling houses).

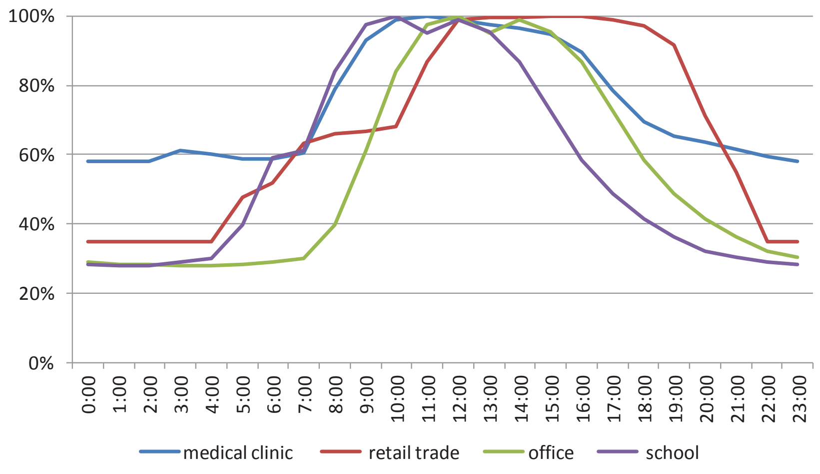


Fig. 2.3. Daily variation curves of services/social sector.

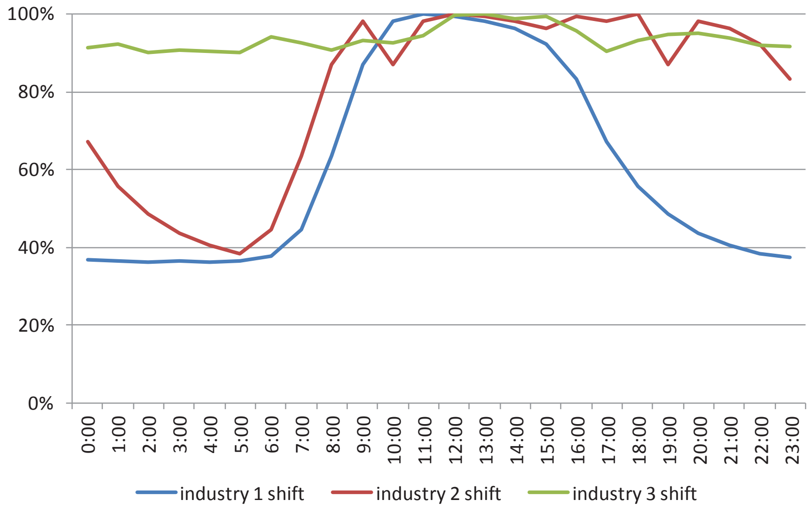


Fig. 2.4. Daily variation curves of industry sector (8-hour work shifts used in the industry production).

According to the above-mentioned figures, three characteristic zones can be specified for variation curves of any typical daily electricity consumption: maximum load area, middle load area and minimum load area (Fig. 2.5).

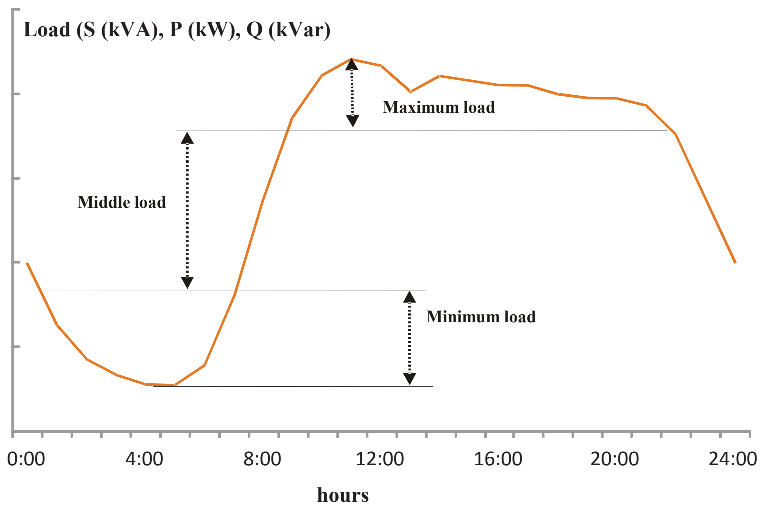


Fig. 2.5. Variation curves of typical daily electricity consumption.

Maximum demand area has a maximum peak load (on peak). Usually, there are one or two maximum power consumptions periods, during the daytime. Middle load area is characterised by a significant one-time increase of the load during the day – in the morning, and its substantial recession takes place at the end of the day. Minimum load area has a minimum load (off-peak); usually this occurs at night. Overall, the total daily variation curve has an alternating power system: rises, peaks and valleys, which generally determine its irregularity and it presents the sum of daily load curves of different consumers.

To sum up, the standard load variation curves allow determining the maximum and minimum loads during the year, month, and day both for the power system and for one transformer substation. In addition, based on the already existing statistical information, a system variation is made, which indicates an increase or decrease in the load for a certain period of time. Using the variation for the forecast of energy consumption (for example, annual energy consumption growth by 0.5 % per year) or maximum capacity, it is possible to calculate its volume for the next several years.

The variation is influenced by a number of factors: social and economic changes in the country, world prices for fossil fuels (or other sources of energy), the tax system, weather conditions, etc.

The results of studies on variation curves of daily electricity consumption for a separate group of consumers and transformer substations in Latvia are set forth in the author's works.

2.2. Smart Grid as the European Conceptual Network Model

The inevitable modernisation of energy systems and modern requirements to meet the growing demand for energy contribute to the creation of a new approach to the management of the electricity system. This approach is reflected in the smart grid concept, where modern technologies are used to solve problems in the field of energy, transport and emissions.

"*A smart grid is an electricity network based on digital technology that is used to supply electricity to consumers via two-way digital communication. This system allows for monitoring, analysis, control and communication within the supply chain to help improve efficiency, reduce energy consumption and cost, and maximize reliability of the energy supply*" [28].

Basically, the smart grid utilises the information communication technology (ICT) to optimise the electrical power system including renewable energy sources (planning, operation and maintenance), and it also obtains the supply and demand data from consumers in real time to manage the peak loads.

Nowadays, the implementation of smart grids and smart grids technologies (SGT) in different regions and countries occurs at different rates, depending on the level of development of the energy system, available energy sources, RES and DER integration, economic factors and adopted local laws.

The European Commission's Smart Grids Task Force has defined the following key characteristics for the future smart grids [32]:

- Active distribution and transmission networks (enhancing efficiency in day-to-day grid operation; achieving the balance between operational expenditure and capital expenditure).

- Active and energy efficient customers (enabling and encouraging direct involvement of consumers in energy usage and management).
- Electrification of transport sector (enabling the network to integrate users with new requirements).
- Renewable energy generation and distribution (ensuring network security, system control and quality of supply).

As a result of the work by the CENCENELEC-ETSI Smart Grid Coordination Group requested through the M/490 mandate, a generic European conceptual model is compiled, which consists of the four main conceptual domains:

- Markets (reflecting the energy market operations).
- Operations (ensures the usage of the grid within its operational constraints and the activities in the market).
- Grid Users (active participants use the grid to transmit and distribute power from generation to the consumers or prosumers) and
- Energy Services (system services, balancing and trading of the electricity generated), depicted in Fig. 2.6 [33]–[36].

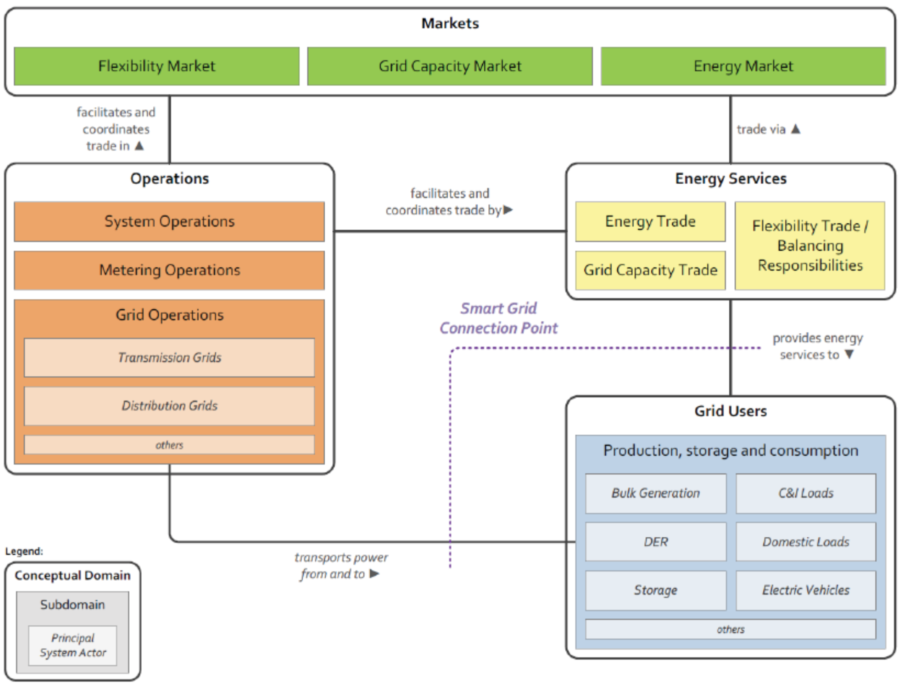


Fig. 2.6. European conceptual model for the smart grid.

Its main aim is to create the process of integration and interoperation between existing and future smart technologies.

2.2.1 Storage and Electric Vehicle Technologies in the Smart Grid

The expected and existing technologies in Smart Grid (the conceptual domain of Grid Users), such as Storage and Electric Vehicles (EVs) will affect the power system planning and operation in the future. They are not necessarily new technologies, but have not been widely used in MV or LV distribution networks before (depends on a country). Storage and EV technologies have both a positive and negative impact on the operation and planning of the network.

2.2.1.1 Storage

Battery energy storage systems (BESS) and supercapacitors (SC) are technologies that store energy via the use of a battery technology and provide customers with electricity in the required period of time[4]. They also improve the reliability and efficiency of the grid and increase the amount of renewable energy generation, which can be integrated in the distribution grid.

The battery energy storage system includes:

- Valve regulated lead acid batteries.
- Lithium ion batteries.
- Vanadium flow batteries.
- Sodium nickel batteries.
- Liquid metal batteries.

Supercapacitor (SC)[5] is a high-capacity electrochemical capacitor with capacitance values much higher than other capacitors (but lower voltage limits) that bridge the gap between electrolytic capacitors and rechargeable batteries. They typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors, can accept and deliver charge much faster than batteries, and tolerate many more charge and discharge cycles than rechargeable batteries. Supercapacitors are used in applications requiring many rapid charge/discharge cycles rather than long-term compact energy storage: within cars, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage or burst-mode power delivery.

The positive and negative characteristics of BESS and SC are as follows:

Positive

- Improving the reliability and voltage quality (a decrease in voltage variations).
- Load levelling (peak shifting).
- Maintaining the power supply in the case of an interruption for a limited period.
- Support and opportunity for integration of renewable energy.

[4] https://powercontinuity.co.uk/knowledge-base/battery-energy-storage-systems-bess/
[5] https://en.wikipedia.org/wiki/Supercapacitor

Negative

- Additional investments are required (micro grid, UPS,...).
- Increased costs for maintenance.
- Expensive technology.

2.2.1.2 Electric Vehicles

Electric vehicles are considered to be a promising solution for coordination of power supply for the power system, and in general they reduce carbon emissions and the growth of oil prices. The trends of development of storage batteries allow the electric vehicles to cover distances up to 500 km on a single charge. The expected growth in the number of electric vehicles not only will increase the demand for electricity, but also will prompt the profiles of peak daily load curve to change, which does not always have a positive effect on the work of local distribution networks. Subsequently, a need arises to either solve more network modernisation problems or to create the optimal planning of electricity supply distribution for all consumers. There are positive and negative characteristics that should be considered when addressing this issue, such as:

Positive

- Charging at home BEVs.
- Vehicle to home (V2H) can be used as battery storage at home (maintaining power supply in the case of an interruption for a limited period).
- Vehicle to grid (V2G) can be used as battery storage in the grid.
- Fast charge in selected places: rural and highway roads/ malls, etc..
- Improving the reliability and voltage quality (a decrease in voltage variations).
- Load levelling (charging during the limited period).
- Support and opportunity for integration of renewable energy.

Negative

- The increase in power demand by households.
- Extended use of battery will reduce the battery lifetime.
- Additional management and control of voltage and load.
- Additional non-adjustable load from electric vehicles will lead to an increase in energy demand, consequently requiring additional power.
- Simultaneous charging of electric vehicles at the same location will lead to distribution of network overload.
- Electricity tariffs have to be differentiated by respective time of the day.

In order to promote the widespread implementation of EVs and reduce all kind of technical, regulatory, commercial and political barriers, CENELEC Smart Grid Coordination Group (SG-CG) and E-Mobility Coordination Group (EM-CG) were established as a response to the EC mandates M/468 [37, 38], M/453 [39] and M/490 [40] in Europe. The main tasks of the appointed Group for Smart Charging (GSC) and Group for Interoperability (WGI) are the following: the coordination of necessary activities to ensure the integration of different systems within the existing regulatory and standard framework in the scope of e-mobility [41].

To mitigate the problems related to the interoperability of diverse EV/EVSE technologies, standardisation organisations set a series of standards to ensure [42]:

- Adequate level of safety.
- Possibility of charging at home and in residential areas in adequate domestic socket-outlets and private charging stations.
- Affordability and ease of use that involves cables and plugs, simple and consistent user interfaces.
- Interoperability of connectors and billing mechanisms throughout Europe.
- Security concerning data privacy, authentication, protection against vandalism and cable theft.
- Durability and robustness of charging equipment.
- Interoperability and connectivity between the charging station and the EVs.
- Secure and reliable communication between components involved in EV charging process and service of the charging station. Interfaces and the overview of actors that can be involved in e-mobility data communication are presented in Fig. 2.7.
- Appropriate consideration of any smart-charging issues with respect to the charging of EVs.

Today in the world, several schemes for connecting the electric vehicle charging stations (EVCS) to the distribution networks have been developed and investigated:

- Uncontrolled charging scheme. The battery charging process can be carried out on vehicle at any time, if necessary. Usually this is a connection to the electricity network of a residential home.
- Conventional charging controlled scheme. The battery charging process can be carried out on vehicle at any time, taking into account the maximum permissible load and power of the equipment of the distribution networks.
- Smart charging scheme. The battery charging process is provided by smart grid technologies, which ensure equalization of the daily load and optimisation operation of the electric network equipment.
- Smart charging V2G-G2V scheme. It is a smart charging scheme, which also provides the process of charging and discharging the batteries (using V2G-G2V technology).

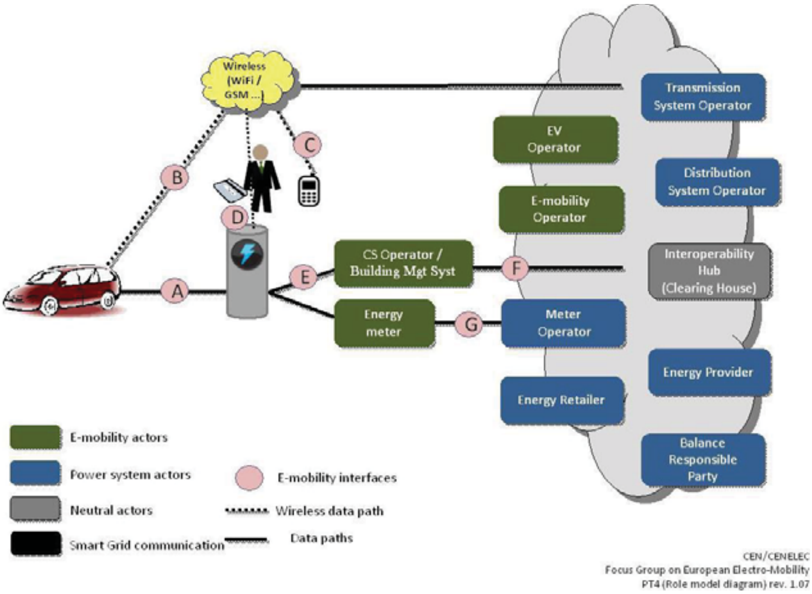


Fig. 2.7. Overview of functions in electro-mobility data communication.

It should be noted that the smart charging V2G-G2V scheme could be available in Latvia by 2030. Worldwide experience with the use of V2H and V2G shows that these technologies will become a vital part in power generation infrastructure. The V2G and V2H technologies can work both as a load and as a generator. This technology offers additional services, such as organisation of reserve stocks and power allocation and voltage regulation to the power system.

2.3. Electric Vehicles and Charging Stations Worldwide and in Latvia

Developing a long-term transport policy, one of the high-priority values for all the countries is the introduction of environmental technologies. One of such innovations is the storage batteries that allow the electric vehicles to cover distances up to 500 km on a single charge. In recent years, many countries have been discussing and even already installing new government programmes, the aim of which is to increase the number of parks for vehicles with zero or close to zero emissions and develop the infrastructure for servicing such vehicles. The afore-mentioned transportation units are the hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), vehicle to grid (V2G), vehicle to home (V2H) and fuel cell electric vehicles (FCEVs), which also have the potential for a significant contribution towards achieving the EU climate protection goals in the transport sector [43].

According to the Global Outlook 2017, 750 thousand units of new EVs were sold worldwide in 2016. Successful sales started in 2010. If less than 2 thousand EVs were sold in

2005, more than 12.48 thousand in 2010, and the number of electric cars (BEVs and PHEVs) exceeded the mark of 1.26 million in 2015 [44], [45].

It should be noted that during these years BEVs (60 %) and PHEVs (40 %) are relatively evenly distributed. The evolution of the EV market all over the world from 2010 to 2016 is shown in Fig. 2.8., where it is seen that in countries such as China, Japan, Norway and the Netherlands 80 % of their total number were registered in 2016.

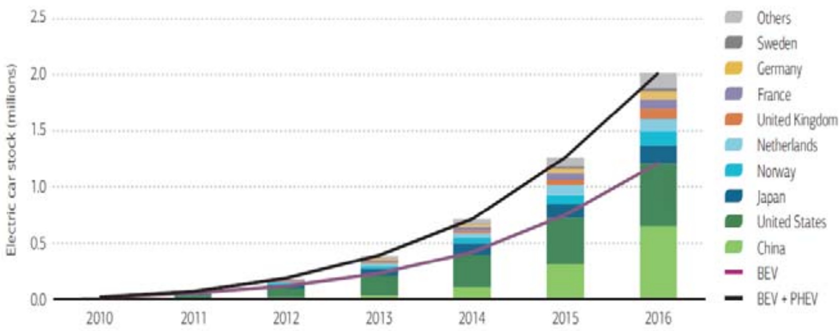


Fig. 2.8. Evolution of the worldwide market of electric vehicles, 2010–2016[6].

The United States of America was the leader in the number of electric vehicles until 2015. In 2016, China became the country with the largest fleet of electric vehicles, possessing one third of world number of electric vehicles, more than 200 million electric two-wheeled vehicles, about 4 million low-speed electric vehicles (LSEV) and more than 300 000 electric buses.

A public charging station is an infrastructure system of publicly accessible charging stations and battery swap stations to recharge electric vehicles. Infrastructure for electric vehicle network is best developed in the countries where there is an annual increase in the number of electric vehicles, so the world leaders are the USA, China and Japan.

In Europe, Eurasia&European regions, such countries are France, the Netherlands, Germany, the United Kingdom and Norway. A review of public charging stations, differentiated in power and charging speed in some of the European countries, showed that in Norway, Denmark and France more than 70 % of stations are the standard charging stations. In the Netherlands, the United Kingdom and Germany, more than 53 % of stations are the accelerated charging stations. Regarding rapid charging, the average indicator is about 10 % of the total number in these countries. An exception is the network of charging stations in Estonia, where the accelerated and rapid charging stations account for 96 % (see Fig. 2.9) [46]. Electric vehicles outnumber public charging stations, indicating that most drivers rely primarily on private charging stations (standard charging, slow).

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[6] Sources: The Global EV Outlook 2017
Others: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Iceland, Ireland, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Poland, Romania, Slovak Republic, Slovenia, Switzerland, Turkey.

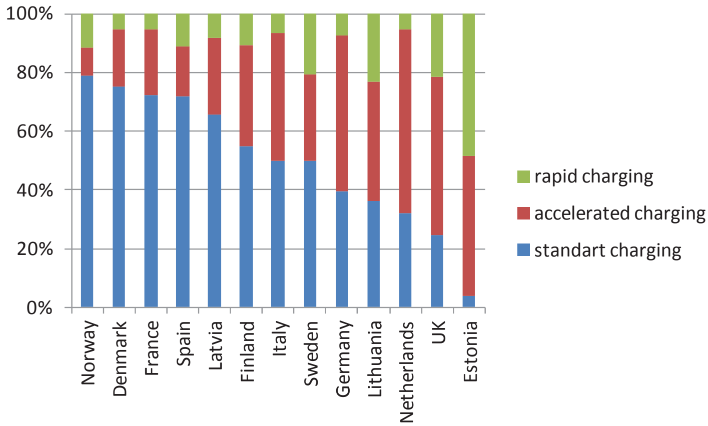


Fig. 2.9. Distribution of charging stations according to the charging speed ((15/09/2016)

The main characteristics of electric vehicle battery are charging time, power demand and the rate of charge (see Table 2.1).

Table 2.1.

Charging Station Modes. Standard Charging Power Levels [47]–[49].

Charging mode	Connection mode (Grid connection)	Alternating current (AC) and direct current (DC) voltage (V) / current (A)
Standard charging (slow) – StEVCS: nominal power 3kVA (1-phase) and 7kVA (3-phase), 6–12 hours	Mode 1 (1 phase/3 phase) and Mode 2 (1 phase/3 phase)	230/16 and 400/16 230/32 and 400/32
Accelerated charging (medium) – AcEVCS: nominal power 7–22kVA (1- or 3-phase, 32A), 1–4 hours	Mode 3 (1 phase/3 phase)	230/32 and 690/250
Rapid charging (fast) – RapEVCS: nominal power 50kVA (DC) and 43kVA (AC), 80 %, less than an hour	Mode 4 (3 phase)	600/400

Thus, it is possible to conclude that governments in these countries already have or are developing investment programmes, and the energy strategies will increase the number of electric vehicles in their territories and start restricting or stop selling petrol and diesel vehicles. Organisation of special zones (such as a city centre, big recreation area and park, as well as areas with restrictions on driving within certain hours, etc.), where vehicles with zero-emission have a priority, will ultimately influence vehicle purchase decision. Some automakers have also announced plans for the development and production of electric vehicles [50], [51]. In many countries, the types and locations of public charging stations have been determined by modelling, where the population, the number of vehicles, the average daily mileage, and the distance between the settlement and the city are the main criteria [52]–[54].

The analysis by the International Energy Agency (IEA), based on the projections of the leading national targets of world countries, as determined by automobile manufacturers and research scenarios, foresees that the number of EVs (passenger cars and light goods vehicles up to 3.5 tonnes) will be from 9 to 20 million in 2020, from 40 to 70 million in 2025, and from 55 to 200 million in 2030.

2.4. An Overview of Public Charging Stations and Vehicles with Electric Engines in Latvia

The transport policy of Latvia is likewise focused on environmentally beneficial technologies. In 2014, using the funds provided by the National Climate Change programme, the Ministry of Environmental Protection and Regional Development of the Republic of Latvia held a project contest for reducing the amount of greenhouse gas emissions in the road transport sector. As a result of the held contest, during the period of 2014–2015 there had been additional funding given for acquiring almost 200 EVs and deals made for installing 235 public charging stations by 2023 [55].

Currently, the number of public charge stations in the territory of Latvia is approximately two times more than 2014, and it is evident that the market of electric vehicles and the infrastructure for public charging stations will broaden [57].

As part of the public procurement of Road Traffic Safety Directorate of the Republic of Latvia (RTSD), an analysis of the location of fast charging stations near the main highways has been made [58]. It is planned that the distance between the charging stations will be from 30 to 50 km. The potential plan for the implementation of geographic locations for 150 accelerated and rapid charging stations, in accordance with the criteria for the number of inhabitants and their daily movements, is presented in Fig. 2.10.

Fig. 2.10. Locations for accelerated and rapid charging stations in Latvia.

First two vehicles of the type were registered in July 2011. Within seven years their number has risen up to 312. As of 1st January 2018, 275 EVs and 37 PHEVs passenger cars have been registered in Latvia, where Volkswagen e-up and Nissan are the most popular EV models. The statistics of registered vehicles by type of engine have been obtained from publications of RTSD [56]. The total number of vehicles with electric engines is shown in Table 2.2.

Table 2.2.

Number of Vehicles with Electric Engines in Latvia, 2011–2017

Type	2011	2012	2013	2014	2015	2016	2017
Passenger cars	2	11	18	192	223	268	368
Light commercial vehicles	2	2	2	6	7	11	13
Buses	0	0	0	0	0	0	1
Motorcycles	0	0	0	0	3	3	5
Mopeds/quadracycle	0	0	0	50	56	58	75
Total	**4**	**13**	**20**	**248**	**289**	**340**	**462**

The proposed study does not consider the location of public charging stations in the cities, and also standard charging stations that are used in other countries.

2.5. Overview of the Research and Methodology for the Integration of Charging Stations

The practical and theoretical research on the field of operation of electric vehicles and the charging stations (including battery swap stations), their power supply and influence on the electric grid is timely and promising. Undoubtedly, the existing modern technologies in the field of electric motors are based on the research of two inventors and researchers Nikola Tesla (1856–1943) and Thomas Edison (1847–1931). However, in our time, it is problematic to single out the most significant authors, since topics relevant to electric vehicles, the charging stations and distribution networks have a very wide range of technical, theoretical and practical developments and research.

Before proceeding to the Doctoral Thesis, the author has studied modern technical and theoretical studies. They reflect different positions and approaches to solve the set goals, and suggest possible actions to ensure the reliability of the electrical network and national environmental safety in the context of the widespread use of vehicles with electric engines.

In the study "Electric Vehicles and Charging Strategies to Meet Urban Mobility Requirements", a methodology was developed to determine the potential of EVs to meet the urban drive needs of province of Modena. In the model, six different types of EVs (from the light quadricycle to the big size sports utility vehicle) were considered. The battery recharge was performed according to four different charging schemes: alternating current (AC), direct current (DC), night and smart/off-peak. The time of the traffic had three peaks (morning, noon and evening) in the working days and two peaks – on the weekend (noon and evening only). The results showed that approximately 40 % of car users could cover all their trips undertaken in one month, depending on the selected recharging strategy. In this article, the possible number of electric vehicles and their behaviour during the working days and weekend was determined. The distribution networks were not considered [59].

The study “Interoperability Analysis of Electrical Networks with Electric Vehicle Charging Devices and Distributed Energy Resources” presents the approach for network studies considering control algorithm testing of EV charging devices and distributed energy resources (DER), grid stability analysis, smart charging and grid power management, software realization and representative test case of 24-hour domain analysis of distribution network with EV charging devices and DER. A set of non-constrained typical load profiles of EV charging modes according to IEC61851 was studied. The three scenarios were considered. The test confirmed that the EV charging represented a significant challenge for distribution network in the case of dynamic simulations. Supervisory control and data acquisition (SCADA) system was used to achieve the goal. To sum up, SCADA, due to high computational efficiency, is very well suited to represent the slow dynamics behaviour of the multi-node network and shows significant impact on the electricity system when the control algorithm is implemented. The proposed system for EV charging monitoring and control can be used to improve the power management control and stability of power grids with distributed energy resources [60].

The use of renewable sources as a possible power supply of charging stations and their influence on the electrical network are considered in three studies, in which the medium voltage direct current (MVDC) network and the rapid charging station (DC) are investigated [61]–[63]. Their main aims are as follows:

- Design of models for various forms of renewable generation, power electronic conversion devices and battery energy storage systems.
- Design of electric vehicle charging station of next generation common DC bus, which utilises on-site renewable generation, level 2 DC quick chargers, DC bus for component connection as well as MVDC.
- Evaluation of system level equipment interaction during various modes of operation to determine applicability of the common DC bus EVCS as well as the applicability of the MVDC network to serve DC loads.
- Determination of the ability of battery chargers (synchronous buck converter) to help mitigate transient propagation in DC power systems.

In the study “Model and Simulation of a DC Electric Vehicle Charging Station Interconnected with a MVDC Network”, a model consisting of a DC network (5 kV) and 3 wind power plants (5 MW each) was developed. The charging station and an industrial facility (10 kW) served as consumers [61].

In the study “Design and Simulation of a DC Electric Vehicle Charging Station Connected to a MVDC Infrastructure”, a charging station for 2 DC charging devices (modelled as batteries) was considered, with solar panels and the voltage converters (total power of 20 kW) [62]. The model was modelled by PSCAD program. In the case study, two connections were considered: when the charging station was a consumer (connected to a DC medium voltage network), and when it acted only as an electric power source (not connected as a load).

In addition to the previous two studies, the model was supplemented by one wind power plant (5 MW), solar panels (1 MW), and battery energy storage (rechargeable battery) and it was considered in “Advancements in Medium Voltage DC Architecture Development with Applications for Powering Electric Vehicle Charging Stations” [63].

In the article “Optimal Charging Scheduling of Electric Vehicles in Smart Grids by Heuristic Algorithms”, an optimisation algorithm to coordinate the charging of EVs was developed and implemented using a genetic algorithm (GA). The methodology was applied to an existing residential low-voltage system. The realistic behaviour of drivers was used to obtain the mobility patterns and parking availability aspect of EVs to improve the charging and discharging process. A comparison between conventional, smart G2V and smart G2V with V2G battery management techniques in the existing residential network was also performed. Four different management techniques were tested in the power system. The results indicated that a smart charging schedule for EVs led to the flattening of the load profile, peak load shaving and the prevention of the aging of power system elements; the V2G technology could be used as battery energy storage [64].

The paper “Economic Scheduling of Residential Plug-In (Hybrid) Electric Vehicle (PHEV) Charging” describes an aggregation method that can be used for scheduling plug-in vehicles for charging. A series of functions were proposed and tested to illustrate the effect of different charging schemes on the total load. For calculation of typical PHEV requirements, the USA National Household Travel Survey (NHTS) database was used. To model the uncertainty inherent in battery state-of-charge and trip duration, the Monte Carlo methods were used. The time-of-use (TOU) rates were analysed to indicate, which scenarios led to the least customer and utility cost. The voltage profiles were obtained for the test system. An analysis of variance showed the effectiveness of the charging scheme [65].

Battery energy storage station, as an infrastructure to EVs, and manage battery stock are the focus of research “A Safety Stock Problem in Battery Switch Stations for Electric Vehicles”. In this study, a theoretical relationship between the number of safety stock, on the arrival rate of EVs, and the charging time of batteries by using queuing theory was formulated [66].

In the study “The Role and the Impact of Electric Vehicles on the Local Power Grid within the Northern Finland Climatic Condition”, the impact of electric vehicles on the local power network in winter seasons (Northern Finland) was assessed. Using MATLAB simulation, the role of electric vehicles within a smart grid based power system was assessed. Analysis results suggest that, within the current logistical and environmental limitations, electric vehicle cannot play an active role in the flattening of the network peak loads. Furthermore, an increase in the overall power consumption is opening new problems related to the necessary increase in power production and improvement of the existing urban distribution network [67].

The study “Design and Power Management of a Grid-Connected DC Charging Station for Electric Vehicles Using Solar and Wind Power” suggests an environmentally-friendly way to supply the needed charging energy for EVs that benefit from renewable energy source. The designed station is intended to make use of wind and solar power, while retaining the connection with electrical grid for emergency cases. Various conditions constituting different cases and scenarios are taken into consideration. The designed system works in the limits of Level 2 DC Charging Standards. The ability of the system to provide either a fast charging or a MPPT charging makes it preferable especially for both residential and public applications. The study shows that such systems can also minimise the effects on the electricity grids, which are caused by EV charging procedures, while making use of RES [68].

The aim of the paper "Large Scale Electric Vehicle Integration and Its Impact on the Estonian Power System" was to simulate the effect of slow and fast electric vehicle charging (EV), which acted as an additional load on the Estonian power system. Two principles of charging the electric vehicles at night and at any time of the day were analysed. The study showed that the integration of electric vehicles in the range of 10 % to 30 % of the total park of cars would have a negligible impact on the operation of the Estonian power system. At the same time, based on fluctuations in market prices for electricity, the greatest impact would occur at night, thus affecting load equalization and increasing the peak load by approximately 4 %. The article made a partial analysis of the possibility of equalizing the load of the country power system [69].

In the paper "Dynamic Frequency Response from Electric Vehicles in the Great Britain Power System", the contribution of EVs to dynamic frequency control was investigated by Matlab/Simulink platform. Two charging modes were considered in two scenarios. The study showed that electric vehicles could greatly reduce the frequency deviations and reduce the operation cost for generators [70].

Based on two scenarios, the paper "Impact of Plug-in Hybrid Electric Vehicles (PHEVs) on the French Electric Grid" established that electric grids could accommodate 72 % of the French vehicle fleet, in the case electricity generation by nuclear plants and hydro stations. The obtained results illustrated an increase in the efficiency of the electricity generation, the decrease of 22.5 % in oil imports and the decrease of 18 % in CO2 emissions due to road transport [71].

The study "Voltage Support by Optimal Integration of Plug-in Hybrid Electric Vehicles to a Residential Grid" provided a linear approach to compute the voltage on a residential grid based on the house instantaneous load and the instantaneous consumption of PHEVs under certain assumptions. The proposed scheme was evaluated under multiple cases in order to test its ability to maintain voltage within safety limits and provide optimal consumption policies. The two cases were evaluated. The first case refers to none PHEV connected. The second case had a slight variation in the resistive value of two lines but this modification was enough to cause voltage limit violation on certain nodes at certain instants of peak demand. The PHEVs were assumed to have a certain initial state of charge (SOC) of batteries: 10 %, 5 % and 50 % of the maximum. As a result, the scheme ability was proposed to maintain voltage within safety limits and provide optimal consumption policies. In addition, charging costs of PHEV were evaluated [72].

The study "The Impact of Charging Plug-in Hybrid Electric Vehicles on the Distribution Grid" estimated the amount of electrical energy for recharging the batteries of PHEV fleet for the period of 2003–2050 in Belgium. Using the TREMOVE model, vehicle kilometres and the number of passenger vehicles were calculated. The increase in demand for electricity under conditions of daily charging of PHEVs was investigated in scenarios of the PRIMES model. In one of the scenarios, it was revealed that 5.1 % of the generated electricity in the year (2030) was needed to charge PHEVs in Belgium. The research also analysed the voltage profile and power losses due to PHEV recharging in a residential sector. The conclusions were as follows: uncontrolled power consumption on a local scale could lead to distribution grid problems [73].

The main aim of "Technical Impacts of Electric Vehicles Charging on an Italian Distribution Network" research was to study the impact of different EV charging scenarios on a real distribution network located in northern Italy. Three different scenarios were considered: the uncontrolled, the dual-tariff and the smart charging scenario. A case of EV charging from renewables was also studied, considering EV charging events in a commercial area using power from solar panels. The research demonstrated that the distribution networks were highly sensitive to a charging strategy. However, if a suitable EV charging strategy were used, the existing grid would support a significant number of EVs avoiding network reinforcements. The smart charging regime could minimise the impact of EV charging on the distribution networks compared with the uncontrolled and dual-tariff charging regime. Charging capability from solar panels at work would have a beneficial effect on the reduction of peak demand in the summer [74].

The paper "Electric Vehicle Charging Characteristics" observed the practical results for a Fiat Elettrico Fiorino HC-S with connections to charge vehicle batteries from household electricity connection 230 V. The study results showed that full charge automobile battery needed 7 hours, with 12–13 A, 230 V, 50 Hz alternating current (household connection). Charging an electrical vehicle at home, the total power for other electricity home consumer is reduced. In case of EV charging, it is worth exploring new technical solutions for creation of a smart charging system, dividing the electricity consumer connection priorities within a household. Along with the growing popularity of electric vehicles, electricity network load will also increase, which can lead to the necessity for household connection power upgrade [75].

The influence of new loads (charging EVs) in the distribution grid on the operation of the distribution grid was presented in "Stochastic and Optimal Aggregation of Electric Vehicles in Smart Distribution Grids" project. For investigation, the four of base days were chosen: summer weekday, summer weekend, winter weekday and winter weekend. The complete picture of electricity market with high wind power penetration in the Danish power system was demonstrated. To make the outcome more realistic, the stochastic data were used, which was generated by certain driving patterns. The stochastic data included driving distance, arriving time and leaving time for 75 EVs. The electrical vehicles start to charge as soon as they arrive home and stop charge until the batteries are fully charged. Conclusions of the research were as follows: due to the fluctuations in the electricity price and the wind power production, it would be wise to charge EVs during off-peak periods of the consumption of electricity. The optimal charging plans were made to reduce the charging costs. The smart charging plans could offer benefits to grid aggregators and EV owners [76].

2.6. Summary of Chapter 2

It is important to indicate that all the scientific research has shown that such sub-sectors as road transport, electricity generation and distribution of electricity to the consumer are of considerable theoretical and practical importance in all regions of the world.

Particular attention has been developed to the mathematical models used to predict and control a distribution network, as well as conduct research on the development of electrical vehicle areas. To establish algorithms and models of EV infrastructure, the researchers from different countries have used the following attributes as constraints: provision the population with vehicles, the average daily mileage of a vehicle, the distance between the destinations, number of individual trips, opening hours and parking lot availability, technical indicators of the distribution network, etc.

The analysis has revealed that the number of electric cars around the globe is more than 1.2 million at present. The best selling BEVs and PHEVs include Tesla's Model S, Nissan's Leaf and Toyota's Prius Plug-in Hybrid. The growing demand for electric cars is triggered by government incentives, including subsidies, exemptions from tolls and parking fees.

Moreover, the statistical information on the total number of electric vehicles (passenger cars, trucks, buses, motorcycles and bicycles) and charging stations of different types in specific places of their operation and location (city, countryside, highway), the behaviour of electric transport users during working days and weekends, price on the electricity markets is necessary and important for planning and development of forecasts in every country of the world.

Despite the increased attention to the development of charging station infrastructure in Latvia, a number of theoretical and practical issues remain unresolved, which is explained by the lack of a wide fleet of road vehicles, and hence the lack of real practical data on consumption, mileage per charge and climatic conditions. The study of medium/low voltage distribution networks in the context of interaction with existing and new electricity consumers is also of particular relevance, since such interaction is carried out on the complex basis of a set of technical norms and standards prevailing in the country.

As a result of everything mentioned above, the author has come to a conclusion that the research on the formation of the infrastructure of charging stations in the cities and settlements is of utmost importance and should be based on the existing available capacity of the low-voltage distribution network and the location of different types of charging stations. Thus, there is a wide range of models and algorithms for carrying out original studies.

Planning of the operation of all components of the power system is based on technical and statistical information on generation and loads. The charging stations for the electric transport are consumers and can store electricity; therefore, the goal of the present Thesis is to develop an algorithm, which will allow studying the local distribution network in accordance with the technical requirements of electric transport, charging infrastructure and ecology.

3. EVALUATION ALGORITHM OF LOCAL DISTRIBUTION NETWORKS, TAKING INTO ACCOUNTS THE PLACEMENT OF ELECTRIC VEHICLE CHARGING STATIONS

The Kyoto Protocol is an important step towards global reduction and stabilisation of GHG emissions. The reduction in greenhouse gas emissions of at least 40 % by 2030 and by 80 % to 95 % by 2050 compared to 1990 levels is the ultimate objective of the Climate Change Convention (UNFCCC). The Transport 2050 roadmap adopted in 2011 is an important element of the efforts to achieve this objective. The purpose of the roadmap is to halve the number of vehicles powered by traditional fuels, such as gasoline and diesel by 2030, since noise exposure and poor air quality have a negative effect on people's health [5].

To achieve this objective, battery electric vehicles and plug-in hybrid vehicles in particular are used around the world. Financial and non-financial incentives to boost the demand for vehicles and charging infrastructure are also offered to residents. These incentives include rebates or tax credits on vehicles, preferential parking spaces, access to restricted highway lanes, discounts for installation of electric vehicle supply equipment (EVSE) and others [77].

Thus, there is a need to solve network modernisation problems or to create the optimal planning of electricity supply distribution taking into account such factors as:

- The additional non-adjustable load from electric vehicles can lead to an increase in energy demand, consequently requiring additional generational power.
- Simultaneous charging of electric vehicles at one location will lead to the overload of distribution network.
- The existing model for energy distribution that depends on certain consumer categories has to be observed while installing new fast charging stations.
- Appropriate implementation of smart grids should be respected for all modes charging of EVs.

3.1. The Overall Framework of the Algorithm

The values of electrical loads determine the choice of all elements of the power supply system: power lines, transformer substations and distribution networks. As a consequence, the information on electrical loads is one of the most important factors in the planning and operation of medium- and low-voltage networks. The charging stations for electric transport are also consumers of electricity. Thus, an algorithm for studying of a low-voltage distribution network in urban and rural areas has been developed in the present Thesis in accordance with the needs of charging stations.

The main tasks of the algorithm are as follows:

- To estimate the power load of the local distribution network and the possible additional load for the daily time intervals.
- To choose the location of charging stations, taking into account the behaviour of car owners at the parking places within 24 hours and the existing electric power load of the local distribution network.
- To choose the location of charging stations, taking into account their interaction with the energy company, including economic and environmental components.
- To investigate the distribution network in accordance with the needs of charging stations, as elements of an intelligent network (smart grid).
- To test the methodology of the algorithm for verifying the accuracy of the equalization of peak loads in the existing distribution network and increasing its reliability and efficiency under the condition of additional load from charging stations.

The algorithm consists of four steps. The configuration is shown in Fig. 3.1. Each step is implemented to solve specific tasks and has the following phases: input, calculation, analysis and decision.

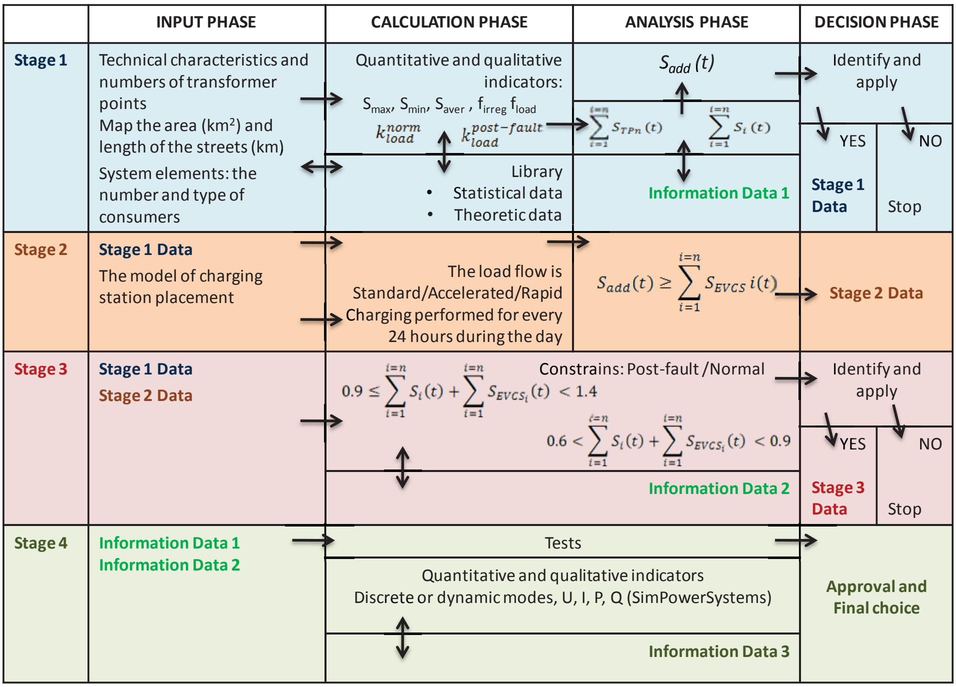


Fig. 3.1. The overall framework of the algorith.

The goal of **Stage 1** is to determine the existing demand of the local area network and capabilities for additional load according to time intervals of the day.

The Input Phase gathers the necessary data about the distribution network and system elements that can be later used during the calculation phase.

Calculation Phase: the quantitative and qualitative parameters of all objects that are needed for analysis are calculated.

Analytical Phase provides new information that can be used in the current test as well as in repeated research steps. The information is summarised in data 1. This phase also considers two possibilities, if $S_{add} > 0$ and if $S_{add} < 0$.

Decision Phase determines the transition to the second stage. There are two different decision phase steps. If $S_{add} < 0$, we return to Input Phase or Stop. IF $S_{add} > 0$, we proceed to Stage 2.

During **Stage 2**, to determine the location and type of the charging station, the optimal model of charging station placement is used. The simplex mathematical optimisation method for linear programming task is used for this purpose.

Input phase: $S_{add} > 0$ value and the optimal model for the charging station location (see Chapter "Algorithmic Description of the Methodology").

Calculation Phase evaluates the total electrical load in the area under consideration for all types of charging stations (slow charging, quick charging and super fast charging).

Analytical Phase compares the total electrical load obtained from electric vehicle charging stations (EVCSs) with potential additional loads for transformer substations. If the $S_{EVCS} \leq S_{add}$ is fulfilled, then there is a transition to the Decision Phase. The Decision Phase determines the transition to the third stage or the return to the first stage (Input Phase).

During **Stage 3**, data of Stage 1 and Stage 2 are combined as the Input Phase. According to the Electrical Codes and Standards, the technical characteristics of transformer substations are verified, which compare the total capacity of the objects with the permissible load of the transformers in the post-fault and normal modes. The information is summarised in Data 2, which are used as a current test as well as in the course of repeated research.

The Decision Phase has two different decisions: YES and NO. If the conditions are not met, we return to Data 1 of Stage 1. If the conditions are met, we proceed to Stage 4.

Stage 4 is algorithm validation. Input Phase: Data from information blocks of the first and third stages (Data 1 and Data 2). The Calculation Phase and Analysis Phase are combined. The validation of the data of the qualitative and quantitative parameters is carried out according to Stage 1. The Analysis Phase explores the quantitative and qualitative indicators, as they have to correspond to their possible practical application.

In addition, Simulink software (MATLAB tools) is also used, which allows evaluating the parameters of distribution networks (voltage, current, active, reactive and full capacity) to existing and additional loads. Due to the large amount of data, all information is summarised in Data 3, and then it is used for analysis of the tests.

The Decision Phase determines approval and the final choice of the distribution network in accordance with the needs of charging stations.

The detailed description of the algorithm methodology, the sequence of the research and the rationale for choosing the methods are available in the further sections of the Thesis.

Approbation of the algorithm for studying of a low-voltage distribution network in urban and rural areas in accordance with the needs of charging stations has been presented and discussed in scientific conferences and published in proceedings and international scientific journals [78]–[80].

3.2. Description of Algorithm Methodology

Figure 3.2 demonstrates the block scheme of the algorithm of operation of the existing local distribution network in the case of introduction of charging stations differentiated in power and charging speed.

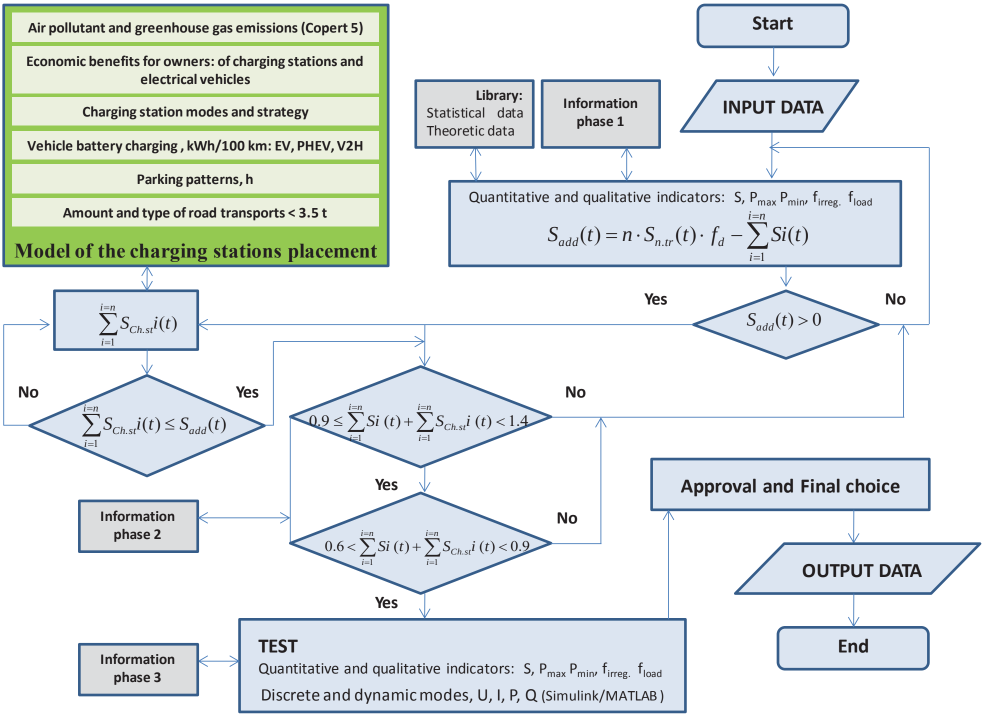


Fig. 3.2. Block scheme of the algorithm.

The working principles of the proposed algorithm are described below.

3.2.1 Stage I. Selecting the Input Data of the Distribution Network

Since charging stations are considered new consumers, it is necessary to investigate the capabilities of the existing local low-voltage power distribution network and demand of consumers.

The distribution network selected for the evaluation should contain as much information about the objects, which have connection to the transformer substation and the plan of territory, as possible. This information can be about the number and type of the objects; the power consumption of the objects and their daily load schedules; the scheme for the distribution network, technical specifications, the number and the location of the transformer substations; length of the streets.

In the case of the absence of input data of the power consumption of the objects and their daily load schedules, there is a reference to the Library module (Excel document archive), which contains the database of the quantitative indicators and load graphs of the eighteen objects. They are represented as follows: private (single family) houses, dwelling houses (2–3-storey), dwelling houses (4–5-storey), dwelling houses (8–12-storey), garages (600–1000 auto), office (or small industries), supermarket, store and market, post-office, local authorities and other institutions, petrol station, manufacture – 1 working shift, manufacture – shift work, catering establishment, school, primary school and kindergarten, health centre, street lighting.

Quantitative indicators are active power (P, kW), reactive power (Q, kVar), apparent power (S, kVA); coefficients of demand for lift installations of residential buildings (k_d); estimated coefficients of reactive power of residential buildings; specific design electric loads of public buildings; daily load of consumers of the micro district; parameters of lighting installations of the transport and pedestrian system of streets and roads and the technical specification of three-phase transformers 10/0.4 kV.

The missed input data in the Library module are estimated by means of statistical and calculating methods on the basis of mathematical statistics and probability theory [29], [30].

Further, the quantitative indicators and load graphs for each object, transformer substation (TS) and distribution network are calculated. The calculations can be carried out for each season, month and day (working day or weekends) depending on the goals and objectives, and with the presence of input data. For the objects, the calculations take maximum (peak), S_{max}, average (middle), S_{aver} , minimum (off-peak), S_{min}, demand and their daily time of use, the load factor (f_{load}) and the irregularity factor (f_{irreg}) [81]–[84].

The load factor (f_{load}) shows the extent of use on the active power for the load curve in a specified time period and is determined by (3.1):

$$f_{load} = \frac{P_1 t_1 + P_2 t_2 + ... + P_{24} t_{24}}{P_{\max}(t_1 + t_2 + .. + t_{24})} = \frac{1}{P_{\max} \times t} \int_0^{24} P(t)dt \qquad (3.1)$$

The irregularity factor ($f_{irreg.}$) is the ratio between the minimum loads by the average peak load in a specified time period (2):

$$f_{irreg.} = \frac{P_{\min}}{P_{\max}} \qquad (3.2)$$

The total load and the schedule on the transformer substation from the consumer groups are determined by (3):

$$\sum_{i=1}^{i=n} S = \sqrt{\sum_{i=1}^{i=n} P^2 + \sum_{i=1}^{i=n} Q^2} \quad (3.3)$$

For the transformer substations, the actual load factor of the transformer in the normal operating mode (k_{load}^{norm}) and the load factor in the post-fault mode ($k_{load}^{post-fauil}$)[7] and peak, middle and off-peak load periods and their daily time period of use are also quantitatively estimated [85]–[90].

The substantiation of the choice of transformers is given to the load requirements according to: $0.5 < k_{load}^{norm} < 0.9$ – the actual load factor of the transformer in the normal operating mode, which depends on the number of transformers in the substation and the load curve of the consumers' power supply (3.4);

$$k_{load}^{norm} = \frac{\sum_{i=1}^{i=n} S_i}{S_{n.tr} \cdot n} \,, \quad (3.4)$$

$0.9 \leq k_{load}^{post-fault} < 1.4$ – the load factor in the post-fault mode (3.5):

$$k_{load}^{post-fauil} = \sum_{i=1}^{i=n} S / S_{n.tr} \cdot (n/2) \,, \quad (3.5)$$

where $\sum_{i=1}^{i=n} S_i$ – load from all consumers;

$S_{n.tr}$ – transformer nominal power;

n – the number of transformers.

Then, quantitative and qualitative indicators are generated in the report (in table and graphically) in Information block 1. On the base of this information, the possible additional load for the temporary daily intervals is calculated by the expression (3.6).

$$S_{add}(t) = 1.4 \cdot S_{n.tr}(t) - \sum_{i=1}^{i=n} Si(t) \cdot f_d \,, \quad (3.6)$$

where $S_{n.tr}$ – the rated power of the transformer, kVA;

1.4 – the max load factor in the post-fault mode;

S_i – the apparent power of the consumers (objects), kVA;

f_d – the diversity factor ≤ 1.

Diversity Factor (f_d) – the ratio, expressed as a numerical value or as a percentage, of the simultaneous maximum demand of a group of electrical appliances or consumers within a specified period to the sum of their individual maximum demands within the same period; the value is always ≤ 1[8]. The f_d is applied to each group of loads and requires a detailed

[7] http://www.electrical-installation.org/enwiki/Estimation_of_actual_maximum_kVA_demand

[8] The World's Online Electrotechnical Vocabulary http://www.electropedia.org/

knowledge and investigation of the conditions. For this reason, $f_d = 0.9$ is the value for general application [91], [92].

If the condition S_{add} (t) > 0 is performed, then the transition to Stage 2 takes place. Otherwise, the algorithm returns to the Input Phase.

3.2.2 Stage II. Implementation of the Optimal Model for the Placement of Charging Stations

As Stage II, a stand-alone model of the charging station location is used to study the algorithm methodology. The aim of this model is to satisfy the necessary hourly (daily) requirements for charging electric transport under the conditions of traditional parking places. The interaction of people's behaviour, urban infrastructure and the power supply system are used as the main attributes. The model allows estimating the low, medium and high penetration demand for charges. The mathematical statistics methods, probability theory and the simplex mathematical optimisation method for linear programming task have been applied to implement this model.

The model is implemented as follows:

- The input data are represented as data of Stage 1 (S_{add}).
- Number of vehicles with a gross weight of less than 3.5 tonnes and their parking within 24 hours in the area.
- The behavior of car owners at the parking places within 24 hours is reviewed and analysed by cluster analysis.
- Technical indicators: charging types (slow/medium/fast) and the most common models of road electric transport are accepted for the calculations.
- On the basis of the list of road transport, a park of possible electric transport is formed;
- The dynamics of changes in harmful emissions from vehicles investigated are examined by COPERT 5 program.
- In accordance with the two criteria – the optimal time of the battery charging (the degree of charging is necessary for the owner of vehicles) and the number of charging stations (charging types – slow, medium, fast) at the places of traditional parking, the load necessary for the charging process is estimated (power consumption).
- To provide the best solution during the process, the load is analysed, several options are tested and then the final choice is presented.
- Having received the final version of the location of the infrastructure and the penetration demand (SEVCS is the load of the charging station) for charges, day-night consumption of energy for charging is estimated and compared with S_{add} (t).

To provide the best solution during the process, the load is analysed, several options are tested and then the final choice is presented.

Having received the final version of the location of the infrastructure and the penetration demand (SEVCS), this is compared with S_{add} (t) by using Equation (3.13).

If Equation (3.13) is performed, the process is completed, and we proceed to Stage 3.

Otherwise, the process returns to the point of infrastructure and the penetration demand. It is necessary to calculate a new load of the charging station.

To illustrate the concept of declarative processes, a block scheme of the model is shown in Fig. 3.3.

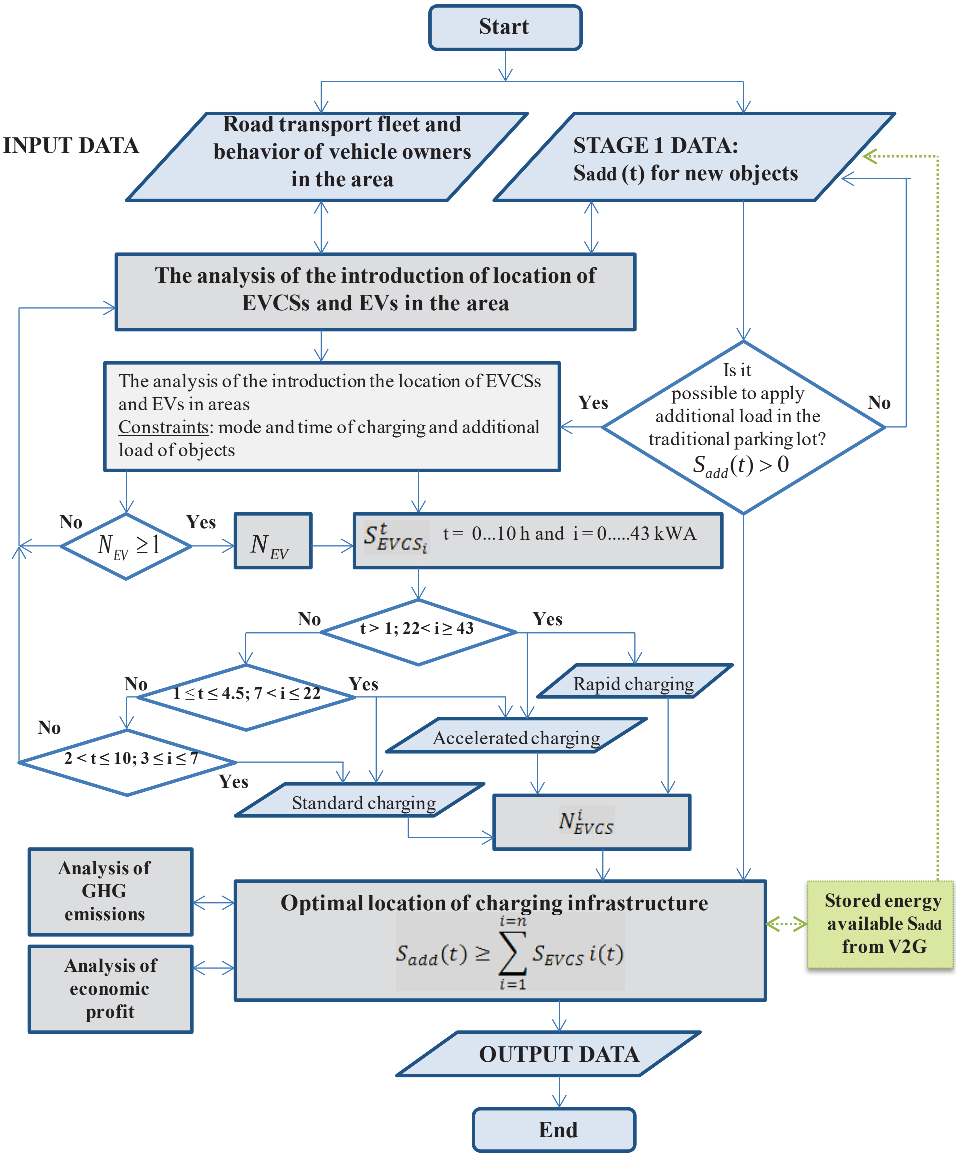


Fig. 3.3. Block scheme of the model of the charging station placement.

3.2.2.1 Description of the Model Methodology

A. Data Collection and Analysis of the Interaction of the Parking Pattern in the Infrastructure of the Area

The analysis of the interaction of the parking pattern in the infrastructure of the area is based on the input data collection represented as three groups. The Input Data of groups are as follows:

Group 1: Data of Stage 1 are the condition $S_{add}(t) > 0$.

Group 2: Number of vehicles with a gross weight of less than 3.5 tonnes and location and duration of parking within 24 hours in the area under consideration. Group 2 requires the information about behaviour of vehicle owners: number of vehicles, location and duration of parking, average daily mileage.

Group 3: Process of electric vehicle battery charging. Group 3 requires the information about electric vehicles: available EVs and PHEVs in the market and electric vehicle battery charging.

Group 2. Since the fleet of electric vehicles is under formation in Latvia, the input data for modelling are the road vehicles with internal combustion engines. The Input Data of the number of vehicles are available from the publications of the National Statistical System of Latvia or at the website of the Road Traffic Safety Directorate [56], [95].

To obtain the Input Data of the location and duration of parking, it is necessary to gather information from different data sources and choose methods for its processing. For the study, the following necessary information has been defined: the total number of vehicles in a parking lot (parking lot volume); the number of vehicles in a parking lot at a given instant of time (parking accumulation for each hour); annual mileage or the daily mileage of vehicles.

The information has been collected using traditional methods, such as monitoring and studying the existing legislative documents, forms and reports on the location and duration of parking near the house, work, shop, etc. [56], [93], [94]. The information has been processed by the correlation analysis, which is a good analytical technique to group or segment identical elements. For the analysis, it is necessary to solve the following tasks:

- To estimate the volume of usage and parking demand within 24 hours in the area.
- To choose the most loaded location of parking according to its volume of usage and demand by the correlation analysis.
- To determine average daily mileage.

To estimate the volume of usage and parking demand in the area, a simple average method has been used. Using this method, the total number of parking spaces of each parking lot is calculated and then it is divided by the total number of type units. The formula for the simple average method is as follows (3.7):

$$\overline{X}=\frac{\sum_{i=1}^{n} x_i}{n}, \tag{3.7}$$

where $\overline{X}$ – sampling mean;

n – a set of observations;

X_i – i-sample component.

The level of correlation is analysed using MS Excel program.

The European Environment Agency (EEA) Guidebook has adopted standardization for all categories of road vehicles, in particular, for vehicles with a total weight of up to 3.5 tons, such as passenger cars (PCs) and light trucks (LCV) [97]. In the present research, only these two categories are considered since currently there are EVs and PHEVs technologies in this segment.

Further, to continue the study, it is necessary to determine the average daily mileage. For this purpose, the statistics of the average annual mileage for these categories of road transport have been used. These are as follows: average annual mileage for vehicles in the country; in urban and rural areas, and vehicles owned by private persons and by legal persons. The data gathered by the author of the Thesis for the period of 2008–2015 have allowed concluding that the average daily mileage in Latvia has been implemented as follows: the indicator for private persons is 37.7 km/day and for legal persons – 70.4 km/day (the range from 63.8 to 200 km/day). In Riga, the situation is as follows (as part of the study conducted for Riga City Council): the indicator for private persons is 24.9 km/day (does not exceed 28 km/day) and for legal persons – 71.2 km/day (the range from 57 to 120 km/day (see Table 3.1) [96]–[98].

Table 3.1.

The average daily mileage for vehicles with a gross weight of up to 3.5 tonnes, km, 2008–2015[9]

	2008	2009	2010	2011	2012	2013	2014	2015
Latvia								
Private persons	44.0	39.8	40.9	37.5	34.9	33.8	35.0	36.0
Legal persons	63.8	64.1	67.8	66.8	73.5	74.5	75.6	76.8
Riga*								
Private persons	25.6	25.7	25.5	22.3	22.4	22.4	27.8	27.8
Legal persons	74.3	73.4	87.8	65.7	76.7	76.7	57.4	57.4

* Taxicabs are not included in this study

<u>Group 3</u>. Analysis of EV and PHEVs availability in the market. According to 2015 and 2016 estimates, the most available full electric or plug-in hybrid electric vehicles with a gross weight of up to 3.5 tonnes in the Latvian market were Volkswagen (VW e-up), Nissan Leaf, BMW i, Tesla and Toyota Prius Plug-in Hybrid [56]. Figure 3.4 shows the share of EVs (2015) discussed in the preceding paragraphs.

[9] These data have been collected by the author of the Thesis and can be used as the main reference in the absence of other information.

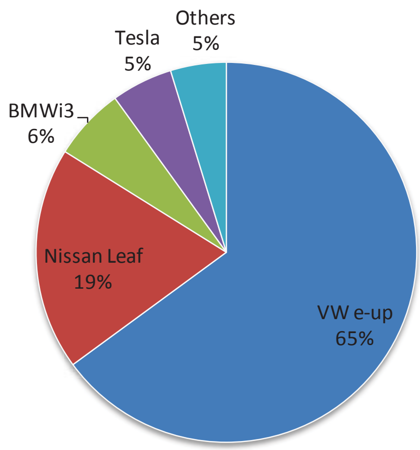


Fig. 3.4. Share of electric vehicles in Latvia, 2015.

Table 3.2 provides some of EV and PHEV specifications, which have been taken on the Internet [99], [100].

Table 3.2.

EV and PHEV Specifications

Model	Technology	Battery capacity (size), kWh	Mileage with one charge, km
Volkswagen e-UP	BEV	19	105
Volkswagen e-Golf	BEV	29	160
Nissan Leaf	BEV	24	135
BMW i	BEV	29	160
2015 Fiat 500e	BEV	29	160
Chevrolet Spark EV	BEV	28	160
Mitsubishi i-MiEV	BEV	30	160
Tesla Model S	BEV	34	160
FIAT Fiorino Elettrico	BEV	21	100
Hyundai IONIQ Plug-in	PHEV	8.9	35
BMW i8	PHEV	7	24
Toyota Prius Plug-in	PHEV	8.8	34
Mercedes C 350e Plug-In Saloon	PHEV	6.2	26
Audi A3 e-tron ultra	PHEV	7	27
Volkswagen Golf GTE	PHEV	8.7	31

To calculate the average power consumption of a single electric vehicle, technical and practical data have been used, taken from the following models popular in Latvia: FIAT Fiorino Elettrico, Volkswagen e-up, Nissan e-NV200 Electric Van.

Most BEVs cover 100 kilometres with 17 kWh and PHEVs cover 29 kilometres with 7 kWh. The gathered data allowed concluding that the mileage, claimed by the manufacturers, of a fully charged EV might be lower than initially specified. The changes in mileage might occur due to seasonal changes (consequently – road quality changes), the work of the interior electric heater, the influence of low temperatures on the battery, as well as due to the operation of air conditioning, charging of other devices in the car (auxiliary systems of EVs) and, of course, due to the individual manner of driving. As a result, the mileage might become reduced by 30 %. In view of the above, the calculations showed that to cover a distance of 100 km the BEV consumes on an average: 24 kWh in the winter, 17 kWh in the summer, and 21 kWh in the spring and autumn.

B. Electric Vehicle Battery Charging

One of the most important parts of EVs is the batteries, which have a strong impact on the cost of the car and its service life. Nowadays, the most frequently used technologies are lithium-nickel-cobalt-aluminum (NCA), lithium-nickel-manganese-cobalt (NMC), lithium-manganese spinel oxide (LMO), lithium titanate oxide (LTO) and lithium-iron phosphate (LFP). The life of the battery depends on cycle stability (the number of times it is fully charged and discharged before being degraded to 80 %of its original capacity at full charge) and the range of years a battery remains useful [101], [102].

Table 3.3.

Charging Time on Electric Vehicle Service Equipment

Charge levels	StEVCS, 1.5kVA AC - 120V, 15A	AcEVCS, 6.6kVA AC - 240V, 30A	RapEVCS, 20-120kVA DC - 400–600V, up to 300A
Driving range per hour charge	8km	36km	110 km, 270km
BMW i3 (22kWh)	15h	4h	To 80 %: 24kW in 30 min
Nissan Leaf (32kWh)	16h	5h	To 80 %: 50kW in 20 min
Chevy Bolt (60kWh)	40h	10h	To 80 %: 50kW in 60 min
Tesla S 85 (90kWh)	60h	15h	To 80 %: 120kWin 40 min

Table 3.3 provides data of charging times on EVSEs from the database of EV makers. The time of charge and driving range with StEVCS, AcEVCS and RapEVCS charge levels are based on charging an empty battery to full actual state of the charge (SOC_{actual}). From practical point of view, using AcEVCS is the most common and preferred routine for everyday charging. At the same time, RapEVCS is not designed to fill the battery completely but if the vehicle has the long travel during the day, it can drive and have the next charging station [103].

The main characteristics of batteries for EVs are charging time, power demand and the rate of charge [104]. Therefore, the process of charging the battery is carried out in accordance with the selected Charging Mode (CM), the initial state of charge ($SOC_{initial}$) and the actual state of the charge (SOC_{actual}) of the battery at the end of the process. In general, a charging action occurs when the SOC level is 15 % or less, because the warning light for the shortage of battery is activated at that level. The communication between EV is determined by ISO 15118 which is designed to support the energy transfer from electric vehicle supply equipment (EVSE) to all types of EVs [105]. Thus, the required state of charge (SOC_{actual}) can be estimated by Equation (3.8).

$$SOC_{actual} = SOC_{initial} + SOC(t), \qquad (3.8)$$

where SOC(t) is the state of battery charging process at an instant of time, minute or hour.

The time depends on the selected mode and power level of the charging station (Chapter 2, Table 2.1).

Below the results present a practical rapid charging process by the Nissan e-NV200 with 24 kWh batteries. The charging process can be expressed as follows:

$$SOC_{actual} = 2.4 + 0.65_{(t = 1)} + 0.74_{(t = 2)} + \ldots + 0.13_{(t = 30)} = 17.15 \text{ kWh}.$$

The battery charging process with an empty battery ($SOC_{initial}$ is 1 %) is charged up to 81 % (17.15kWh) in 30 minutes. If the charging process is started with $SOC_{initial}$ = 20 %, 18 minutes are needed, when $SOC_{initial}$ = 40 %, 15 minutes are necessary. These processes are shown in Fig. 3.5.

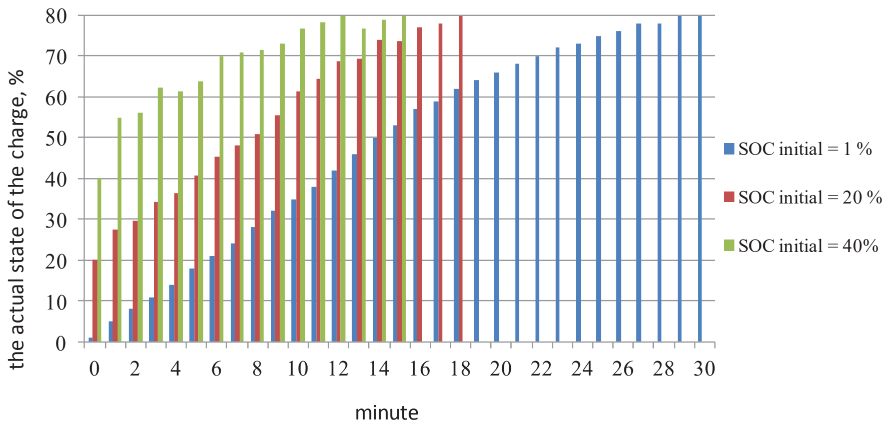


Fig. 3.5. Rapid charging process, SOCactual.[10]

It is important to note that the range of vehicles with electric or hybrid types of engines is expanding every by year, so it is impossible to consider the entire spectrum of the existing battery. The technology assessment of BEVs and PHEVs conducted by the California Environmental Protection Agency presented an increase in the average mileage per full

[10] Source: The practical information provided by the owners of the Nissan e-NV200. www.mmxenergy.lv

charge of the battery by 45 % by the end of 2016 compared to 2010. It is still expected to increase it substantially by 2025 [106].

Analysis of the interaction parking pattern in the infrastructure of the area is carried out on the basis of input data and is as follows:

First, the location and duration of parking lots can be estimated in accordance with information about behaviour of ICE vehicle owners. The passenger car is in motion only a small percentage of the day time. During the remaining time, it is parked near a dwelling house, an office building, and a special parking facility or another convenient place.

The number of observations of parking lots was collected by the author of the Thesis and used as the main reference for estimation of the behaviour of car owners, as shown in Table 3.4 below.

Table 3.4.

Number of Observations of Parking Lots

Type of parking lot	Number of observations									
	1	2	3	4	5	6	7	8	9	10
Multi-family houses (2–3-storey)	10	8	11	7	8	9	11	14	10	13
Multi-family houses (4–5-storey)	34	31	24	28	31	34	30	32	26	27
Multi-family houses (8–12-storey)	43	31	24	38	41	44	40	32	26	27
Large parking lot (or garage)	500	350	220	150	110	90				
Office (or small industries)	40	42	50	55	100	86				
Manufacture – 1 working shift	105	56	98							
Manufacture – shift work	96	98	64							
Grocery stores	60	70	55							
Supermarket	558	504	721							
Health centre	120	110	86							
Kindergarten	6	4	5							
School	11	18	8							

The period of time that a car remains at a parking space varies. The behaviour of car owners can be interpreted as follows: more than 50 % of cars from 8:00 pm to 7:00 am are on parking lots near dwelling houses and on large parking lots. Figure 3.6 shows that car users leave home from 6:00 am to 8:00 am, which corresponds to the start of the business day, and from 6:00 pm to 11:00 pm they return home. Figure 3.7 shows that more than 50 % of cars were near the office building and the health centre between 7:00 am and 8:00 pm, and near the grocery store between 7:00 am and 9:00 pm.

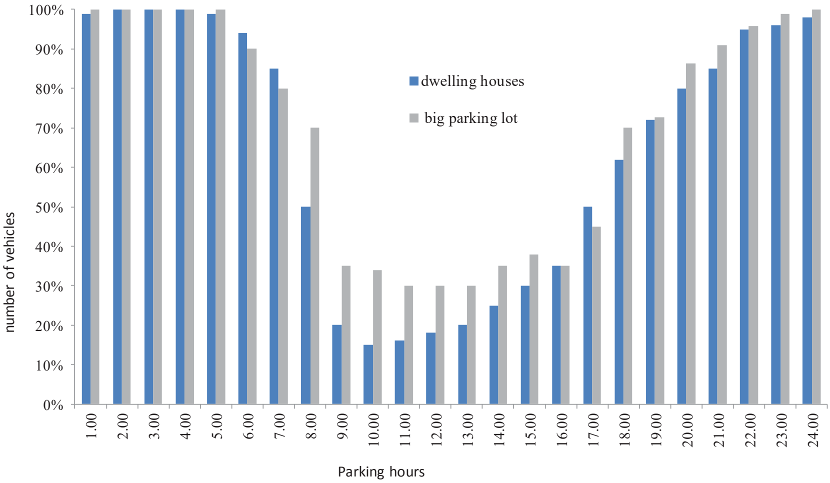


Fig. 3.6. The distribution of the parking duration: the dwelling houses and large parking lots.

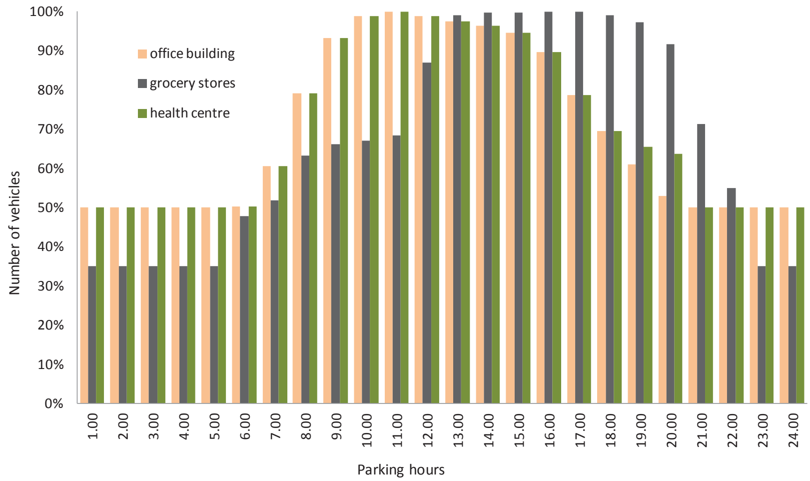


Fig. 3.7. The distribution of the parking duration: the office building, the grocery store and the health centre.

Second, the average daily mileage for vehicles in the country has been estimated in accordance with the average annual mileage. Thus, the range is from 24.9 to 200 km/day.

Third, in accordance with kWh/100 km of consumption, vehicles can be further classified into three groups (small, medium, large) (see Table 3.5). For each group, the following data are of importance: the maximum charging and maximum time of the charge from an empty battery to a full one. The number of hours required for charging a storage battery using slow charging (StEVCS) varies from 6 to 12 hours, medium charging (AcEVCS) requires from 1 to 4.5 hours and fast charging (RapEVCS) takes 30 to 55 minutes.

Table 3.5.

Current Details and Charging Time for the range of 100 km (BEV and PHEV).

Charging Mode*	StEVCS – Mode 1 (3–7 kVA)	AcEVCS – Mode 3 (7–22 kVA)	RapEVCS – Mode 4 (43 kVA)
Small (EV > 16 kWh)	2–5 h	1–2.5 h	0.35 h
Medium (16 ≤ EV≤ 22 kWh)	3.5–8 h	1–3.5 h	0.5 h
Large (22 <EV≤ 30 kWh)	4.5–10 h	1.5–4.5 h	0.65 h

*See Chaper 2 Table 2.1.

The next stage is to define the placement of charging stations and the load of distribution network. According to the penetration demand and possible additional load, the number of EVs (NEV) is calculated by Equation (3.9).

$$N_{\Sigma EV}^{t} = \frac{S_{add_i}^{t}}{S_{EV_i}^{t}} \quad , \qquad (3.9)$$

where $S_{\mathrm{add}_i}^{t}$ – the additional load in the period of time i. The minimum additional load occurs in the winter season, whereas the maximum one – in the summer season.

$S_{\mathrm{EV}_i}^{t} = \sqrt{P_{\mathrm{EV}_i}^{2} + Q_{\mathrm{EV}_i}^{2}}$ – the load that represents charging for one EV in the period of time. At calculations QEV = 0 was accepted.

If the condition $N_{EV_i}^{t} > 0$ is performed, then the transition to the next stage takes place. Otherwise, the algorithm returns to the point of infrastructure and the penetration demand (input data of groups), where it is necessary to calculate a new load of the charging station.

Finally, the results of the analysis of the possible additional load of objects, mode and time of charging station constraints ($S_{EVCS_i}^{t}, where\ t = 0 \ldots 10\ hours\ and\ i = 0 \ldots .43\ kVA$) and interaction parking pattern in the infrastructure of the area show the parking availability pattern that allows assuming possible scheduling of charging stations. This process is performed by using the IF function in Excel. Table 3.6, as an example, reflects the results of data. IF statement has two results of comparison: True or False.

Table 3.6.

Possible Scheduling Scheme for the Charging Station

Time (t), h	Parking lot, $S_{add}(i)$	IF(3 ≤ S n:00 ≥43)
0:00	$S_{0:00}$	FALSE
1:00	$S_{1:00}$	FALSE
2:00	$S_{2:00}$	FALSE
.....	$S_{n:00}$	TRUE
23:00	$S_{23:00}$	FALSE
0 < t ≥ 10	t = n	

Next stage is to define the charging mode and number of the charging stations according to the constraints for the public EVCSs.

Constraints are classified by EVCS type as follows:

- *Constraint I: $t > 1$ (hour) is period of time interval and $i \geq 43$ (kVA)* is the rated input power of charging station. If criteria are performed, this means that in the considered period of time the public RapEVCSs and AcEVCSs can be loaded. If No, then Constraint II shall be used.
- *Constraint II: $1 \leq t \leq 4.5$ (hour) and $7 < i \leq 22$ (kVA).* If criteria are performed, this means that in the considered period of time the public AcEVCSs and StEVCSs can be loaded. If No, then Constraint III shall be used.
- *Constraint III: $2 < t \leq 10$ (hour) and $3 \leq i \leq 7$ (kVA).* If criteria are performed, this means that in the considered period of time the public StEVCSs can be loaded.

This calculation is also performed by using the IF function that identifies which criteria as a whole are performed and which of the criteria performed are absent (see Table 3.7).

Table 3.7.

Scheduling Scheme for the Charging Station according to the Constraints:

A. Parking lot, $S_{add}(i)$

Time (t), h	Parking lot, $S_{add}(i)$	Constraint I	Constraint II	Constraint III
0:00	$S_{0:00}$	TRUE or FALSE	TRUE or FALSE	TRUE or FALSE
1:00	$S_{1:00}$	...	...	...
2:00	$S_{2:00}$	...	...	...
.....	$S_{n:00}$	...	...	...
23:00	$S_{23:00}$	...	...	...

B. Parking lot, t_i

Parking lot, t_i	Time (Constraint I)	Time (Constraint II)	Time (Constraint III)
Parking lot 1, t_i	$0 < t \leq 10$	$0 < t \leq 10$	$0 < t \leq 10$
Parking lot 2, t_i			
....	...	...	...
Parking lot N, t_i	...	...	...

If constraints are performed, the algorithm determines the number of the public charging stations. Otherwise, the algorithm returns to the analysis of the interaction parking pattern in the infrastructure of the area.

To estimate the total number of EVCSs, the three modes of EVCSs (and three cars are connected) simultaneously per hour have been considered. It means that StEVCS (9.7 %) + AcEVCS (30.6 %) + RapEVCS (59.7 %) = 100%EVCSs (see Table 3.3). EVCSs represent the load for the main transformer per hour and their total number is defined by the following Equation (3.10):

$$N_{EVCS} = \frac{9.7\% S_{add}(t)}{7} + \frac{30.6\% S_{add}(t)}{22} + \frac{59.7\% S_{add}(t)}{43} = N_{EVCS_{St}} + N_{EVCS_{Ac}} + N_{EVCS_{Rap}} \quad , \quad (3.10)$$

where $N_{EVCS_{St}}$ – the number of StEVCS;

$N_{EVCS_{Ac}}$ – the number of AcEVCS;

$N_{EVCS_{Rap}}$ – the number of RapEVCS.

Equation (3.10) allows determining the total number of stations differentiated by modes. However, the main criterion for choosing and deciding on the number of charging stations is the possible additional load.

In the framework of economic expediency, the operation within 24 hours a day and differentiated tariffs for electricity are taken into account for installing public charging stations. The tariffs for electricity for legal persons are differentiated by 3 time zone tariffs: the maximum tariffs are from 8:00 am to 10:00 am and from 5:00 pm to 8:00 pm; day tariffs (77 % of the maximum tariff) are from 7:00 am to 8:00 am, from 10:00 am to 5:00 pm and from 8:00 pm to 11:00 pm on weekdays; the night and weekend tariffs (46 % of the maximum tariff) are from 11:00 pm to 7:00 am [107].

In general, all the three modes of EVCSs may be applied to a parking pattern in the infrastructure of the area. Therefore, to determine the specific locations of stations it is necessary to use the optimisation process at this stage, which is solved by the simplex method in Excel Solver [108], [109].

C. Optimisation of the Placement of Charging Infrastructure and the Ecological and Economic Aspects

Optimisation of the location of charging infrastructure is carried out on the basis of the data, which were obtained before. Additionally, there are the ecological and economic aspects, as well as the opportunity of using the Grid-to-Vehicle (V2G)/Vehicle-to-Grid (G2V) technology is considered.

Placement of Charging Stations Based on the Simplex Algorithm

The simplex algorithm11 is a linear mathematical model which allows finding the optimal or best outcome 110]. The placement problem of charging stations has the following formulation: the location of objects of parking lots (C_1, C_2, ...,C_n) and the possible additional load of objects (c_1, c_2,... ,c_n) are known. Three modes of charging stations (B_1, B_2, B_3) and the additional load for EVCSs per hour (b_1, b_2, b_3) are also indicated. Unit load for EVCSs is 7, 22, 43 kVA. It is assumed that charging stations are open 24 hours day.

Mathematical formulation of linear equations for both the objectives and the constraints are expressed by the following equations:

The objectives:

$$F(x) = b_1 \cdot x_1 + b_2 \cdot x_2 + \cdots + b_n \cdot x_n \rightarrow \max \text{ (min)}$$

[11] https://study.com/academy/lesson/using-linear-programming-to-solve-problems.html

The constraints:

$$\begin{cases} a_{11} \cdot x_1 + a_{12} \cdot x_2 + \cdots + a_{1n} \cdot x_n \le c_1 \\ a_{21} \cdot x_1 + a_{22} \cdot x_2 + \cdots + a_{2n} \cdot x_n \le c_2 \\ a_{m1} \cdot x_1 + a_{m2} \cdot x_2 + \cdots + a_{mn} \cdot x_n \le c_n \end{cases}$$

$$x_j \ge 0; j = \overline{1, N}$$

Subsequent actions take place at the analysis phase according to Equation (3.11), as well as the transition occurs to the decision phase (Stage 2 Data, see Fig. 3.1). Therefore, the total load of charging stations on the local distribution network ($\sum_{i=1}^{i=n} S_{EVCS}\ i(t)$) is estimated. This load cannot be higher than the additional load in Stage 1, calculated before.

$$\sum_{i=1}^{i=n} S_{EVCS}\ i(t) = S_{EVCS_{St}}(t) \cdot N_{EVCS_{St}} + S_{EVCS_{Ac}}(t) \cdot N_{EVCS_{Ac}} + +S_{EVCS_{Rap}}(t) \cdot N_{EVCS_{Rap}} \quad (3.11)$$

Location and number of charging stations are provided in Table 3.8.

Table 3.8.

Location and Number of Charging Stations

	Parking lot 1	Parking lot 2	....	Parking lot N	Total
StEVCS	x	x	x	x	x
AcEVCS	x	x	x	x	x
RapEVCS	x	x	x	x	x

Analysis of Exhaust Emissions of Motor Vehicles based on COPERT 5 Software

The ecological aspect of this algorithm is the analysis of emissions in urban and rural areas, using the COPERT 5 program, reflecting dynamics of changes in harmful emissions in the structure of road transports.

To analyse the possible change of the emissions in the use of vehicles with internal combustion engines (ICE) and BEV technologies, the following comparison has been proposed: if the number of ICE technologies is 100 % of the total passenger cars (PCs) and light trucks (LCV) and if the number of BEV technologies is more than 50 % (high penetration), less than 10 % (low penetration) and from 10 % to 50% (medium penetration) of the total passenger cars (PCs) and light trucks (LCV) in the area according to the daily mileage for private persons and legal persons.

COPERT 5 is a software tool used to calculate air pollutant and greenhouse gas emissions from road transport as described in the 2006 IPCC Guidelines and EMEP/EEA Emission Inventory Guidebook – 2016 [111]–[113]. As the basis data for the model, the following information is provided: the number of vehicles, mileage for passenger cars and light-duty trucks, ambient temperature variations during months and others. The summary of the data used to calculate emissions for road transport is presented in Fig. 3.8. Estimation of GHG emissions, air pollutants and effects of cold-start emission is a substantial factor to analyse the change in the emissions in urban and rural areas.

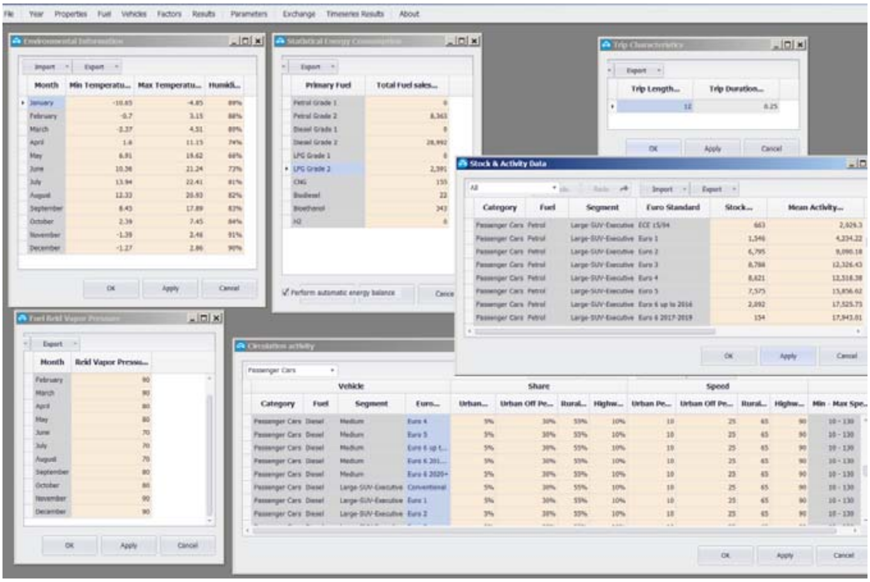


Fig. 3.8. COPERT 5: Activity data.

BEV technology has an electric engine that works only owing to the energy stored in the batteries, so there are no emissions. The PHEVs have an electric engine but at the same time they run on fossil fuel. They have a low level of GHGs, which is influenced by the fossil fuel consumption. As an example, the results of emissions by COPERT 5 program are illustrated in Fig. 3.9.

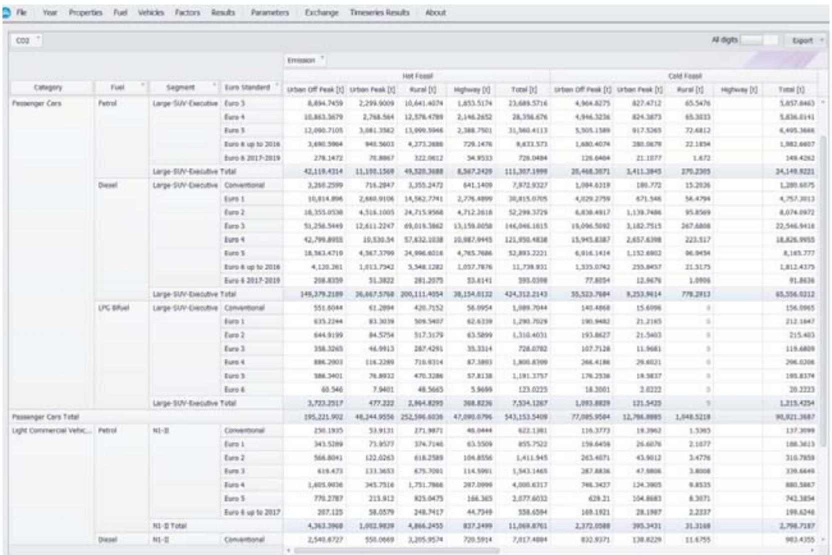


Fig. 3.9. Results of CO_2 emissions by COPERT 5 program.

COPERT 5 allows determining the fuel consumption for each type of vehicle engine. Chapter 4 of the Doctoral Thesis considers the consumption of primary and secondary energy resources, greenhouse gas emissions and the consumption of electricity in the country until 2030 in the case of widespread use of road electric.

Distribution Network and Vehicle-to-Grid/Grid-to-Vehicle Technologies

Currently, researchers implement V2G/G2V technologies in the distributed generation (DG) system and distribution network, and benefits of these technologies for private and legal buyers and sellers of electricity are being investigated, since these technologies allow not only storing and using electricity, but also supplying electricity to the distribution networks.

The main factors for the implementation of V2G/G2V technologies are the growth of V2G/G2V fleet and the use of smart grid technologies to manage commercial and household loads. The reason is that V2G/G2V technologies are one of the elements of a two-way charging system and have the potential benefits, such as: they provide back-up power and load balancing, reduce peak loads and the uncertainty in forecasts of daily or hourly electrical load, integrate renewable electricity generation into the grid when it is available etc. Although V2G operation mode reduces the lifetime of modern vehicle batteries, the charging/discharging infrastructure will be deployed at places necessary for people [114]–[116].

Taking into account that the average daily vehicle mileage is used, the power limited by vehicle's (V2G) stored energy is calculated:

$$P_{V2G_{storage}} = P_{V2G} - P_{as} - P_{V2G}\frac{l}{100}, \quad (3.12)$$

where P_{V2G} – energy consumption of V2G, kWh/100km;

P_{as} – auxiliaries service (the consumption for cooling or heating etc). According to various sources, on average it is 15 %–30 % of the maximum stored energy;

l – average daily mileage of EV, km.

One V2G battery does not influence the energy supply system. However, if hundred cars are introduced to the system, it can improve the efficiency of power distribution.

Available S_{add} from V2Gs will also affect the possible additional load for new objects in the area.

The Analysis of Economic Profit from EV Integration

The economic aspect of this algorithm is the interaction and management of needs of the two parties – the driver and the service operator/owner of charging stations. The driver needs electricity in the battery for driving, flexible tariffs for electricity during the day and convenient charging technical solution. The service operator wants the maximum use of charging stations during the day and to get economic benefits from this business.

Assuming that charging stations are open 24 hours a day, the electricity tariff system, differentiated by the time of the day, can stimulate owners of charging stations and owners of electrical vehicles to participate in the power market.

It should be noted that V2G technology will contribute to the economic benefits in the future. For this purpose, in the future it will be necessary to create an appropriate infrastructure for discharging. Moreover, the V2G owner can use the stored energy not only for selling it back to the grid, but also to meet household needs.

Thus, having received the optimal location of the infrastructure, the consumption of energy for charging is estimated and compared with $S_{add}(t)$ by Equation (3.13).

$$S_{add}(t) \geq \sum_{i=1}^{i=n} S_{EVCS}\, i(t) \tag{3.13}$$

If Equation (3.13) is performed, the algorithm goes to STAGE 3. Otherwise, the algorithm returns to the first stage, the input data point of infrastructure and the penetration demand, where it is necessary to calculate a new load of the charging station.

The result of the optimal model for the placement of charging stations is the decision phase with output data (Stage 2 data).

3.2.3 Stage III. Verification of the Transformer Substation in the Post-fault and Normal Modes

During the third stage, according to the Network Codes[12] and standards, the technical characteristics of transformer substations and equations (1, 2, 3) of Stage 1 are verified during the calculation phase and analysis phase. Input phase for the calculation phase and analysis phase is the quantitative indicators of data of Stage 1 and Stage 2.

Then, the total capacity of the objects with the permissible load of the transformers in the post-fault and normal modes is compared.

The post-fault mode is calculated by Equation (3.14). If one transformer is disconnected (in the case of a two-transformer substation) during the repair or minimum load, one transformer can be overloaded by 140 % within 6 hours a day, but no more than 5 days.

$$0.9 \leq \sum_{i=1}^{i=n} S_i(t) + \sum_{i=1}^{i=n} S_{EVCS_{i(t)}} < 1.4 \tag{3.14}$$

The normal mode is calculated by Equation (3.15). At two-transformer substations it is customary to use the type of transformers with the equal (similar) technical characteristics that provide the following parameters: the maximum load of power supply objects; the daily schedule of loading of objects; the number of hours of maximum load according to the actual load schedule of the objects.

$$0.5 < \sum_{i=1}^{i=n} S_i(t) + \sum_{i=1}^{i=n} S_{EVCS_{i(t)}} < 0.9 \tag{3.15}$$

[12] Network Codes by ENTSO-E. Network codes are a set of rules drafted by ENTSO-E, with guidance from the Agency for the Cooperation of Energy Regulators.

Formation of the calculated data is carried out in the form of a report in the information block 2. Analysis phase analyses the report and determines the fulfillment of the conditions (the normal and post-fault modes).

The final result of Stage 3 is the decision phase – identification and application – where the decision is met (Yes) or not met (No). If the conditions are met, go to Stage 4. If at least one of the conditions is not met, further studies are not performed, the algorithm is interrupted (Stop).

3.2.4 Stage IV. Validation of the Algorithm, Taking into Account the Specific Location of Electric Vehicle Charging Stations

At the fourth stage, verification of transformer substations and power supply facilities is conducted to ensure that the methodology of the algorithm provides a theoretically reliable result. For Stage 4, the Input phase is the data 1 of Stage 1 and data 2 of Stage 3. At the calculation phase, quantitative and qualitative indicators for transformer substation are tested according to the following two conditions.

The first condition is compliance with reliability requirements of power supply to the local distribution network in accordance with the Latvian and European quality standards, since they must correspond to their practical application. To fulfil this condition, the parameters and coefficients of the local distribution network are calculated in accordance with the condition of the calculation process discussed above.

The second test is the assessment of the correct placement of connection at the charging stations with existing objects (reliable operation of the electrical network and the absence of an emergency situation) and assessment of the efficiency of their use for the power supply scheme under consideration [93], [117].

For this condition, using Simulink Simscape Power Systems (SimPowerSystems), the distribution network is modelled and tested in dynamic mode for parameters such as voltage U, current I, active P and reactive power Q [118].

Simulation of the modes allows for the evaluation of the operation of the existing distribution network (voltage, current, active, reactive and apparent power) in accordance with the electric vehicle demands of charging stations and as an element of smart grids. In addition, SimPowerSystems software allows testing if the U, I, P, Q parametres do not create emergency situations for the network.

Data block 3 is used to collect information at the calculation phase and analysis phase. Their data are used for the analysis, as well as in the course of repeated analytical studies.

The final step is the approval and final choice for a local distribution network in accordance with the needs of electric vehicles.

3.3. Algorithm Testing. Effective Urban Electrical Network Infrastructure with the Development of Public EVCSs

The evaluation algorithm of a local distribution network, taking into account the electric vehicle charging infrastructure presented in the Thesis, has been applied to low-voltage distribution networks of Latvian electricity Distribution Company (Sadales tīkls JSC).

3.3.1 Stage I. Selecting the Network Architecture of Urban Area

To test the algorithm, the residential micro-district in Riga has been chosen, where in the territory of the city district there are 25 transformer substations (TS). In our case, we are interested only in a certain territory location of TS-1 (TR 2x1250/10/0.4 kV) that provides electricity for 1656 individual customers, as shown schematically in Fig. 3.10.

The consumers of TS-1 (TR 2x1250/10 /0.4 kV) are: 2 office buildings, 4 grocery stores, 12 dwelling houses (three-storey buildings with 12 consumers each), 24 dwelling houses (five-storey buildings with 60 consumers each), large parking place (for 500 vehicles), 2 catering services, health centre, police department, post office and a kindergarten. The length of the streets is 3.1 km. [13]

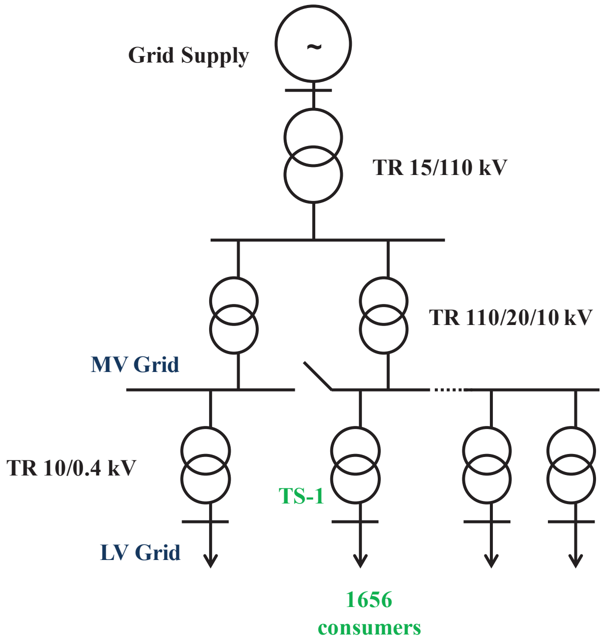


Fig. 3.10 Test scheme of the distribution network.

In the context of the proposed methodology, the quantitative indicators and daily load graphs of the objects and transformer substation have been determined for the working days of all seasons. In order to perform a 24-hour simulation of load curves, the average daily load

[13] Rīgas pilsētas apkaimes. https://apkaimes.lv/statistika/

schedules of electricity consumers have been taken from the library module, which provides information about technical specification of three-phase transformers 10/0.4 kV and load graphs of objects from Latvenergo JSC (a state-owned electric utility company in Latvia) [119].

The estimation of electricity consumption is performed in the following two steps.

Step 1: a time period of maximum, minimum and average daily electricity consumption for each group of consumers, as well as the load factor and load curve irregularity factor are determined. Annex I (Table I-1 and Table I-2) provides the input data for each object on the working days depending on the season with the total load of transformer substation (TS). Due to the fact that consumers have very similar profiles of daily load curve and have the same energy consumption tariff plans, it has been decided that the research can be carried out using the general average daily data of the said objects.

Seasonal electricity consumption profiles show that the maximum power consumption occurs in the winter season, whereas minimum consumption occurs in the summer season. Thus, the study is carried out for the average daily data of the winter season.

The load in maximum (peak), average and minimum (off-peak) demand periods and its daily time period of use are quantitatively estimated. All factors characterising the electrical load for each consumer obtained in the process of calculation are demonstrated in Table 3.9.

Table 3.9.

Factors Characterising the Electrical Load for Consumers

	Household sector			Tertiary sector					
	Dw. house (3-st)	Dw. house (5-st)	Park. lot (for 500 veh.)	Office-indust.	Groc. store	Post office/ police depart.	Cater. service	Kinder garten	Health centre
S_{max}, MVA	5.37	16.21	3.24	164.57	83.25	7.39	9.24	7.38	13.61
S_{min}, MVA	8.70	26.27	4.78	221.97	114.69	9.97	12.20	12.25	18.35
$S_{average}$, MVA	3.04	9.18	1.83	111.38	40.76	5.00	4.13	4.00	9.21
f_{load}	0.62	0.62	0.68	0.74	0.73	0.74	0.76	0.60	0.74
$f_{irreg.}$	0.35	0.35	0.38	0.50	0.36	0.50	0.34	0.33	0.50

Further, based on the consumption of objects, the load of the household sector and that of the tertiary sectors have been calculated. The information allows evaluating the largest and smallest load over time intervals.

Figure 3.11 illustrates the electricity consumption profiles of the household and tertiary sectors on a working day (winter).

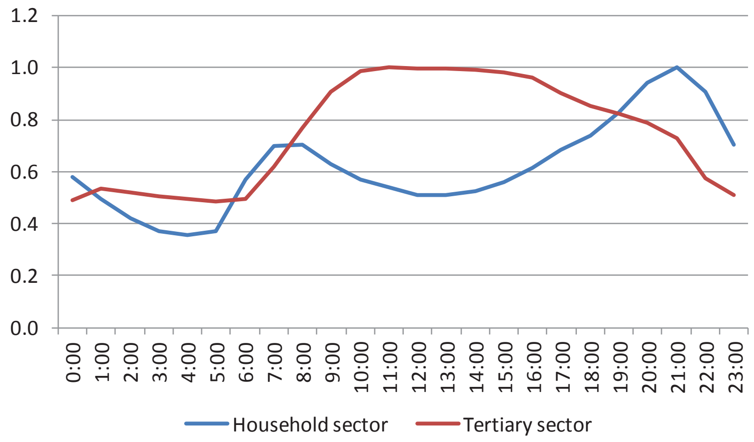


Fig. 3.11. Profiles of electricity consumption on a working day.

According to the above-mentioned graph, time periods for daily schedule are as follows:

Household sector is characterised by the maximum consumption from 7:00 am to 9:00 am and from 5:00 pm to 11:00 pm, the minimum consumption takes place from 00:00 am to 6:00 am. The load factor is 0.62. The load curve irregularity factor is 0.35.

Tertiary sector has the maximum consumption from 8:00 am to 8:00 pm, the minimum consumption takes place from 9:00 pm to 8:00 am. The load factor is 0.75. The load curve irregularity factor is 0.49.

They two graphs show that all peaks of the consumption occur between 8 am and 9 am and between 5 pm and 8 pm and the minimum consumption occurs between 00:00 am and 7:00 am. Then, all quantitative and qualitative indicators are generated in data block 1.

Step 2: Based on the data received, the total load of objects and the possible additional load are calculated. The total load of objects per hour can be calculated as follows:

$$\sum_{i=1}^{i=n_c} S_i(t) = n_1 \cdot S_1 + n_2 \cdot S_2 + n_c \cdot S_k \,, \qquad (3.16)$$

where n_c – the number of objects;

S_k – the load of object per hour, kVA.

As example, the $\Sigma S_{(t = 00:00)}$ can be calculated as follows:

$$\sum_{i=1}^{i=49} S_{oo:oo} = 12 \cdot 4.99 + 24 \cdot 15.06 + 1 \cdot 4.66 + 2 \cdot 124.81 + 4 \cdot 43.96 + 2 \cdot 5.57 + 2 \cdot 9.54 + 1 \cdot 4.00 + 1 \cdot 10.32 + 1 \cdot 7.12 = 903.07\ kVA$$

All factors characterising the load of urban area obtained in the process of calculation are illustrated in Fig. 3.12. The data of total load of the objects in the urban area, S (MVA) are given in Annex I (Table I-3).

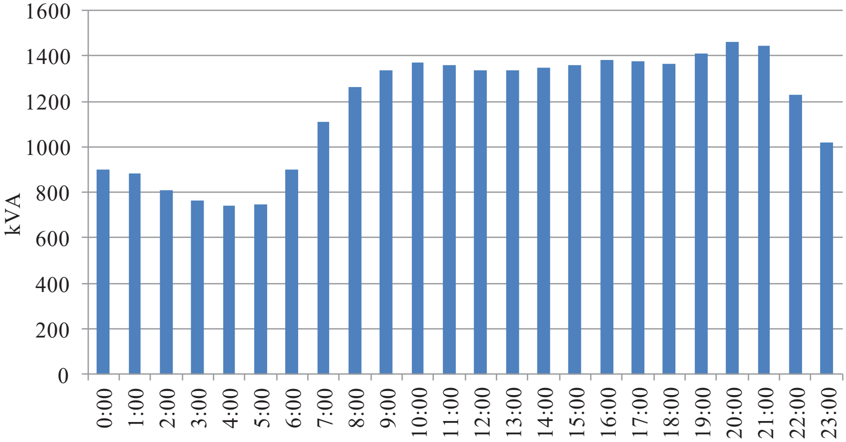


Fig. 3.12. Total load of the objects in the urban area.

Calculation results of the total load of objects per hour show that the peak demand is from 7:00 pm to 9:00 pm. The load factor (f_{load}) is 0.81. The irregularity factor ($f_{irreg.}$) is 0.51.

All in all, it can be concluded that the largest load in the urban district is observed from 7:00 am to 11:00 pm, whereas the minimum load is observed from 11:00 pm to 7:00 am.

The possible additional load for 9 objects is estimated for implementation of Stage 2. These 9 objects are chosen to simplify optimisation and reduce the processing time of penetration demand charging data. All data per hour are presented in Annex I (Table I-4).

Taking into account the total load of objects in the urban area and the rated power of the transformers, the possible additional load is calculated for the temporary daily intervals by Equation (3.6).

$$S_{add\,(t=23:00\ to\ 07:00)} = 1.4 \cdot 1250 - 1017.23 \cdot 0.9 = 834.49\ kVA$$

$$S_{add\,(t=23:00\ to\ 07:00)} = 1.4 \cdot 1250 - 1459.99 \cdot 0.9 = 436.00\ kVA$$

Table 3.10 provides data for the possible additional load per hour, i.e., every hour there is an opportunity to apply additional load.

Table 3.10.

The Additional Load per Hour (Winter)

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Sadd, kVA	937.24	957.17	1021	1064.7	1085	1079.7	940.44	748.43	614.03	545.73	514.95	523.38	547.75	547.37	538.12	525.01	507.9	510.44	518.34	481.77	436.01	450.7	645.91	834.49

Since condition $S_{add}(t) > 0$ is performed, transition to Stage 2 is carried out at the Decision Phase.

3.3.2 Stage II. Implementation of the Optimal Model for the Placement of Charging Stations

The input data of groups are as follows:

- Data of Stage 1. The possible additional load on TS-1: $S_{add\ (t=00:00\ to\ 23:00)}$ = 436.01 kVA. $S_{add(t\ =\ 23:00\ to\ 07:00)}$ = 834.49 kVA and $S_{add\ (t\ =\ 07:00\ to\ 23:00)}$ = 436 kVA. The possible additional load for objects: Annex I (Table I-4).
- Road transport fleet and behaviour of vehicle owners in the urban district.

The fossil fuel vehicle (FV) owners in this urban area are the following: 638 – private persons (vehicles that are owned by private persons – residents of the said microdistrict) and 71 – legal persons (vehicles that are owned by legal persons – consumers of the said microdistrict service buildings). The location of public parking lots for vehicles are: 2 office buildings, 4 grocery stores, 12 dwelling houses (3-storey buildings), 24 dwelling houses (5-storey buildings), large parking place (for 500 vehicles), 2 catering services, health centre, police department, post office and a kindergarten. The parking period near the police department, post office, kindergarten, grocery stores and catering services is restricted to the specified duration (free parking for one hour) due to the limited amount of space near buildings (the number of parking lots varies from 5 to 10). Therefore, placement of public charging stations on this car parking is not considered economically viable to implement. Grocery stores and catering services should be economically interested in EVCS location. The charging station powers a car, while its owner is shopping or dining. The parking demand in accordance with the time intervals is presented in Fig.3.13.

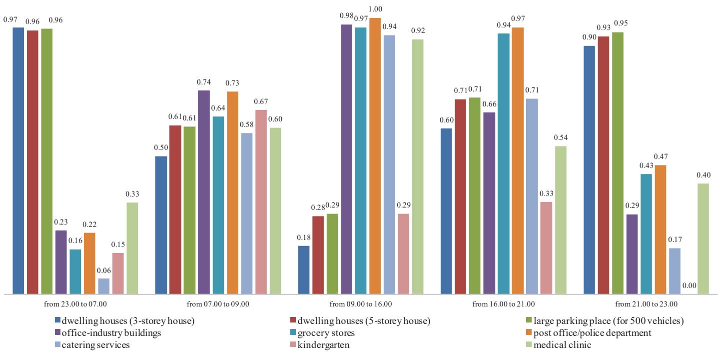


Fig. 3.13. Parking lot demand in accordance with the time intervals.[14]

Car parking near the dwelling houses (3-storey buildings), post office, police department, catering services and kindergarten cannot be recommended as places for public EVCSs, since they have less than 10 parking lots.

Since the average daily mileage in this urban area is not known, for calculations the data obtained earlier have been used to describe the model methodology. Hence, the daily mileage

[14] Annex II (Table II-1 and Table II-2) provides the data on location of parking lots, dynamics of usage and parking demand on working days.

of EVs owned by a private person is 24.9 km/day and that by a legal person is 71.2 km/day. Thus, private persons need to charge EVs once two days. Since there is no information about cars of non-resident persons (guest consumers who live and work in another district and charge the vehicles as needed) that could be charged, further calculations will be carried out provided that EVs will be charged every day to cover a distance of 100 km. To obtain the results, it is necessary to define the number of vehicles that could be integrated in the energy distribution network of the said microdistrict on the daily basis, according to the possible additional load.

To reach the above-stated objective, it is assumed that every car has identical battery capacity, $P_{\mathrm{EV}_i}^t = 24\ kWh$ or $S_{\mathrm{EV}_i}^t = \sqrt{24^2 + 0^2}$ to get results in similar units.

The number of EVs (N_{EV}) is calculated by Equation (3.9). For example, the minimum additional load occurs at 8:00 pm; consequently, $N_{\Sigma EV}^{20:00} = \frac{436.01}{24} = 18$. Hence, 432 of EVs can be integrated per day or 60.9 % of the car fleet in this urban area.

The obtained results of the parking demand (see Fig. 3.14) illustrate that condition $N_{EV_i}^t > 0$ is performed and the integration of EVs in the single urban district is as follows:

- from 7.00 am to 9.00 am, the minimum number of EVs is 23;
- from 9.00 am to 4.00 pm, the minimum number of EVs is 21;
- from 4.00 pm to 9.00 pm, the minimum number of EVs is 18;
- from 9.00 pm to 11.00 pm, the minimum number of EVs is 19;
- from 11:00 pm to 7:00 am, the minimum number of EVs is 35.

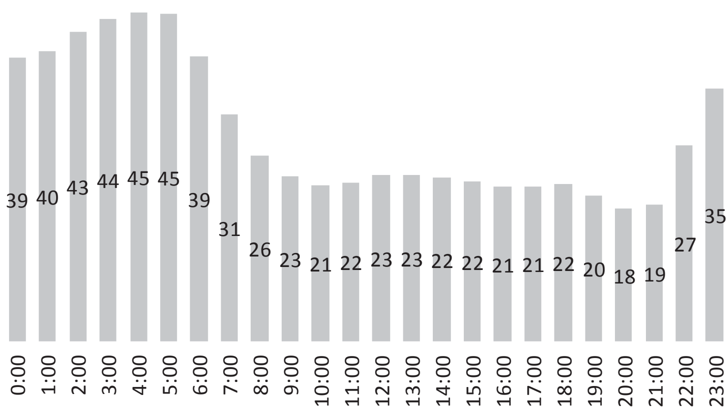


Fig. 3.14. Number of EVs in accordance with the additional load over a period of time.

It is also essential to estimate the additional load of objects, mode and time of charging station constraints ($S_{EVCS_i}^t, where\ t = 0 \ldots 10\ hours\ and\ i = 0 \ldots .43\ kVA$). This process is performed by using the IF function in Excel and has two results of comparison: True or False.

Possible scheduling scheme for the charging station is estimated only for office building, grocery store, dwelling house (5-storey building), large parking place (for 500 vehicles) and health centre. All results are presented in Annex II (Table II-3). The results reveal that the constraints $0 < t \geq 10$ and $3 \leq S_i \geq 43$ are performed for all objects, only a large parking lot is the exception from 9:00 pm to 2:00 am (FALSE).

As these objects require a detailed consideration, the next stage is to define the charging mode and number of the charging stations according to the constraints for the public EVCSs, Annex II (Table II-4 A. Standard Charging Power Levels; B. Standard Charging Time Levels).

Constraints are as follows:

- Constraint I: $t > 1$ (hour) and $i \geq 43$ (kVA).
- Constraint II: $1 \leq t \leq 4.5$ (hour) and $7 < i \leq 22$ (kVA).
- Constraint III: $2 < t \leq 10$ (hour) and $3 \leq i \leq 7$ (kVA).

Comparison of the constraint results has shown that the charging process will be carried out within 24 hours a day, if the EVCSs will be placed in the parking lots as follows:

- Dwelling house (5-storey): Standard charging.
- Large parking lot: Standard charging can be applied only 18 hours a day, but unavailable during 24 hours.
- Office building: Standard charging, Accelerated charging and Rapid charging.
- Grocery store: Standard charging, Accelerated charging and Rapid charging.
- Health centre: Standard charging and Accelerated charging.

Thus, constraints are performed only by four objects (a large parking lot does not participate in the subsequent calculations) and now the algorithm determines the numbers of the public charging stations. To estimate the total number of EVCSs, Equation (3.10) is used:

$$N_{EVCS} = \frac{9.7\% \cdot 436.01}{7} + \frac{30.6\% \cdot 436.01}{22} + \frac{59.7\% \cdot 436.01}{43} = 18$$

Thus, the total number of the public charging stations is 18 (6 of each mode). Further testing will be based on the analysis of the interaction parking pattern in the infrastructure of the area, by using the simplex method in Excel Solver. The following assumptions have justified the implementation of the said method: the functions are linear in nature, parameters are certain, and negative values are unacceptable.

Optimal Location of the Charging Infrastructure

An optimisation goal is to find the location of the charging infrastructure in the existing urban area, which meets the requirements of the parking and charging of vehicles, and at the same time the load of these charging stations does not exceed the allowable additional load on the transformer substation.

The placement problem of charging stations has the following formulation: the location of objects of parking lots (C_1 is a dwelling house (5-storey building), C_2 is an office building, C_3 is a grocery store and C_4 is a health centre) and the possible additional load of objects (c_1 = 13.13 kVA, c_2 = 110.98 kVA, c_3 = 57.35, c_4 = 9.18 kVA) are known. Three modes of charging stations (B_1 – StEVCS, B_2 – AcEVCS, B_3 – RapEVCS) and the additional load for

EVCSs per hour (b_1 = 18.53 kVA, b_2 = 58.25 kVA, b_3 = 113.85 kVA) are indicated. Unit load for EVCSs is 7, 22, 43 kVA. It is assumed that the charging process of high penetration demand is examined.

The linear problem has the following formulation for both the objective and the constraints. For a given objective function, the optimisation problem can be written as follows:

$$F(x) = 18.53 \cdot x_1 + 58.25 \cdot x_2 + 113.85 \cdot x_n \rightarrow \text{max.}$$

The constraints:

$$7 \cdot x_1 + 22 \cdot x_2 + 43 \cdot x_3 \leq 13.13$$
$$7 \cdot x_1 + 22 \cdot x_2 + 43 \cdot x_3 \leq 110.98$$
$$7 \cdot x_1 + 22 \cdot x_2 + 43 \cdot x_3 \leq 57.35$$
$$7 \cdot x_1 + 22 \cdot x_2 + 43 \cdot x_3 \leq 9.18$$
$$x_j \geq 0; j = \overline{1,4}$$

Now, it is possible to find the optimal solution using the simplex LP solving method:

The first solution, Annex II (Fig.ure II-1), has shown that only parking of dwelling house solution satisfies Solver's test for optimality. Therefore, the second test has been performed, Annex II (Fig.ure II-2). It has demonstrated that the criteria are satisfied for the other objects under study.

To complete the optimal solution properly, the third solution is necessary in order to satisfy all constraints, Annex II (Fig. II-3). The data from the first and second solutions have been used. As a result, constraints have been satisfied and an optimal solution has been found. There are no other feasible options.

The location and number of public charging stations have been received according to the requirements of the parking of vehicles and allowable additional load on the transformer substation (see Table 3.11). The calculations have shown that StEVCSs make up 44.5 %, AcEVCSs account for 22.2 %, RapEVCSs – 33.3 % of the overall number of public charging stations.

Table 3.11.

The Location and Number of Public Charging Stations

	Parking near a dwelling house	Parking near an office building	Parking near a grocery store	Parking near a health centre	Total
StEVCS	7	-	-	1	8
AcEVCS	-	4	-	-	4
RapEVCS	-	2	4	-	6
					18

Having received the optimal location of the infrastructure, the charging load (the objective function value) is estimated by Equation (3.11).

$$\sum_{i=1}^{i=n} S_{EVCS}(20:00) = 7 \cdot 8 + 22 \cdot 4 + 43 \cdot 6 = 402\ kVA$$

Subsequent actions are taken at the analysis phase. The consumption of energy for charging (SEVCS) is estimated and compared with $S_{add}(t)$ by Equation (3.13).

$$436.01(S_{add}) \geq 402.0(\sum_{i=1}^{i=n} S_{EVCS})$$

Thus, it was revealed that Equation (3.13) is performed, the total load of charging stations is less than the additional load and the test goes to next stage.

Analysis of GHG Emissions Based on COPERT 5

To analyse the change in the GHG emissions in this urban area, the passenger cars (PCs) and light trucks (LCV) with ICE and EV technologies have been proposed for consideration in the following three scenarios:

- *Scenario 1* – The number of FV technologies is 709 (100 %). Vehicles with petrol engine – 400. Vehicles with diesel engine – 309.
- *Scenario 2* – The number of FV technologies is 277 (39 %) and the number of EVs is 432 (61 %). The number of EVs has been previously discussed in the Thesis. Vehicles with petrol engine – 156. Vehicles with diesel engine – 121. Battery electric vehicles – 432.
- *Scenario 3* – The number of FV technologies is 509 (71.8 %) and the number of EVs is 200 (28.2 %). The calculation of the number of EVs will be shown below. Vehicles with petrol engine – 287. Vehicles with diesel engine – 222. Battery electric vehicles – 200.

Since the minimum number of EVs that can be charged per hour, as well as the number and modes of EVCSs have been defined above, for Scenario 3 NEV per day is defined as follows: 24 (from StEVCS) + 32 (from AcEVCS) + 144 (from RapEVCS) = 200 of EVs.

The daily mileage of EV owned by a private person is 24.9 km/day or 9088.5 km/year and that by a legal person is 71.2 km/day or 25988 km/year.

The calculation results of fuel consumption and GHG emissions for the three scenarios obtained by COPERT V software are shown in Figs. 3.15 and 3.16.

In Scenario 2, fossil fuel consumption is reduced by 61.191 %; GHG emissions – by 61.190 %. The total fuel consumption is reduced by 61.0 %. The electricity consumption is 0.4 % (0.037 TJ) of the total fuel consumption. Analysis of the results obtained for Scenario 3 shows that fossil fuel consumption is reduced by 28.419 %, while GHG – only by 28.423 %. The total fuel consumption is reduced by 28.3 %. The electricity consumption is 0.1 % (0.017 TJ) of the total fuel consumption.

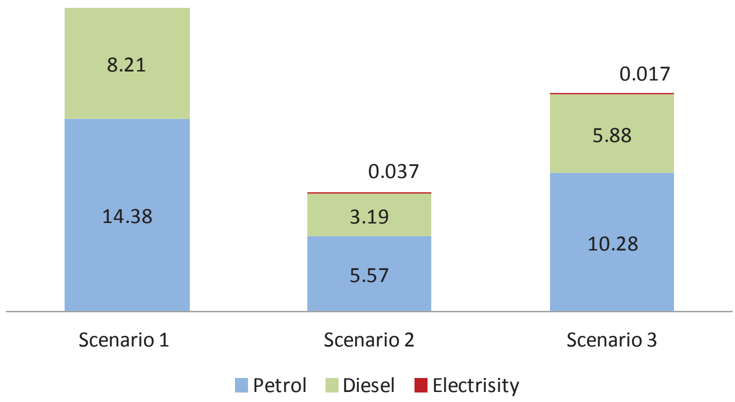


Fig. 3.15. The results of the fuel consumption by fuel type, TJ.

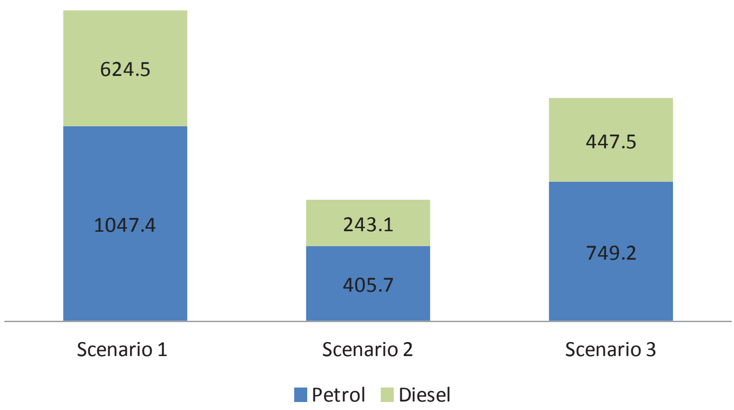


Fig. 3.16. The results of the GHG emissions by fuel type, tonne.

Comparing the results of the modelled scenarios and the data on the fuel consumption, one can see that Scenario 1 is the most unfavourable as to the control over such fuel consumption and GHGs from the vehicles. Analysis of Scenarios 2 and 3 allows for the conclusion that despite a similar number of transport vehicles it is possible to cut fuel consumption and the volume of relevant emissions by using EVs.

Available S_{add} *from V2G Technologies*

Assuming that V2G technology cars will be used in Scenario 2 and Scenario 3, in the volume of 10 % of the total EVs, V2G/G2V technology has been assessed as the one that can increase the additional load on the electrical network. As such, the average daily vehicle mileage (private and legal persons) is 29.53 km/day, P_{as} is 30 % and battery capacity (24kWh) has been used to calculate the available S_{add} from V2G by Equation (3.12).

$$P_{V2G_{storage}} = 24 - 3.6 - 24 \cdot \frac{29.53}{100} = 9.7\ kWh$$

As expected, in Scenario 2 the stored energy available S_{add} from V2G is 209.8 kVA and 97.1 kVA in Scenario 3 (S_{add} for new objects, STAGE 1 DATA).

It should be noted that calculation does not include all possible conditions of the electricity transmission back to the grid. Moreover, the car owner of V2G technology can use the stored energy for the household needs.

Analysis of Economic Profit from EV Integration

With the help of the electricity tariff system, differentiated by the time of the day, it is possible to stimulate the private and legal consumers to participate in the power market. Currently, Latvian households and other users have the opportunity to use a two-tariff system and a three-tariff system that include the use of tariffs according to the time of the day. Based on consumers' response to day-time pricing, consumers can be classified as EV consumers and EVCS consumers. The electricity distribution differential tariffs (without VAT) have been applied to calculate [120].

Assuming that these rates will be used by the EV consumers, owners of BEV and V2G technology, the cost of a single charge per 100 km will be as follows:

- A two-tariff system, in the case of charging
  - night zone and weekends (11:00 pm to 7:00 am) – 0.90 EUR;
  - day zone (7:00 am to 11:00 pm) – 1.34 EUR.
- A three-tariff system, in the case of charging
  - maximum hour zone (8:00 am to 10:00 am and 5:00 pm to 8:00 pm) – 3.10 EUR;
  - day zone (7:00 am to 8:00 am, 10:00 am to 5:00 pm, 8:00 pm to 11:00 pm) – 2.75 EUR;
  - night zone and weekends (11:00 pm to 7:00 am) – 2.57 EUR.

During the day, taking into account the average mileage of the car, the owner of V2G technology contributes to the network 9.7 kWh, while receiving an income of 0.39 EUR (where 1 kWh = 0.04 EUR/kWh).

If, these rates are used by the EVCS consumers, for example, public rapid charging stations on parking lots near office buildings, it will be difficult to evaluate the revenue from one EV because this refers to economic and business studies.

Thus, the result of Stage 2 is the output data on the load of the charging stations, their location, type and quantity in the urban area (see Table 3.12), and further testing proceeds to Stage 3.

Table 3.12.

Output Data of Stage 2

	Number of EVCSs	SEVCS, kVA*
StEVCS	8	56
AcEVCS	4	88
RapEVCS	6	258
Total	18	402

*minimum additional load occurs at 8:00 pm

3.3.3 Stage III. Verification of the TS-1 in the Post-fault and Normal Modes

During the third stage, the total load of the objects with the permissible load of the transformers in the post-fault and normal modes is compared.

The post-fault mode: $0.9 \leq 1.34 < 1.4$

The normal mode: $0.5 < 0.67 < 0.9$

As the conditions are met, we proceed to Stage 4.

3.3.4 Stage IV. Validation of the Algorithm, Taking into account the Specific Location of Electric Vehicle Charging Stations

At the fourth stage, the quantitative and qualitative indicators for transformer substation are tested according to the two conditions. The data blocks 1 and 2 are used as input data.

To fulfil the first condition, the calculation process of Stage 1 of this algorithm (the parameters and coefficients of the local distribution network are calculated) is used. Since, at the decision phase of output data (data of Stage 2), the location of public charging stations has been completed, and it has been revealed that the public charging stations can be located on parking lots near a dwelling house, office building, grocery store and a health centre. For these objects, as well as for the transformer substation the parameters and coefficients have been calculated (see Table 3.13). Annex II (Table II-5 and Table II-6) provides the data for objects with EVCSs and the total load of transformer substation (TS-1) in the winter season.

Table 3.13.

The Factors Characterising the Electrical Load for Objects with EVCSs

	Dwelling houses (5-storey building)	Office buildings	Grocery stores	Health centre	TS-1
S_{max}, MVA	396.16	416.13	376.02	20.61	1675.79
S_{min}, MVA	637.43	530.94	501.76	25.35	1026.82
$S_{average}$, MVA	227.42	309.76	206.04	16.21	1421.15
f_{load}	0.621	0.78	0.75	0.81	0.85
$f_{irreg.}$	0.36	0.58	0.41	0.64	0.61

Further, all quantitative and qualitative indicators are generated in data block 3.

Thus, by just using charging load of EVCSs, the parameters and coefficients have improved:

f_{load}:

- for dwelling houses (5-storey building) from 0.620 to 0.621;
- for office buildings from 0.74 to 0.78;
- for grocery stores from 0.73 to 0.75;
- for health centre from 0.74 to 0.81;
- TS-1 from 0.81 to 0.85.

$f_{irreg.}$:

- for dwelling houses (5-storey building) from 0.35 to 0.36;
- for office buildings from 0.50 to 0.58;
- for grocery stores from 0.36 to 0.41;
- for health centre from 0.50 to 0.64;
- TS-1 from 0.51 to 0.61.

The results show that the extent of the transformer substation power use and factors that characterise the load objects increase, implying an increase in the reliability and effectiveness of the network as such.

Before carrying out the second condition, the urban distribution network is modelled, using Simulink Simscape Power Systems (SimPowerSystems). The discrete model consists of the following blocks: Three-Phase Source, Three-Phase Transformer (TS-1 2x1250 kVA), Three-PhaseV-I Measurement 2 (real and reactive power, voltage and current), Distributed Parameter Line 7, Three-Phase Series RLC Load (linear series RLC load) with only normal modes being considered, disregarding emergency and transition modes, etc. Three-PhaseV-I Measurement 2 and Power-1 (3ph, Instantaneous) are concerned with the substation buses of 10/0.4kV results for the same parameters.

Thus, to validate the algorithm, two work modes have been simulated:

- Work mode A is a model of the existing urban local network;
- Work mode B is a model of the same network with added charging stations on parking lots.

Figure 3.17 shows the test system for the substation buses of 10/0.4kV, where the local network model includes the local charging infrastructure.

Comparison of the test results without and with the charging stations has shown that while creating a charging infrastructure in the urban district, the total load for TS-1 increases by 14.8 %, which does not exceed the maximum permissible values for a transformer substation TR 2x1250 / 10 / 0.4 kV. For the substation buses the process of changes in all three phases happens at present within the margins of 11.59 %–13.34 % (there is an increase) and voltage within the margins of 0.04 %–0.16 % (there is a decrease).

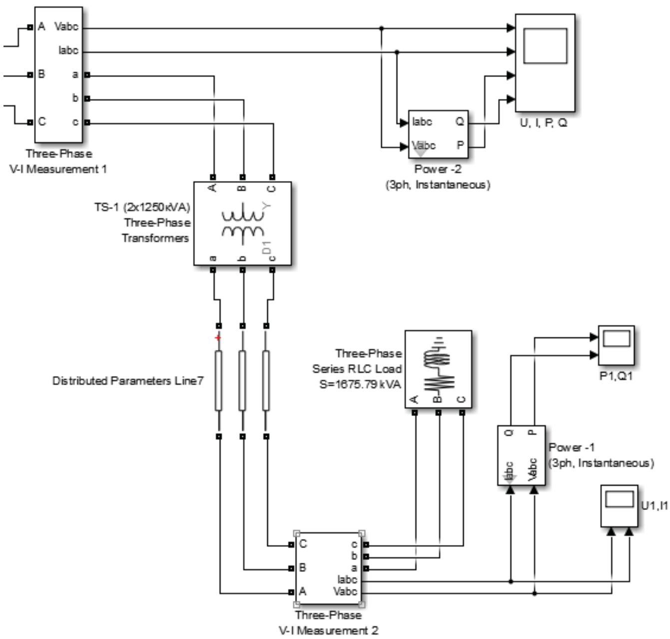


Fig. 3.17. Reference network model
(part: the substation buses of 10/0.4kV, Work mode B).

Graphical simulation results for the same parameters of the PhaseV-I Measurement 2 /Signal:2 (Work mode B) are shown in Fig. 3.18.

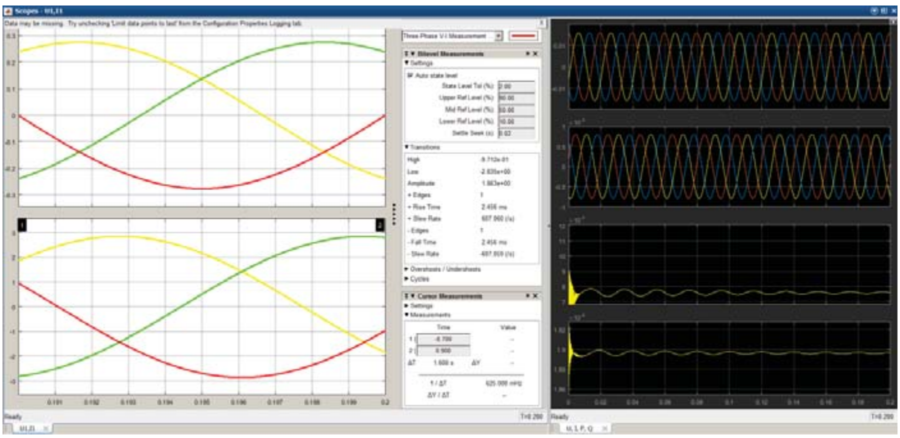


Fig. 3.18. PhaseV-I Measurement 2 /Signal:2 (Work mode B).

The results of the analysis of the two work modes have the following features:

- The quantitative and qualitative factors that characterise the distribution network load increase, implying an increase in the reliability and effectiveness of the network as such.
- The possible additional load exceeds the total demand of charging stations in the area. Consequently, this load does not lead to network overloads, does not affect the quality of power and does not require the replacement of the transformer substation TS-1.
- The obtained test results illustrate that standard charging stations account for 44.5 % of the total number of charging stations, accelerated charging stations make up 22.2 % and rapid charging stations – 33.3 %. At high EVs penetration, when the operating of all EVCSs happens within 24 hours a day, the average daily electricity consumption is increased by 14.8 %.

Testing allows concluding that the methodology of the algorithm results in the acquisition of theoretically valid results.

3.4. Summary of Chapter 3

In Chapter 3, the structure of the algorithm has been considered; its four stages have been investigated in order to study a local distribution network taking into account the placement of the electric vehicle charging station.

At all the stages, the specific tasks have been solved and implemented. Each stage contains four phases (input, calculation, analysis and decision) with transitions and data blocks.

During the first stage, the possible additional load has been calculated for the time intervals.

Within the second stage, the maximum load on the local distribution network has been estimated using the model of EV charging station placement.

The three key criteria, such as human behaviour, urban infrastructure and energy supply system have been studied in great detail. The total load of EV charging stations cannot be higher than the additional load at Stage 1calculated before.

During the third stage, according to the Electrical Codes and Standards, the technical characteristics of transformer substation have been verified; the total load of the all objects (existing and EVCSs) have been compared with the permissible load of the transformer in the post-fault and normal modes.

Stage 4 of this algorithm confirms the compliance with reliability requirements of power supply to the local distribution network in accordance with the Latvian and European quality standards. The location of the charging stations near existing objects and assessment of the efficiency of their use for the power supply scheme under consideration has been estimated.

Thus, it is proposed using the algorithm for studying low-voltage distribution networks of residential areas. The algorithm can also be adapted both to city districts and to rural regions.

4. ANALYSIS AND DEVELOPMENT OF LONG-TERM FORECAST OF ENERGY CONSUMPTION IN LATVIA BY 2030

In 1990, Latvia had very high total greenhouse gas (GHG) emissions. In 2016, the total GHG emissions were reduced by 56.2 %15. This progress was due to transition from a centrally planned economy to a market economy, as a result of improving efficiency in the energy sector and switching to renewables. The current trend of development shows good performance to meet its national targets for 2020 and 2030 [7], [128].

Sustainable Development Strategy of Latvia until 2030 adopted in 2010 corresponded in line with Energy Union 2030 Framework for Climate and Energy. The strategic objective stipulated in the document is to increase the renewable energy sources (RES). Towards the 2020 target of 40 %, in 2016 renewable energy represented 37.2 % of energy consumed in Latvia. The future target is to increase the RESs share up to 50 % by 2030 and reduce Latvia's fossil energy resource imports. The national obligations have also been adopted: to reduce GHG emissions to 17.2 % by 2020 below 1990 levels and to 6 % in 2030 below 2005 levels. One of the goals of this strategy is related to the use of environmentally-friendly technologies in the road transport sector. The current development level of vehicle technologies, the expected promotion of emerging technologies and existing policies for reducing GHG emissions allow investigating energy consumption by 2030 in Latvia. Thus, this chapter considers two scenarios of short-term forecasting of Latvia's energy sector development by 2030, where the focus is mainly placed on road transport. The results of the scenarios are compared considering the parameters such as the number of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV), their electricity consumption and SEG emissions in the sub-sector of road transport.

To fulfill the scenarios, the IEA-ETSAP16 methodology and the MARKAL model have been used [121]–[123]. Based on this model, national economic development and energy consumption forecasts, comprising the existing GHG emissions reduction policies and measures, have been carried out in nearly 70 countries of world, including Latvia. At present and in terms of the future investigations, the MARKAL model is implemented for the following tasks:

Emission projections for the energy sector:

- Projections of GHG emissions for: national use; UNFCCC National Communications (from 2nd NC); monitoring of EU GHG emissions (Commission Decisions 280/2004/EC and 2005/166/EC).
- Projections for other gases (SO_2, VOC, NOx, PM2.5, NH_3) for national use and Convention on Long-Range Transboundary Air Pollution.

[15] Eurostat. Greenhouse gas emission statistics - emission inventories. http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics#Trends_in_greenhouse_gas_emissions
[16] IEA-ETSAP www.iea-etsap.org

Projections of energy use:

- Seldom direct use for national strategies: Evaluation of impact of introduction of different RES and energy efficiency targets.
- Mainly use for research projects: Identifying least-cost solutions for energy system planning and evaluation of impact of introduction of energy and emissions taxes.

This modelling approach is also used for:

- Bottom-up technology rich optimisation model.
- All energy system from resource extraction to end-use as represented by a Reference Energy System (RES) network.
- Spread of action between supply and demand.
- Emissions taxes and constraints.
- Identification of the most cost-effective pattern and mix of resource use and technology deployment over time under varying constraints and alternate futures by optimising system costs. Provision of estimates of energy prices; demand activity; GHG and other emission levels; mitigation costs.
- Scenario approach: establishes baselines and the implications of alternative futures.
- Sensitivity analysis.
- Possibility to deal with uncertainty with stochastic analysis.

Figure 4.1 describes the main MARKAL building blocks, such as primary energy supply (local inputs, imports and exports), energy services processing and transformation sector, energy demand (energy end-use processes, technologies and energy sectors and sub-sectors).

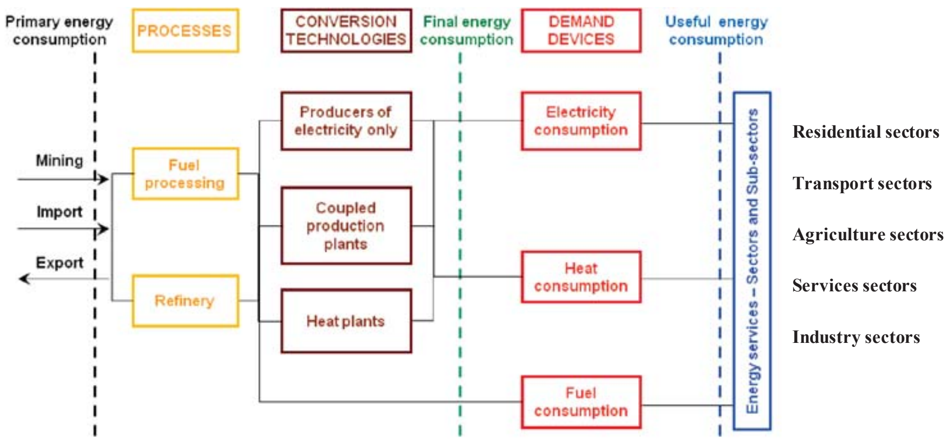


Fig. 4.1. Schematic representation of the MARKAL model blocks.

Supply and demand of energy resources are integrated in such a way that in the event of a change in one of them, the model selects the best combination of energy technologies and energy sources, which may be introduced in the existing energy system. The model chooses a combination of technologies and provides energy resources distribution that minimises the cost of the entire power system as a final result.

Since 1995, the MARKAL- Latvia (MARKAL-LV) country model has been used for the national level studies. "Latvia's Seventh National Communication and Third Biennial Report under the United Nations Framework Convention on Climate Change" and other research results and scientific articles (where concentrates on modelling with the MARKAL-LV package) provide a detailed description of the MARKAL-LV model [124]–[127].

4.1. The Modelling Framework and Scenarios

The starting point for the modelling of forecast is the following main indicators: the existing and future energy system of Latvia (incl. the energy and environmental policy); the energy consumption and energy resources structure by the national economy sectors (incl.: the quantities and costs of primary and secondary energy resources; the technologies of energy and emission reduction); macroeconomic indicators for the past period, from 1990 to 2016, and the country's expected economic development data up to 2030 (gross domestic product (GDP), development of the national economy (surplus value), living standards (consumption or expenditure by households, incl. personal expenditure forecasts) and demographic development of the population, etc.

Survey of the main indicators provided every five years from 2000 to 2030 is shown in Table 4.1, in constant 2010 prices (2010 as the base year). The main indicators from 2000 to 2030 for each year are available in Annex III (Fig. III-1).

Table 4.1.

The Main Macroeconomic Indicators, 2000–2030.

Years	2000	2005	2010	2015	2020	2025	2030
Number of population, thous.	2367.5	2238.8	2097.6	1977.5	1938.7	1926.8	1923.9
Number of inhabitants per household, thous.	2.6	2.5	2.5	2.5	2.3	2.3	2.3
Number of households, thous.	921.7	879.5	825.6	796.2	800.1	760.6	723.3
GDP, M€(2010)	12396.6	18380.4	17937.9	21328.2	25355.9	28707.8	31749.7
Private consumption (excluding private transport), M€(2010)	7397.9	10688.7	11248.7	13016.5	16158.4	18386.0	20339.5
Taxes, M€(2010)	1832.0	2642.8	1991.2	2747.1	3333.0	3727.9	3997.4

It is important to note that the actual calculation of the Latvian emissions and the dynamics of the development of road transport in MARKAL-LV model are made using the COPERT 5 model. The fuel consumption, average mileage and emission simulation for all types of engines are simulated in COPERT 5 model, taking into account tighter emission

European standards and emission degradation due to catalyst wear, as well as the emission effects of hot, cold-start and evaporation. The summary of the activity indicators and EF used is presented in Table 4.2.

Table 4.2.

Activity Indicators and Sources Used for Emission Calculation in Road Transport

Activity data	Source of activity data	Remarks
Fuel consumption	Consumption calculated by COPERT 5 model	Calibrated with national statistics. Deviation is less than 0.01 %
Number of vehicles by fuel and types of engine	Road Traffic Safety Directorate and expert calculation	For calculation cars are used that have permission to participate in traffic, are grouped by fuel type, engine power, age and vehicle categories according to the emission control system
Distance travelled by vehicles by fuel and vehicle type	Road Traffic Safety Directorate and expert calculation	Based on the average data, car classes are modelled by fuel type, engine power, age and vehicle categories
Emission factors	National specifics for CO_2 emissions, COPERT 5 emission factors for CH_4 and N_2O	CO2 emission factors are based on carbon content in fuel: EF petrol is 71.18; EF diesel oil is 74.75; EF liquid petroleum gas is 62.75; EF biomass (ethanol and biodiesel) is 70.8

Overview of both historical and projected trends of the road transport sector is shown in Table 4.3 and Annex III (Table III-2). The following main indicators are included: the passenger kilometers per year; average mileage per vehicle a year; total mileage of vehicles a year (types of vehicles: passenger cars, light-duty vehicles (LDV < 3.5 tonnes), buses, heavy-duty vehicles (HDV > 3.5 tonnes)), freight tonne kilometres (LDV and HDV) of vehicles a year. The electric motorcycles and mopeds are not included in the modelling because there is a lack of technical and economic data.

Table 4.3.

Historical and Projected Trends in the Road Transport Sector

	Years	2000	2005	2010	2015	2020	2025	2030
Average mileage per vehicle a year, 1000 km/vehicle	Cars	13.4	16.1	14.4	12.6	13.0	13.2	13.3
	LDV/ HDV	37.8	38.1	42.9	33.8	35.6	37.0	38.1
	Bus	59.2	61.4	64.2	57.0	58.6	59.5	60.1
Total mileage of vehicles a year, Mkm	Bus	170.7	220.2	231.9	219.6	211.4	199.9	189.1
	Cars	4223.2	6987.3	7584.8	7733.1	8724.7	9251.9	9605.1
	LDV/ HDV	1635.8	2005.2	2325.8	2502.4	2762.2	2932.7	3055.4
Freight tonne kilometres of vehicles a year, Mtk	LDV /HDV	4789.0	8547.0	10590.0	14690.0	15753.8	16494.9	17068.8
Passenger kilometers a year, Mpkm	Bus	3012.2	3743.6	2822.7	2831.0	2724.8	2576.5	2437.3
	Cars	11500.0	12111.5	12312.3	13542.6	15279.2	16202.4	16821.0

The starting information for the fuel consumption calculation of BEVs and PHEVs is the data presented in the reports and studies [129]–[132].

The historical and projected trends from 2015 to 2030 for the BEV and PHEV technologies accepted for the present research are shown in Table 4.4.

Table 4.4.

The Historical and Projected Trends in the Road Transport Sector

Year		Small passenger cars	Medium passenger cars	Large passenger cars	LDV/HDV/ Buses
	Electrical energy stored in batteries	9–12 kWh	12–18 kWh	18–34 kWh	24–180 kWh
	BEV				
2015-2030	Electricity, %	100	100	100	100
	PHEV				
2015	Electricity/Petrol or Diesel, %*	25/75	35/65	45/55	35/65
2020	Electricity/Petrol or Diesel, %*	30/70	40/60	50/50	40/60
2025	Electricity/Petrol or Diesel, %*	35/65	45/55	55/45	45/55
2030	Electricity/Petrol or Diesel, %*	40/60	50/50	60/40	50/50

*Consumption of electricity and fossil fuels in percentage.

Thus, the starting point for the two scenarios assumes the existing national policies of Latvia as well as energy and climate targets for 2020 and 2030. The both scenarios have been proven:

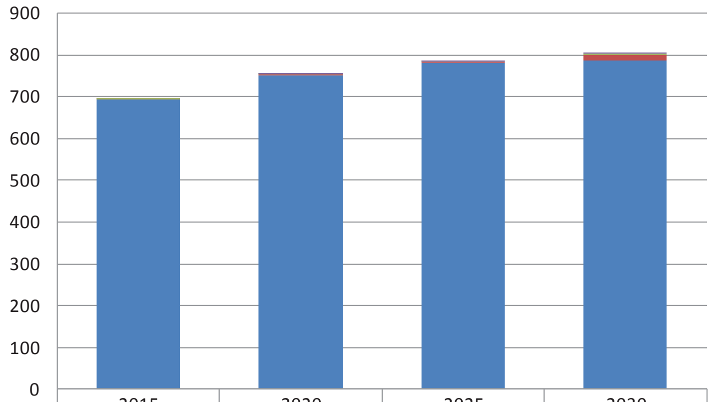
- *BASE scenario* assumes the targets, which are focused on current situation in branches of the economy and their development trends.
- *EV_Strategy scenario* assumes the targets, where the subsequent formation of road transport is based on electric vehicles of at least 160 000 (20 %) by 2030.

The characterisation of the scenarios modelled and used for further analysis of the results is given below. We use the following abbreviations for our scenarios throughout the report:

BASE – Baseline scenario and EV_STR – Strategic scenario.

Scenario 1. Baseline Scenario

In the BASE scenario, the vehicle fleet starts to shift to plug-in hybrid electric vehicles (petrol and diesel) and battery electric vehicles after 2020 without specific supporting policies. The ratio of battery electric vehicles and plug-in hybrid electric vehicles (petrol and diesel) is assumed as follows: 0.07 % in 2020, 0.4 % in 2020 and 2.15 % in 2030 of the total road transport fleet[17]. Thus, in comparison with 2015, the total number of BEV and PHEV technologies will increase 2.4 times in 2020, 13.5 times in 2025 and 75.1 times in 2030, (see Fig. 4.2).



	2015	2020	2025	2030
PHEV (diesel oil)	0.000	0.013	0.052	0.225
PHEV (petrol)	0.012	0.101	0.580	3.178
BEV	0.218	0.445	2.466	13.876
Other road vehicle technologies	692.852	752.122	780.335	786.132

Fig. 4.2. Rate of road vehicle technology deployment in the BASE scenario until 2030, thous.

Furthermore, the study shows that the use of BEV and PHEV technologies increases the electricity consumption in the road transport sector more than 2.5 times in the period from

[17] The detailed table of the stock is provided in Annex III (Table III-3).

2015 to 2020, 5.1 times in the period from 2020 to 2025 and 4.8 times in the period from 2025 to 2030 (see Table 4.5).

Table 4.5.

BASE: The Electricity Consumption by BEV and PHEV technologies, MWh

	2015	2020	2025	2030
Cars				
PHEV (diesel oil)	0.00	3.33	14.97	106.71
PHEV (petrol)	2.96	31.60	232.71	1657.23
BEV	424.40	877.30	5091.14	29373.43
Total for cars, MWh	427.35	912.23	5338.83	31137.37
LDV/HDV				
PHEV (diesel oil)	0.00	5.70	41.17	109.56
PHEV (petrol)	0.00	11.39	86.08	219.12
BEV	118.23	356.02	757.79	1562.40
Total for LDV/HDV, MWh	118.23	373.11	885.04	1891.08
Buses				
PHEV (diesel oil)	0.00	7.50	57.81	24.03
PHEV (petrol)	0.00	15.46	125.26	320.26
BEV	0.00	93.71	761.30	1490.15
Total for buses, MWh	0	116.67	944.37	1834.45
Grand Total, MWh	545.58	1402.00	7168.24	34862.90

MARKAL-LV model has considered all types of fuel consumption in road transport. Fuel consumption has increased by around 1.6 % in 2020, but has reduced by 2.2 % in 2025 and by 16.8 % in 2030 compared to 2015. Hence, using different fuels various changes have taken place: petrol and ethanol consumption has decreased by 70.7 %, diesel oil and biodiesel consumption by 33.6 %, whereas LPG consumption has increased by 196.8 % and electricity by 6290 % in 2030 compared to 2015. Figure 4.3 shows the trend in fuel consumption and types of fuel between 2000 and 2030[18].

[18] More detailed table of the fuel consumption and types of fuel are provided in Annex III (Table III-4).

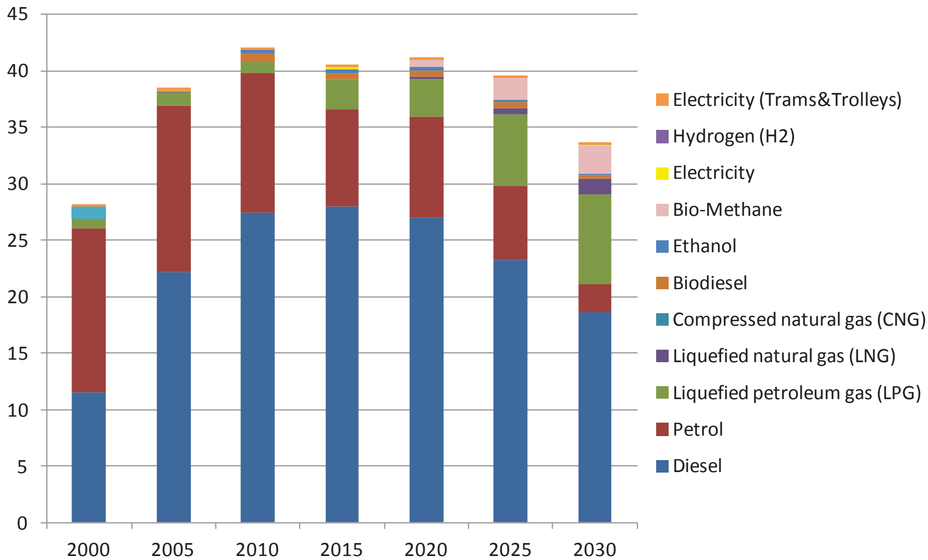
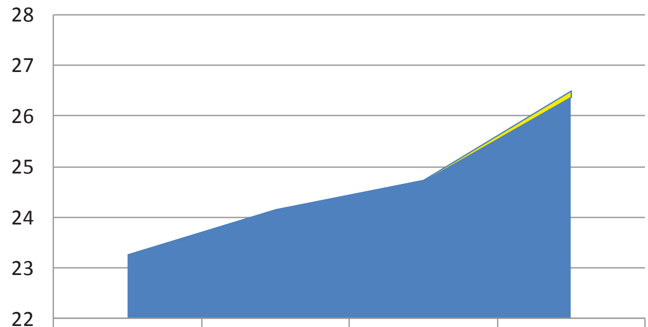


Fig. 4.3. BASE: fuel consumption and types of fuel, 2000 – 2030, PJ.

Therefore, the electricity consumption by the road transport sector accounts for 0.02 % of the total electricity consumption by economic sectors in 2020, as well as it will make up 0.1 % and 0.47 % in 2025 and 2030, respectively (Fig. 4.4).



	2015	2020	2025	2030
Road transport (without Trams&Trolleys)	0.00	0.01	0.03	0.13
Other sectors	23.27	24.16	24.72	26.38

Fig. 4.4. BASE: electricity consumption, 2000 – 2030, PJ.

The share of total GHG emissions in the road transport is about a quarter over the whole period of review. Figure 4.5 shows total trends of GHG emissions in kt of carbon dioxide equivalents (kt CO_2 eq.), where the road transport sub-sector is included in the period of 2000–2030. The total volume of GHG emissions have decreased by 1.49 % by 2030 and road transport – by 19.15 % compared to 2015 in this scenario. The reasons are changes in fuel type and amount of fuel used.

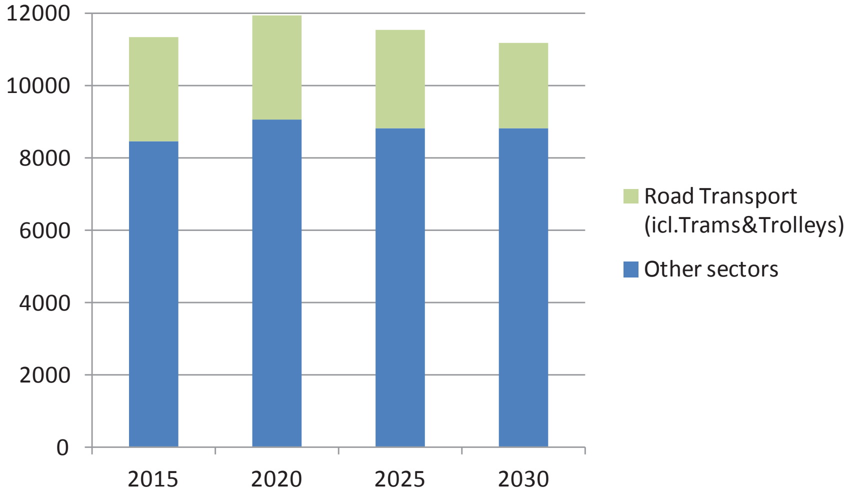
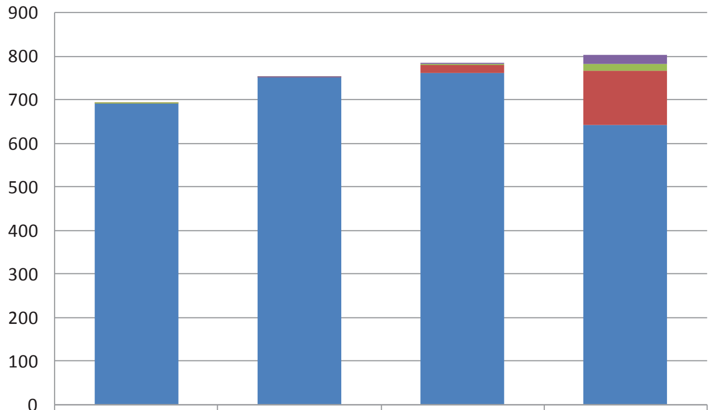


Fig. 4.5. BASE scenario: GHG emissions, 2000–2030, kt CO_2 eq.

Scenario 2. Strategic Scenario

The EV_STR scenario envisages that the vehicle fleet will be more actively increasing owing to the demand for PHEVs and BEVs after 2020. This is substantiated by the political measures taken to increase the number of electric vehicles and develop the infrastructure for charging these vehicles in the country. The rate of change gets bigger sharply from 2025 to 2030, reaching the share of 15.5 % of EVs and 0.045 % of PHEVs by 2030 of the total road transport park, as it can be seen in Fig. 4.6. However, the total share of EVs is 0.27 % in 2020, 2.85 % in 2025 and 20 % in 2030 of the total road transport fleet[19].

[19] The detailed table of the stock is provided in Annex III (Table III-5)



	2015	2020	2025	2030
PHEV (diesel oil)	0.000	0.055	1.248	21.701
PHEV (petrol)	0.012	0.200	1.606	14.370
BEV	0.218	1.764	19.447	124.604
Other road vehicle technologies	692.852	750.662	761.132	642.736

Fig. 4.6. Rate of road vehicle technology deployment in the EV_STR scenario until 2030.

In addition, the results obtained demonstrate that electricity consumption has increased more than 9.6 times in the period from 2015 to 2020, 11.6 times in the period from 2020 to 2025 and 6.9 times in the period from 2025 to 2030 (see Table 4.6).

Table 4.6.

EV_STR: Electricity Consumption by BEV and PHEV technologies, MWh

	2015	2020	2025	2030
Cars				
PHEV (diesel oil)	0	13.64	467.99	11085.73
PHEV (petrol)	2.96	63.20	651.94	7317.21
BEV	424.40	3509.20	39225.01	254810.18
Total for cars, MWh	427.35	3586.04	40344.95	273213.12
LDV/HDV				
PHEV (diesel oil)	0	34.18	538.96	4115.60
PHEV (petrol)	0	17.09	247.02	2515.09
BEV	118.23	1210.48	13732.63	70803.57
Total for LDV/HDV, MWh	118.23	1261.74	14518.61	77434.26
Buses				
PHEV (diesel oil)	0	14.99	96.35	721.04
PHEV (petrol)	0	30.92	154.16	1576.68
BEV	0	374.83	6471.06	71911.83
Total for buses, MWh	0	420.75	6721.58	74209.55
Grand total, MWh	545.58	5268.53	61585.14	424856.93

In this scenario, the trend of total fuel consumption and types of fuel are the same as in the BASE scenario (see Fig. 4.7). However, there have been changes for the two types of fuel –

electricity and diesel oil. A swift increase in the total number of EVs in 2030 has resulted in the change of diesel fuel and electricity proportion. Thus, the amount of diesel fuel consumed decreased 1.6 times (-38.6 %) in 2030 compared to 2015, and at the same time the amount of electricity increased more than 778 times (+77772%)[20].

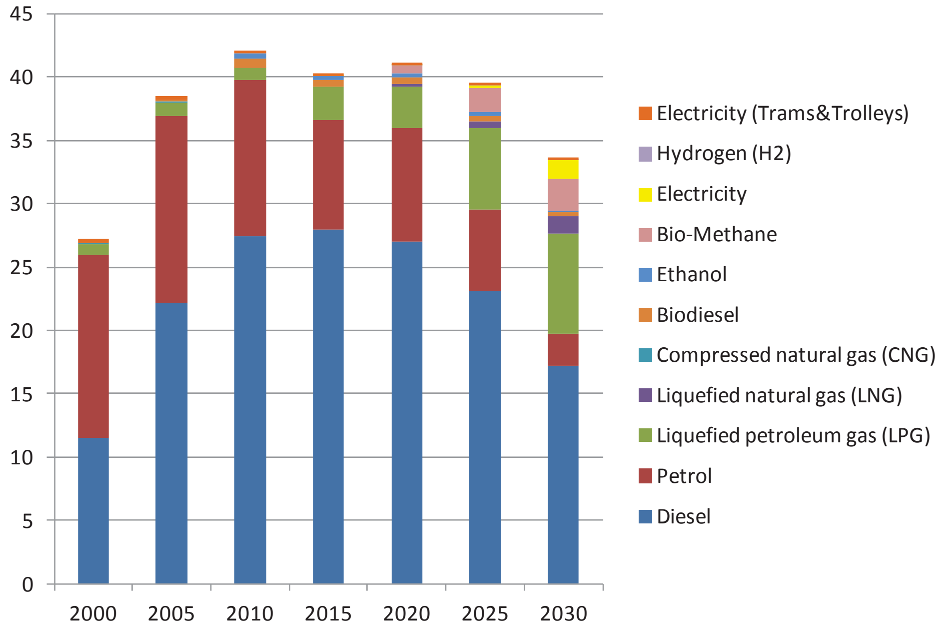
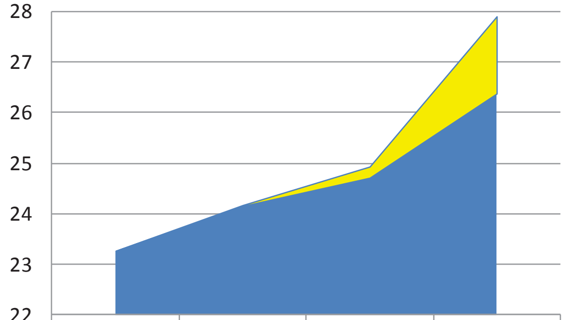


Fig. 4.7. EV_STR: fuel consumption and types of fuel, 2000–2030, PJ.

Thus, it is envisaged that the electricity consumption by the road transport sector will account for 0.08 % of the total electricity consumption by economic sectors in 2020, as well as it will take up 0.89 % and 5.48 % in 2025 and 2030, respectively (Fig.4.8).

[20] More detailed table of the fuel consumption and types of fuel are provided in Annex III (Table III-6).



	2015	2020	2025	2030
Road transport (without Trams&Trolleys)	0.00	0.02	0.22	1.53
Other sectors	23.27	24.16	24.72	26.38

Fig. 4.8. EV_STR: electricity consumption, 2000 – 2030, PJ.

In EV_STR scenario, the total GHG emissions for 2030 have decreased by 6.01 % and road transport – by 30.18 % compared to 2015 (Fig. 4.9). The main reason for a decrease of emissions is growth of electricity consumptions and a decrease in diesel oil in the road transport sub-sector.

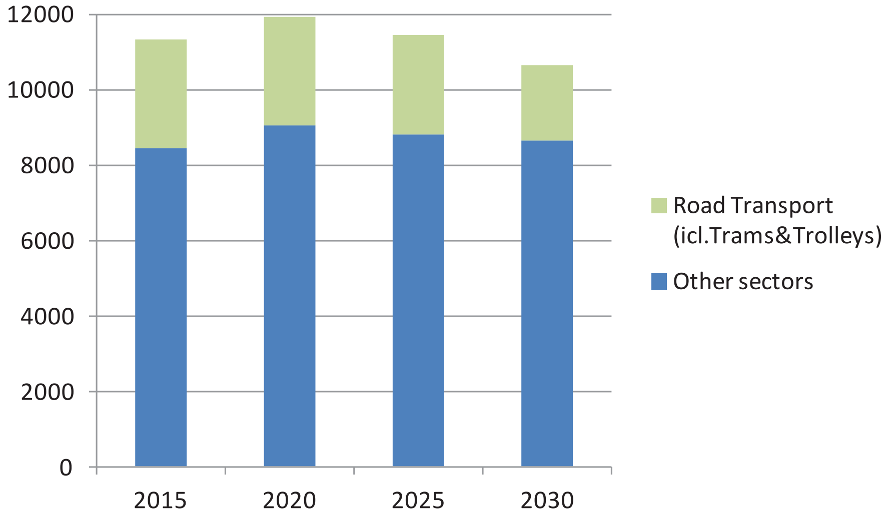


Fig. 4.9. EV_STR: GHG emissions, 2000–2030, kt CO_2 eq.

4.2. Analysis and Comparison of the Results

The development of the fleet of electric vehicles and infrastructure for their charging are the solutions to reduce greenhouse gas emissions in the country, which have been considered within the framework of two scenarios.

Baseline scenario is founded on the actual situation of the energy system of Latvia and the electric vehicle fleet development trends for 2030. Therefore, this is taken as the starting point for comparison.

The strategic scenario is based on the same development of the energy system of Latvia, but assuming that 20 % of the road transport fleet will be electric vehicles. This can be achieved as a result of aggregate measures, such as motivation for buying electrical vehicles and creating affordable infrastructure and charging networks.

Comparing the data given in the scenarios for the number of EVs, the author of the Thesis has obtained the following results:

- 2020: in the EV_STR scenario, the number of BEVs is 4 times more and that of PHEVs is 2.2 times more than in the BASE scenario.
- 2025: in the EV_STR scenario, the number of BEVs is 7.9 times more and that of PHEVs is 4.5 times more than in the BASE scenario.
- 2030: in the EV_STR scenario, the number of BEVs is 8.9 times more and that of PHEVs is 10.6 times more than in the BASE scenario.

As shown in Fig. 4.10, in scenarios there is a large gap in the number of EVs. In EV_STR scenario, the structure of vehicles is characterised not only by higher share of BEVs and PHEVs, but also by the difference in the use of PHEV technologies in comparison with the BASE scenario. If in the BASE scenario PHEVs that use petrol dominate, 19 % of PHEVs (petrol) and 1 % of PHEVs (diesel), whereas in case of EV_STR scenario PHEVs that use diesel fuel dominate, 9 % of PHEVs (petrol) and 13 % of PHEVs (diesel).

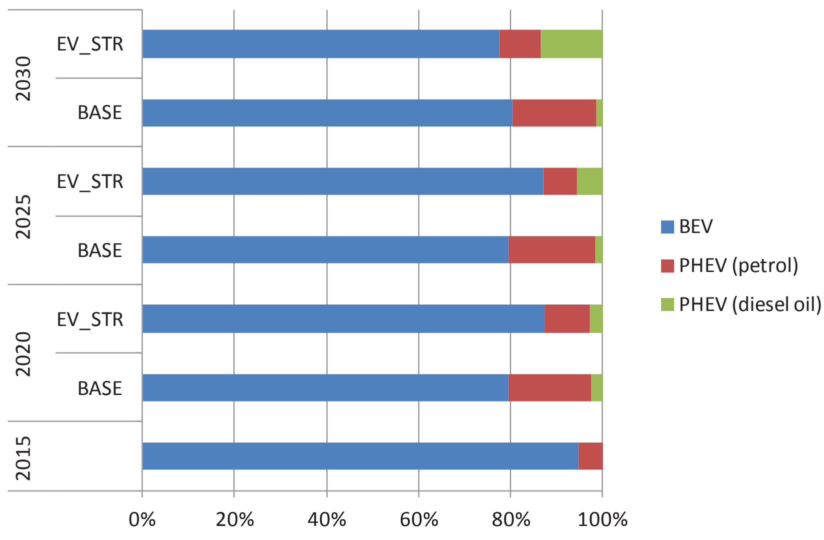


Fig. 4.10. BEV and PHEV stock, 2015–2030, %.

Comparing the results of the consumption of electricity by road transport during the 15-year period, in case of EV_STR scenario the consumption will grow substantially, more than

12 times as compared with the BASE scenario (see Fig. 4.11). This difference is due to the structure of road transport fleet; mainly the share of EVs is used in scenarios. The total consumption of electricity in the EV_STR scenario is higher by 0.00058 % (0.013 PJ) in 2020 than in the BASE scenario and by 5.3 % (1.4 PJ) in 2030.

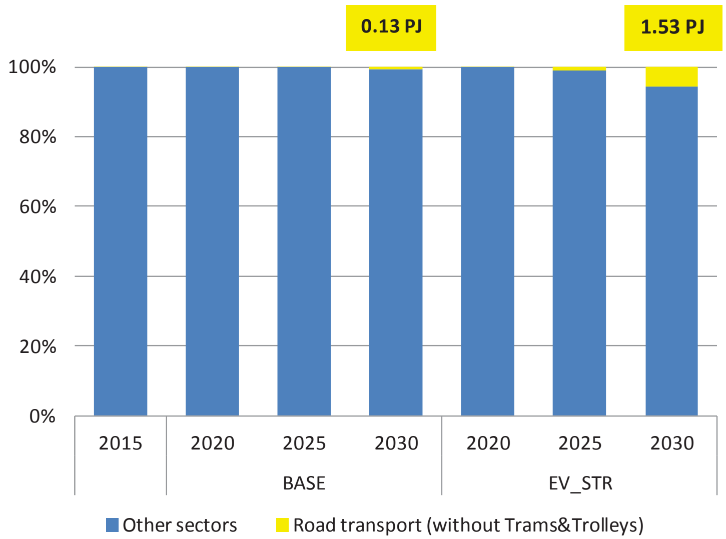


Fig. 4.11. Total consumption of electricity, 2015–2030, %.

The modelling results reveal that the total greenhouse gas emissions and GHG emissions from the road transport in both scenarios indicate a decrease in 2030 with respect to 2005 (Fig. 4.12). However, comparing the EV_STR scenario with the BASE scenario it has been found out that the total greenhouse gas emissions are reduced by 0.7 %, and in the road transport sector – by 0.27 % in 2020, and by 0.42 % and 1.86 in 2025 and by 4.59 % and 13.65 in 2030, respectively.

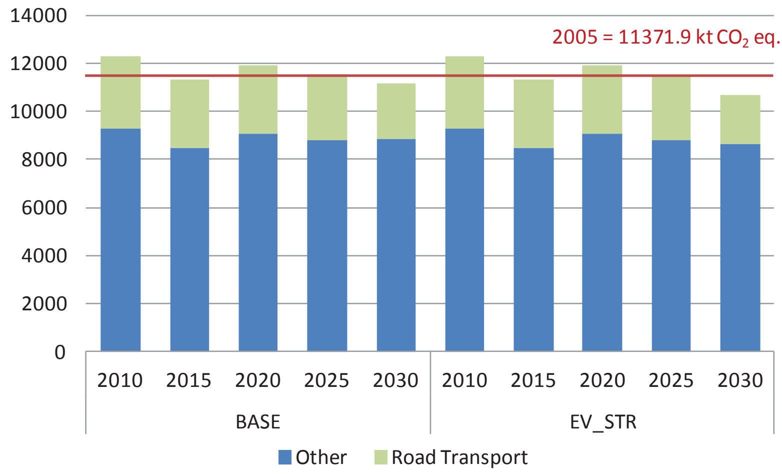


Fig. 4.12. A comparison of GHG emissions by two scenarios, 2010–2030, kt CO_2 eq.

The comparison of the two scenarios with respect to 2005 allows concluding:

- In 2020, the BASE scenario includes an increase in the consumption of fossil fuels by 3.30 % and an increase in GHG emissions by 5.02 %.
- In 2030, in the BASE scenario there will be a 23.49 % decrease in fossil fuel consumption and GHG emissions will reduce by 1.80 %.
- In 2020, the EV_STR scenario includes an increase in the consumption of fossil fuels by 3.26 % and an increase in GHG emissions by 4.18 %.
- In 2030, in the EV_STR the fossil fuel consumption will reduce by 27.19 % and GHG emissions will reduce by 9.69 %.

Comparing the results of the modelled scenarios, it can be observed that the EV_STR scenario is the most suitable one for fulfilling the tasks of the national targets for 2020 and 2030, as it allows achieving 9.69 % below 2005 level by 2030, whereas the BASE scenario – only 1.8 %.

4.3. Summary of Chapter 4

Chapter 4 has examined the time period of 2000–2030, during which it has been found that if the road transport fleet consists of 20 % of electric vehicles, the goal set regarding GHG emissions for 2030 will be fulfilled. The study takes a scenario approach. The first scenario (baseline scenario) examines the impact of gradually substituting fossil fuels with electricity (2.15 % EVs in 2030) in the road transport fleet. The second scenario (strategic scenario) examines the impact of faster replacement of fossil fuels with electricity (20 % EVs in 2030) as energy sources for vehicles. Analysis of the two scenarios allows for the conclusion that by 2030 it will be possible to decrease the fossil fuel consumption and the GHG emissions owing to the use of efficient vehicles, such as battery electric vehicles and plug-in hybrid electric vehicles, despite the increase of transport vehicle fleet. It has been found out that if the strategic scenario is implemented, the goal set for 2030 will be achieved.

Practical application of the proposed scenarios has been used in the actual project initiated by the Ministry of Transport "Study on the scenarios for the implementation of the Directive 2014/94/EU of the European Parliament and of the Council of 22 October 2014 on the introduction of alternative fuels" („Pētījums par Eiropas Parlamenta un Padomes 2014. gada 22. oktobra Direktīvas 2014/94/ES par alternatīvo degvielu ieviešanu scenārijiem”. Nr. SM2017/04).

However, it should be noted that the key factors for the implementation of the strategic scenario must be met in the country:

- The number of electric vehicles should reach 0.27 % by 2020 of the road transport fleet. In the period between from 2020 to 2025, it is necessary to register at least 5000 electric vehicles, and about 35000 starting from 2025.
- It is also necessary to actively develop the infrastructure of charging stations on the main roads of the country, the cities and rural areas, and to stimulate the service sector in order to create centres for servicing and repairing electric vehicles.
- It is also necessary to raise public awareness of the role of clean technologies in everyday life of an ordinary person, which will affect the consumer choice when buying cars.

CONCLUSIONS

The research has shown that to implement the Latvian National Development Plans it is necessary to pay special attention to the road transport sub-sector, where during many years the annual increase in energy consumption and greenhouse gas emissions has been observed. Thus, the investigation of the potential for development of a fleet of vehicles with engines working on alternative fuels (cars with hybrid engines, clean electric motors, etc.) is of critical importance in promoting the decrease in consumption of fossil fuels and in retaining the growth of GHG emissions.

The analysis of road transport fleet has revealed that the growing demand for electric vehicles in Latvia and worldwide is currently triggered by government incentives, including subsidies, exemptions from tolls and parking fees.

Moreover, despite the increased attention to the development of infrastructure of charging stations, in Latvia a number of theoretical and practical issues remain unresolved, which is explained by the lack of real practical data on electricity consumption of cars and mileage per charge. This also related to the study of low-voltage distribution networks in the context of their interaction with electrical vehicle charging stations (as new electricity consumers).

The analysis of seasonal and daily energy consumption of several household and service sector objects with installed charging stations, as well as an estimation of possible tariffs differentiated by the time of the day has indicated that with the help of the electricity tariff system it is possible to stimulate the private and legal consumers to participate in the power market. Owners of buildings (objects) that will provide the services of charging stations from their distribution network may receive economic benefits.

For this purpose, several factors should be considered: estimation of equipment cost of charging stations, its proper installation into the local network, and an accurate study of possible economic profit from such an investment into the energy trading business.

Within the framework of the present research, the structure of the algorithm of a local distribution network in accordance with the needs of electric vehicle charging stations has been considered and tested. At all the four stages, the specific tasks have been solved and implemented. For completeness and accuracy studies, the algorithm is presented together with a test case.

The result testing allows concluding that the methodology of the algorithm leads to the acquisition of theoretically valid results.

The proposed algorithm allows investigating the local distribution network of a residential area and obtaining the optimal solution for creating infrastructure on its territory of district, in accordance with the requirements of residents (owners of electric vehicles) simultaneously ensuring the reliability of the power supply network in the urban or rural area.

Analysis of a long-term forecast of energy consumption in Latvia till 2030 indicates that the current trend of development of the country shows good performance to meet its national targets in the energy sector. The strategic scenario has considered preconditions that could accelerate the use of electric vehicles, which is a positive sign in the future. The results of the scenario allow concluding that it is possible to decrease the fossil fuel consumption and the

GHG emissions owing to the use of efficient electric vehicles, despite the expected increase of road transport fleet. If the strategic scenario is implemented, the national obligations will be achieved by 2030.

FURTHER RESEARCH

The present research has revealed several opportunities for further research.

First, the new algorithm described in the research should be adapted to the existing distribution network and planning tools for its application in the future.

Second, it is necessary to create blocks where a smart tariff plan controls the charging of an electric vehicle within 24 hours. This will make it possible to theoretically estimate the charging at any time, and offer charging at the time when the consumer demand for electricity in the network is low. Smart tariff plan will reduce the cost of payment by EV owners, will control other charging sites located in the area and will reduce the demand for electricity at peak times, thus ensuring flexibility, stability and reliability of the distribution network operation.

Third, in further studies it is planned to create a new block, where generation from renewable energy sources (such as solar, wind energy, and others) will be calculated and taken into account when estimating additional capacity in the area.

Fourth, the algorithm considers only three basic criteria, such as the vehicle owners' behaviour, urban infrastructure and the power supply system. In the further research this algorithm can be expanded with more additional factors and criteria to improve real-time applicability situations.

The author is more than happy to support or take part in further research with the interested parties.

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APPENDIX I

Table I-1. Household Sector, S (kVA)

	dwelling houses (3-storey house)			dwelling houses (5-storey house)			large parking place (for 500 vehicles)			street lighting		
	winter	autumn/ spring	summer	winter	autumn/ spring	summer	winter	autumn/ spring	summer	winter	autumn/ spring	summer
0:00	59.8	59.1	48.7	361.4	354.6	283.6	4.7	4.6	3.4	7.1	5.5	3.2
1:00	50.6	49.9	41.1	305.4	299.6	239.6	4.3	4.3	3.2	7.0	5.5	3.1
2:00	43.0	42.4	35.0	259.6	254.7	203.7	4.2	4.2	3.1	5.2	4.1	2.3
3:00	38.3	37.9	31.2	231.6	227.3	181.7	3.9	3.8	2.9	4.3	3.3	1.9
4:00	36.5	36.0	29.7	220.4	216.3	172.9	3.3	3.2	2.4	4.3	3.4	1.9
5:00	38.5	38.0	31.3	232.6	228.2	182.5	2.9	2.8	2.1	4.4	3.4	1.9
6:00	59.5	58.8	48.4	359.6	352.8	282.1	2.7	2.6	2.0	3.1	2.4	1.4
7:00	73.3	72.4	59.6	442.7	434.4	347.3	2.4	2.4	1.8	2.4	1.9	1.1
8:00	73.8	72.8	60.0	445.5	437.1	349.5	2.1	2.1	1.6	2.3	1.8	1.0
9:00	66.2	65.3	53.8	399.7	392.2	313.6	1.8	1.8	1.3	1.2	0.9	0.5
10:00	60.0	59.2	48.8	362.4	355.5	284.3	2.0	1.9	1.4	1.2	0.9	0.5
11:00	56.8	56.0	46.2	342.8	336.3	268.9	2.2	2.1	1.6	1.2	1.0	0.6
12:00	53.3	52.7	43.4	322.2	316.1	252.8	2.4	2.3	1.8	1.5	1.2	0.7
13:00	53.7	53.0	43.6	324.1	318.0	254.3	2.5	2.5	1.9	1.5	1.1	0.6
14:00	55.2	54.5	44.9	333.4	327.1	261.6	2.6	2.6	1.9	1.3	1.0	0.6
15:00	58.6	57.9	47.7	354.0	347.3	277.7	2.6	2.6	1.9	1.3	1.0	0.6
16:00	64.3	63.5	52.3	388.5	381.2	304.8	2.7	2.6	2.0	2.1	1.7	0.9
17:00	71.4	70.5	58.1	431.5	423.4	338.5	3.0	3.0	2.2	3.0	2.4	1.3
18:00	77.0	76.0	62.6	465.1	456.3	364.9	3.5	3.5	2.6	4.8	3.7	2.1
19:00	86.4	85.3	70.3	522.1	512.2	409.6	4.0	3.9	2.9	5.6	4.4	2.5
20:00	98.5	97.2	80.1	594.9	583.7	466.8	4.1	4.0	3.0	5.8	4.5	2.6
21:00	104.4	103.0	84.9	630.4	618.5	494.6	4.3	4.3	3.2	6.6	5.1	2.9
22:00	94.2	93.0	76.6	568.8	558.1	446.3	4.6	4.5	3.4	7.3	5.7	3.3
23:00	73.0	72.1	59.4	440.8	432.5	345.9	4.8	4.7	3.5	7.2	5.6	3.2

Table I-2. Tertiary Sector, S (kVA)

	office-industry buildings			grocery stores			post office/police department			catering services			kindergarten			health centre		
	winter	autumn/ spring	summer	winter	autumn/ spring	summer	winter	autumn/ spring	summer	winter	autumn/ spring	summer	winter	autumn/ spring	summer	winter	autumn/ spring	summer
0:00	249.6	217.9	194.4	175.8	175.8	175.8	11.1	11.1	11.1	19.1	19.1	17.2	4.0	3.8	3.5	10.3	9.8	9.0
1:00	287.5	251.0	223.9	174.2	174.2	174.2	12.9	12.9	12.9	20.6	20.6	18.5	6.4	6.0	5.7	11.9	11.3	10.4
2:00	279.6	244.1	217.8	167.8	167.8	167.8	12.6	12.6	12.6	19.9	19.9	17.9	6.4	6.0	5.6	11.6	11.0	10.1
3:00	271.7	237.2	211.6	163.0	163.0	163.0	12.2	12.2	12.2	18.7	18.7	16.9	6.3	5.9	5.6	11.2	10.7	9.8
4:00	267.0	233.1	207.9	163.0	163.0	163.0	12.0	12.0	12.0	15.3	15.3	13.7	6.1	5.7	5.3	11.0	10.5	9.6
5:00	260.7	227.5	203.0	166.2	166.2	166.2	11.7	11.7	11.7	11.2	11.2	10.1	5.9	5.6	5.2	10.8	10.2	9.4
6:00	222.8	194.4	173.5	219.0	219.0	219.0	10.0	10.0	10.0	8.3	8.3	7.4	5.4	5.1	4.7	9.2	8.7	8.0
7:00	268.6	234.4	209.1	282.9	282.9	282.9	12.1	12.1	12.1	9.5	9.5	8.5	7.9	7.4	7.0	11.1	10.5	9.7
8:00	350.7	306.1	273.1	335.7	335.7	335.7	15.8	15.8	15.8	10.4	10.4	9.3	11.4	10.7	10.1	14.5	13.8	12.7
9:00	413.9	361.3	322.3	394.8	394.8	394.8	18.6	18.6	18.6	12.4	12.4	11.2	12.2	11.5	10.8	17.1	16.3	14.9
10:00	439.2	383.4	342.0	444.4	444.4	444.4	19.7	19.7	19.7	13.6	13.6	12.2	11.7	11.0	10.3	18.2	17.2	15.9
11:00	443.9	387.5	345.7	450.8	450.8	450.8	19.9	19.9	19.9	15.4	15.4	13.8	11.6	10.9	10.2	18.4	17.4	16.0
12:00	439.2	383.4	342.0	450.8	450.8	450.8	19.7	19.7	19.7	17.5	17.5	15.7	11.0	10.4	9.7	18.2	17.2	15.9
13:00	432.9	377.8	337.1	454.0	454.0	454.0	19.5	19.5	19.5	20.4	20.4	18.4	9.9	9.3	8.7	17.9	17.0	15.6
14:00	428.1	373.7	333.4	457.2	457.2	457.2	19.2	19.2	19.2	23.1	23.1	20.8	8.6	8.1	7.6	17.7	16.8	15.5
15:00	420.2	366.8	327.3	457.2	457.2	457.2	18.9	18.9	18.9	23.4	23.4	21.1	7.5	7.1	6.7	17.4	16.5	15.2
16:00	398.1	347.5	310.0	458.8	458.8	458.8	17.9	17.9	17.9	24.4	24.4	22.0	6.8	6.4	6.0	16.5	15.6	14.4
17:00	349.1	304.8	271.9	458.8	458.8	458.8	15.7	15.7	15.7	24.0	24.0	21.6	6.2	5.8	5.5	14.4	13.7	12.6
18:00	308.1	268.9	239.9	454.0	454.0	454.0	13.8	13.8	13.8	23.5	23.5	21.2	5.9	5.6	5.2	12.7	12.1	11.1
19:00	290.7	253.7	226.4	446.0	446.0	446.0	13.1	13.1	13.1	23.4	23.4	21.1	5.9	5.5	5.2	12.0	11.4	10.5
20:00	282.8	246.8	220.2	420.4	420.4	420.4	12.7	12.7	12.7	23.4	23.4	21.1	5.7	5.3	5.0	11.7	11.1	10.2
21:00	273.3	238.6	212.8	372.4	372.4	372.4	12.3	12.3	12.3	23.3	23.3	21.0	5.2	4.9	4.6	11.3	10.7	9.9
22:00	263.8	230.3	205.5	238.2	238.2	238.2	11.9	11.9	11.9	22.5	22.5	20.2	4.7	4.4	4.1	10.9	10.4	9.5
23:00	257.5	224.8	200.5	187.0	187.0	187.0	11.6	11.6	11.6	20.5	20.5	18.4	4.2	3.9	3.7	10.6	10.1	9.3
Σ, kVA	7899.2	6895.0	6151.3	7992.4	7992.4	7992.4	355.0	355.0	355.0	443.7	443.7	399.3	177.0	166.6	156.2	326.6	310.2	285.2

Table I-3. The Data of Total Load from Objects of Urban Area, S (MVA)

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
winter	0.90	0.88	0.81	0.76	0.74	0.74	0.90	1.11	1.26	1.34	1.37	1.36	1.34	1.34	1.35	1.36	1.38	1.38	1.37	1.41	1.46	1.44	1.23	1.02
autumn/spring	0.86	0.84	0.77	0.72	0.70	0.70	0.86	1.07	1.21	1.28	1.31	1.30	1.27	1.27	1.28	1.30	1.32	1.32	1.32	1.36	1.41	1.39	1.18	0.97
summer	0.75	0.73	0.68	0.64	0.62	0.62	0.76	0.94	1.07	1.14	1.18	1.17	1.15	1.15	1.16	1.17	1.19	1.19	1.18	1.21	1.24	1.22	1.02	0.84

Table I-4. Possible Additional Load for Objects, kVA

	dwelling houses (3-storey house)	dwelling houses (5-storey house)	large parking place (for 500 vehicles)	office-industry buildings	grocery stores	post office/police department	catering services	kindergarten	health centre
0:00	7.69	23.22	2.50	198.43	121.00	8.95	8.50	13.55	16.41
1:00	8.39	25.32	2.80	181.37	121.36	8.15	7.82	11.38	15.00
2:00	8.95	27.04	2.88	184.92	122.80	8.31	8.14	11.41	15.29
3:00	9.30	28.09	3.19	188.48	123.88	8.47	8.66	11.48	15.58
4:00	9.44	28.51	3.73	190.61	123.88	8.57	10.21	11.70	15.76
5:00	9.29	28.05	4.10	193.45	123.16	8.69	12.05	11.83	15.99
6:00	7.71	23.29	4.31	210.51	111.29	9.46	13.37	12.31	17.41
7:00	6.68	20.17	4.53	189.90	96.91	8.53	12.81	10.04	15.70
8:00	6.65	20.07	4.78	152.93	85.04	6.84	12.41	6.89	12.64
9:00	7.21	21.79	5.05	124.49	71.73	5.59	11.49	6.12	10.29
10:00	7.68	23.19	4.94	113.12	60.58	5.08	10.97	6.60	9.35
11:00	7.92	23.92	4.74	110.98	59.14	4.99	10.17	6.70	9.18
12:00	8.18	24.69	4.56	113.12	59.14	5.08	9.22	7.21	9.35
13:00	8.15	24.62	4.40	115.96	58.42	5.21	7.90	8.23	9.59
14:00	8.04	24.27	4.33	118.09	57.71	5.31	6.70	9.37	9.76
15:00	7.78	23.50	4.33	121.65	57.71	5.47	6.54	10.36	10.06
16:00	7.35	22.21	4.28	131.60	57.35	5.91	6.10	11.03	10.88
17:00	6.82	20.59	3.96	153.64	57.35	6.90	6.26	11.57	12.70
18:00	6.40	19.33	3.52	172.12	58.42	7.73	6.50	11.80	14.23
19:00	5.69	17.20	3.13	179.94	60.22	8.09	6.54	11.86	14.88
20:00	4.79	14.46	3.02	183.50	65.98	8.25	6.54	12.05	15.17
21:00	4.35	13.13	2.78	187.76	76.77	8.44	6.58	12.43	15.52
22:00	5.11	15.45	2.57	192.03	106.98	8.63	6.98	12.94	15.88
23:00	6.70	20.24	2.39	194.87	118.49	8.76	7.86	13.39	16.11

APPENDIX II

Table II-1. Volume of Usage and Parking Demand

	dwelling houses (3-storey house)	dwelling houses (5-storey house)	large parking place (for 500 vehicles)	office-industry buildings	grocery stores	post office/police department	catering services	kindergarten	health centre
0:00	10	29	489	13	7	1	0	0	33
1:00	10	29	494	13	7	1	0	0	33
2:00	10	30	499	13	7	1	0	0	33
3:00	10	30	499	13	7	1	0	0	33
4:00	10	30	499	13	7	1	0	0	33
5:00	10	30	499	13	7	1	0	0	33
6:00	9	27	449	18	9	1	1	1	33
7:00	8	24	399	47	19	2	1	3	43
8:00	5	21	349	56	41	4	3	2	62
9:00	2	10	160	65	48	5	3	1	85
10:00	1	8	140	76	54	5	3	0	99
11:00	1	7	120	75	55	5	4	1	105
12:00	1	7	120	75	55	5	4	1	104
13:00	2	7	120	75	55	5	4	1	104
14:00	2	8	140	76	55	5	4	1	96
15:00	2	9	152	76	55	5	4	1	97
16:00	3	12	210	76	56	5	4	1	85
17:00	4	16	274	61	56	5	4	2	53
18:00	6	21	349	60	55	5	4	2	53
19:00	7	25	413	37	54	5	2	1	52
20:00	8	26	431	35	51	5	2	0	50
21:00	8	27	454	31	45	4	1	0	45
22:00	9	28	478	20	16	2	1	0	42
23:00	10	29	489	15	12	1	0	0	39

Table II-2. Parking Demand Coefficients, k_{pd}

period of time	dwelling houses (3-storey house)	dwelling houses (5-storey house)	large parking place (for 500 vehicles)	office-industry buildings	grocery stores	post office/police department	catering services	kindergarten	health centre
from 23.00 to 07.00	0.97	0.96	0.96	0.23	0.16	0.22	0.06	0.15	0.33
from 07.00 to 09.00	0.50	0.61	0.61	0.74	0.64	0.73	0.58	0.67	0.60
from 09.00 to 16.00	0.18	0.28	0.29	0.98	0.97	1.00	0.94	0.29	0.92
from 16.00 to 21.00	0.60	0.71	0.71	0.66	0.94	0.97	0.71	0.33	0.54
from 21.00 to 23.00	0.90	0.93	0.95	0.29	0.43	0.47	0.17	0.00	0.40

Table II-3. Possible Scheduling Scheme for the Charging Station

	5-st. dw.h, kVA	$3 \leq S_i \geq 43$; 0< t ≥ 10	park. lot, kVA	$3 \leq S_i \geq 43$; 0< t ≥ 10	office build., kVA	$3 \leq S_i \geq 43$; 0< t ≥ 10	grocery store, kVA	$3 \leq S_i \geq 43$; 0< t ≥ 10	health centre, kVA	$3 \leq S_i \geq 43$; 0< t ≥ 10
0:00	23.22	TRUE	2.50	FALSE	198.43	TRUE	121.00	TRUE	16.41	TRUE
1:00	25.32	TRUE	2.80	FALSE	181.37	TRUE	121.36	TRUE	15.00	TRUE
2:00	27.04	TRUE	2.88	FALSE	184.92	TRUE	122.80	TRUE	15.29	TRUE
3:00	28.09	TRUE	3.19	TRUE	188.48	TRUE	123.88	TRUE	15.58	TRUE
4:00	28.51	TRUE	3.73	TRUE	190.61	TRUE	123.88	TRUE	15.76	TRUE
5:00	28.05	TRUE	4.10	TRUE	193.45	TRUE	123.16	TRUE	15.99	TRUE
6:00	23.29	TRUE	4.31	TRUE	210.51	TRUE	111.29	TRUE	17.41	TRUE
7:00	20.17	TRUE	4.53	TRUE	189.90	TRUE	96.91	TRUE	15.70	TRUE
8:00	20.07	TRUE	4.78	TRUE	152.93	TRUE	85.04	TRUE	12.64	TRUE
9:00	21.79	TRUE	5.05	TRUE	124.49	TRUE	71.73	TRUE	10.29	TRUE
10:00	23.19	TRUE	4.94	TRUE	113.12	TRUE	60.58	TRUE	9.35	TRUE
11:00	23.92	TRUE	4.74	TRUE	110.98	TRUE	59.14	TRUE	9.18	TRUE
12:00	24.69	TRUE	4.56	TRUE	113.12	TRUE	59.14	TRUE	9.35	TRUE
13:00	24.62	TRUE	4.40	TRUE	115.96	TRUE	58.42	TRUE	9.59	TRUE
14:00	24.27	TRUE	4.33	TRUE	118.09	TRUE	57.71	TRUE	9.76	TRUE
15:00	23.50	TRUE	4.33	TRUE	121.65	TRUE	57.71	TRUE	10.06	TRUE
16:00	22.21	TRUE	4.28	TRUE	131.60	TRUE	57.35	TRUE	10.88	TRUE
17:00	20.59	TRUE	3.96	TRUE	153.64	TRUE	57.35	TRUE	12.70	TRUE
18:00	19.33	TRUE	3.52	TRUE	172.12	TRUE	58.42	TRUE	14.23	TRUE
19:00	17.20	TRUE	3.13	TRUE	179.94	TRUE	60.22	TRUE	14.88	TRUE
20:00	14.46	TRUE	3.02	TRUE	183.50	TRUE	65.98	TRUE	15.17	TRUE
21:00	13.13	TRUE	2.78	FALSE	187.76	TRUE	76.77	TRUE	15.52	TRUE
22:00	15.45	TRUE	2.57	FALSE	192.03	TRUE	106.98	TRUE	15.88	TRUE
23:00	20.24	TRUE	2.39	FALSE	194.87	TRUE	118.49	TRUE	16.11	TRUE
S_{min}	**13.13**		**2.39**		**110.98**		**57.35**		**9.18**	

Table II-4. Constraints for the Public EVCSs

A. Standard Charging Power Levels

TIME	Dwelling house	Constraint I	Constraint II	Constraint III
0:00	23.22	FALSE	TRUE	TRUE
1:00	25.32	FALSE	TRUE	TRUE
2:00	27.04	FALSE	TRUE	TRUE
3:00	28.09	FALSE	TRUE	TRUE
4:00	28.51	FALSE	TRUE	TRUE
5:00	28.05	FALSE	TRUE	TRUE
6:00	23.29	FALSE	TRUE	TRUE
7:00	20.17	FALSE	FALSE	TRUE
8:00	20.07	FALSE	FALSE	TRUE
9:00	21.79	FALSE	FALSE	TRUE
10:00	23.19	FALSE	TRUE	TRUE

11:00	23.92	FALSE	TRUE	TRUE
12:00	24.69	FALSE	TRUE	TRUE
13:00	24.62	FALSE	TRUE	TRUE
14:00	24.27	FALSE	TRUE	TRUE
15:00	23.50	FALSE	TRUE	TRUE
16:00	22.21	FALSE	TRUE	TRUE
17:00	20.59	FALSE	FALSE	TRUE
18:00	19.33	FALSE	FALSE	TRUE
19:00	17.20	FALSE	FALSE	TRUE
20:00	14.46	FALSE	FALSE	TRUE
21:00	13.13	FALSE	FALSE	TRUE
22:00	15.45	FALSE	FALSE	TRUE
23:00	20.24	FALSE	FALSE	TRUE
	13.13			

TIME	Large parking lot	Constraint I	Constraint II	Constraint III
0:00	2.50	FALSE	FALSE	FALSE
1:00	2.80	FALSE	FALSE	FALSE
2:00	2.88	FALSE	FALSE	FALSE
3:00	3.19	FALSE	FALSE	TRUE
4:00	3.73	FALSE	FALSE	TRUE
5:00	4.10	FALSE	FALSE	TRUE
6:00	4.31	FALSE	FALSE	TRUE
7:00	4.53	FALSE	FALSE	TRUE
8:00	4.78	FALSE	FALSE	TRUE
9:00	5.05	FALSE	FALSE	TRUE
10:00	4.94	FALSE	FALSE	TRUE
11:00	4.74	FALSE	FALSE	TRUE
12:00	4.56	FALSE	FALSE	TRUE
13:00	4.40	FALSE	FALSE	TRUE
14:00	4.33	FALSE	FALSE	TRUE
15:00	4.33	FALSE	FALSE	TRUE
16:00	4.28	FALSE	FALSE	TRUE
17:00	3.96	FALSE	FALSE	TRUE
18:00	3.52	FALSE	FALSE	TRUE
19:00	3.13	FALSE	FALSE	TRUE
20:00	3.02	FALSE	FALSE	TRUE
21:00	2.78	FALSE	FALSE	FALSE
22:00	2.57	FALSE	FALSE	FALSE
23:00	2.39	FALSE	FALSE	FALSE
	2.39			

TIME	Office building	Constraint I	Constraint II	Constraint III
0:00	198.43	TRUE	TRUE	TRUE
1:00	181.37	TRUE	TRUE	TRUE
2:00	184.92	TRUE	TRUE	TRUE
3:00	188.48	TRUE	TRUE	TRUE
4:00	190.61	TRUE	TRUE	TRUE
5:00	193.45	TRUE	TRUE	TRUE
6:00	210.51	TRUE	TRUE	TRUE
7:00	189.90	TRUE	TRUE	TRUE
8:00	152.93	TRUE	TRUE	TRUE
9:00	124.49	TRUE	TRUE	TRUE
10:00	113.12	TRUE	TRUE	TRUE
11:00	110.98	TRUE	TRUE	TRUE
12:00	113.12	TRUE	TRUE	TRUE
13:00	115.96	TRUE	TRUE	TRUE
14:00	118.09	TRUE	TRUE	TRUE
15:00	121.65	TRUE	TRUE	TRUE
16:00	131.60	TRUE	TRUE	TRUE
17:00	153.64	TRUE	TRUE	TRUE
18:00	172.12	TRUE	TRUE	TRUE
19:00	179.94	TRUE	TRUE	TRUE
20:00	183.50	TRUE	TRUE	TRUE
21:00	187.76	TRUE	TRUE	TRUE
22:00	192.03	TRUE	TRUE	TRUE
23:00	194.87	TRUE	TRUE	TRUE
	110.98			

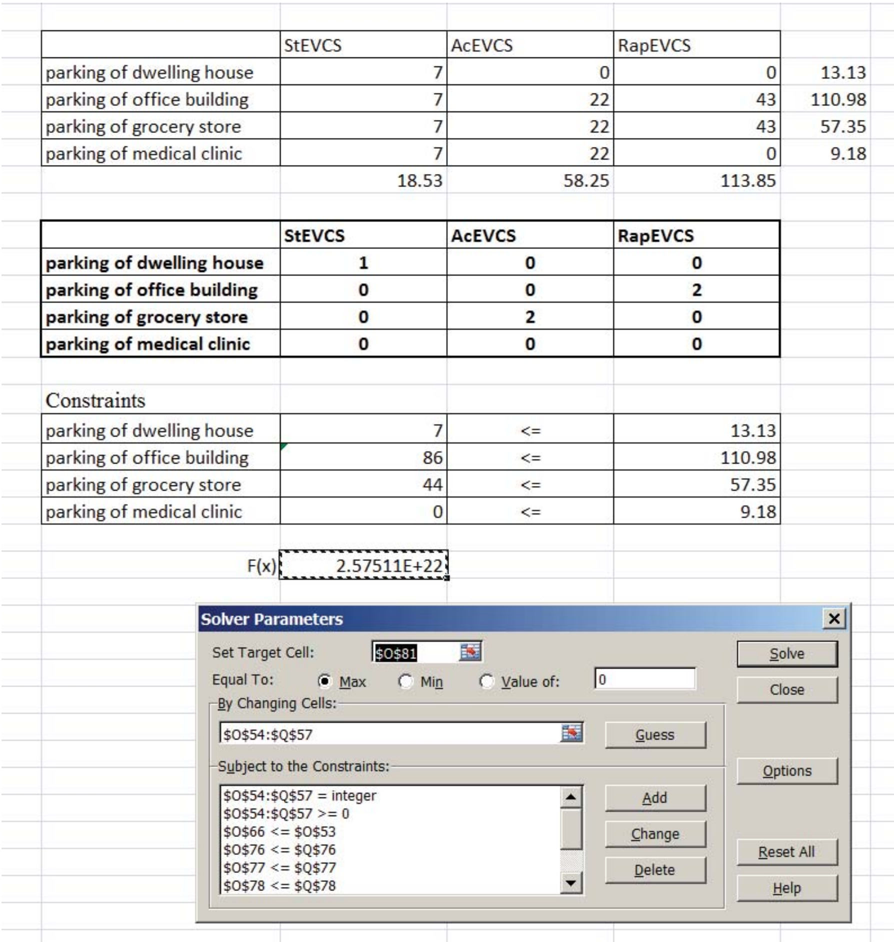
TIME	Grocery store	Constraint I	Constraint II	Constraint III
0:00	121.00	TRUE	TRUE	TRUE
1:00	121.36	TRUE	TRUE	TRUE
2:00	122.80	TRUE	TRUE	TRUE
3:00	123.88	TRUE	TRUE	TRUE
4:00	123.88	TRUE	TRUE	TRUE
5:00	123.16	TRUE	TRUE	TRUE
6:00	111.29	TRUE	TRUE	TRUE
7:00	96.91	TRUE	TRUE	TRUE
8:00	85.04	TRUE	TRUE	TRUE
9:00	71.73	TRUE	TRUE	TRUE
10:00	60.58	TRUE	TRUE	TRUE
11:00	59.14	TRUE	TRUE	TRUE
12:00	59.14	TRUE	TRUE	TRUE
13:00	58.42	TRUE	TRUE	TRUE
14:00	57.71	TRUE	TRUE	TRUE
15:00	57.71	TRUE	TRUE	TRUE
16:00	57.35	TRUE	TRUE	TRUE
17:00	57.35	TRUE	TRUE	TRUE

18:00	58.42	TRUE	TRUE	TRUE
19:00	60.22	TRUE	TRUE	TRUE
20:00	65.98	TRUE	TRUE	TRUE
21:00	76.77	TRUE	TRUE	TRUE
22:00	106.98	TRUE	TRUE	TRUE
23:00	118.49	TRUE	TRUE	TRUE
	57.35			

TIME	Health centre	Constraint I	Constraint II	Constraint III
0:00	16.41	FALSE	TRUE	TRUE
1:00	15.00	FALSE	TRUE	TRUE
2:00	15.29	FALSE	TRUE	TRUE
3:00	15.58	FALSE	TRUE	TRUE
4:00	15.76	FALSE	TRUE	TRUE
5:00	15.99	FALSE	TRUE	TRUE
6:00	17.41	FALSE	TRUE	TRUE
7:00	15.70	FALSE	TRUE	TRUE
8:00	12.64	FALSE	TRUE	TRUE
9:00	10.29	FALSE	TRUE	TRUE
10:00	9.35	FALSE	TRUE	TRUE
11:00	9.18	FALSE	TRUE	TRUE
12:00	9.35	FALSE	TRUE	TRUE
13:00	9.59	FALSE	TRUE	TRUE
14:00	9.76	FALSE	TRUE	TRUE
15:00	10.06	FALSE	TRUE	TRUE
16:00	10.88	FALSE	TRUE	TRUE
17:00	12.70	FALSE	TRUE	TRUE
18:00	14.23	FALSE	TRUE	TRUE
19:00	14.88	FALSE	TRUE	TRUE
20:00	15.17	FALSE	TRUE	TRUE
21:00	15.52	FALSE	TRUE	TRUE
22:00	15.88	FALSE	TRUE	TRUE
23:00	16.11	FALSE	TRUE	TRUE
	9.18			

B. Standard Charging Time Levels

	Constraint I	Constraint II	Constraint III
Dwelling house (5-storey)	0	14	24
Large parking lot	0	0	18
Office building	24	24	24
Grocery store	24	24	24
Health centre	0	24	24



	StEVCS	AcEVCS	RapEVCS	
parking of dwelling house	7	0	0	13.13
parking of office building	7	22	43	110.98
parking of grocery store	7	22	43	57.35
parking of medical clinic	7	22	0	9.18
	18.53	58.25	113.85	

	StEVCS	**AcEVCS**	**RapEVCS**
parking of dwelling house	**1**	**0**	**0**
parking of office building	**0**	**0**	**2**
parking of grocery store	**0**	**2**	**0**
parking of medical clinic	**0**	**0**	**0**

Constraints

parking of dwelling house	7	<=	13.13
parking of office building	86	<=	110.98
parking of grocery store	44	<=	57.35
parking of medical clinic	0	<=	9.18

F(x) 2.57511E+22

Fig. II.1. The first solution.

	StEVCS	AcEVCS	RapEVCS	
parking of office building	0	22	43	110.98
parking of grocery store	0	0	43	57.35
parking of medical clinic	7	0	0	9.18
	11.53	58.25	113.85	

	StEVCS	**AcEVCS**	**RapEVCS**
parking of office building	**0**	**2**	**1**
parking of grocery store	**0**	**0**	**1**
parking of medical clinic	**1**	**0**	**0**

Constraints

parking of office building	87.00	<=	110.98
parking of grocery store	43.00	<=	57.35
parking of medical clinic	7.00	<=	9.18

F(x) 1.75797E+22

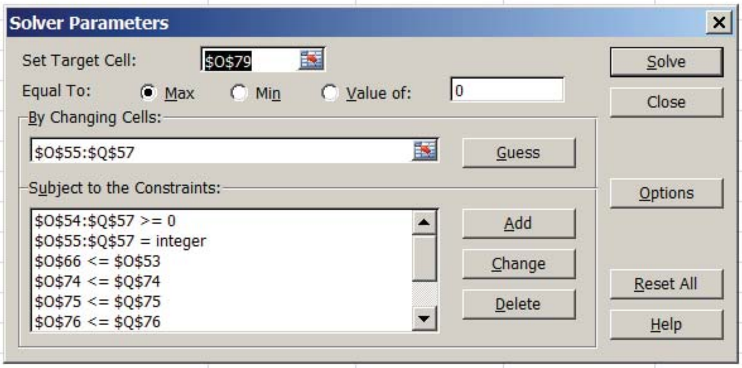


Fig. II-2. The second solution.

	StEVCS	AcEVCS	RapEVCS
parking of dwelling house	1	0	0
parking of office building	0	2	1
parking of grocery store	0	0	1
parking of medical clinic	1	0	0

F(x) 144

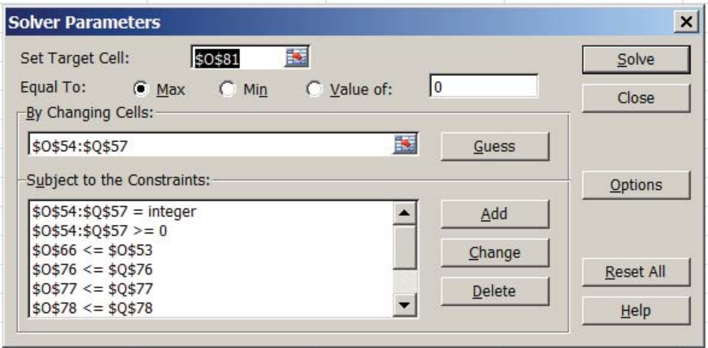


Fig. II-3. The third solution.

Table II-5. Data for Objects with EVCSs in the Winter Season, S (kVA)

	Dwelling houses (5-storey house)	Office buildings	Grocery stores	Health centre
0:00	368.45	336.62	218.83	17.32
1:00	312.41	374.53	217.23	18.89
2:00	266.65	366.63	210.84	18.56
3:00	238.63	358.73	206.04	18.23
4:00	227.42	353.99	206.04	18.04
5:00	239.56	347.67	209.24	17.78
6:00	366.58	309.76	261.99	16.21
7:00	449.71	355.57	325.93	18.10
8:00	452.51	437.72	378.68	21.50
9:00	406.74	500.92	437.82	24.11
10:00	369.38	526.20	487.38	25.16
11:00	349.77	530.94	493.77	25.35
12:00	329.22	526.20	493.77	25.16
13:00	331.09	519.88	496.97	24.90
14:00	340.43	515.14	500.17	24.70
15:00	360.98	507.24	500.17	24.37
16:00	395.53	485.12	501.76	23.46
17:00	438.50	436.15	501.76	21.43
18:00	472.12	395.07	496.97	19.74
19:00	529.09	377.69	488.98	19.02
20:00	601.94	369.79	463.40	18.69
21:00	637.43	360.31	415.45	18.30
22:00	575.79	350.83	281.17	17.91
23:00	447.84	344.51	230.02	17.65

Table II-6. Data of TS-1 with EVCSs in the winter Season, S (MVA)

	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
TS-1, MVA	1.17	1.15	1.09	1.05	1.03	1.03	1.17	1.36	1.50	1.57	1.60	1.59	1.56	1.56	1.57	1.59	1.60	1.60	1.59	1.63	1.68	1.66	1.47	1.28

APPENDIX III

Table III-1.The Main Indicators from 2000 to 2030 annually

	Number of population, thous.	Number of inhabitants per household, thous.	Number of household, thous.	GDP, M€(2010)	Private consumption (excl. private transport), M€(2010)	Taxes, M€(2010)
2000	2367.5	921.7	2.6	7397.9	12396.6	1832.0
2001	2337.2	909.0	2.6	7758.8	13197.5	1922.9
2002	2310.2	904.1	2.6	8252.6	14135.0	2031.3
2003	2288.0	895.1	2.6	8891.6	15326.6	2224.1
2004	2263.1	884.6	2.6	9746.3	16604.2	2422.1
2005	2238.8	879.5	2.5	10688.7	18380.4	2642.8
2006	2218.4	872.0	2.5	12796.2	20565.7	3076.1
2007	2200.3	868.7	2.5	14142.1	22618.0	3565.3
2008	2177.3	857.2	2.5	13023.9	21815.6	3020.2
2009	2141.7	837.1	2.6	10924.8	18673.8	1957.7
2010	2097.6	825.6	2.5	11248.7	17937.9	1991.2
2011	2059.7	817.0	2.5	11568.2	19082.5	2115.2
2012	2034.3	822.0	2.5	11900.0	19852.4	2332.9
2013	2012.6	823.3	2.4	12524.9	20334.8	2497.1
2014	1993.8	803.8	2.5	12680.0	20712.7	2595.6
2015	1977.5	796.2	2.5	13016.5	21328.2	2747.1
2016	1959.5	797.0	2.5	13458.8	21799.3	2926.2
2017	1942.2	797.8	2.4	14394.5	22791.0	3011.0
2018	1923.3	798.5	2.4	15205.1	23857.9	3137.4
2019	1900.8	799.3	2.4	15691.8	24620.0	3236.7
2020	1877.6	800.1	2.3	16158.4	25355.9	3333.0
2021	1853.4	792.2	2.3	16637.3	26058.2	3424.8
2022	1828.4	784.3	2.3	17113.3	26778.2	3519.3
2023	1802.8	776.4	2.3	17568.6	27437.8	3605.6
2024	1777.0	768.5	2.3	17972.7	28063.8	3666.3
2025	1751.4	760.6	2.3	18386.0	28707.8	3727.9
2026	1726.2	753.1	2.3	18790.5	29337.9	3786.6
2027	1701.4	745.7	2.3	19166.3	29923.1	3838.5
2028	1677.2	738.2	2.3	19549.7	30520.0	3891.0
2029	1654.0	730.7	2.3	19940.7	31128.7	3943.9
2030	1634.4	723.3	2.3	20339.5	31749.7	3997.4

Table III-2. The Main Indicators and Projected Trends of Road Transport Sector

	Total mileage of vehicles a year, Mkm			Average mileage per vehicle a year, 1000 km/vehicle		
	Bus	Cars	LDV/HDV	Bus	Cars	LDV/HDV
2000	170.72	4223.16	1635.77	59.18	13.37	37.78
2001	211.76	5267.31	1872.26	71.93	15.89	42.31
2002	237.07	5488.93	1893.53	72.08	16.17	42.58
2003	238.82	5960.35	1919.02	69.59	16.32	41.10
2004	218.71	6538.28	1955.51	60.77	16.44	40.07
2005	220.15	6987.35	2005.24	61.44	16.14	38.14
2006	224.48	7970.80	2216.70	61.10	16.14	37.66
2007	225.23	9091.49	2538.45	60.11	16.38	38.67
2008	235.96	8619.21	2368.63	60.33	15.58	38.32
2009	232.45	7466.92	2052.89	63.72	13.95	38.03
2010	231.93	7584.81	2325.82	64.25	14.44	42.85
2011	239.12	7009.90	1887.52	64.57	13.20	32.07
2012	203.22	6701.45	1954.34	54.87	12.27	30.79
2013	209.96	6660.50	2159.99	54.83	11.81	32.12
2014	205.69	7218.67	2301.32	53.55	12.17	32.38
2015	219.62	7733.09	2502.36	57.05	12.57	33.78
2016	217.98	7931.41	2554.33	57.35	12.66	34.14
2017	216.33	8129.73	2606.30	57.65	12.74	34.50
2018	214.68	8328.05	2658.27	57.95	12.82	34.86
2019	213.03	8526.37	2710.24	58.25	12.90	35.22
2020	211.39	8724.70	2762.20	58.57	12.99	35.60
2021	209.09	8830.14	2796.30	58.75	13.04	35.87
2022	206.79	8935.58	2830.40	58.93	13.08	36.14
2023	204.49	9041.02	2864.50	59.11	13.12	36.41
2024	202.19	9146.46	2898.60	59.29	13.16	36.68
2025	199.88	9251.88	2932.70	59.48	13.20	36.97
2026	197.72	9322.53	2957.24	59.60	13.23	37.19
2027	195.56	9393.18	2981.78	59.72	13.26	37.42
2028	193.40	9463.83	3006.32	59.84	13.29	37.65
2029	191.24	9534.48	3030.86	59.96	13.32	37.88
2030	189.08	9605.12	3055.40	60.09	13.34	38.11

Table III-3. Rate of EV Technology Deployment in the BASE Scenario until 2030

	2015	2020	2025	2030
Cars				
PHEV (diesel oil)	0	10	35	200
PHEV (petrol)	12	95	544	3106
BEV	211	422	2410	13763
Total of cars	223	527	2989	17069
LDV/HDV				
PHEV (diesel oil)	0	2	11	23
PHEV (petrol)	0	4	23	46
BEV	7	20	41	82
Total of LDV/HDV	7	26	75	150
Buses				
PHEV (diesel oil)	0	1	6	2
PHEV (petrol)	0	2	13	26
BEV	0	2	16	31
Total of buses	0	5	34	60
Total	230	559	3098	17279

Table III-4. BASE Scenario: The Fuel Consumption and Types of Fuel, 2000–2030

Types of fuel	2000	2005	2010	2015	2020	2025	2030
Diesel	11.47	22.18	27.45	28.00	27.03	23.28	18.59
Petrol	14.52	14.73	12.31	8.58	8.92	6.48	2.51
Liquid petroleum gas (LPG)	0.87	1.09	0.99	2.69	3.31	6.39	7.97
Liquefied natural gas (LNG)	0.00	0.00	0.00	0.00	0.19	0.56	1.33
Compressed natural gas (CNG)	0.07	0.07	0.00	0.00	0.00	0.00	0.00
Biodiesel	0.00	0.11	0.75	0.56	0.53	0.45	0.36
Ethanol	0.00	0.00	0.35	0.31	0.32	0.23	0.09
Bio-Methane	0.00	0.00	0.00	0.00	0.68	1.98	2.50
Electricity	0.00	0.00	0.00	0.00	0.01	0.03	0.13
Hydrogen (H2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity (Trams&Trolleys)	0.27	0.29	0.24	0.19	0.19	0.20	0.20
Total, PJ	27.20	38.47	42.09	40.51	41.18	39.61	33.69

Table III-5. Rate of EV Technology Deployment in the EV_STR Scenario until 2030

	2015	2020	2025	2030
Cars				
PHEV (diesel oil)	0	41	1094	20777
PHEV (petrol)	12	190	1524	13714
BEV	211	1688	18568	119392
Total of cars	223	1919	21185	153882
LDV/HDV				
PHEV (diesel oil)	0	12	144	864
PHEV (petrol)	0	6	66	528
BEV	7	68	743	3716
Total of LDV/HDV	7	86	953	5108
Buses				
PHEV (diesel oil)	0	2	10	60
PHEV (petrol)	0	4	16	128
BEV	0	8	136	1496
Total of buses	0	14	162	1684
Total	230	2019	22300	160674

Table III-6. EV_STR Scenario: The Fuel Consumption and Types of Fuel, 2000–2030

Types of fuel	2000	2005	2010	2015	2020	2025	2030
Diesel	11.47	22.18	27.45	28.00	27.02	23.09	17.18
Petrol	14.52	14.73	12.31	8.58	8.92	6.48	2.51
Liquid petroleum gas (LPG)	0.87	1.09	0.99	2.69	3.31	6.39	7.97
Liquefied natural gas (LNG)	0.00	0.00	0.00	0.00	0.19	0.56	1.33
Compressed natural gas (CNG)	0.07	0.07	0.00	0.00	0.00	0.00	0.00
Biodiesel	0.00	0.11	0.75	0.56	0.53	0.45	0.34
Ethanol	0.00	0.00	0.35	0.31	0.32	0.23	0.09
Bio-Methane	0.00	0.00	0.00	0.00	0.68	1.98	2.50
Electricity	0.00	0.00	0.00	0.00	0.02	0.22	1.53
Hydrogen (H2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Electricity (Trams&Trolleys)	0.27	0.29	0.24	0.19	0.19	0.20	0.20
Total, PJ	27.20	38.47	42.09	40.32	41.18	39.60	33.66