EIMANTAS NENIŠKIS

INTEGRATED ASSESSMENT OF LEAST-COST DECARBONIZATION PATHWAYS OF TRANSPORT AND ENERGY SECTORS

DOCTORAL DISSERTATION

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INTEGRATED ASSESSMENT OF LEAST-COST DECARBONIZATION PATHWAYS OF TRANSPORT AND ENERGY SECTORS

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Social Sciences, Economics (S 004)

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ABBREVIATIONS

AE – Alkaline electrolyzer
ASR – Absorbed Solar Radiation
BEV – Battery electric vehicle
bdc – Bounds on new capacity addition
CCGT – Combined cycle gas turbine
CCS – Carbon capture and storage
CHP – Combined Heat and Power
CNG – Compressed natural gas
CO2 – Carbon dioxide
COP – Conference of Parties
CSP – Concentrated solar power
DH – District heating
EU – European Union
EV – Electric vehicle
FCEV – Fuel cell electric vehicle
GHG – Greenhouse gas
GT – Gas turbine
HPP – Hydropower plant
ICE – Internal combustion engine
InterOff – Scenario with interconnections cut off after 2040
IPCC – Intergovernmental Panel on Climate Change
LCOE – Levelized cost of electricity
MSW – Municipal solid waste
NDC – Nationally determined contribution
NECP – National energy and climate plan
OLR – Outgoing Longwave Radiation
PEM – Proton exchange membrane
PHEV – Plug-in hybrid electric vehicle
PP – Power Plant
PSHPP – Pumped storage hydropower plant
PV – Photovoltaic
P2H – Power-to-heat
RedFlexi – Scenario with reduced interconnection flexibility
RES – Renewable energy source
RHPP – Reservoir hydropower plant
RoR HPP – Run-off-river hydropower plant
SOE – Solid-oxide electrolyzers
SSH – Saturdays, Sundays and Holidays
TCO – Total cost of ownership
TES – Thermal energy storage
Unc – Uncontrolled EV charging
USSR – Union of Soviet Socialist Republics
V1G – Unidirectional vehicle-to-grid system

V2G – Bidirectional vehicle-to-grid system
VehDistr – Scenario with changing vehicle age distribution
VRES – Variable renewable energy sources
WACC – Weighted average cost of capital
WW2 – World war 2
ZeroCO_2 – Scenario with CO_2 emissions constrained to reach zero level by 2050

NOMENCLATURE

a – intermediate value for calculating TTB
act – activity level
b – intermediate value for calculating TTB
c – intermediate value for calculating TTB
d – intermediate value for calculating TTB
dr – discount rate
e – selected vehicle age group
f – fuel type (diesel, petrol, hybrid, BEV, FCEV, CNG,…)
fxC – fixed costs
h – technology
i – modelled day type
invC – investment costs
j – modelled hour
k – date
l – car class (A-B; C-D; E-F; J-M)
m – mass
n – number of elements
o – travel mode (short or long-distance travel)
objF – objective function
p – price
q – first year
r – discount rate
s – selected car class
t – modelling year / time period
tm – technology's operating mode
u – new/used vehicle
v – speed
varC – variable costs
y – vehicle age group
z – modelled season
α – share of passenger-kilometres by class l
β – share of passenger-kilometres by age group y
δ – depreciation rate
ε – vehicle age
θ – fuel share in fuel blend
η – efficiency of the technology
τ – time slice
μ – time period
A – a set of dates
C – cost
DF – discount factor
E – energy
F_{reg} – car registration fee

FCR – fuel consumption rate
I – investment costs
LT – lifetime
OR – occupancy rate
P – installed capacity
PR – power relation coefficient
P – installed capacity. It originates from the common denoting of a power plant's installed capacity in MW – units of active power (P).
T – target
TCR – time consumption rate
TFC – total fixed costs
TIC – total investment costs
TTB – travel time budget
TV – traffic volume
TVC – Total variable costs
UDFC – user defined fixed costs
UDVC – user defined variable costs
X – output
Δt – length of time period

INTRODUCTION

Relevance of research topic

The atmosphere's GHG concentrations have rapidly risen since the industrial revolution, causing increased average global temperature. It is already 0.99 °C higher compared to the pre-industrial period (Masson-Delmotte et al., 2021), and the adverse effects of current climate change can be seen in changes in the availability of water as a resource, shifting habitats of certain animal and plant species, reduced crop yields, increased climate extremes and heat-related deaths (Field et al., 2014). Further global temperature increases would increase the severity and spread of the adverse effects.

Various international treaties have been signed to address climate change, of which probably the most important is the Paris Agreement, as, for the first time, all nations joined in efforts to combat climate change. In the Paris Agreement, a global target of stabilizing the average global temperature increase to below 2°C compared to the pre-industrial period and striving to keep it below 1.5°C was set. According to the Agreement, each country has to submit nationally determined contributions – action plans on emission reduction and adaptation to the impacts of climate change. The contributions must be updated every five years, raising its ambitions each time. (Kuyper, Schroeder, & Linnér, 2018) In a follow-up to Paris Agreement, 137 countries have pledged to decarbonize their economies in the second half of the 21st century or earlier. However, the decarbonization of the economies needs radical changes in all economic sectors that require massive investments. Therefore, nationally determined contributions should be based on detailed analyses of the future development of various sectors and the cost-effectiveness of different emission abatement measures to choose the best course of action for successfully reaching carbon neutrality goals.91% of global CO_2 emissions come from fuel combustion. In comparison, the remaining 9% are fugitive emissions, mainly related to fossil fuel extraction, refinement and transportation (IEA, 2021a). Most of the fuel combustion CO_2 emissions arise from electricity and heat generation (44%), followed by the transport sector (22%), while the rest is from industry (20%), buildings (9%) and other (2%) sectors (IEA, 2021a). Furthermore, from 2010, emissions in the electricity and heat generation and transport sectors saw the most significant annual growth, 1.3% and 1.8%, respectively. CO_2 emissions grew by 0.3% per year in the industry, by 0.35% in the buildings sector and decreased by 0.6% in other sectors. Considering the highest emission levels and emission increase rates, the primary focus should be placed on the electricity and heat generation and the transport sector when devising decarbonization action plans.

Electrification of different sectors and ensuring that electricity is produced from RES is often considered a go-to decarbonization pathway. However, the intermittency of electricity generation in the wind and solar power plants limits the use of these sources because electricity supply and demand have to be equal at each moment in time. If electricity is produced from fossil fuels, then the success of electrification as an emission abatement measure might be hindered. Therefore, various power flexibility measures are needed to enable high penetration of VRES in electricity generation. Typically, most power flexibility comes from thermal and hydropower plants, which can ramp up or down their output depending on the demand. However, in a RES-based power system, flexibility on the supply side is rather limited, so flexibility has to come from the demand side, leading to a shift in paradigm from the generation following consumption patterns to consumption following generation patterns. The flexibility on the demand side can come from various sectoral interrelations. It was estimated that vehicle-to-grid services, smart hydrogen production through electrolysis and power-to-heat technologies are the essential sectoral interrelations that increase electricity demand flexibility.

This doctoral thesis presents a developed model for assessing least-cost decarbonization pathways of power, district heating and transport sectors, considering the potential of sectoral interrelations in increasing power system flexibility.

Scientific problem

Transport electrification is likely to play a major role in transport decarbonization. Even though electric and hydrogen vehicles have no tailpipe CO_2 emissions, the electricity needed to charge electric vehicles or produce hydrogen is not necessarily carbon-free. On the contrary, most countries still heavily rely on electricity generation from fossil fuels. Therefore, the effectiveness of transport electrification as an emission abatement measure depends on the fuel mix in the energy sector. If fossil-fuel power plants are not replaced by carbon-free options, the overall emission might even increase (Siksnelyte-Butkiene & Streimikiene, 2022).

Furthermore, transport electrification would substantially increase the electricity demand. For instance, it was estimated that electricity consumption in road transport could reach 13–26% of total electricity demand by 2050 in the U.S. (Fox-Penner, Gorman, & Hatch, 2018) and 15% in the EU (Kasten, Bracker, Haller, & Purwanto, 2016). Also, electric vehicle charging primarily occurs in the evening, increasing the electricity demand evening peak, which is particularly problematic for power systems with high penetration of solar power plants (Muratori & Mai, 2021). Such systems might have an excess supply of electricity generated in solar power plants at midday, followed by a rapid decline in generation in the evening when electricity demand peaks (Krietemeyer, Dedrick, Sabaghian, & Rakha, 2021). Therefore, power plants that can ramp up their output quickly have to compensate for the loss of electricity generation in solar power plants. Traditionally gas-fired power plants were used for this role. However, reliance on fossil fuel power plants can negate some of the environmental benefits of solar power plants. Alternatively, energy storage technologies could be used to store excess energy during mid-day and release it when needed, but energy storage comes at a high cost. On the other hand, electric vehicle charging with proper infrastructure and smart charging management can be flexible and contribute to balancing the power system (Muratori & Mai, 2021), reducing the need for balancing plants or energy storage. Such cross-sectoral interrelations significantly impact how the power system will operate in the future. Therefore, they should be considered when devising decarbonization action plans.

Energy planning models that work based on minimising total discounted costs are commonly used to determine how the energy sector should develop to reach various strategic targets, including emission reduction in the least-cost way. However, the cross-sectoral interrelations between the power and transport sectors are often neglected, even though they might have a substantial impact. Several models created within the Balmorel and PyPSA-Eur-Sec-30 modelling frameworks were used to investigate the impacts of transport and energy sectors' coupling on the least-cost development of the energy system (T. Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018; Gea-Bermúdez et al., 2021; Gunkel, Bergaentzlé, Græsted Jensen, & Scheller, 2020; Juul & Meibom, 2012; Kiviluoma & Meibom, 2010, 2011). Nonetheless, in all of these models, except (Juul & Meibom, 2012), the transport sector development was assumed instead of determined by the model. However, optimising transport investments could provide valuable insights as it determines the least-cost transport development pathway and enables the model to choose between flexibility from power and transport sector coupling and other flexibility means. Furthermore, these models either perform optimization for a single year (T. Brown et al., 2018; Juul & Meibom, 2012; Kiviluoma & Meibom, 2010, 2011) or use a myopic optimization foresight (Gea-Bermúdez et al., 2021; Gunkel et al., 2020). If optimization is performed only for a year, then the model does not provide the optimal decarbonization pathway. Instead, it calculates just what could a cost-optimal system be under certain emission constraints. Optimization with myopic foresight can provide the decarbonization pathway. However, F. Fuso Nerini (Fuso Nerini, Keppo, & Strachan, 2017) showed that optimization with myopic foresight might result in delayed investments and notably higher costs for achieving decarbonization targets than optimization with perfect foresight. Some models cover energy and transport sectors and optimise with perfect foresight (Balyk et al., 2019; C. Butler et al., 2020; Daly & Fais, 2014; Dodds, 2021; European Commission. Joint Research Centre. Institute for Energy and Transport., 2013; Kannan & Turton, 2014; McCollum, Yang, Yeh, & Ogden, 2012), but as optimization with perfect foresight is more computationally demanding, these models typically have a lower temporal resolution (12–144 time slices per modelled year vs 384–8760 in abovementioned models with myopic foresight or optimization of a single year), which limits the representation of cross-sectoral interrelations. Out of these models with perfect foresight, only the Swiss TIMES model (Kannan & Turton, 2014) includes smart EV charging, and none includes V2G services.

None of the models found in the scientific literature that covers power, district heating, and transport sectors includes all of these aspects: works by minimizing total discounted costs, optimizes transport investments, has perfect optimization foresight and has a relatively high temporal resolution needed to represent cross-sectoral interrelations adequately. Therefore, a scientific problem was formulated based on performed literature analysis: **How to economically co-optimize power, district heating and transport sectors' decarbonization pathways considering cross-sectoral interrelations?**

Research object

Pathways of power, district heating and transport decarbonization.

Research aim

To develop an integrated power, district heating and transport sectors model to assess the least-cost decarbonization pathways, which ensure near-zero carbon emissions.

Research objectives

1. To identify the interrelations between power, district heating and transport sectors in the context of reaching carbon neutral economy;
2. To perform an analysis of methods and models applied for the assessment of power, district heating and transport sectors' development, interrelations and sectoral measures for climate change mitigation;
3. To prepare methodology and integrated model for the analysis of least-cost pathways for decarbonization of the power, heat and transport sectors;
4. To perform an analysis of least-cost decarbonization pathways of power, district heating and transport sectors for the Lithuanian case by applying the developed model;
5. To perform comparative scenario analysis, considering different technological options and constraints, to test the robustness of the modelling results.

Research methods

A systemic scientific literature analysis was used to identify the decarbonization options of power, district heating and transport sectors as well as sectoral interrelations. Also, a comparative analysis was performed on methods and models applied by other researchers for the assessment of transport and energy sectors' development, interrelations and sectoral measures for climate change mitigation. Based on this analysis, it was identified that the most suitable approach for the integrated analysis of least-cost pathways for decarbonization of the power, heat and transport sector is an energy planning model that relies on optimization of the development and operation of modelled sectors by minimizing the total discounted costs. The MESSAGE modelling framework was chosen to develop an integrated least-cost decarbonization model for these sectors. The model was created for the Lithuanian case, though the developed modelling approach could be applied to other countries with some modifications. Two databases, one for the power and district heating sectors and another for the transport sector, filled with all necessary data for the model, were created within Microsoft excel in easing the model use. Databases have inbuilt scripts that convert data tables to text format readable by the modelling software. A comparative scenario analysis of fifteen scenarios, considering different technological options and constraints, was performed to test the robustness of the modelling results.

Scientific novelty

To fill a research gap in the scientific literature, integrated transport and energy sectors model for assessing the least-cost pathways, which ensure near-zero carbon emissions, was developed. The model covers power, district heating and transport sectors. In the model, the six biggest district heating systems and one additional system, representing all other district heating systems in the country, were modelled. The transport sector includes passenger and freight transport. Personal and public transport constitutes passenger transport. Road and rail transport options were considered for each transport type, except for personal transport, as it has only road vehicles. The developed model optimizes operation and investments in all modelled sectors using perfect foresight optimization. The modelling time horizon covers four five-year periods from 2020 to 2040 and two ten-year periods from 2040 to 2060. Each modelled period is represented by 12 seasons, corresponding to months; each season by two-day types – workdays and SSH (Saturdays, Sundays and Holidays); and each day type by 24-time slices. In total, each modelled period is split into 576 time slices. A relatively high temporal resolution was selected to represent variable renewable energy sources and cross-sectoral interrelations adequately. Such integrated transport and energy sectors model was created for the Lithuanian case for the first time. Furthermore, the created model has two unique features: probabilistic wind speed representation for wind power plants and vehicle age distributions.

The problem with representing wind power generation in aggregated time models is almost a total loss of variability when averaging. For this reason, a probabilistic approach was developed to properly represent fluctuations in wind power generation in an energy planning model with an aggregated temporal resolution. The main idea is to represent the possible wind power output variations using wind probability curves. For this reason, wind speed probability curves were set for each modelled day type. Wind speed distribution data of each modelled season and day type was approximated with 24 data points. Twenty-four data points were used so that each data point could be assigned to one hourly time slice to represent seasonal wind speed probability distribution in a single typical day. Then, these approximated wind distributions were shuffled using a developed algorithm to mimic wind variability. Finally, generated wind curves were used with the power curves of wind power plants to create generation curves for wind power plants.

In energy planning models, modelled technologies retire at a set lifetime. It is a reasonable assumption for power plants and heating plants, as they are rarely shut down before their expected lifetime unless a political decision is made. However, vehicles built in a particular year are gradually scrapped due to accidents and wear and tear. Tattini and Gargiulo (2018) addressed this problem by utilizing a new feature of TIMES and applying a survival probability curve. Unfortunately, this approach does not support non-declining vehicle age distributions because it would mean that the survival probability would have to exceed 100% for specific ages. For instance, Cyprus, Czech Republic, Estonia, Latvia, Lithuania, Malta, Poland, Romania, and Slovakia have non-declining vehicle age distributions (Held, Rosat, Georges, Pengg, & Boulouchos, 2021), meaning that used vehicles are imported. If used vehicles are imported, it gives a skewed bell shape for a vehicle age distribution, peaking at some vehicle ages greater than 0. Failing to account for such vehicle age distributions might yield too optimistic changes in the transport sector and overestimated emission reductions. For this reason, a unique approach was developed to represent non-declining vehicle age distributions and their changes. In this approach, vehicles are differentiated by build year, and constraints are placed to set the share of travel demand that vehicles made in specific years have to satisfy.

Furthermore, to account for some of the transport sector's behavioural aspects, travel time budget and inconvenience costs for electric vehicles were modelled. The travel time budget sets how much time can be spent on travelling, so the model considers the costs of different travel modes and their speeds, and it prevents the model from satisfying all travel demands with cheap but slow public transport modes. Inconvenience costs for electric vehicles were modelled to consider range anxiety and inconveniences that come from shorter driving ranges, longer fuelling times, and less accessible fuelling stations compared to ICE vehicles.

The model was developed for Lithuania's case because of already acquired data in Lithuanian Energy Institute. However, the model can be adapted for other countries after some modifications.

Research limitations

The main research limitations are related to data availability, selected modelling method and software limitations. The model needs a lot of techno-economical data to correctly represent modelled technologies (power plants, heating plants, electricity imports and exports, vehicles, and fuel supply). However, such data for specific power plants and heating plants, except for installed capacities and, in some cases, efficiencies, is not publicly available. Therefore, data from energy catalogues were used instead. Furthermore, acquired data on road travel patterns covers only April to October 2020, in which seasonal patterns were substantially affected by the coronavirus pandemic with lockdown measures. Attempts were made to acquire travel pattern data for the year 2021. Unfortunately, they were unsuccessful. Also, Lithuania's freight delivery pattern data, transport operation, and maintenance costs were unavailable, so data from the scientific literature was used instead. Though rail transport was modelled, its representation is limited to the current state due to a lack of data. Unfortunately, it is unclear how much rail electrification in Lithuania costs, how much electric trains cost, and how passenger rail travel and freight volumes could change in the future. Another limitation related to data availability is the lack of travel surveys in Lithuania, which could enable the inclusion of travellers' heterogeneity in the model. Finally, since the model was designed to analyse the decarbonization pathways, it is essential to emphasise the high uncertainty associated with future technology, fuel, emission, electricity import, and other costs.

Energy planning models have an embedded assumption of perfect markets and financial rationality, meaning that the cheapest options will always be chosen if not constrained. For the power and district heating sectors, these assumptions are reasonable. However, in the transport sector, especially in passenger transport, non-monetary factors like travel time, convenience, looks, and others play a significant role. For this reason, travel time budget and inconvenience penalties for EVs were implemented. Unfortunately, most of the behavioural aspects were not considered.

The MESSAGE modelling framework was developed in 32-bit architecture, meaning that the model size is limited to around 2 gigabytes (around 1 million equations and 1.4 million variables). Therefore, various simplifications had to be applied to fit the modelling limits. First, an aggregated temporal resolution was used, which hinders the representation of variability in RES. A probabilistic approach was developed for modelling wind power plants to mitigate some drawbacks of aggregated temporal resolution. However, the model does not consider possible prolonged periods with low wind speeds and low irradiance. As a result, the required energy storage size might be significantly underestimated. Second, an aggregated spatial resolution was used. The Lithuanian power grid was represented by a few technologies and energy forms (nodes), neglecting any grid limitations. Therefore, the model can not identify in which part of the country the power plants should be built. However, the six biggest district heating systems were represented, covering 71% of total district heating demand. The remaining district heating systems were grouped and represented as one. In the transport sector model, journeys were differentiated only into short and long-distance travel during freight delivery nationally and internationally. A more detailed representation of travel by distance could provide a better picture of different vehicle type roles in decarbonized future travel. Third, fuel supply was considered unlimited, i.e. each modelled year, an unlimited amount of fuel can be supplied at a fixed price. It is particularly problematic in the case of biomass and liquid biofuels, as increased production might require increased forest cutting and more land for energy crops. Consequently, the modelling results might yield unsustainable biomass and liquid biofuel production and consumption. Also, the energy systems of neighbouring countries were not modelled. Instead, interconnections were modelled as technologies that can import and export electricity at a set price and are limited only by throughput capacity. As neither electricity generation capabilities nor electricity demands of neighbouring countries are considered, the possibility of importing and exporting electricity might be overestimated.

Possible practical applications of the developed model and modelling results

The developed model calculates the least-cost long-term development pathways for the energy and transport sectors under certain assumptions to achieve strategic targets like decarbonization or ensuring energy security. Therefore, it is well-suited to provide valuable insights for developing energy strategies. In the EU, Member States are required to every ten years prepare national energy and climate plans (NECP) that set out national objectives for energy security, internal energy market, energy efficiency, decarbonization of the economy and research, innovation and competitiveness for the next ten year period (The European Parliament & Council of the European Union, 2018). Also, these plans have to be updated by 2024 and every ten years thereafter. Furthermore, each Member State every ten years has to prepare long-term strategies covering at least 30 years, in which action plants are set to achieve the overall climate targets. However, the developed modelling approach could prove beneficial not only for the EU countries but many other countries as well since, under the Paris Agreement, each country has to submit nationally determined contributions and update them every five years. Even though the model was developed for the Lithuanian case, the same modelling approach can be used to create a model for any country.

At the time of thesis preparation, a LIFE IP EnerLIT project has started and will last till the end of 2030 to support the implementation of Lithuania's NECP (Lietuvos Respublikos aplinkos ministerija, 2022). The project includes activity A1.2 Improving the modelling process. The developed integrated model of power, district heating and transport sectors for Lithuania could be potentially used in this activity, contributing to already used models and models under development.

Dissertation structure

The doctoral thesis has 261 pages without the Annex, 113 figures and 51 tables, of which 25 are given in Annex A. In total, 317 literature sources were referenced. The thesis consists of three main parts: 1. Literature review; 2. Cross-sectoral power, district heating and transport MESSAGE model; 3. Results. In the first part, climate change, CO_2 emissions and international efforts to reduce GHG emissions are overviewed, and decarbonization options, effects and sectoral interrelations are investigated. Furthermore, studies on the least-cost decarbonization of transport and energy sectors are compared. The second part of the thesis describes the selected modelling framework and the developed modelling approach. The last part presents modelled scenarios and modelling results.

1. LITERATURE REVIEW

1.1. Climate change, CO_2 emissions and international efforts to reduce GHG emissions

1.1.1. The effects of climate change

Earth's temperature depends on the balance of Absorbed Solar Radiation (ASR) and emitted energy from the earth's surface to space, called Outgoing Longwave Radiation (OLR). Any disturbance in the balance is a source of climate change. Greenhouse gases tip this balance by absorbing infrared radiation emitted by the earth's surface, i.e. reducing OLR (Dewitte & Clerbaux, 2018). A net positive energy balance causes an increase in surface temperatures. Since the preindustrial period, the concentrations of greenhouse gases (GHG) in the troposphere (the lowest part of the atmosphere that contains most of the atmospheric mass) have increased significantly, the concentration of carbon dioxide (CO_2) rose by 42.7%, methane (CH_4) by 154.0% and nitrous oxide by 21.5% (Blasing, 2016). As a result, global temperature increased by 0.99 °C compared to the pre-industrial period (Masson-Delmotte et al., 2021), and the impacts of climate change are already visible (Field et al., 2014):

- Changes in precipitation and snow/ice melting affect the availability of water as a resource as well as its quality;
- Various land and water species have shifted their habitats, migration patterns, seasonal activities, the interaction of species and abundances;
- Adverse effects on crop yields;
- Increase in heat-related deaths and decrease in cold-related deaths in certain regions;
- Climate-related extremes, like heat waves, droughts, heavy precipitations, floods and cyclones.

According to IPCC (Field et al., 2014), even a two-degree increase in global temperatures would pose severe and widespread risks:

- In North America, high risks of increased damages from wildfires and urban floods, as well as increased heat-related human mortality;
- In South America, very high risks of reduced water availability, food production and food quality, increased flooding and landslides;
- In Europe, medium risks of increased damages from floods and high risks of water restrictions and damage increase from extreme heat events and wildfires;
- In Africa, high risks of compounded stress on water resources and very high risks of reduced crop productivity, food security and livelihood, also a very high risk of vector- and water-borne diseases;
- In Asia, medium risks of drought-related water and food shortages, high risks of increased flood damages and very high risks of heat-related human mortality;
- In Australasia, medium risks of increased flood damage and high risks of significant changes in the composition and structure of coral reef systems;

- In oceans, medium risks of reduced fisheries catch potential at low altitudes, high risks of coastal inundation and habitat loss, and very high risks of increased mass coral bleaching and mortality.

1.1.2. Global CO_2 emission trends

The observed increase in GHG concentrations since 1750 and the resulting warming of the atmosphere, oceans and land, without any doubt, were influenced by human activities (Masson - Delmotte et al., 2021). Global annual anthropogenic GHG emissions amount to 48.9 Gt CO_{2eqv}, of which the majority (36.4 Gt CO_{2eqv}) is CO_2 emissions (World Resources Institute, 2021). The emissions have risen since the industrial revolution, with extremely rapid growth since the 1950s. More than half of CO_2 emissions since the industrial revolution have been emitted over the last three decades and almost a quarter since 2010 (See Figure 1) (Global Carbon Project, 2021).

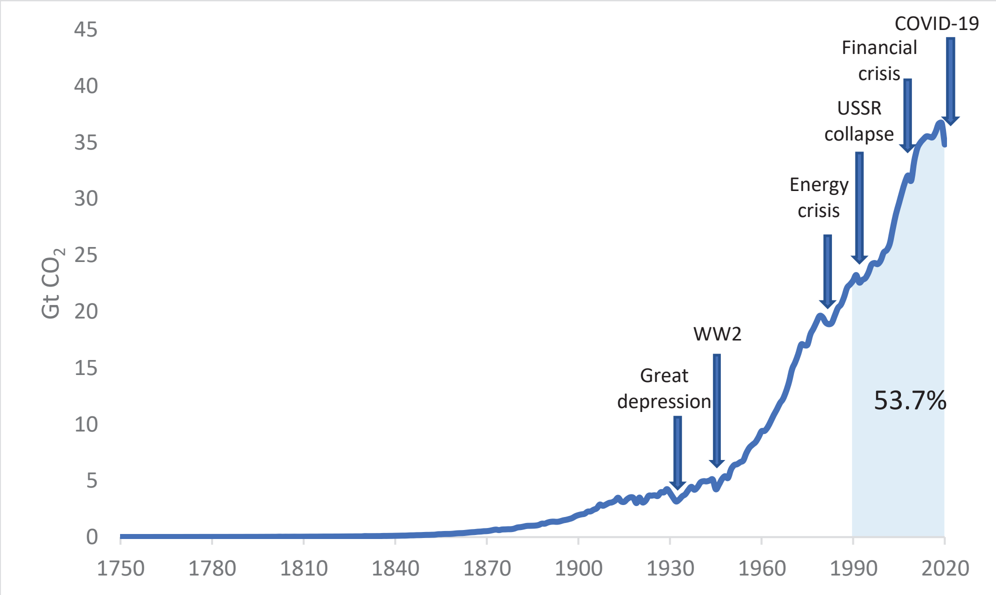

Figure 1. Trends in global CO_2 emissions

Source: created by the author based on (Global Carbon Project, 2021) data

Till 1960 most of the emission increase could be attributed to the U.S. and Europe. These two regions were responsible for 84% of global cumulative CO_2 emissions by then. However, since 1960 emissions in Asia began to grow rapidly, especially in China after 1970, with an extremely high rate since the 2000s. In 2006, China became the most CO_2-emitting country and continues to be to this day. Currently, the most emitting countries are China, the U.S., India, Russia, Japan, Iran, Germany, Saudi Arabia, South Korea and Indonesia. Considering EU-27 as a country, it would be a third in CO_2 emissions, just behind China and the U.S. (Global Carbon Project, 2021)

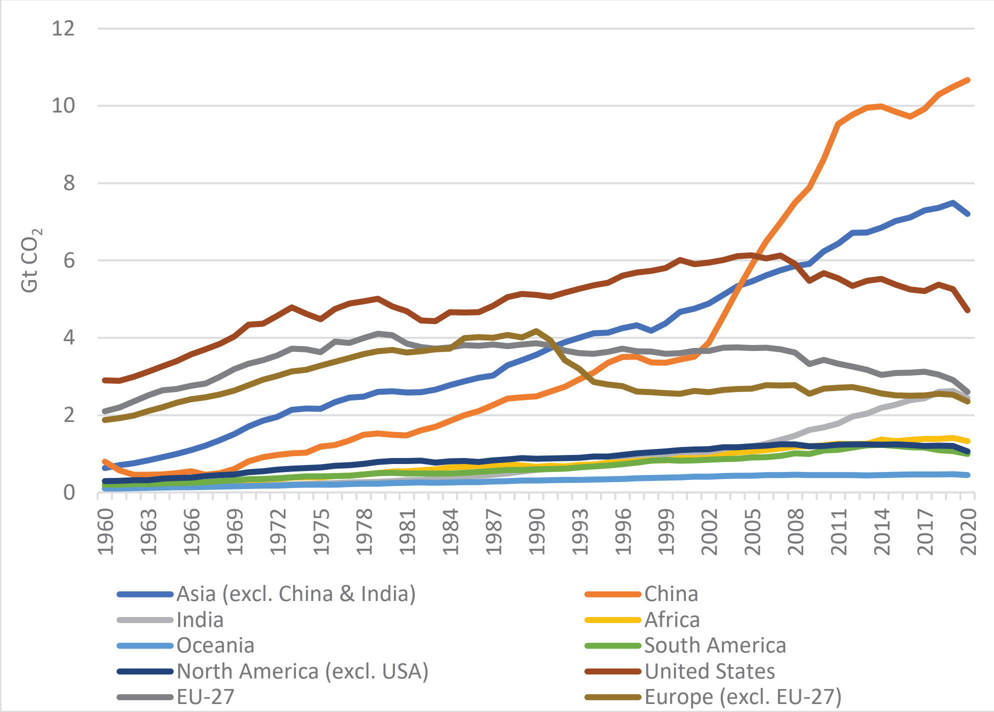

Figure 2. CO_2 emission trends by region

Source: created by the author based on (Global Carbon Project, 2021) data

In the past, some events had emission-reducing effects, for example, the Great Depression, World War 2 (WW2), the energy crisis, the collapse of the USSR, the 2008 financial crisis (Aktar, Alam, & Al-Amin, 2021). The most recent event that substantially impacted emissions is the coronavirus pandemic. In 2020, CO_2 emissions were 2.6 Gt lower than in 2019. A reduction of such magnitude has never been observed (Le Quéré et al., 2021). In the absence of a cure, the governments initiated lockdowns, with compulsory closure of various services, institutions and industries. Mobility was substantially curbed. Sikarwar et al. (2021) estimated that reduced travel contributed 58%, decreased power generation 29% and a partial shutdown of the industry 10% to COVID-related emission reduction. However, according to R. Li (2021), it is likely that post-pandemic emissions will rebound because current economic recovery plans prioritize economic development and neglect energy efficiency.

On the surface, it seems the previously mentioned events significantly impacted emission reductions, saving multiple giga-tons, but these are just minor dents when looking at overall emission trends. Even global lockdowns and decreased industrial activities due to COVID resulted in only a 5% reduction in annual CO_2 emissions, which greatly illustrates the magnitude of necessary changes to reach climate neutrality.

If we are to look at emissions from fuel combustion by sector (see Figure 3), it can be seen that most CO_2 emissions come from electricity and heat generation (44%), followed by the transport sector (22%) (IEA, 2021a). Emissions from just these two sectors amount to two-thirds, and the rest is from industry (20%), buildings (9%) and other (2%) sectors. Emissions from fuel combustion comprise 91% of total emissions. In comparison, the remaining 9% are fugitive emissions mainly caused by the flaring of natural gas at oil extraction facilities and refineries, gas leakage in pipelines and methane release in coal extraction and transportation.

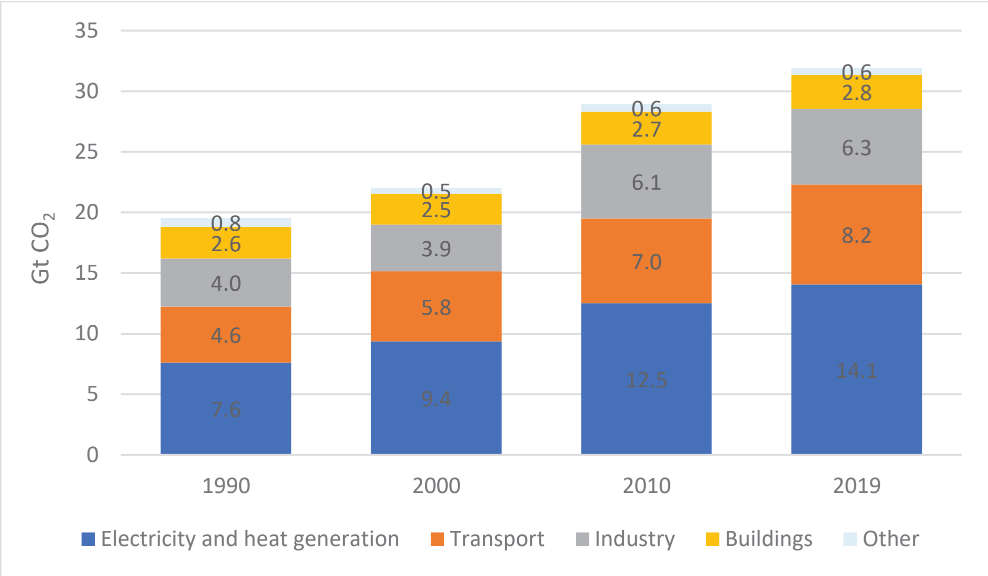

Figure 3. Global CO_2 emissions from fuel combustion by sector, 1990–2019

Source: created by the author based on (IEA, 2021a) data

From 1990 to 2019, emissions grew most rapidly in electricity and heat generation as well as transport sectors, by 85% and 78%, respectively. Emissions in the industry grew by 58%, but mainly during 2000–2010. Since 2010, on average, emissions in the electricity and heat generation sector annually increased by 1.3% and in the transport sector by 1.8%, while in the industry, only by 0.3%. Emissions in the building sector saw a 0.35% increase; in other sectors, they decreased by 0.6%.

It is estimated that the remaining carbon budget to limit global warming, with a 50% probability, to 1.5°C is 420 Gt CO_2, and 2°C is 1270 Gt CO_2, equivalent to 11 and 32 years at 2021 emission levels (Friedlingstein et al., 2021). Therefore, radical changes are needed in all economic sectors to reach carbon neutrality, but a particular focus should be placed on transport and the supply of electricity and heat, as these sectors have the most significant emission reduction potential. As EU Commissioner McGuinness said at the press conference on the EU Taxonomy Complementary Climate Delegated Act: "We do need to use all the tools at our disposal to achieve climate neutrality. Because we have less than 30 years to get there, so we need to act now." (European Commission, 2022)

1.1.3. International efforts to reduce GHG emissions

Acknowledging the risks of climate change, an international effort was made to address growing global emissions by adopting United Nations Framework Convention on Climate Change (UNFCCC) in 1992, which established a process toward its ultimate objective – limiting GHG concentrations in the atmosphere to a level, which prevents harmful human interference with the climate system within a sufficient time frame for ecosystems to naturally adapt to the climate change (Kuyper et al., 2018; United Nations, 1992). A conference of Parties (COP) – an authoritative body comprised of all UNFCCC parties, agreed that industrialised countries should be the ones to take the first emission reduction steps while developing countries should follow suit later. This Agreement culminated in the 1997 Kyoto Protocol – an international treaty with legally binding targets that require reducing emissions in Annex I (industrialised/developed) countries on average by 5.2% (around 16.8 Gt CO_{2eqv} reduction) compared to the 1990 level that had to be met by 2012 (Maamoun, 2019). However, before ratifying, the US Senate requested the inclusion of maximum flexibility in emission reduction options and that non-Annex I or, in other words, developing countries would contribute as well. Since the latter condition was not met, the US, the most prominent GHG emitter then, did not ratify the Agreement. In 2011, Canada also withdrew from the Agreement. Despite the Agreement, global GHG emissions continued to grow. On the other hand, from 2007 to 2012, the number of countries with climate mitigation policies increased, and an emission trading system was established (Kuyper et al., 2018). A. Kuriyama and N.Abe (2018) performed an ex-post assessment to determine the emission mitigation effect of the Kyoto Protocol. They estimated that the reduction of 0.95 Gt CO_{2eqv} could be attributed to the Kyoto Protocol. Another study addressed the effectiveness of the Agreement by implementing a generalized synthetic control method (GSCM) to compare the emissions of the developed countries that ratified the Agreement with a scenario of "No-Kyoto" (Maamoun, 2019). The results showed approximately a 7% emission reduction.

In 2012, a Doha amendment was adopted to establish a second commitment period of the Kyoto Protocol spanning from 2013 to 2020. At that time, parties agreed to reduce GHG emissions by at least 18% compared to the 1990 level (UNFCCC, n.d.). However, it had to be ratified by 144 parties (excluding the EU) to enter into force, yet it was done only in 2020. Acceptance of amendment at the end of the commitment period resulted in the ambiguity of the Doha amendment and Kyoto Protocol post-2012 validity. (Tran, 2021)

The negotiations on climate mitigation measures beyond the Kyoto Protocol started back in 2007, but parties managed to agree only in Paris 2015 (Hirst, 2020). While the Kyoto Protocol mainly focused on emission reduction in developed countries, the Paris Agreement set a global target of stabilizing the average global temperature increase to below 2°C compared to the pre-industrial period, striving to keep it below 1.5°C. In 2007, China became the highest gross GHG emitter, shifting the focus from historical emissions to growing emissions in rapidly developing countries like China, India, Brazil, South Africa, and Mexico. Significant contributions by these countries became necessary to achieve climate mitigation targets. In the Paris Agreement, for the first time, all nations joined in efforts to combat climate change. According to the Agreement, each country has to prepare, communicate and fulfil nationally determined contributions (NDCs). Unfortunately, there is no clear link between NDCs and the ultimate goal of the Agreement. Thus, the sum of all submitted contributions will likely be insufficient to achieve global targets. The success of the Agreement relies on increasing emission reductions along the way. For this reason, under the Agreement, each country has to submit updated NDCs every five years, each time raising its ambitions. (Kuyper et al., 2018) However, it is essential to mention that the Paris Agreement does not have NDC enforcement mechanisms, i.e. non-complying countries will not face any repercussions. In a follow-up to Paris Agreement, 137 countries have pledged to decarbonize their economies in the second half of the 21st century or earlier. The first two countries that achieved carbon neutrality were Bhutan and Suriname. Uruguay plans to do so by 2030, Finland by 2035, Austria and Iceland by 2040, Germany and Sweden by 2045, but most target to achieve it by 2050. China, Kazakhstan and Ukraine plan to do it a decade later. These targets were passed into law in six countries (Denmark, France, Hungary, New Zealand, Sweden and the U.K.). EU, Canada, Chile, South Korea, Fiji, and Spain have proposed legislation in the works, and 24 countries, including U.S. and China, made these targets an official policy. However, at the moment, more than 72% of pledges are still on the discussion level. (Wallach, 2021)

1.2. Power, heat and transport decarbonization options, effects and sectoral interrelations

As mentioned in the Section, **Global CO2 emission trends**, electricity and heat generation, as well as transport, are responsible for two-thirds of global CO_2 emissions, and they have the fastest-growing emissions levels of all sectors. Transport electrification will likely play a substantial part in transport decarbonization, if not the main. However, the effectiveness of electrification as an emission abatement measure relies on the electricity generation mix. In the case of power generation from fossil fuels, overall emissions might even increase. Furthermore, transport electrification would not only increase the electricity demand but also would affect the electricity consumption curve, potentially requiring appropriate changes in the power system. On the other hand, it is possible to adjust EV charging patterns according to generation fluctuations in wind and solar power plants. Such energy balancing could allow higher penetration of intermittent renewables and reduce electricity market prices (Neniškis, 2019). For these reasons, it is necessary to analyze how these two sectors could develop in the future, considering sectoral interrelations, to determine the most cost-effective decarbonization pathways.

In this section, scientific literature was reviewed to identify potential options to decarbonize the electricity and district heating supply and transport sector. Moreover, the potential impacts of these options were investigated, and sectoral interrelations between the power and transport sectors were analysed.

1.2.1. Power and heat decarbonization options

The electricity supply sector is regarded as the first sector which can be decarbonized (Papadis & Tsatsaronis, 2020). On the surface, the technologies for green transition are already there. Multiple countries have achieved low-carbon power generation. According to Our World in Data (Ritchie & Roser, 2020), 20 countries have carbon-neutral electricity generation share exceeding 90% and 33 exceeding 80%. For example, Paraguay produces 98% of all electricity in hydropower plants, Norway 92% in hydropower and 7% in wind power plants, France 69% in nuclear, 11% hydro, 7% wind and 3% in solar power plants, Sweden 44% in hydro, 31% in nuclear and 16% in wind power plants. However, most countries still rely on fossil fuels to produce electricity and heat. Each country has different demands, different resource availability and financial capabilities. Therefore, there is no universal way how to decarbonize energy generation. This section covers different decarbonization options for the two most GHG emitting sectors – power and heat generation and transport, emphasizing the pros and cons of each technology.

Hydropower. 28 of these 33 countries (that exceed 80% carbon-neutral electricity generation) have a substantial hydropower share in the electricity production mix. It is mature and cheap to run renewable electricity-generating technology (IEA-ETSAP & IRENA, 2015). The output depends on the river flow, which has relatively low variability. Noticeable changes are on the seasonal level. This technology is suitable for base-load generation. Hydropower plants come in two configurations: with a reservoir and without (a run-of-river plant). Larger hydropower plants typically have reservoirs, which provide the ability to postpone generation, giving load-following and balancing of variable renewable generation capabilities (Dimanchev, Hodge, & Parsons, 2021; Harby et al., 2020). Its main problems are substantial up-front costs, long payback periods, impacts on ecosystems and water availability, displacement of people, and most importantly, such power plants' placement and output depend on river water as resource availability (IEA-ETSAP & IRENA, 2015). Currently, hydropower share in the global electricity generation mix is 16% (4.3 PWh/year) (International Energy Agency, 2021). It is estimated that global theoretical hydropower potential, i.e. if all available river water is used, is 36-128 PWh/year; however, 8–26PWh/year is technically exploitable, and 8–21 PWh/year is economically feasible (Hoes, Meijer, van der Ent, & van de Giesen, 2017). By far, from all continents, Asia has the highest hydropower theoretical potential, with 48% of global potential, followed by South America with 19%, Africa with 15% and North America with 13%. Europe's hydropower potential is comparatively low, just 4%, Oceania's 0.7% and Australia's 0.3%. According to the HYDROPOWER EUROPE (Fry, Schleiss, & Morris, 2021), 46.5% of economically feasible and 28% of technologically feasible global hydropower potential is already utilized. Europe has developed 71% of its economically feasible hydropower potential (IEA, 2021b).

Wind power. Just a decade ago, it was considered that wind power was at an economic disadvantage compared with conventional power generation (Valentine, 2011). However, now, it has reached cost parity and has become one of the cheapest power sources (Lazard, 2021). New wind onshore projects even manage to undercut the operating costs of already built coal power plants (IRENA, 2021a). Besides being climate neutral and a cheap power source, wind power plants also have other benefits. For example, it can be built on pre-existing farmlands, taking little space on the ground and not disrupting production (Just Energy, 2018), which is an opportunity for the farmers to earn additional income by leasing land or making contracts with energy suppliers. Furthermore, the wind is widely available and can be utilized in distributed generation near consumers, reducing grid losses (Pepermans, Driesen, Haeseldonckx, Belmans, & D'haeseleer, 2005). Also, the wind is a barely-tapped resource. The available wind power potential is theoretically 20 times higher than current global energy consumption (Tong, 2010). As a result of the benefits, in 2020, despite the coronavirus pandemic, there was a remarkable windpower growth, with 111 GW of new wind power plants (expansion almost double compared to 2019 58GW), which is around a third of the total new installed capacities (IRENA, 2021b). However, like all technologies, wind power has also drawbacks. It adversely affects wildlife, including insects, birds, bats, and terrestrial and marine mammals (Schöll & Nopp-Mayr, 2021). It causes noise-induced (Botelho, Arezes, Bernardo, Dias, & Pinto, 2017) and moving shadow, called "shadow flicker", annoyance (Haac, Darlow, Kaliski, Rand, & Hoen, 2022). Also, some consider it degrades the landscape aesthetically, though some consider it a positive addition to the landscape (A. Butler & Wärnbäck, 2019). Even though wind as a resource is widespread, it has uneven distribution worldwide, with some countries having more favourable wind speeds for wind power development (Badger et al., 2021). Another drawback is that wind power plants have high upfront costs, approximately 75% of total costs (Krohn, Morthorst, & Awerbuch, 2009). However, the most significant drawback is its intermittency, as wind power plants' output depends on variable wind speeds, which are very difficult to predict. This intermittency threatens the power system's reliability and costs, especially at higher wind power penetration levels (Ren, Liu, Wan, Guo, & Yu, 2017). With higher wind power penetration, the need for spinning reserves increases (typically provided by hydro or gas-fired power plants) to quickly balance reduced electricity generation when wind speeds drop. Furthermore, high wind penetration leads to output curtailment, reducing the economic efficiency of wind power plants. A possible solution to these issues is energy storage which stores the excess power in times of high winds and provides it to the grid once wind speeds are low. However, large-scale energy storage is costly. Korchinski (2012) estimated that the cost-optimal wind penetration is under 20%, and Lion Hirth estimated (2015) around 20%. Nevertheless, eight countries exceed this number: Denmark with 48.6%, Uruguay 40.3%, Lithuania 36.3%, Ireland 31.6%, Portugal 26.8%, Luxembourg 24.5%, Spain 22.9% and the United Kingdom 21.1% (International Energy Agency, 2021). In the case of Denmark, it is fortunate to have neighbouring countries of Norway and Sweden with a substantial share of hydropower, which is perfectly suitable to balance wind power fluctuations (Green, 2012). Uruguay has its own ample hydro resources. As for Lithuania, this number is somewhat misleading since it shows penetration in electricity generation, but Lithuania imports most of consumed electricity. In 2020, wind power covered only 13% of Lithuania's electricity needs, including the grid losses (Litgrid, 2021a).

Solar energy is probably the most abundant and widely available energy resource. However, the potential output of solar power plants depends on solar irradiance, which decreases toward the poles, reducing the cost-effectiveness. Nevertheless, Germany proved that solar power could be successfully adopted at relatively high latitudes. Even though Germany is in the same latitude range as the northern part of the U.S. and south of Canada, it produces 8.8% of its electricity from solar power plants (International Energy Agency, 2021). It plans to double its installed capacity by 2030 (Ministry for Economic Affairs and Energy, 2020). There are two main types of solar power plants, namely, concentrated solar power (CSP) and photovoltaic (PV). CSP plants use reflectors to concentrate solar rays to produce steam by directly heating water or heating the transfer fluid, which gives off heat in the heat exchanger to boil the water. Produced steam turns the turbine, which is connected to the generator. In principle, it is very similar to other thermal power plants. The main advantages of this technology are higher inertia and the possibility of storing excess energy in thermal energy storage. PV systems work on a different principle. They convert light to electricity by utilizing the photovoltaic effect in the P-N junction – two joined semiconductor layers, one of which has excess electron holes (absence of electrons) and other excess free electrons. PV cells are typically made from silicon doped with materials that alter the number of electron holes and free electrons, such as phosphorus and boron. Globally in 2020, 127 GW of new solar power plants were installed (IRENA, 2021b), of which only 0.2 GW were CSP plants (IEA, 2021c). PVs are mainly preferred over CSP plants because they have a significantly lower levelized cost of electricity (LCOE) (see Figure 4). Furthermore, PV modules do not have moving parts unless fitted with solar trackers, so they need little maintenance and do not produce noise pollution. Also, PVs have excellent scalability. This technology is not bound to a utility scale in the MW range, which requires millions in investments. For several thousand euros, a small solar panel system can be installed on the rooftop to generate most of the electricity consumed by a household. A study in Australia shows that rooftop solar power plants even positively affect housing prices (Best, Burke, Nepal, & Reynolds, 2021). A 3.5 kW system increases the value by around 4%. Unfortunately, PV plants have a high direct impact area on land, with 15 km^2 required to produce 1 TWh of electricity per year; for CSP plants, this number is 19.3 km^2/TWh (Trainor, McDonald, & Fargione, 2016). For comparison, the area of the direct impact of nuclear power plants is only 0.13 km^2/TWh, and of gas power plants, 0.19–0.95 km^2/TWh. Wind power plants occupy 1.31 km^2 per TWh of annual electricity generation, 127 km^2/TWh if considering the spacing between power plants. However, the land occupied by wind power plants can be used for other purposes, like agriculture. Small-scale PV installations can be built on existing roofs, but utility-scale solar power plants are placed on the ground, on which they cast a shadow, making land unsuitable for agriculture. However, some researchers, like A.Weselek et al. (2019), might disagree as there are examples of agrophotovoltaic systems where is a synergy between power generation in photovoltaics and food production. Such systems are especially promising in hot and arid climates. However, there are just a few facilities with agrophotovoltaic systems applied, and there is a lack of research on how much shade affects crop yields and quality.

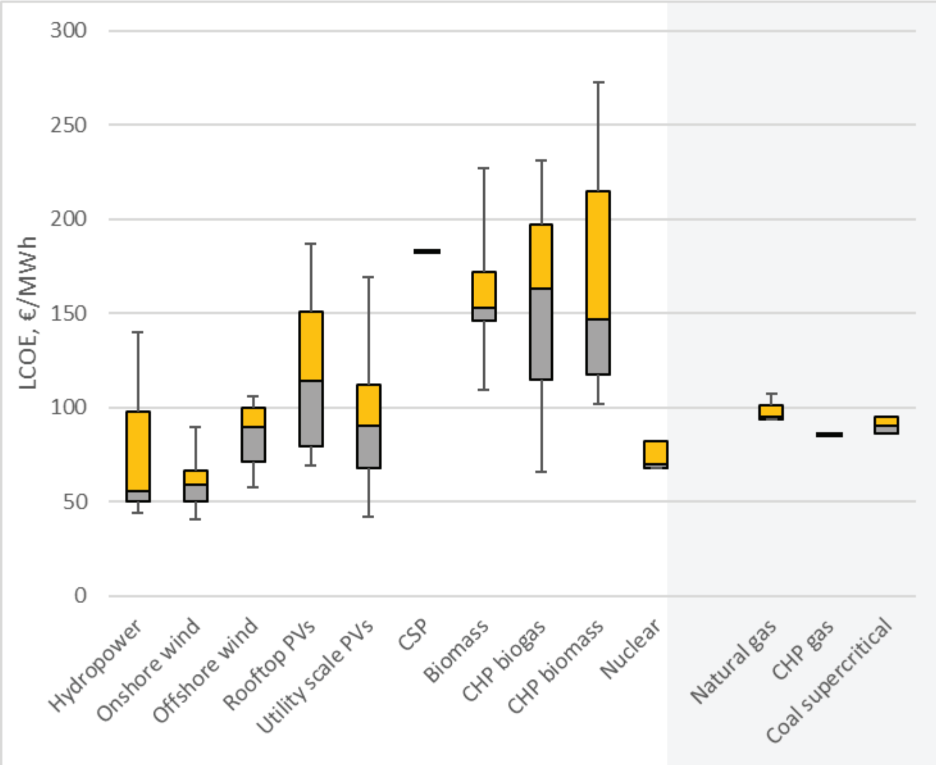

Figure 4. Levelized cost of electricity of different power plants built in 2018 in EU-27[1]

Source: created by the author based on (IEA, 2021a) data

Another problem with PVs is that in a system with a very high penetration of PV power plants, there might be an excess supply of electricity generated in solar power plants at mid-day, followed by a rapid decline in generation in the evening when electricity demand peaks (Krietemeyer et al., 2021). Traditionally, this imbalance of electricity demand and solar power generation was managed by balancing it with gas-fired power plants, which can quickly ramp up their output. However, reliance on fossil fuel power plants can negate some of the environmental benefits of solar power plants. Alternative solutions include load shifting and storage technologies to store excess energy during mid-day and release it when needed, but storage comes at a high cost. California Independent System Operator raised this issue back in 2012, and their public affairs group, to raise awareness of this problem, came up with a "duck curve" – an electricity demand curve with subtracted solar, which resembles the silhouette of a duck (Staple, 2017) (See Figure 5). PVs have near-zero

[1] Except for nuclear power plants as there no nuclear power plants built in EU-27 between 2008 and 2018, so data on power plants in China, South Korea and U.S. were used instead.

marginal costs; thus, by the merit order, they are always preferred, pushing out more expensive thermal power plants from mid-day trading (Wilkinson, Maticka, Liu, & John, 2021). With an increasing share of PVs in a system, thermal power plants would be gradually phased out due to loss of profitability, resulting in reduced systems inertia and resilience, which these power plants provide.

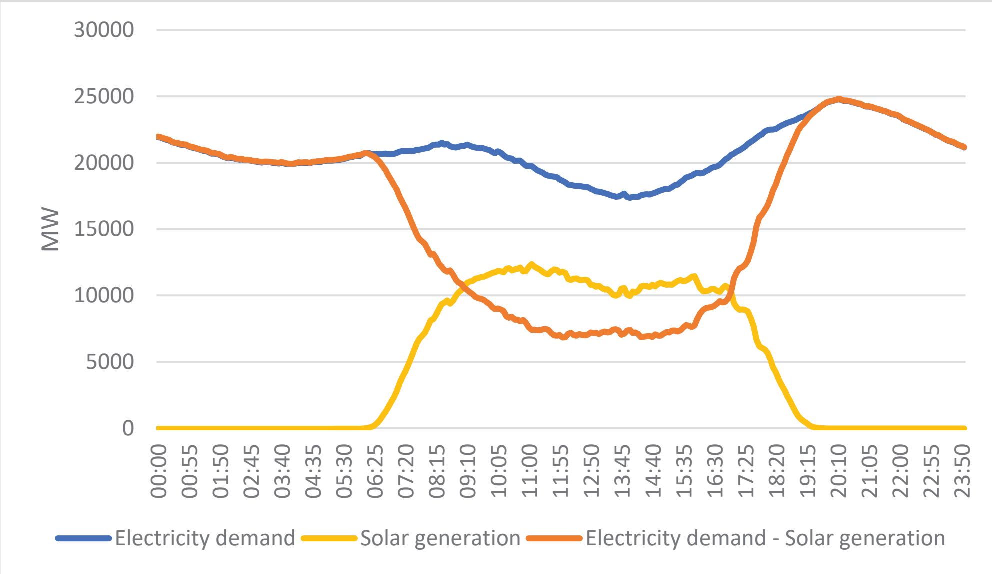

Figure 5. A duck curve – subtracted solar generation from electricity demand in California on 24 April 2021

Source: created by the author based on (CAISO, 2022) data

Bioenergy. The use of bioenergy dates back to ancient times when humans learned how to start a fire, and it remained the primary resource till the industrial revolution, sparked by the invention of the coal-powered steam engine (Ozin, 2019). The industrial revolution brought a fossil-fuel era which lasts to this day. Nevertheless, bioenergy is still relevant today. According to A.Brown and P.Frankl (2017) from IEA, it is the most important RES as it can provide low-carbon electricity, heat and transport fuels. Also, its contribution to consumed global primary energy is more than two times greater than solar and wind energy combined (Ritchie & Roser, 2020). S.Ladanai and J.Vinterbäck (2009) from the Swedish University of Agricultural Sciences further state that biomass can become the most significant and sustainable energy source.

Biomass is widely available and fairly distributed (Beuchelt & Nassl, 2019). It was estimated that the global technical potential of bioenergy as a primary energy source in 2050, considering sustainability criteria, like land needs for food and feed production and nature conservation, could reach 44–75 PWh/yr (Haberl, Beringer, Bhattacharya, Erb, & Hoogwijk, 2010) (28–47% of current global primary energy demand). The highest potential is in Latin (9–16 PWh/yr) and North (6–12 PWh/yr) Americas, while the lowest is in the Middle East and North Africa (~2 PWh/yr). Europes bioenergy potential is 4–8 PWh/yr. Bioenergy development could prove especially beneficial for regions with a high dependency on energy imports, like the European Union, which imports 60% of its energy needs (Eurostat, 2022), substituting imported fossil fuels with local bioenergy. Such a transition would improve energy security and provide new opportunities for local businesses in addition to environmental benefits (Arasto et al., 2017).

One of the most significant benefits of bioenergy is its versatility. Biomass and derived biofuels can be used for electricity generation, heat generation, combined heat and power generation, co-firing, and even transport. Though bioenergy constitutes the majority of used renewable energy, its share in the global electricity mix is only around 2.7%, way below hydropower's share of 16.8% and windpower's 6.1% (Ritchie & Roser, 2020). In the transport sector, biofuels account for only 3% of fuel demands, mainly in the form of biodiesel and ethanol (IEA, 2021d). However, from 2000 to 2019, it saw a substantial growth rate of 13%, almost six times as much as transport energy demands. In comparison, on average, electricity use in transport grew by 3.5% (World Bioenergy Association, 2021). Bioenergy saw the most success in heat production. In 2019, 4.3 PWh of heat was generated in heating and combined heat and power plants, of which 0.5 PWh used renewable sources (World Bioenergy Association, 2021). 97% of renewable heat generation is from biomass. However, it is essential to mention that direct heat production, where fuel is used directly for cooking and heating purposes at the end-use level, is more than 13 times higher than heat generation in heating and CHP plants. In 2018, 19% of direct heat came from biomass (World Bioenergy Association, 2020).

Biomass-fired power plants have reliable electricity generation as they are dispatchable and operate similarly to conventional fossil fuel power plants (Arasto et al., 2017). Even though most operational biomass power and CHP plants have not been designed to balance the grid, their operation could be optimized to incorporate some balancing aspects, supporting higher penetration of variable renewable sources. However, emerging bioenergy technologies could provide even more flexibility (Schildhauer et al., 2021). In the transitional period, it might be beneficial to retrofit existing coal power plants to use biomass since, according to Bunn et al. (2019), retrofitting is more economical in ensuring required power reserves than building new gas-fired power plants.

With rising population and living standards, food and other resource demand increase globally, leading to intensified agricultural and industrial activities and worsening already serious waste problems (Tripathi, Hills, Singh, & Atkinson, 2019). It is especially problematic in developing countries where most biomass wastes are either burned in the open or left to decompose, causing adverse environmental impacts. However, these biomass residues can be used more sustainably by combusting them in waste to energy plants or in the production of biofuels.

On the flip side, bioenergy has the most significant impact on land use of all sources used in electricity generation. Trainor et al. (2016) estimate that to produce 1 TWh of electricity per year, an area of 810 km^2 is needed to provide sufficient amounts of biomass. Thus, unsustainable bioenergy practices can lead to a decline in mature forests and forests in general, negating the environmental benefits of bioenergy as the idea of its carbon neutrality is based on the fact that during biomass growth, the amount of CO_2 absorbed is equivalent to emitted during combustion. Furthermore, with increasing biomass demand, land used for other purposes, like food production, might be converted for growing energy crops instead, reducing food supply. Also, land-use change and residual biomass removal can affect soil erosion and soil quality (Wu et al., 2018). However, choosing appropriate areas, plant types, technologies, and management practices can mitigate the adverse effects.

It should be noted that looking toward the decarbonization of the economy, materials currently derived from fossil fuels can be replaced by materials from biomass but not from other renewable sources. Even though there is some research on it, for example, CO_2 to plastics, it is unlikely to be economically viable by 2050 (Beuchelt & Nassl, 2019). Therefore, if material production from biomass is prioritized, it is questionable if enough of these resources will be left for energy needs.

Another drawback to electricity generation from biomass associated with significant land impact is its difficulty to scale. As fuel has to be brought from large dispersed areas, it is rather difficult to ensure a stable fuel supply for large biomass-fired power plants. Thus, to no surprise, the largest biomass power plant is Alholmens kraft, with an electrical output of 256 MW (Alholmens Kraft, 2020), which pales in comparison with the most considerable fossil fuel, hydropower and nuclear power plants which are in the range of multiple gigawatts.

However, the cost is the most significant aspect of electricity generation from biomass, limiting its adoption. In most cases, electricity produced in these power plants is substantially more expensive than in fossil fuel, nuclear, or even other renewable power plants (See Figure 4). It is a bit different story with heat generation. For example, Sweden produces almost 70% of direct and district heat from biomass, Finland 55% and Brazil 50% (Pelkmans, 2021). It might seem odd that it is economically attractive to generate heat from biomass but not electricity. In Finland in 2019, the price of forest chips in heat production was €21/MWh, considerably lower than the price of hard coal (€39/MWh) and natural gas (€47/MWh) (Statistics Finland, 2020). Therefore biomass as a fuel is preferred. However, capital costs play a more significant role in power production, and biomass power plants have substantially higher up-front costs than fossil fuel power plants. For instance, a biomass CHP plant is 37% more expensive per megawatt than coal CHP plant and almost three times as expensive as a combined cycle CHP plant fired by natural gas (Kofoed-Wiuff et al., 2021). For electricity-only power plants, the difference would be even greater. Furthermore, natural gas power plants have higher electrical efficiency. For these reasons, it is more economical to utilize biomass in heat generation and, in the case of CHP, to have electricity as a secondary product.

Nuclear power is the second-largest low-carbon electricity source in the world, with 10.4% of the global electricity mix (Ritchie & Roser, 2020). However, a heated debate exists about its future role in climate mitigation targets. Nuclear proponents argue that nuclear energy reduces the use of fossil fuels, providing environmental benefits and "Without nuclear, our action on climate will be more difficult, more expensive, and more likely to fail" (Hansen et al., 2019). In contrast, others object by stating that new nuclear power plants should be built economically and on time to be considered a feasible option, but practice shows otherwise. Thus, "<…> spending on new nuclear power significantly reduces our chances in effectively responding to climate change." (Dorfman et al., 2019). Nuclear power seems to be a cheap and reliable low-carbon electricity source (See Figure 4). However, these power plants are prone to substantial cost overruns due to magnitude, complexity, and long construction times. For example, unit 3 in Finish Olkiluoto nuclear power plant should have been ready by 2010 at the cost of €3 billion, but it was started only at the beginning of 2022 after spending around €11 billion in total (Vanttinen, 2020). This example is not extraordinary. Gilbert et al. analysed 180 nuclear projects and found that 92% had cost overruns with an average of 117% construction cost escalation (Gilbert, Sovacool, Johnstone, & Stirling, 2017).

On the positive side, nuclear fuel is relatively abundant and relatively cheap. It is estimated that there are more than 8 million tons of recoverable uranium: 1 million at extraction and processing price under 40 $/kg, 1 million at 40–80 $/kg, 4 million at 80–130 $/kg and 2 million at 130–260 $/kg (NEA & IAEA, 2020). These uranium reserves would last over a hundred years at the current nuclear power generation level. Furthermore, there are also unconventional uranium resources, where uranium is a minor byproduct, like phosphate rocks, black shale and lignite. These additional unconventional resources hold additional 39 million tons. Also, seawater contains an almost endless amount of uranium – over 4 billion tons. Unfortunately, developing a cost-effective way to extract uranium from seawater is challenging as uranium concentration is only 3–4 parts per billion. Most nuclear reactors use a "once-through" fuel cycle, where after a certain period, the fuel is removed and considered waste, even though 99% of its potential energy remains (Price & Blaise, 2002). It is because the operation of these reactors is based on splitting the U-235 isotope. Fresh nuclear fuel typically has around 3.5–5% of U-235, while the rest is U-238, which is non-fissile (World Nuclear Association, 2021a). Used fuel holds around 1% of U-235, under 1% of fissile plutonium produced in the reactor, 3% of various fission products and 95% U-238. The remaining U-235 can be recycled to save around 10–15% of mined uranium. However, there is an even more efficient way to use uranium. Fast breeder reactors can turn U-239 into fissile plutonium, producing more fissile material than it consumes. Fast-breeder reactors could power the world for thousands of years with reasonably assured resources. Unfortunately, these reactors are more expensive, less reliable and pose serious proliferation risks (Cochran et al., 2010).

Another benefit of nuclear power is its small land footprint. Nuclear power plants are typically built at large capacities, where each unit is around 1000 MW, and it is not uncommon to have multiple units on the same site. It is estimated that the land footprint of a nuclear power plant is just around 0.13 km^2/TWh, well below other electricity generation options (Trainor et al., 2016). However, the effects might be widespread in the case of a catastrophic accident, like one in Chornobyl or Fukushima. For example, after the Chornobyl accident, vast territories of Ukraine, Belarus and Russia were contaminated, and traces of released radionuclides were detectable all around the northern hemisphere (World Nuclear Association, 2022). The estimated costs of the Chornobyl accident are roughly 700 billion dollars (Samet & Seo, 2016), which is more than the entire GDP of Argentina. The fear of potential accidents can even cause political tensions. For example, the Belarusian Astravets nuclear power plant, built around 40 km from Lithuania's capital Vilnius caused a backlash from Lithuania, which prohibited electricity imports from Belarus (Sytas, 2020).

Also, the is a problem – nuclear waste. Based on the half-life[2] and level of radioactivity, it is categorized into three groups: low-level (90% of waste volume with 1% of radioactivity), intermediate-level (7% of volume with 4% of radioactivity) and high-level (3% of volume and 95% of radioactivity) (World Nuclear Association, n.d.). Low-level radioactive waste comprises items and materials, like tools and clothing, that are lightly contaminated by mostly short-lived radionuclides. Low-level radioactive waste is stored in near-surface (at ground level or in caverns) storage facilities. Intermediate-level waste contains traces of long-lived radionuclides, e.g. chemical sludge, fuel claddings and materials from dismantled reactors (Kurniawan et al., 2022). It takes up to a thousand years for such waste to reach the radioactivity level of uranium ore. Therefore, it needs a higher degree of containment and isolation. Intermediate-level waste with a higher concentration of long-lived radionuclides has to be stored in a geological repository. The most problematic is high-level radioactive waste, like spent nuclear fuel, with high concentrations of short- and long-lived radionuclides. Initially, it has to be shielded and cooled in special storage ponds (World Nuclear Association, 2021b). After it is cooled, it can be either reprocessed or moved to dry storage. Most countries see deep geological repositories as the best long-term solution. However, even though nuclear energy has been used to produce electricity for more than six decades, at the moment, there are no operational, geological repositories for high-level radioactive waste, but it is expected that the first one will launch in 2023 (Conca, 2021).

Carbon capture and storage (CCS) is a set of technologies for capturing and long-term storage of CO_2 emissions, with the potential to substantially reduce CO_2 emissions from various industrial plants, including power plants, released into the atmosphere (Y. Wang et al., 2022). CCS systems can efficiently capture 85–95% of CO_2 emissions (Eldardiry & Habib, 2018), so if paired with a biomass-fired power plant, it could help achieve negative emissions since carbon dioxide absorbed through photosynthesis would be stored underground after biomass combustion. CCS involves three processes: CO_2 capture, transportation and storage. CO_2 emissions can be captured using pre-combustion, post-combustion and oxy-fuel combustion technologies. Pre-combustion capture refers to CO_2 capture before the combustion process through fuel gasification (conversion to hydrogen and CO_2), post-combustion to CO_2 extraction from flue gas and oxy-fuel to carbon capture after combustion in an almost pure oxygen environment (Madejski, Chmiel, Subramanian, & Kuś, 2022). Pre-combustion and oxy-fuel combustion carbon capture technologies must be included in power plant design, but post-combustion can be implemented in an existing power plant (Carpenter & Long, 2017). However, post-combustion capture is a less efficient and costlier option. On the other hand, pre-combustion capture technology can be applied only to new gasification plants, which generally have higher capital costs than conventional fossil-fuel plants. Oxy-fuel combustion capture can be applied to a broader range of power plant types, but the high cost of oxygen

[2] Half-life shows the time it takes for nuclear waste to loose half of its radioactivity.

production limits its development. Furthermore, all three carbon capture technologies reduce the power plant's efficiency (energy penalty) due to additional energy required for carbon capture processes, like reheating solvents and compressing CO_2. Energy penalties have wide ranges for each described technology, but mean values for pre-combustion carbon capture are around 18.4%, post-combustion 24.7%, and oxy-fuel 21.6% (Thorbjörnsson, 2014).

Kheirinik, Ahmed and Rahmanian (2021) estimated the costs for different carbon capture technologies and found that the cost of avoiding a ton of CO_2 emissions is equal to £60.4 in pre-combustion capture, £124.7 in post-combustion and £206.6 in oxy-fuel. In euros, correspondingly, €71.8/t CO_2, €148.3/t CO_2, and €245.7/t CO_2. Even though pre-combustion has the lowest capture cost, it requires the highest investments. Integrated coal gasification combined cycle (IGCC) power plant with pre-combustion carbon capture cost 1.6 times more than pulverized coal power plant with oxy-fuel combustion carbon capture and 4% more than pulverized coal power plant with post-combustion carbon capture. Furthermore, IGCC power plant uses slightly more fuel than pulverized coal power plants. As a result, the IGCC power plant has the highest LCOE of these three options. Although a power plant with oxy-fuel carbon capture has the lowest investments and LCOE, this technology has not succeeded commercially.

Once the CO_2 is captured, it is compressed and transported to storage. Transportation mode is selected based on geographical location. For short-distance CO_2 transportation, road and rail transportation usually are the most economical options, while pipelines are for long-distance transportation, and ships are for sea transportation (Y. Wang et al., 2022). CO_2 can be stored in various geological storages, like depleted oil and gas fields, saline aquifers, coal seams and basalt formations. However, there are some concerns about the safety of geological carbon storage (Ma et al., 2022). First, there is the risk of direct leakage through injection or production wells. Second, underground injection of CO_2 might cause earthquakes and breaks in the caprock, resulting in CO_2 leakage. Third, a leakage might occur due to the damage caused by naturally occurring earthquakes.

Despite the high potential to reduce CO_2 emissions in power generation and industry in general, large-scale carbon capture and storage development faces the major obstacle of high costs. (Ma et al., 2022) The most significant cost component has carbon capture, while underground storage has the lowest.

The heat pump is a device that transfers heat from one environment to another at a higher than the source temperature (Britannica & T. Editors of Encyclopaedia, 2013). Therefore, the source substance or space is cooled, and the other is heated. The heat pump consists of these major components: compressor, condenser, expansion valve, evaporator, coolant and fans, used to facilitate heat exchange between the evaporator and cooled environment and also between the condenser and heated environment. Compressors and fans require electrical energy to run. Therefore, a heat pump can be seen as an electric heater. However, it has far greater efficiency than a conventional electric heater. Heat pump's coefficient of performance (a ratio between heat output and electricity consumption)[3] varies from 2 to more than 6 (Barco-Burgos, Bruno, Eicker, Saldaña-Robles, & Alcántar-Camarena, 2022), while conventional electric heaters have efficiency below 1. Heat pumps for heating are widespread, with almost 180 million units providing heat globally (IEA, 2021e). It is becoming common to install heat pumps in newly built buildings in many countries, but heat pumps currently provide only around 7% of heat demands in buildings (IEA, 2021e). However, heat pumps in district heating are uncommon though it holds great potential to reduce emissions.

Sweden has one of the highest heat pump utilization rates in Europe. It saw substantial investments into large heat pumps connected to the district heating system in the 80s, totalling 2.5 GW, but since 1990 there have been no new installations (Johansson, 2021) due to high electricity prices and taxation (Averfalk, Ingvarsson, Persson, Gong, & Werner, 2017). Around one-third of heat was produced in heat pumps and electric boilers during the peak in 1990, but it has dropped to just 10% since then as the focus shifted towards biomass and waste-based heat generation (Averfalk et al., 2017). On the other hand, since 2000, decentralized small-scale heat pumps have become rather popular in Sweden.

With increasing cheap electricity production from variable renewable sources, heat pumps in district heating systems might become more popular as this heating option can provide the required flexibility by efficiently producing heat using excess electricity generation from variable sources during peak times (load-shifting) (Barco-Burgos et al., 2022). Furthermore, strategically placed heat pumps near consumers can enable the use of low temperatures in the heating network by raising the temperature to desired near the consumer, and such advanced systems would decrease heat losses in the network. Both benefits of balancing variable renewable sources and enabling low-temperature use can be achieved simultaneously by adding heat storage, which is considerably less expensive than batteries or other means of electricity storage. Also, heat pumps in reverse operation can provide centralized cooling. However, the widespread use of heat pumps in district heating faces various challenges, like power grid limitations, high investment costs, lack of standards and policies, as well as public acceptance. (Barco-Burgos et al., 2022)

There are more low-carbon electricity and heat generation options than discussed in this section, like a wave, tidal and geothermal plants, but these were deemed low potential due to localization and high costs.

1.2.2. Transport decarbonization options

Biofuels are the most widely adopted low-carbon fuel in petroleum-dominated transport, accounting for 3% of transport fuel demand (1 PWh) (IEA, 2021d). In comparison, the share of electricity use in transport is more than twice lower – 0.4 PWh (IEA, 2022). One of the most significant advantages of biofuels is that biofuel

[3] Coefficient of performance is used for heat pumps as it is a measure of heat transfer in relation to energy input (electricity), while efficiency is a measure of energy output to the input and exceeding 100% would mean the breaking of the first law of thermodynamics. For these reasons, different terms to indicate performance are used for heat pumps and other heat sources, though in a sense, they are equivalent.

blended with petroleum fuel can be used in the current internal combustion engine vehicle fleet without any modifications. According to the U.S. Department of Energy (Alleman et al., 2016), using biodiesel blends up to 20% does not require any changes to the vehicle. In the case of petrol, up to 10% bio-ethanol blend can be safely used in current petrol cars (Ghadikolaei et al., 2021). Higher biofuel blends may require modifications to the seals, gaskets, fuel tank, fuel pump, fuel injection system and calibration of the electronic control unit (Alleman et al., 2016; Ghadikolaei et al., 2021). Most of the EU-27 Member States (Saint-Supéry & De Simone, 2020), the U.S. (O'Malley, 2021), the U.K. (Saint-Supéry & De Simone, 2020), Australia, Brazil, Canada, Japan, South Korea (Ebadian, van Dyk, McMillan, & Saddler, 2020) and probably some other countries have already enacted requirements on minimum biofuel use or minimum biofuel content in transport fuels. In addition, China planned to implement a nationwide requirement to use the E-10 blend (10% ethanol and 90% petrol) by the end of 2020, but due to feedstock shortage, implementation was slowed (Yunfeng, 2021). So far, 15 out of 31 of China's provinces have managed to fully or partially implement the use of the E-10 blend. Countries typically mandate low-level biofuel blends under 10%, except for Brazil, which requires a 27% bioethanol blend in petrol (Ebadian et al., 2020). Wider adoption of biofuels faces several barriers. First, vehicles that support high biofuel blends are more expensive, but on the other hand, manufacturers claim that the main reason for high prices is low such vehicle demand, giving a "chicken and egg" problem (Ghadikolaei et al., 2021). Second, large impact on the land, as with bioenergy in general, which could affect deforestation, biodiversity and food supply (de Blas, Mediavilla, Capellán-Pérez, & Duce, 2020). Third, adverse effects on vehicle performance. High-level biodiesel blends gel at higher temperatures than conventional diesel. This is particularly problematic in colder climates. However, it can be addressed with in-built fuel heaters, insulation or additives.

Electric vehicle sales have seen a spectacular rise, from 0.03 million cars in 2011 to 2.1 million in 2019, accounting for 2.6% of global car sales (IEA, 2020), but they are still often considered an expensive alternative. However, with each year purchase price difference between EVs and conventional ones diminishes. For instance, the price for a new Volkswagen Golf mk8 starts from €28.5 thousand, while the price of an equivalent Volkswagen ID.3 is from €37 thousand (Volkswagen, 2022a). The difference is 30%. It still might seem a lot for some, but when considering the total cost of ownership (TCO), electric vehicles might already be cheaper as they have lower energy and maintenance costs. Liu et al. (2021) estimated that electric vehicles with 200 miles range could reach cost parity with an equivalent ICE car in six years. Also, the report by Element Energy (2021) for The European Consumer Organisation shows that EVs have the lowest lifetime TCO at the EU level among new medium-sized cars, and it will have in small and large car segments from 2024 and 2026, respectively. However, the first owners, which determine the vehicle fleet mix, incur higher depreciation costs due to high upfront costs. EVs are the most economically beneficial for second and third users. For first-time owners, it is expected that small and medium-sized cars will become the cheapest powertrain after 2025 and 2026, respectively.

Electric vehicles also have other benefits that can be attractive to users, zero tailpipe emissions, faster and smoother acceleration, and quieter operation (Liu et al., 2021). Even though EVs have zero tailpipe emissions, the electricity they consume might be generated in fossil-fuel power plants. Therefore, the effectiveness of electric vehicles as an emission reduction measure depends on the electricity generation mix (Franzò & Nasca, 2021). In countries with coal-dominated electricity generation, like Poland, emissions might even increase with rising EV penetration (Sobol & Dyjakon, 2020). However, EVs can reduce not only GHG emissions but also other harmful emissions, like NO_x and $PM_{2.5}$ (Mehlig, Woodward, Oxley, Holland, & ApSimon, 2021). Tailpipe emissions affect low-income communities the most since more affordable housing in cities is often situated near roads with heavier traffic (Guijarro, 2019; Ossokina & Verweij, 2015), resulting in disproportionally high health costs for these communities (Welch, 2017). Electric vehicles have the additional benefit of being quieter than internal combustion engine (ICE) vehicles. However, the modelling results show that a complete transition to electric vehicles could improve the acoustic environment by up to 10% (Campello-Vicente, Peral-Orts, Campillo-Davo, & Velasco-Sanchez, 2017). The improvement is insignificant as the primary noise source is tyres rather than engines (Holtsmark & Skonhoft, 2014).

Conversely, some might still prefer ICE vehicles regardless of the potential EV benefits. One reason is range anxiety – the fear of being stranded due to complete battery depletion in the middle of the trip (Neubauer & Wood, 2014). Improved charging infrastructure can help reduce range anxiety and enable EV drivers to travel longer distances (Neubauer & Wood, 2014). However, charging network expansion can be costly, so investors are likely to wait for substantial demand for charging stations. At the same time, EV adoption and subsequent charging demand are limited by the lack of charging infrastructure.

Another benefit of electric vehicles is that they can contribute to energy security – for instance, the EU-27 imports more than 90% of crude oil and petroleum products (Eurostat, 2022). Switching to EVs could help reduce reliance on energy imports as they would be powered by locally produced electrical energy. On the other hand, the EU also imports the majority of batteries. However, it can be seen as a diversification of import types and sources (Di Felice, Renner, & Giampietro, 2021). Unfortunately, almost 60% of global cobalt needed in manufacturing lithium-ion batteries is produced in the Democratic Republic of Congo, infamous for child labour (Di Felice et al., 2021). Furthermore, over 90% of lithium is produced in just three countries: Australia, Chile and Argentina (Di Felice et al., 2021). Lithium extraction from brine is detrimental to the environment as it is water-intensive and polluting, thus potentially leading to environmental injustice in these regions (Di Felice et al., 2021).

In essence, **fuel cell electric vehicles (FCEV)** are electric vehicles as electric motors provide propulsion. However, they are unique as they have inbuilt fuel cells for electricity generation instead of relying on stored energy in the battery. FCEVs still have batteries or supercapacitors, but onboard electricity generation enables the use of considerably smaller batteries compared to BEVs. The range of FCEV cars exceeds 500 km (based on only two available models – Toyota Mirai and Hyundai Nexo), which is comparable to high-end electric car models, though still inferior to petrol and diesel cars. Range anxiety is less of a problem with FCEV than with BEV, given that the hydrogen fueling infrastructure is in place, as hydrogen refuelling takes only minutes, like in conventional cars. However, at the end of 2020, there were only 553 hydrogen refuelling stations worldwide (275 in Asia, 200 in Europe, 75 in North America, 2 in the Middle East and 1 in Australia) (FuelCellsWorks, 2021), which pales in comparison to more than 285 thousand public EV charging stations just in Europe (Statista Research Department, 2022). Furthermore, FCEVs are pretty expensive. Toyota Mirai's price starts at 49.5 thousand dollars, and Hyundai Nexo's at 61 thousand dollars (Williams, 2022). The lack of infrastructure and model choices also the high purchase price of FCEV are the major barriers to the broader adoption of FCEV. Unsurprisingly, there are just 26 thousand FCEV cars, almost 6 thousand buses and 3 thousand commercial vehicles (IEA, 2021f).

Fuel cells convert the chemical energy of pressurized hydrogen in the tank and oxygen from the air to generate electricity. This electrochemical process emits only water; for this reason, FCEVs are considered to be zero-emission vehicles. On the other hand, hydrogen production is often far from emission-free, though it has the potential to be so. Several hydrogen production methods exist, but steam methane reforming is the most widely used, accounting for 76% of global hydrogen production (Ochu, Braverman, Smith, & Friedmann, 2021). Steam methane reforming is a process in which methane and steam are heated to produce hydrogen and carbon monoxide (CO). CO is used in a further reaction with steam to produce more hydrogen and CO_2 (water-gas shift reaction). The second most popular method, with 22% of global hydrogen production, is coal gasification (Ochu et al., 2021), in which coal is gasified to form carbon monoxide for a water-gas shift reaction. Hydrogen produced using these two methods is called "grey hydrogen" (Ochu et al., 2021). Steam methane reforming has a lower CO_2 intensity at around 8–12 kg CO_2/kg of H_2, while coal gasification is around 18–20 kg CO_2/kg of H_2 (Blank & Molly, 2020). Most CO_2 emissions can be avoided by applying carbon capture and storage. Hydrogen produced in such a system is called "blue hydrogen". The last method discussed and the most important in terms of decarbonization is production through electrolysis, which currently accounts for just 2% of the global hydrogen supply (Ochu et al., 2021). However, typically it is treated as a byproduct in electrolytic chlorine and sodium hydroxide production (K. Li et al., 2021). Though electrolysis does not emit any GHG emissions, it requires quite a lot of electricity, which, considering the current global electricity mix, is primarily produced in fossil-fuel power plants. The indirect CO_2 intensity of hydrogen production through electrolysis is 16 kg CO_2/kg H_2 in the EU, 21 kg CO_2/kg H_2 in the U.S. and 35 kg CO_2/kg H_2 in China, making it less climate-friendly than the steam methane reforming process in the EU and even than coal gasification in the U.S. and China (Blank & Molly, 2020). Nevertheless, in principle, electricity from renewable sources could be used in electrolysis producing carbon-free hydrogen, called "green hydrogen" (Ochu et al., 2021). Unfortunately, "green hydrogen" is not cost-competitive at the moment as it costs 5.6–6.6 \$/kg H_2, while only 1.3 \$/kg H_2 using the steam methane reforming process (Ochu et al., 2021).

1.2.3. Overview of sector coupling as a means to increase the power system flexibility

The concept of sector coupling, which originated in Germany, has been gaining more and more attention. Originally it referred to the electrification of various end-use sectors to reduce fossil-fuel use in these sectors and enable new balancing services that could help achieve higher penetration of variable renewable sources in electricity generation (Van Nuffel, Gorenstein Dedecca, Smit, & Rademaekers, 2018). However, recently the concept has broadened, and the European Commission defines it as “a strategy to provide greater flexibility to the energy system so that decarbonization can be achieved in a more cost-effective way” (Van Nuffel et al., 2018). Even though this definition covers the whole energy system, including both the supply and demand sides, only the coupling of power supply with district heating supply and power supply with the transport sector are investigated in this section, as these sectors are responsible for most GHG emissions and therefore are the main focus of the thesis.

Cogeneration can be seen as the first step in integrating electricity and heating sectors, dating back to the late 1880s in Europe when most industrial plants had their coal-fired cogeneration plants to produce steam and electricity for their own industrial needs (Hinrichs, 2004). However, with decreasing costs and improved reliability of centralized electricity supply, industrial facilities switched to more convenient electricity purchases from the grid but still produced heat locally. In the 1970s in Europe, the district heating sector saw a major development due to increasing heating fuel and oil prices, as cogeneration could provide efficient electricity and heat production. In comparison, combined heat and power generation require almost two times less fuel to provide the same amounts of electricity and heat than separate generation in power and heating plants (Hinrichs, 2004).

Of course, at the time, the integration of power and heating sectors was not seen as a measure to increase energy systems flexibility as there was no such need. Electricity was supplied mainly by dispatchable fossil fuel, nuclear, or hydropower plants, and generation from variable renewable sources was non-existent. However, as nations recognized the dangers of human-induced climate change, the need to switch to non-fossil energy sources arose. Due to abundance and rapidly decreasing costs, wind and solar electricity generation have gained popularity, but the high penetration of these sources is problematic because of their variable nature. It is possible to use energy storage, like batteries or pumped storage hydropower plants, but the required magnitude of storage to balance a fully renewable system would be absurdly large. For example, EU-27 would need at least 320 TWh storage without additional balancing measures, equivalent to 10% of annual demand (Rasmussen, Andresen, & Greiner, 2012). However, various flexibility and balancing options can substantially reduce required electricity storage.

Electricity and district heating coupling can provide some of the necessary flexibility, and balancing needs to support a renewable-based energy system. For example, power to heat through electric boilers and heat pumps can be used to convert excess electricity generation in the wind and solar power plants to heat and supply it to the district heating system (Averfalk et al., 2017). However, other heat sources are needed when there is low electricity generation from variable renewable energy sources (VRES). In IEA Bioenergy's study by A.Arasto et al. (2017), the authors emphasise that biomass combined heat and power plants can complement the use of heat pumps when considering the balancing of VRES as the output of photovoltaics drops in winter, especially in northern regions, while the electricity demand of heating pumps increases with heating demand. Since the electricity supply decline coincides with the increase in heat demand, it makes CHP plants a well-fitting option. Unfortunately, as CHP plants have high investment costs, operating only during low-wind and overcast hours is quite expensive, leading to the need to sell energy at a high price to recuperate costs and earn profits. It is not a big problem for older CHP plants that have already paid back or converted fossil-fuel plants, but it might make new biomass CHP plants an unattractive investment. On the other hand, heat can be provided by heating plants and electricity by other power plants during those low-VRES hours. However, when considering a decarbonized system, there are few choices for electricity generation (nuclear, biomass, fossil fuel CCS power plants), but the occasional operation is as problematic for them as for biomass CHP plants. Alternatively, electricity storage could be used, but it is expensive and would require immense storage sizes, as stated before. Therefore, some combination of these technologies could prove more cost-efficient.

In his doctoral thesis, Svante Monie (2022) compared simulation results of different Swedish heating system structures and found that the most economically attractive structure is comprised of CHP plants, heat pumps and thermal energy storage (TES) in an existing district heating network, considering high shares of VRES electricity generation. The results show that PV-dominated power systems have better synergy with heat pumps and seasonally operated TES, while wind-dominated with CHP plants and short-term TES.

Yi-Kuang Chen et al. (2021) used a model developed with the Balmorel modelling framework to analyze decarbonization pathways for centralized and decentralized heating sectors and assess the impacts on the power sector. The study covers Nordic countries (except Iceland), Baltics, Belgium, France, Germany, Netherlands, Poland and the UK. The modelling results show that electrification of the heating sector is the most cost-efficient way to replace fossil fuel-based heat generation. In the transitional period, decentralized heating switches to electric heating, heat pumps, gas boilers, and hybrids, but by 2050, it will switch almost entirely to heat pumps. Centralized heating transitions to electricity and biomass-based heating. The authors calculated and compared different scenarios, including with and without extensive district heating expansion and found that district heating expansion reduced electricity load peaks and wind power curtailments due to larger district heating storage capacities and flexible CHP operation.

Stine Mueller et al. (2014), in their paper, showed that a combination of CHP plants and heat pumps, at assumed capacities of 15 GW and 16 GW, can reduce positive and negative residual load (electricity consumption minus electricity generation from variable renewable sources) peaks by 14% and 33%. The calculations were made for the year 2030 in Germany.

Another critical aspect of the power system to which sector coupling can contribute is reserve supply. The power reserves are necessary to ensure the delicate balance of the power system, where electricity generation and consumption must be equal at any point in time. Most electricity is sold and bought in a day-ahead market. Unfortunately, it is impossible to precisely predict generation (especially for VRES) and consumption for the next day. An intra-day market covers the discrepancies by trading on the day of the delivery. However, disbalances might still occur due to various reasons, for instance, as a consequence of failure. The balancing market is the last stage of electricity trading before delivery. Dispatchable fossil-fuel power plants primarily provide balancing services, but these power plants are gradually being decommissioned under the decarbonization trend. Thus, new reserve capacities are needed for the replacement. A. Boldrini et al. (2022) analysed the technical potential of district heating to provide balancing reserves (Frequency Containment Reserve and Frequency Restoration Reserve) in the EU. Authors argue that power-to-heat and CHP technologies in district heating systems have the potential to provide the required reserves. The modelling results show that CHP plants could contribute 84% and power-to-heat technologies the remaining 16% in 2050, though the contribution of power-to-heat technologies could be increased in redesigned district heating systems. Using the Finish example, Juha Haakana et al. (2016) estimated that CHP plants could yield up to 20% higher profits by participating in the reserve market.

Magni, Quoilin and Ateconi (2022) investigated how a district heating system with thermal energy storage could contribute to the flexibility of the future Italian power system and the provision of reserves. The simulation was run with a dispatch model Dispa-SET. Simulation results show that a large deployment of district heating with TES can substantially increase the system's flexibility, especially regarding reserves. Furthermore, it was estimated that the integration of heat pumps could reduce VRES curtailment by up to 75%. However, in the results, the large integration of CHP plants negatively affected RES generation, but CHP plants' participation in the reserve market proved to be more cost-efficient than power-to-heat units'.

It seems there is a consensus in the scientific literature that the electricity and district heating sector coupling can significantly contribute to the flexibility of a renewable-based power system. The most often included technologies in studies investigating power and heating sectors coupling are CHP plants and thermal storage, leading to a belief that these are the most crucial components of future district heating systems.

When considering the decarbonization pathways, it is also important to consider power and transport sector interrelations, as transport electrification is likely to play a major role in transport decarbonization. However, even though vehicles that run on electricity directly, like BEVs, or indirectly, like FCEVs powered by hydrogen produced through electrolysis, have zero carbon tailpipe emissions, the electricity used to charge electric vehicles or produce hydrogen is not necessarily carbon-free. On the contrary, most countries still heavily rely on fossil-fuel power plants to satisfy their electricity needs. Furthermore, transport electrification would substantially increase the electricity demand. PeterFox-Penner et al. (2018) estimated that electricity use in light-duty vehicles could reach 13–26% of total electricity demand by 2050 in the U.S. In the roadmap 2050 project, it is calculated that extensive EU road transport electrification (80% of all passenger cars BEVs and 20% PHEV) would increase electricity consumption in road transport to 740 TWh, which is equivalent to 15% of the estimated total electricity demand in 2050 (Kasten et al., 2016). New power plants would have to be built, or underutilized existing capacities would have to be used to a greater extent to provide additional electricity for electrified transport. However, as Runsen Zhang and Shinichiro Fujimori (2020) stated in their research letter, "<…> transport electrification without the replacement of fossil-fuel power plants leads to the unfortunate result of increasing emissions instead of achieving a low-carbon transition.". Unfortunately, the solution is not as simple as building more solar and wind power plants because generation from these variable sources has to be balanced. What makes matters worse, EV home charging, without charge management, could exacerbate the problem of the "duck curve" (See: *Solar energy* under Section *Power and heat decarbonization options*) in a power system with high PV penetration as EV charging peaks in the evening when electricity generation in solar power plants declines sharply (Muratori & Mai, 2021). On the other hand, EV charging with proper infrastructure and management can be flexible and contribute to balancing the power system (Muratori & Mai, 2021).

Jovanovic, Beyhan and Bayram (2021) investigated EV charging scheduling potential to flatten the "duck curve". Using a bi-objective approach, their analysis was based on real-world data on California's electricity consumption and charging sessions at a university campus. The first objective was to minimize the ramp-up requirements in the power system, and the second was to maximize the profits of charging stations and the quality of the charging service. Computational results showed that scheduling EV charging could flatten the "duck curve", i.e. reduce ramp-up requirements in the power system. However, it requires 2 to 3 times larger charging capacity than the case without scheduling, meaning significantly higher investment costs into charging infrastructure. Unfortunately, it is possible to reduce ramp-up requirements at lower charging capacities at the expense of the satisfaction level of charging requests.

Chandrashekar, Liu and Sioshani (2017) showed that giving the power system operator the ability to adjust EV charging times based on system operation and wind availability can significantly reduce the costs associated with the uncertainty and variability of wind. Furthermore, EV owners do not have to give the power system operator complete charging control; two hours of control are sufficient to provide the most cost benefits. In the analysed case, the ancillary costs for wind integration are estimated to be 0.46$/MWh of wind power when EVs are charged immediately upon arrival at the charging station. Giving complete charging control to the power system operator would reduce integration costs to 0.09 $/MWh and 2-hour charging control to 0.15 $/MWh.

A different study was carried out by Madzharov, Delarue and D'haeseleer (2014), in which they analysed how different EV penetration rates affect the power system using a unit commitment model. They found that the analysed power system can only support up to 10% EV penetration if vehicles are charged randomly (without centralized scheduling) as power demand, including the reserves, exceeds generation capacity at noon and evening. It can be argued that in real life, new power plants would be built to satisfy additional demand to power EVs. Nevertheless, the paper still shows some valuable insights. For example, they found that centrally controlled EV charging showed the ability to smoothen the demand curve by charging vehicles during low-demand hours, i.e. during the night and between morning and evening peaks. Furthermore, it enabled the system to support fully electric vehicle stock without additional power plants. However, electricity generation costs increased by 1% per 10% of EV penetration as more electricity had to be produced in more expensive power plants. It should be noted that intermittent renewables were not modelled, and the primary focus of the paper was to demonstrate the proposed modelling algorithm.

The next step from controlled charging, also known as smart charging or unidirectional vehicle-to-grid system (V1G), is a bidirectional vehicle-to-grid system (V2G), where electric vehicles could provide short-term power storage. V2G could prove especially beneficial in power systems with high penetration of variable renewable sources as vehicle batteries could be charged when there is an excess generation from renewable sources and sold back to the grid when the electricity supply drops.

Xing Yao et al. (2022) used a power dispatch and expansion model to estimate the potential of V1G and V2G to reduce the emissions and costs of the power system and improve the utilization of RES in China. Calculations were performed for the years 2017-2030. Based on the modelling results, they found that:

1. V1G and V2G can reduce the total costs and emissions of the power system. The benefits increase with the number of vehicles participating in vehicle-to-grid systems. If all electric vehicles would participate in V1G, then total costs could be reduced by 2.02%, and in the case of V2G, by 2.08%. Furthermore, CO_2 emissions could be reduced by 2.27% and 2.95%, respectively.
2. The benefits of V2G over V1G seemed to be limited as China in 2030 should still have a high share of electricity production in coal power plants, which prevents significant price differences in peak-valley hours on which the profitability of the V2G system relies. Furthermore, the battery degradation in V2G due to additional charge-discharge cycles limits from what price difference vehicle owners could profit. However, it is expected that V2G would have higher benefits in the power system with high penetration of variable renewable sources.
3. As Evs' participation in vehicle-to-grid services increases, more new wind power plants are built in the modelling results. However, the opposite is true for PVs, as fewer are built.
4. Vehicle-to-grid systems can smooth load fluctuations and facilitate the transmission of power production from high-cost areas to low-cost areas.

In their paper, Forrest et al. (2016) examined how smart charging and V2G impact the required size of stationary energy storage to support a high share of renewable electricity generation. A case study on California was used, with a 50% RES target in 2030 and 80% in 2050. Eight scenarios were calculated: two for 2030, with smart and uncontrolled charging at 29% EV penetration, and six for 2050, with V2G, smart and uncontrolled charging at 50% and 80% EV penetrations. Based on the modelling results, it was estimated that a system with an 80% renewable portfolio with uncontrolled EV charging would require energy storage capacity equivalent to 60% of installed renewable capacity and size, reaching 2.3% of annual electricity generation from RES. Smart charging showed the potential to reduce the required capacity to 16% and size to 0.6% while applying the V2G system could eliminate the need for stationary energy storage.

However, Luca de Tena and Pregger (2018) argue that Forrest et al.'s (2016) demonstrated V2G benefits over smart charging are exaggerated as the costs of additional battery degradation were not accounted for. In their calculations (Luca de Tena & Pregger, 2018) for Germany and Europe, which included degradation costs, V2G showed little benefits over smart charging as V2G utilization was low. However, they also found that smart charging could reduce residual peak load (by 3.5–4.5 GW in the analysed case) and improve systemic efficiency by up to 10%. On the other hand, they highlight that vehicle-to-grid can not fully balance variable renewable generation alone, even at an optimal integration.

There is also an option of indirect transport electrification through the use of FCEV that run on hydrogen produced by electrolysis. Electrolytic hydrogen production can be controlled to provide demand response (load shifting) service, similar to smart charging. Furthermore, it has the benefit of smart charging as produced hydrogen can be stored on-site in relatively cheap tanks before filling into FCEVs. Therefore, unlike EV charging, vehicles do not have to be present at the fuelling station to increase electricity consumption to counterbalance excessive electricity generation from RES. On the other hand, electrolyzers should be oversized to have the flexibility to balance electricity generation from intermittent sources, which means greater investment costs. Dai Wang et al. (2018) demonstrated that electrolyzers oversized by 25% and serving 0.75 million FCEVs[4] could reduce ramp-up requirements in California's power system by 18% and ramp-down requirements by 26%, while oversized by 50% could reduce by 22% and 33%, respectively.

Furthermore, Oldenbroek et al. (2021) showed that combined electrolytic hydrogen production and large-scale hydrogen storage, FCEVs could fully balance a renewable-based power, heating and transport system. It is worth mentioning that grid-connected FCEVs could provide V2G service as BEVs in their model. From their modelling results, the authors found that as low as a 43% FCEV passenger car fleet could provide sufficient capacity for balancing. Modelled countries include Denmark, Germany, France, Great Britain and Spain.

Though green hydrogen production combined with FCEVs has the potential to contribute to the balancing of the power system significantly, enabling higher penetration of variable renewable sources, its broad application might be hindered by high infrastructure and vehicle costs and low overall efficiency. The well-to-wheel efficiency of FCEVs, i.e. considering the whole energy chain from the electricity source to the motive power, is around 30% (assuming green hydrogen), which is significantly lower than 61% of BEVs (FCH JU, 2010). On the other hand, FCEVs

[4] Actually, in D. Wang et al's model, a number of 1.5 million FCEVs was used. However, it was assumed that only half of the hydrogen supplied is by electrolysis.

typically have a better range and substantially lower refuelling times. For heavy-duty vehicles, these benefits might outweigh the additional costs.

1.3. Studies on least-cost decarbonization of transport and energy sectors

In scientific literature, various options are proposed on how transport, electricity, and heating sectors could be decarbonized, including sector coupling. However, it is unlikely that any single measure would be sufficient to transition to a carbon-free energy system, as each measure has its benefits and drawbacks. For this reason, it is essential to look for complementary combinations. Furthermore, even if some combination of measures in principle can support a carbon-free system, it does not mean it is the optimal solution. It should also be the most cost-effective that reach set environmental goals.

Gea-Bermúdez et al. (2021) used a Balmorel optimization model ('The Balmorel Open Source Project', 2013), which minimized total discounted costs, to investigate the role of sector coupling for green transition in Northern-Central Europe. The model covers the electricity, heating and transport sectors. The development and operation of the power and heating sectors are optimized in ten-year steps from 2025 to 2045. However, transport development is assumed, although its operation is also optimized. The developed model has a relatively high spatial resolution based on existing wholesale electricity bidding zones, covering Belgium, Denmark, Finland, Germany, Netherlands, Norway, Poland, Sweden and the UK. This study puts into competition different electricity and heat generation options, energy storage, the expansion of interconnections and district heating, CCS and synthetic gas (hydrogen and synthetic natural gas) units. Furthermore, the sector coupling was accounted for through power-to-heat technologies, power-to-synthetic gasses, and smart EV charging. Different scenarios were calculated using different combinations of enabled and disabled investments in transmission, power-to-heat, biomass unit and synthetic gas production capacities, transport decarbonization and high/low wind potential. The modelling results revealed the importance of sector coupling and how sector coupling could lead to paradigm change where "The electricity system moves from a system where generation adapts to demand, to a system where demand adapts to generation". The scenarios with transport decarbonization and power-to-heat investments enabled showed the highest GHG emission reductions – a 92% decrease in the energy sector by 2045, compared to the 1990 level and a 76% reduction in all sectors.

The applied modelling approach has some limitations, most of which can be attributed to the necessary simplifications due to computational limitations. The assumption of perfect markets and economic rationality, neglecting behavioural aspects, was made. However, it is typical for such types of models. Possible improvements to this approach could include optimising transport sector development and the inclusion of V2G services. Furthermore, district heating could be differentiated by major cities. Also, an increased temporal resolution could provide more accuracy toward peak power capacity and storage size estimations. On the other hand, it should be noted that increasing detail for certain aspects often requires a reduction in detail in others because of computational limitations.

T. Brown et al. (2018) demonstrated that having a high spatial and temporal resolution in an optimization model is possible. They used the PyPSA-Eur-Sec-30 (Tom Brown, Victoria, Zeyen, & Neumann, 2020) open-source model that enables hourly and country-resolved investment modelling of the European energy system covering thirty European countries to calculate the cost-optimal system that reaches 95% CO_2 reduction. The analysis includes the electricity, heat and transport sectors. T. Brown et al. modelled different scenarios with different demand and flexibility assumptions for transport and heating sectors to assess the benefits of sector coupling. The modelling results showed that in a cost-optimal energy system, electricity generation is dominated by wind and solar power, while heat generation is by heat pumps. Furthermore, flexible sector coupling through BEVs, synthetic fuels, district heating, heat pumps, and thermal energy storage could eliminate the need for stationary storage and reduce total system costs by 28%. Coupled with cross-border power transmissions, it could reduce costs by 37% compared to the case of rigid sector coupling and no cross-border power trading. Such a flexible system could provide 95% emission reduction at marginally higher costs than today's energy system.

The optimization in the model is based on minimising total discounted costs as in the previously mentioned Balmorel model. However, it should be noted that investments and operations are optimized for a single year based on 2011 data. Therefore, unlike the Gea-Bermúdez et al. (2021) model, it does not calculate the optimal decarbonization pathway; instead, it calculates just what a cost-optimal system could be. Furthermore, biomass for energy use was not considered "<…>given concerns about the sustainability of fuel crops and given that sustainable second-generation biofuels will be needed for the hard-to-defossilised sectors not considered in the model". Also, vehicle composition (vehicle investment) was not optimized but given exogenously. Depending on the scenario, transport demands were met either by BEVs or FCEVs.

Kiviluoma and Meibom (2010) used a Balmorel model to investigate how wind power can affect the cost-optimal investments into other electricity generation forms and what flexibility measures could be utilized to support wind power development. Scenarios based on different assumptions on fuel prices, investment costs of the wind power plant and flexibility options (power-to-heat; V2G) were calculated for 2035. The analysis was conducted on a hypothetical system based on Finland's data. In the modelling results, wind and nuclear power plants dominate the power generation in a high fossil-fuel and CO_2 prices scenario. However, natural gas power plants are preferred over nuclear power plants in a low prices scenario. The modelling results are also sensitive to wind power investment costs. In scenarios with flexibility measures from the heat sector and EVs, investment costs decreased from €900 /kW to €700 /kW, increasing wind power penetration from 8% to 29%. Scenarios without flexibility measured showed lower wind power penetration.

The model by Juha Kiviluoma and Peter Meibom boasts high temporal resolution – a year is represented by 26 selected weeks, each at hourly resolution. Furthermore, three areas were modelled to represent better the heating sector, including the capital region, aggregated industrial heat demand, and other district heating systems. Also, the model includes a capacity balance equation, which ensures adequate generation and reserve capacities. On the flip side, as in T. Brown et al.'s (2018) model, only a single year was modelled, and the EV number was assumed. Also, the model does not consider FCEV.

In a subsequent paper, Kiviluoma and Meibom (2011) continued the analysis by investigating what benefits could provide a significant penetration of electric vehicles (around half of the car fleet) for the power system. In addition, they coupled the Balmorel model with a WILMAR unit commitment and dispatch model to achieve better modelling accuracy. The authors used the WILMAR model to calculate the regulation of electricity generation due to errors in electricity load and wind power forecasts. This approach enabled better estimations of the benefits of flexibility coming from EVs. Though the authors made significant improvements, the prior mentioned drawbacks were not addressed.

Juul and Meibom (2012) tackled one of these shortcomings – they used a Balmorel transport add-on, which enabled them to optimize transport investments. The model was given investment choices of internal combustion cars, EVs, PHEVs and FCEVs. In the initial runs, they realized that FCEVs were too expensive, and the model did not choose them. The year 2030 was chosen for the analysis, focusing on Scandinavian countries and Germany. The modelling results showed that the investments in PHEVs are the most beneficial of all transport options considered for all countries modelled. The introduction of PHEVs reduced system costs by 3%. Interestingly, the application of V2G showed only slight cost improvements. However, it is worth mentioning that additional electricity demand in Finland and Germany was met primarily by increasing the generation of coal power plants. With assumed data, wind power plants were not as competitive as coal power plants in Germany and Finland's maximum wind target was achieved before introducing PHEVs. Although this model included transport investment optimization, only cars were modelled, and calculations were performed for the year 2030. A model might yield different results when considering deep decarbonization pathways towards 2050.

Another study with a Balmorel model by Gunkel et al. (2020) investigates the effects of three different EV charging strategies, passive charging (a synonym for uncontrolled charging), smart charging and V2G, on the energy sector in Europe towards 2050. Furthermore, varying degrees of flexibility from EV charging were put into perspective with the flexibility of interconnections expansion. The model covers the power and district heating sectors and electric vehicles for Nordics, Baltics and central north-west Europe. The modelling results reveal that the cost-optimal way to achieve carbon neutrality in the power sector by 2050 relies on electricity generation in the wind, solar, nuclear, hydropower and biomass power plants (descending order by share). Furthermore, the authors conclude that increasing the flexibility of EV charging reduces the system costs significantly and decreases the need for stationary energy storage. However, smart charging and V2G compete with other sector coupling technologies, like power-to-heat. Also, an increase in EV charging flexibility triggers the replacement of PVs with wind power plants. The effects of flexible EV charging on average electricity price were estimated to be marginal, but it reduces price variability substantially. The modelling results also suggested a synergy between charging flexibility and the expansion of interconnections as higher throughput capacity enables larger instalments of VRES due to “better market coupling and spatial smoothing”.

Though this study examines the cost-optimal development pathways towards 2050 in 10-year steps for the power and heating sector, the transport sector development is not optimized, and only electric cars are considered. Furthermore, the model was “<…>run four times separately from 2020 to 2050, taking over the investment decisions from the previous simulation period”, meaning that the solution is not necessarily optimal for the whole 2020-2050 period but instead just for separate 10-year periods. A paper by Fuso Nerini et al. (2017) showed that “myopic[5] planning might result in delayed strategic investments and in considerably higher costs for achieving decarbonization targets compared to estimates done with perfect foresight[6] optimization energy models”.

The Joint Research Centre has developed a JRC-EU-TIMES model (European Commission. Joint Research Centre. Institute for Energy and Transport., 2013) using a TIMES modelling framework (IEA-ETSAP, 2013) that supports perfect and myopic foresight. The JRC-EU-TIMES model was designed to analyze the role of various energy technologies in meeting European goals related to energy and climate change, and quite a few publications (Blanco, Gómez Vilchez, Nijs, Thiel, & Faaij, 2019; Blanco, Nijs, Ruf, & Faaij, 2018a, 2018b; Commission of the European Union. Joint Research Centre. Institute for Energy and Transport., 2015; European Commission. Joint Research Centre, 2017, 2018a, 2018b; Nijs et al., 2015; Sgobbi, Nijs, et al., 2016; Sgobbi, Simões, Magagna, & Nijs, 2016; Simoes, Nijs, Ruiz, Sgobbi, & Thiel, 2017; Thiel et al., 2016) were prepared based on the modelling results. This model covers the power, district heating and transport as previously discussed models and the whole energy system for EU-28 countries plus Switzerland, Iceland and Norway. Furthermore, the investments and unit operations are optimized for all sectors, including transport. However, as the model has a large geographical scope, covers the whole energy system and is rich in technologies, a few time-slices are used to decrease computational times. JRC-EU-TIMES only uses 12 time-slices to represent a year, which is way below several hundred to 8760 used in previously mentioned models. Low temporal resolution hinders the representation of the variability of renewable sources and leads to overestimating RES penetration and underestimating the need for flexibility measures (Kober & Panos, 2021).

Other models developed within the TIMES modelling framework also tend to use few time slices. For instance, the Australian (AusTIMES) (C. Butler et al., 2020; Reedman, 2019), U.K. (UKTM) (Daly & Fais, 2014), Scottish TIMES models (Dodds, 2021; Scotland, Scottish Government, & APS Group Scotland, 2018) use 16 time-slices, Danish (TIMES-DK) (Balyk et al., 2019) use 32, Californian (CA-TIMES) (McCollum et al., 2012) 48 and Swiss TIMES energy system model (STEM)

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[5] Myopic foresight means that the foresight of years for optimization is shorter than the full time horizon analysed. Therefore, the optimization is performed iteratively to cover the whole time horizon.

[6] Perferct foresight means that the foresight of the model covers analysed time horizon fully.

(Kannan & Turton, 2014) 144. However, the TIMES modelling framework seems to be able to support at least 2016 time slices (Panos, 2019). Although low temporal resolution leads to underestimating the flexibility needed for VRES integration, according to T. Kober and E. Panos (Kober & Panos, 2021), having more than 672 time-slices does not improve the model accuracy.

The comparison of the abovementioned models' features is given in Table 1 and Table 2. Compared features include modelling framework, optimization type (single year, myopic and perfect foresight), spatial resolution, temporal resolution (number of time slices), biomass use in electricity and heat generation, power to heat (P2H) technologies (heat pumps, electric boilers), CCS, hydrogen production through electrolysis, how the transport sector development is determined (assumed or optimized), smart EV charging, V2G EV charging, biofuel use in transport. Features that could not be determined were marked "N/A".

Table 1. The comparison of features of energy planning models that cover power, district heating and transport sectors (1st out of 2)

Source	Modelling framework	Optimization	Spatial resolution	Number of time slices	Biomass in power and heat gen.	P2H	CCS	Hydrogen through electrolysis	Transport sector development	Smart EV charging	V2G	Biofuels in transport
(Gea-Bermúdez et al., 2021)	Balmorel	Myopic foresight	Northern and Central Europe, based on bidding zones	384	+	+	+	+	Assumed	+	-	+
(T. Brown et al., 2018)	PyPSA-Eur-Sec-30	Single year	Thirty European countries	8760	-	+	-	+	Assumed	+	+	-
(Kiviluoma & Meibom, 2010)	Balmorel	Single year	Finland (3 areas used for the heating sector)	4368	+	+	+	-	Assumed	+	+	-
(Kiviluoma & Meibom, 2011)	Balmorel	Single year	Finland (3 areas used for the heating sector)	8760	+	N/A	N/A	-	Assumed	+	+	-
(Juul & Meibom, 2012)	Balmorel	Single year	Scandinavian countries and Germany	1176	+	+	-	+	Optimized	+	+	N/A
(Gunkel et al., 2020)	Balmorel	Myopic foresight	Nordics, Baltics and central north-west Europe	8760	+	+	-	-	Assumed	+	+	-

Source: created by the author

Table 2. The comparison of features of energy planning models that cover power, district heating and transport sectors (2nd out of 2)

Source	Modelling framework	Optimization	Spatial resolution	Number of time slices	Biomass in power and heat gen.	P2H	CCS	Hydrogen through electrolysis	Transport sector development	Smart EV charging	V2G	Biofuels in transport
(European Commission. Joint Research Centre. Institute for Energy and Transport., 2013)	TIMES	Perfect foresight	EU-28 countries plus Switzerland, Iceland and Norway	12	+	+	+	+	Optimized	-	-	+
(C. Butler et al., 2020)	TIMES	Perfect foresight	Australia (16 zones)	16	+	+	+	+	Optimized	-	-	+
(Daly & Fais, 2014)	TIMES	Perfect foresight	UK (90 wind energy regions)	16	N/A	N/A	-	+	Optimized	-	-	N/A
(Dodds, 2021; Scotland et al., 2018)	TIMES	Perfect foresight	Scotland (single region)	16	+	+	+	+	Optimized	-	-	-
(Balyk et al., 2019)	TIMES	Perfect foresight	Denmark (East and West)	32	+	+	-	+	Optimized	-	-	+
(McCollum et al., 2012)	TIMES	Perfect foresight	California (single region)	48	+	N/A	+	+	Optimized	-	-	+
(Kannan & Turton, 2014)	TIMES	Perfect foresight	Switzerland (single region)	144	+	+	-	+	Optimized	+	-	+

Source: created by the author

From the literature review of studies on the least-cost decarbonization of transport and energy sectors, the following conclusions were made:

- The most suitable tool to determine the least-cost decarbonization pathways is an energy planning model that relies on optimization by minimizing the total discounted costs. There are quite a few different modelling frameworks to develop such models, like Balmorel, Markal, MESSAGE, TIMES, OSeMOSYS, PyPSA, etc. Note: mostly Balmorel and TIMES models were discussed under this section, not because they are better equipped for this task but because the publications with these models were better suited to the topic.
- A model with perfect foresight, i.e. the optimization is performed for the whole modelling time horizon, could be the best choice to determine the least-cost development pathways. Myopic planning might result in delayed strategic investments and higher costs for reaching emission abatement targets.
- When analyzing decarbonization pathways, it is essential to account for sector coupling as it could provide substantial flexibility benefits that enable the integration of VRES at lower costs. However, a relatively high temporal resolution should be used in the models to represent the flexibility needs adequately.
- Optimizing transport investments could provide valuable insights as it determines the least-cost transport development pathway and enables the model to choose between flexibility from power and transport sector coupling and other flexibility means.

None of the models found in the scientific literature covers power, district heating and transport sectors, and includes all four of the previously mentioned aspects, i.e. works by minimizing total discounted costs, has perfect foresight, has relatively high temporal resolution and optimizes transport investments.

To fill a research gap in the scientific literature, integrated transport, power and district heating sectors model for assessing the least-cost pathways, which ensure near-zero carbon emissions, was developed. The model includes all four abovementioned aspects. The model was developed for Lithuania’s case. However, the model can be adapted for other countries with some modifications.

During the development process, it was noticed that the transport modelling approaches used in other energy planning models do not consider the possibility of imported used vehicles, constituting the vast majority of newly registered cars in Lithuania. Though it is not the case in major countries, it is not unique to Lithuania either, as Cyprus, Czech Republic, Estonia, Latvia, Malta, Poland, Romania, and Slovakia have non-declining vehicle age distributions (Held et al., 2021). If all newly registered vehicles are brand new, it is expected to see a declining vehicle age distribution because as vehicles age, more and more vehicles are scrapped and replaced by new ones. If used vehicles are imported, it gives a skewed bell shape for a vehicle age distribution, peaking at some vehicle age greater than 0. Failing to account for such vehicle age distributions might yield too optimistic changes in the transport sector and overestimated emission reductions. Furthermore, in energy planning models, vehicles typically retire at a set lifetime[7], i.e. the number of vehicles added to the stock remains constant until the end of the lifetime. However, in real life, the number of vehicles gradually decreases due to wear and tear. Jacopo Tattini and Maurizio Gargiulo addressed this problem by utilizing a new feature of TIMES and applying a survival probability curve (Tattini & Gargiulo, 2018). Unfortunately, this approach does not support non-declining vehicle age distributions because it would mean that the survival probability would have to exceed 100% for specific ages. For this reason, a unique approach was designed for this thesis to represent non-declining vehicle age distributions and their changes.

[7] In general, energy planning models use lifetimes to determine when installed capacity should be removed. This approach is reasonable for power plants as investment decisions are made assuming a lifetime for technology, and typically, power plants reach those lifetimes, if not closed due to a political decision.

2. CROSS-SECTORAL POWER, DISTRICT HEATING AND TRANSPORT MESSAGE MODEL

The MESSAGE modelling framework was chosen for the creation of the model for integrated assessment of least-cost decarbonization pathways of power, district heating and transport sectors due to several reasons:

1. It calculates the least-cost development pathway by minimising the system's total discounted costs;
2. The optimization is performed with perfect foresight;
3. The modelling framework has high flexibility, i.e. the modeller can freely define temporal and spatial resolution, technologies (processes), resources, energy forms (commodities) and various constraints;
4. It is widely used. The UK's academic and policy literature review (Hall & Buckley, 2016) showed that the MESSAGE modelling framework is the second most used modelling framework in the UK after MARKAL family frameworks, including TIMES;
5. It can be acquired free of charge;

TIMES modelling framework was seriously considered for this model as it works on the same principles as MESSAGE but is more commonly chosen in the scientific literature. However, these modelling frameworks have a steep learning curve, and as the functionality of both frameworks is very similar, MESSAGE was chosen due to prior experience.

2.1. MESSAGE modelling software

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a modelling framework designed to create medium to long-term energy system models for energy planning, scenario development, and energy policy analysis. (International Institute for Applied System Analysis, 2012; 'MESSAGE', 2013) Originally, MESSAGE was developed at International Institute for Applied Systems Analysis (IIASA) in Vienna. However, International Atomic Energy Agency (IAEA) acquired the newest version of MESSAGE software at the time and made several improvements, of which the user interface was the most significant enhancement (International Atomic Energy Agency, 2007). A special agreement between IAEA and IIASA allows using MESSAGE within IAEA and its Member States free of charge (International Institute for Applied System Analysis, 2012, 2020).

MESSAGE software was used to develop models for various studies. For example:

- A study to assess open and closed nuclear fuel cycle options for France (Velasquez, e Estanislau, Costa, & Pereira, 2020);
- A multi-criteria analysis of nuclear power in the global energy system (Lehtveer, Makowski, Hedenus, McCollum, & Strubegger, 2015);
- An analysis of the impacts of wind and solar PV deployment on the structure and operation of the electricity system (Johnson et al., 2017);

- Research on renewable energy technology integration for the island of Cyprus (Taliotis et al., 2017);
- Study on the potential role of nuclear energy in national climate change mitigation strategies (International Atomic Energy Agency, 2021);
- An analysis of PHEV's role in maximizing the integration of variable renewable sources in Brazil's power system (Soares M.C. Borba, Szklo, & Schaeffer, 2012).

The main principle of how MESSAGE works is based on optimising the objective function under set constraints. Usually, this objective function is the sum of all discounted costs (International Atomic Energy Agency, 2007) (see equation (1)). These costs include fixed, variable, investment, emissions-related, and other user-specified costs. In MESSAGE, it is assumed that costs related to operation and maintenance (variable and fixed costs) are incurred in the middle of the year, while investment costs are at the beginning of the year. Therefore different discount factors are applied for these types of costs.

$$objF = \sum_t (DF_1(t) \times \Delta t \times (TVC_t + TFC_t) + DF_2(t) \times \Delta t \times TIC_t); \qquad (1)$$

where: $DF_1(t)$ – discount factor for discounting from the middle of the year; $DF_2(t)$ – discount factor for discounting from the beginning of the year; Δt – the length of period t in years; t – time period, with values ranging from 1 to n. TVC_t – total variable costs in period t; TFC_t – total fixed costs in period t; TIC_t– total investment costs in period t;

The model calculates cost values for each period instead of each year unless the period length is one year. It is assumed that costs are spread uniformly between period years. Thus, costs in a period are first discounted to the beginning of that period and then to the beginning of the first modelling year.

$$DF_1(t) = \prod_{i=1}^{t-1} \left(\frac{1}{1+dr}\right)^{\Delta i} \cdot \sum_{j=0}^{\Delta t-1} \frac{\left(\frac{1}{1+dr}\right)^{j+\frac{1}{2}}}{\Delta t}; \qquad (2)$$

where: $\sum_{j=0}^{\Delta t-1} \frac{\left(\frac{1}{1+dr}\right)^{j+\frac{1}{2}}}{\Delta t}$ – average discount factor for discounting from the middle of period years to the beginning of period t, $\prod_{i=1}^{t-1} \left(\frac{1}{1+dr}\right)^{\Delta i}$ – discount factor for discounting from the beginning of period t to the beginning of the first modelling year, dr – discount rate, Δt – the length of period t in years, Δi – the length of period i in years

$$DF_2(t) = \prod_{i=1}^{t-1} \left(\frac{1}{1+dr}\right)^{\Delta i} \cdot \sum_{j=0}^{\Delta t-1} \frac{\left(\frac{1}{1+dr}\right)^{j}}{\Delta t}; \qquad (3)$$

where: $\sum_{j=0}^{\Delta t-1} \frac{\left(\frac{1}{1+dr}\right)^{j}}{\Delta t}$ – average discount factor for discounting from the beginning of period years to the beginning of period t

$$TVC_t = \sum_{tm} \sum_{\tau} \left(act_{tm,\tau,t} \times \eta_{tm,t} \times varC_{tm,\tau,t} \right) + UDVC(act_{tm,\tau,t}); \qquad (4)$$

where: $act_{tm,\tau,t}$ – the activity level of technology in some operation mode tm, time slice τ and period t, expressed in how much of the main input is consumed; $\eta_{tm,t}$ – efficiency of technology; $varC_{tm,\tau,t}$ – variable cost rate by technology and operation mode, time slice and period; $UDVC(act_{tm,\tau,t})$ – user-defined variable costs, which are a function of the activity level.

$$TFC_t = \sum_{tm} \sum_{\mu=t-LT}^{t} \left(ncap_{tm,\mu} \times fxC_{tm,t} \right) + UDFC\left(ncap_{tm,\mu}\right); \qquad (5)$$

here: $ncap_{tm,\tau}$ – annual capacity addition of technology tm in period μ; LT – a lifetime of a technology; $fxC_{tm,t}$ – fixed cost rate by technology and period; $\sum_{\mu=t-LT}^{t}\left(ncap_{tm,\mu}\right)$ – total installed capacity of technology in period t; $UDFC\left(ncap_{tm,\mu}\right)$ – user-defined fixed costs, which are a function of annual capacity addition.

$$TIC_t = \sum_{tm} \left(ncap_{tm,t} \times invC_{tm,t} \right) \qquad (6)$$

here: $invC_{tm,t}$ – investment cost rate of technology tm in period t.

Optimization in MESSAGE is performed either with glpk or cplex optimiser. Both can be configured to use different calculation methods, but typically a simplex algorithm is used as “experimentation on a wide variety of linear programs has shown that it provides the best overall performance” (IBM, 2018). Conceptually, all feasible solutions to linear programming problems can be represented by a polytope bounded by set constraints. A simplex algorithm works by scanning for the vertice of such polytope that yields the best results (Karloff, 2009). However, the simplex algorithm solves only maximization problems. Therefore, the minimization problem has to be transformed into a maximization problem. According to the duality theory, the optimization problem can be viewed from two perspectives, called primal and dual. If the minimization problem is primal, then maximization is dual and vice versa. Primal is the original problem, and dual is derived. If primal has an optimal solution, so does the dual, and the values of objective functions coincide at optimal points, meaning that a solution to both primal and dual can be achieved by solving either. MESSAGE’s cost minimization problem is primal, and revenue maximization is dual. Primal has two types of variables – activity and capacity, while dual has a single type – shadow prices. Each constraint in primal has an associated shadow price in dual, which shows how much the objective function value would change if the right-hand side of the constraint equation would be changed by one unit. For example, in the case of electricity demand constraint in primal, the associated shadow price in dual shows how much it would cost to produce one additional unit of electricity. It can be interpreted as a marginal cost of electricity, i.e. electricity market price. In

MESSAGE, all activity and capacity values are taken from the primal solution and all marginal prices from dual.

In MESSAGE, the minimization of total discounted costs of the modelled system ensures that exogenously set demands are satisfied in a least-cost way throughout the whole modelling time horizon, forming a partial equilibrium at each time slice. The solution is limited by constraints, some of which are inbuilt, and others can be user-defined. For example, demand and energy balance constraints are inbuilt, which forces the model to satisfy exogenously set demands and ensures energy balance in the system. In other words, considering the whole supply chain, the supply must cover set demands. There also can be user-defined constraints like limits on CO_2 emissions or the penetration of specific technologies. If the model cannot find a solution where all constraints are always satisfied, it gives an error of an infeasible solution.

Essentially, MESSAGE models are partial equilibrium models as they focus on one to several markets, typically on electricity and district heating, neglecting economic interactions with other markets. In MESSAGE, demands are perfectly inelastic and set exogenously, while the supply is determined by the modelled supply chain – a set of linked technologies and energy forms. Since the model minimises total discounted costs, cheaper production is always preferred, giving an ascending price supply curve (See Figure 6). The point of equilibrium determines the quantity and price of the products, and such points are calculated for each modelled time slice as supply and demand change throughout the day.

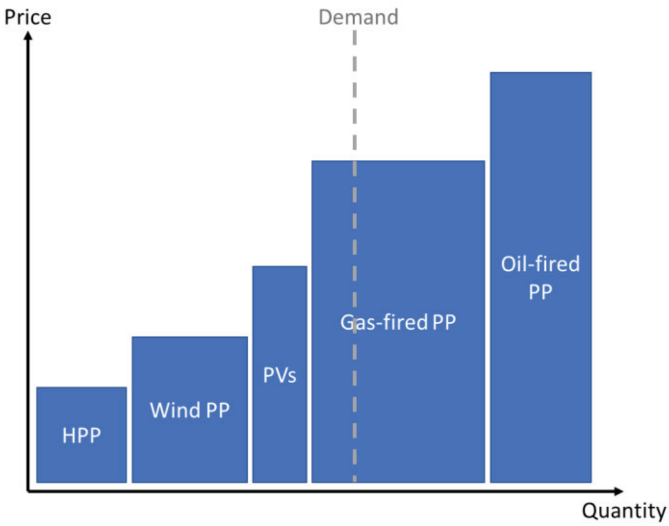


Figure 6. Partial equilibrium in MESSAGE

Source: created by the author

In MESSAGE, the supply chain is defined through the reference energy system, called the "energy chain".

2.1.1. Energy chain

MESSAGE software is a flexible framework that enables detailed modelling of various systems. Even though it was designed to be used to develop energy system models, it can be used to model other systems due to its flexibility in how the model structure is defined. Model structure in MESSAGE is defined by the so-called *energy chain*[8]. This *energy chain* comprises *energy forms*, *technologies*, *resources,* and *energy levels*. *Energy form* is some product/commodity produced or consumed by *technologies*, representing processes that produce or transform one *energy form* into another. *Resources* are depletable *energy forms* for which it is possible to set usage limits. An *energy level* is a group of energy forms. Usually, *energy levels* are used to group *energy forms* into primary, secondary, and final energy. Such grouping corresponds to the one used in statistical energy balances. Primary energy refers to extracted or produced and cleaned energy sources in their natural state, e.g. Hard coal, lignite, peat, firewood, biogas, municipal and industrial waste, crude oil, and natural gas. Secondary energy is a transformation product of primary or other secondary energy sources. Electricity, heat, and petroleum products are just several examples of secondary energy. Final energy refers to primary and derived energy carriers consumed by industry, construction, transport, and other sectors. Even though, as mentioned, in MESSAGE models, energy levels are usually used to represent primary, secondary, and final energy, it is not a prerequisite. Therefore, expanding this grouping to use a completely different one is possible. An energy chain of a straightforward energy system model is given below in Figure 7.

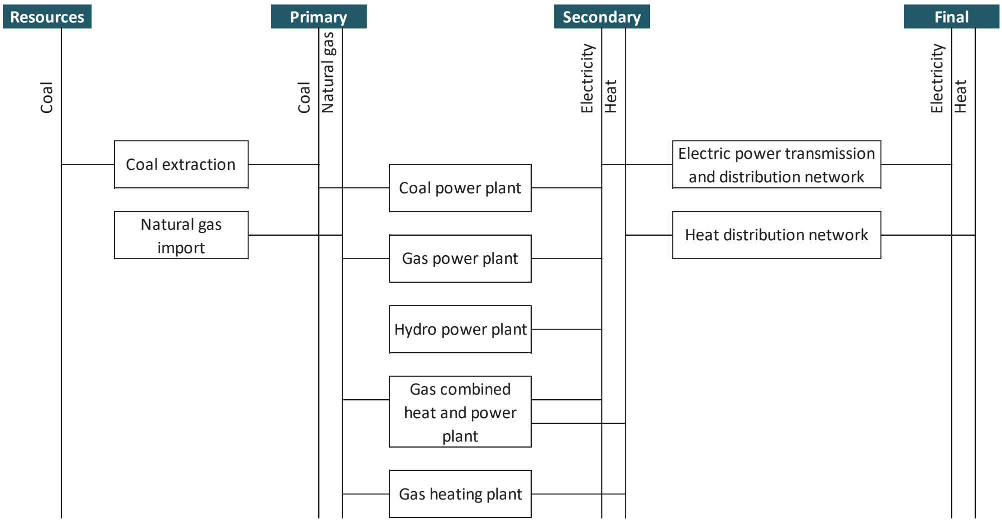


Figure 7. Energy chain of simple energy system model

Source: created by the author

This example has four *energy levels*: Resources, Primary, Secondary, and Final. Coal is the only available resource in this system. The coal extraction process

[8] Terms used within MESSAGE modelling software are given in italics.

(technology) turns it into useable fuel – Coal in the Primary *energy level*. Natural gas is also modelled as a fuel in the Primary *energy level*. However, it is assumed that there are no local natural gas resources, so it has to be imported. Imports in MESSAGE are modelled by adding technology, which produces imported *energy form* but has no input. Fuels in the Primary *energy level* are transformed into electricity, and heat *energy forms* in the Secondary *energy level* by *technologies* representing different heating plants, power plants, and combined heat and power plants. In this case, hydropower plant technology does not have any inputs but outputs electricity (In more complex models, it can be connected to water storage, representing a dam fed by a river. Multiple hydropower plants can be modelled in a cascade arrangement.). To account for grid losses, there are *technologies* that represent electricity and heat transmission and distribution networks, which use electricity and heat from the Secondary *energy level* to produce corresponding energy forms in the Final energy level. Energy demands are set for energy forms in the last energy level.

2.1.2. Techno-economic parameters

A set of parameters are used to define technology. There are various parameters, but the only prerequisite parameter is the output. All other parameters are optional. The parameters can be grouped into two broad categories technical and economic. Technical parameters include:

- Input or multiple inputs – energy forms consumed by technology;
- Output or multiple outputs – energy forms produced by a technology;
- Output efficiency – the efficiency of input-to-output conversion;
- Coefficients for related inputs – a ratio of related input to the primary input;
- First and last year – modelling year from which technology is enabled and disabled;
- Historical capacity – defines the capacities and the years of instalment for already operational units;
- Lifetime – number of years for which the installed capacity can operate after the year of instalment;
- Minimum utilization rate – a minimum fraction of installed capacity at which the technology must operate;
- Operation time – a maximum fraction of the year for which the technology can operate;
- Construction time – time required to build a new unit.

Technical parameters also include various constraints:

- Bounds on activities that can put various limits on technology operation;
- Linked storage constraints on activities that link the operation of the technology with some storage;
- Constraints type 1 and 2 – two groups of user-defined constraints that link activities or capacities of different technologies;
- Power change that limits how quickly the technology can ramp up and ramp down its output;

- Bounds on new capacity additions that limits how much new capacity can be installed per modelling period;
- Bounds on total installed capacity.

The MESSAGE modelling framework has other technical parameters, which were not described above as they were not used when developing a model.

There are four economic parameters:

- Variable costs – costs that depend on production volumes;
- Fixed costs – costs that depend on installed capacity;
- Investment costs – costs incurred to build additional capacity;
- Emission costs – the cost of CO_2 emission allowances.

It is worth mentioning that modelled technologies can have one or several activities, and having multiple activities enables the modelling of different operation modes. For example, some CHP plants can work in condensing mode, in which it produces only electricity, or in CHP mode, in which it produces both electricity and heat. Parameters related to an operation, like inputs, output, efficiencies and variable costs, can be defined for each activity separately.

2.1.3. Temporal resolution

MESSAGE modelling software is based on 32-bit architecture. For this reason, there are limitations on maximum model size, as the generated equation matrix is initially stored on Random-access memory, also known as operating memory. Theoretically, the 32-bit architecture allows using a maximum of 4 GB of RAM. However, in reality, this number is lower due to certain memory reservations. Additionally, as the model size increases, computational time can become an issue. There is a non-linear relation between the number of equations and computational time. At maximum MESSAGE model size, optimization time can exceed 20 hours. Often energy planning models are calibrated by trial and error, which means that it takes almost a month to run 30 consecutive optimizations.

Model size mainly depends on the number of *technologies*, modelled years, and temporal resolution. Probably the biggest impact has a temporal resolution. The higher the resolution, the bigger the model because almost a complete set of defined equations has to be generated for each time slice. High temporal resolution means that each modelled year is represented by many time slices, e.g. 8760, where each time slice corresponds to one hour in a year. Most of the time, such a high number of time slices is impossible. Therefore, some kind of aggregation is necessary. It can be done by having larger time slices so that a one-time slice would represent 2, 3, 4, or more hours. Another way is to use representative days. Each modelled year is split into any number of seasons. Then, single or multiple representative days are selected or derived for these seasons. Representative days can be selected using simple heuristics, picking multiple periods with different meteorological conditions and load curves, random selection, or more advanced techniques like clustering and optimising representative periods (Poncelet, Höschle, Delarue, Virag, & D'haeseleer, 2017). Another approach is to derive these representative days by creating their profiles instead of picking them. Profiles can be created by averaging, using clustering centroids or a probabilistic approach. Whether picked or derived, representative days are split into time slices.

Let us assume that a modelled year is represented by 12 seasons, corresponding to each month in a year. Each season is represented by two representative days: typical workdays and typical off-work days. Each representative day is split into hour-long time slices. Such a model would have 576 (12*2*24) time slices. However, if temporal aggregation would be done only by increasing the size of time slices, then each time slice should be around 15 hours long to have a similar time slice count as in the before-mentioned case. Usually, temporal aggregation with representative days is more beneficial since it can decrease the number of time slices and still retain the ability to model hourly fluctuations. It is crucial when modelling energy systems with a large share of renewable sources.

MESSAGE modelling software uses a combination of both approaches (see Figure 8), i.e. the user has to select representative seasons and daytypes and specify the size of time slices. However, it is possible to model as many seasons as there are weeks in a year; also, up to 7 different daytypes, corresponding to weekdays, can be used for each season and up to 71 time slices for each daytype, enabling higher than fully hourly temporal resolution. Temporal aggregation can be done by increasing the size of time slices, using representative days, or both.

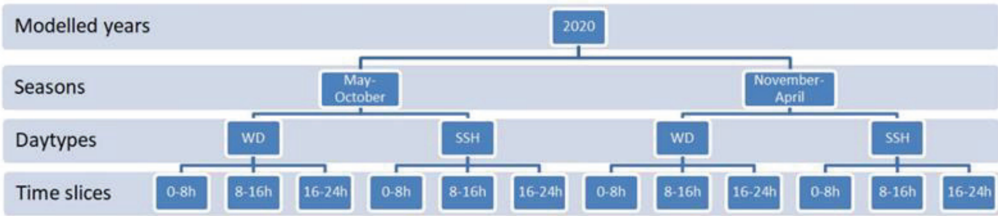


Figure 8. Temporal aggregation in MESSAGE

Source: created by the author

2.2. Model structure

The developed model consists of two hard-linked models: one covering the power and district heating sectors and another covering the transport sector.

The power and district heating sectors model covers eight markets: the electricity market and 7 district heating markets (6 of the biggest Lithuanian cities and 1 for all other district heating systems). These two sectors were modelled in a single model because combined heat and power (CHP) plants provide electricity and heat. Also, heat pumps use electricity to produce heat.

The transport sector model covers road and rail transportation of passengers and freight. Air and water transportation were excluded from this model because of four main reasons:

1. Technological difficulties in decarbonizing these transportation modes;
2. Data availability;
3. Limited effect on the power sector as direct electrification is unlikely;
4. Increase in model size.

It is worth mentioning that even though rail transport was modelled, its representation is practically limited to the current state due to a lack of data.

Unfortunately, it is unclear how much rail electrification costs, how much electric trains cost, and how passenger rail travel and freight volumes could change in the future.

The transport sector is linked to the power sector through the consumption of electricity and hydrogen (See Figure 9). In the case of a vehicle to the grid (V2G), electricity stored in electric vehicles could potentially be provided back to the grid.

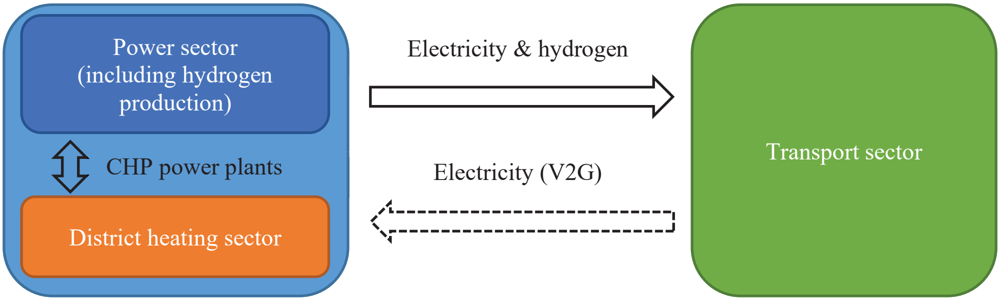


Figure 9. Sectoral interlinkages

Source: created by the author

2.3. Time horizon and temporal resolution

At the moment of model development, the latest available data was from 2020, so 2020 was selected as the first modelling year. All monetary values are discounted to the first year. The modelling time horizon covers four five-year periods from 2020 to 2040 and two ten-year periods from 2040 to 2060. Each modelled period is represented by 12 seasons, corresponding to months; each season by two-day types – workdays and SSH (Saturdays, Sundays and Holidays); and each day type by 24 time slices. In total, each modelled period is split into 576 time slices. A relatively high temporal resolution was selected to represent variable renewable energy sources (VRES) adequately.

2.4. Discounting

A 4% social discount rate was applied following recommendations in EU Impact Assessment Guidelines (Hermelink & de Jager, 2015; Van Bossuyt, 2015). Though countries that opt for a social discount rate on average use a 3.3% discount rate, others that lean more on a financial perspective apply, on average 5.7%, which probably corresponds to WACC (Hermelink & de Jager, 2015). In energy planning models, lower discount rates result in a more significant contribution of RES, while higher ones are more favourable to fossil fuel-fired technologies (García-Gusano, Espegren, Lind, & Kirkengen, 2016). It is because power plants that utilize RES have high investment costs but low running costs. On the contrary, fossil fuel power plants have relatively low investment costs but high running costs. The 4% social discount rate applied in this model reflects the view of society on future costs and benefits compared to present ones (European Comission, 2015, p. 55).

2.5. Modelling principles of power and district heating sector

As previously mentioned, the electricity and district heating supply model covers eight markets: one for electricity and seven for district heating, six of which are of the largest Lithuanian cities, while the seventh cover the remaining district heating markets. The model focuses on supply in these markets. Meanwhile, the energy demands are externally set for the model. The developed model includes the following:

- Gas and oil-fired thermal power plants;
- Gas, biomass and waste-fired cogeneration plants;
- Biomass-fired boiler plants;
- Onshore and offshore wind power plants;
- Solar power plants;
- Hydropower plants;
- Electricity imports and exports;
- Electricity storage facilities;
- Power reserves;
- Fuel supply (natural gas, fuel oil, biomass, waste);
- Hydrogen production by electrolysis;
- Carbon capture and storage;
- CO_2 emissions accounting;
- Constraints on domestic electricity generation, electricity and heat production from renewable sources.

Created power and district heating sector model has a unique feature – a probabilistic representation of electricity generation in wind power plants, which was developed to improve the representation of wind variability in energy planning models with aggregated temporal resolution.

A simplified energy chain of the electricity and district heating model is presented in Figure 10.

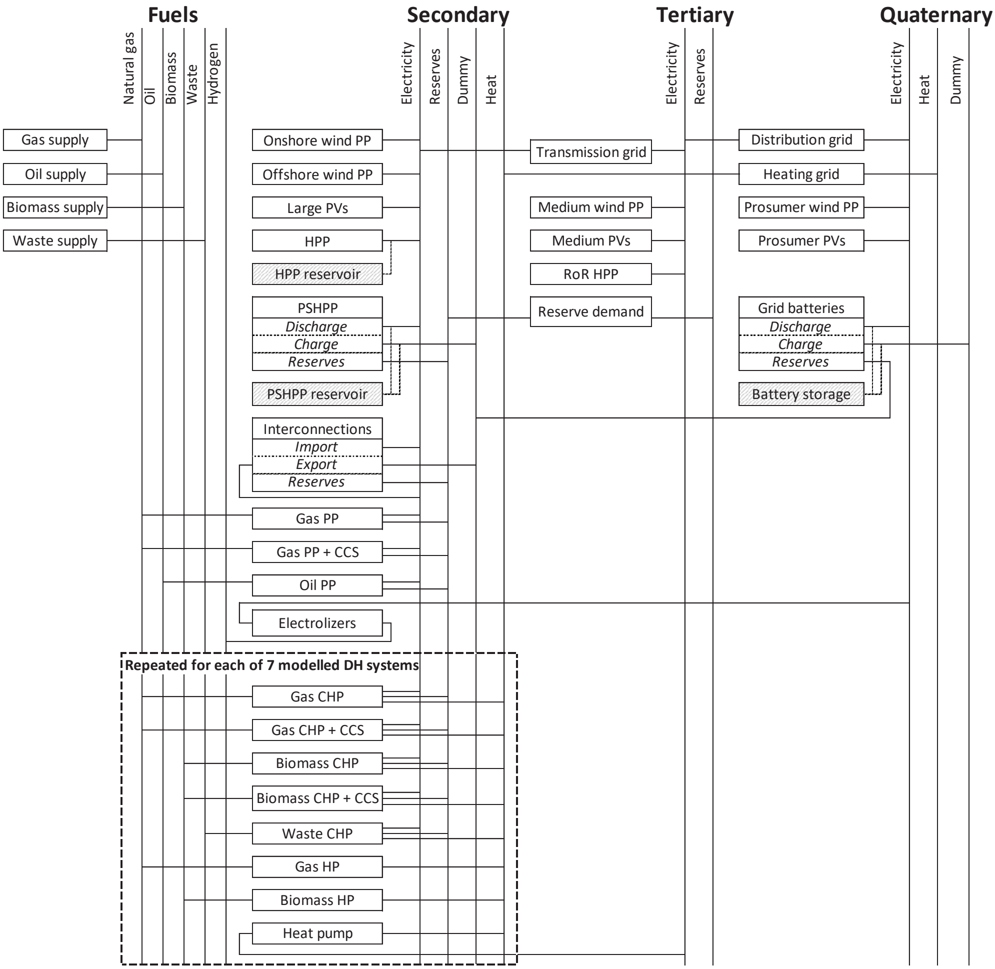


Figure 10. Simplified energy chain of power and district heating sectors in the model

Source: created by the author

2.5.1. Electricity and district heating demand

Demands are the driving force in the MESSAGE model since the model optimizes the energy supply chain to ensure demands are satisfied in a least-cost way. As the name implies, there are demands for electricity and district heating in the power and district heating sectors. In MESSAGE, demands are set exogenously. Thus, the demand changes throughout the modelling periods have to be estimated outside the MESSAGE.

According to the Lithuanian electricity transmission system operator (Litgrid, 2021a), in 2020, Lithuania's total final electricity consumption was equal to 10.977 TWh, of which 4.24 TWh was consumed in industry, 0.091 TWh in transport, 0.258 TWh in agriculture, 3.059 TWh in households, and 3.328 TWh in the service sector and by other consumers. Transmission and distribution losses are 0.997 TWh, equal to 8.3% of total electricity demands, not including the charging of the pumped storage hydropower plant. Around 2.1% (Civitta, 2015) is in the transmission grid, and 6.2% in the distribution grid.

Electricity consumption is not static, as it changes throughout the seasons, weeks and days. For instance, Figure 11 highlights how electricity consumption in Lithuania changes with the month. Electricity consumption is lowest during the summertime, while it is highest in December and January. Figure 12 shows electricity demand variations throughout the week. It is apparent that electricity consumption is lower during the weekends. Furthermore, the shape of the consumption curve is somewhat different between workdays and weekends. Consumption is at its lowest at night since most businesses are closed and residents are asleep. Demand rises after 5 a.m. as people wake up and prepare for the workday. It peaks around 9–10 a.m. on workdays and 10–11 a.m. on weekends. At this moment, most of the businesses are open. Afterwards, the demand slightly reduces. Then, around 5–6 p.m., there is another peak that corresponds to the end of typical work hours, which is superseded by a gradual decrease. The morning peak tends to be higher than the evening peak during workdays, while it is the opposite on weekends.

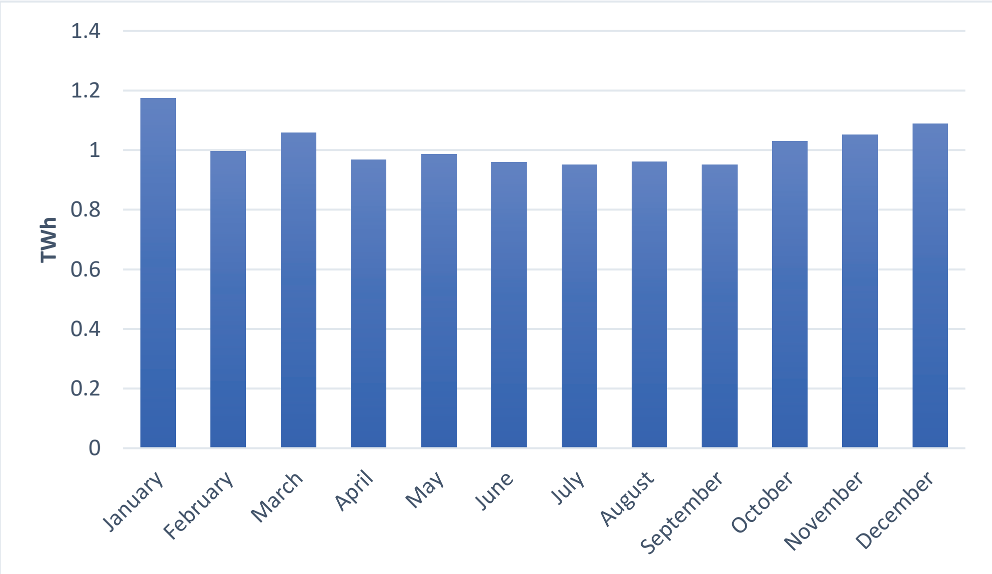


Figure 11. Total final electricity consumption in Lithuania in 2019 by month

Source: created by the author based on (Litgrid, 2021b) data

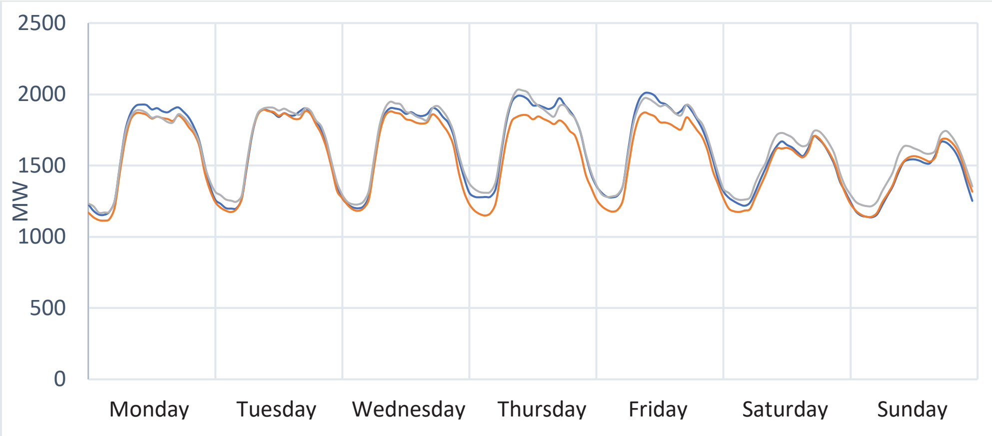


Figure 12. Variations in electricity demand from 07-01-2019 to 27-01-2019[9] by the weekday in Lithuania

Source: created by the author based on (Litgrid, 2021b) data

An electricity demand profile for the model was created based on the statistical data (Litgrid, 2021b). A year in the model is represented by twelve months, and each month by two day types – workdays (WD) and Saturdays, Sundays and holidays (SSH), so hourly values of corresponding days were averaged to create a profile (see Figure 13). The profile determines temporal variations in consumption. However, the magnitude depends on assumed annual electricity consumption. However, it is worth mentioning that exogenously set electricity demands do not include electricity consumption in transport, district heating heat pumps and energy storage as it is endogenously calculated.

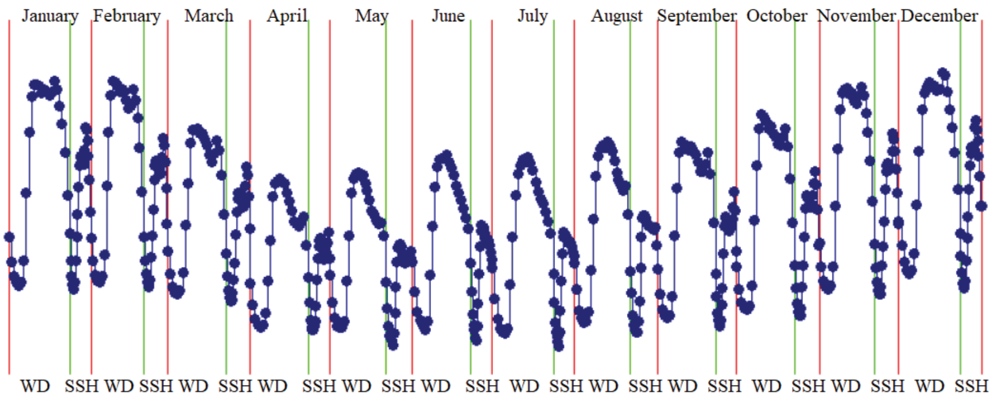


Figure 13. Electricity consumption profile used in the model

Source: created by the author based on (Litgrid, 2021b) data

[9] The first week of January was omitted because January 1 is Tuesday and it is off-work day.

In 2020, 49 licensed heat suppliers operated in 60 Lithuanian cities and district municipalities. 19 suppliers are unregulated independent heat producers and 26 are regulated independent heat producers. In total, throughout 2020, 8,02 TWh of heat was generated by the heat suppliers (Lietuvos šilumos tiekėjų asociacija, 2021a), of which, according to the latest openly available detailed overview of heat providers' activities (Lietuvos šilumos tiekėjų asociacija, 2018), 32.6% was supplied to Vilnius, 15.9% to Kaunas, 10.2% to Klaipėda, 5.4% to Šiauliai, 4.3% to Panevėžys, 2.6% Alytus and 29% to other district heating systems. District heating demand profiles were created based on project BENTE data (Lindroos et al., 2018) (see Figure 14). The same profile was used for all district heating systems.

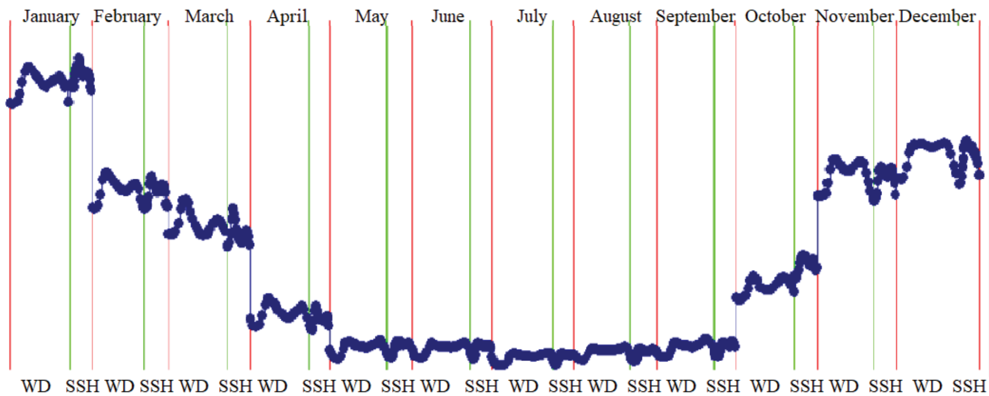


Figure 14. District heating consumption profile used in the model

Source: created by the author based on (Lindroos et al., 2018) data

Demand assumptions for modelled years are given in the **Definition of the scenarios** section.

2.5.2. Electricity-only thermal power plants

Electricity-only thermal power plants burn fuel to produce a single product – electricity. Such power plants were modelled by representing them with technologies with two operation modes, called *alternative activities* in MESSAGE (See Figure 15). One operation mode is for electricity generation, and the second is for power reservation. In electricity generation mode, the technology uses fuel as an input to produce electricity as an output. In power reservation mode, there is no input, only reserves as an output. Technology can work in both modes simultaneously by allocating available capacity between the two modes. For instance, a 100 MW power plant can use 80 MW for electricity production and the remaining 20 MW for the reserves. The model chooses how capacity is allocated at each time slice endogenously. Reserve modelling is explained in greater detail in the section **Reserves**. Inputs and outputs and technical and economic parameters define power plants.

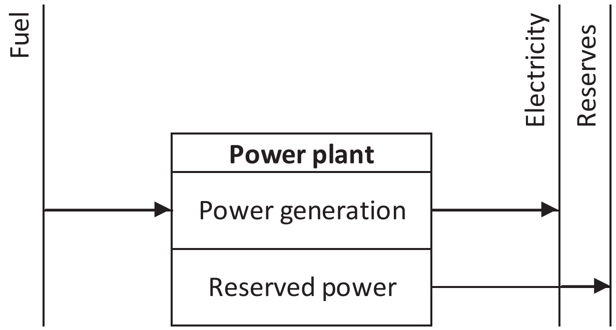


Figure 15. Electricity-only thermal power plant in the energy chain

Source: created by the author

The developed model contains four electricity-only thermal power plant technologies:

- Combined cycle gas turbine (CCGT) in Lithuania power plant (unit 9);
- Gas turbines (GT) in Lithuania power plant (units 7–8);
- Mažeikiai oil power plant[10];
- New CCGT power plant.

Techno-economic parameters for all modelled technologies are given in Techno-economic parameters. These parameters for electricity-only thermal power plants are given in Table A.1.

2.5.3. Combined heat and power plants

Combined heat and power (CHP), unlike electricity-only thermal power plants, produce not only electricity but also heat for the district heating system. CHP plants can be differentiated into steam extraction and backpressure power plants. The difference between these two types is that steam extraction power plants can change the ratio of electricity and heat production, while in backpressure power plants, this ratio is fixed.

CHP steam extraction plants were modelled by technology with three operation modes: condensing mode, CHP mode and reserved power mode (see Figure 16). Condensing mode represents the operational regime of electricity-only generation, while CHP mode combines heat and electricity generation at a fixed share, corresponding to the ratio of maximum power and heat outputs. Since the model allows allocating installed capacity to work on different modes simultaneously, technology can change the electricity and heat production ratio by changing how much capacity is allocated to each mode. Reserved power mode works the same way as in electricity-only thermal power plants. In total, 9 CHP stream extraction technologies were modelled:

- Vilnius gas 3rd CHP plant;

[10] Mažeikiai oil power plant is actually a combined heat and power plant, but in this model it was treated as electricity-only thermal power plant, because it does not supply heat to the district heating system, instead it supplies heat for the oil refinery.

- Kaunas gas CHP plant;
- 7 CCGT CHP plants. One for each region modelled.

CHP back pressure plants' technologies have only a single operation mode – CHP mode. These power plants produce electricity and heat at a fixed ratio. It was considered that backpressure plants do not participate in reserve supply because of limited operational flexibility. 16 back pressure CHP plant technologies were modelled:

- Four waste CHP plant technologies for Vilnius, Kaunas, Klaipėda, and Other regions;
- Eight biomass CHP plant technologies. One for each region modelled plus one additional for the Kaunas region;
- Two gas CHP plant technologies for Alytus and Other regions;
- Vilnius gas/biomass 2nd CHP plant;
- One waste heat CHP plant for the Other regions.

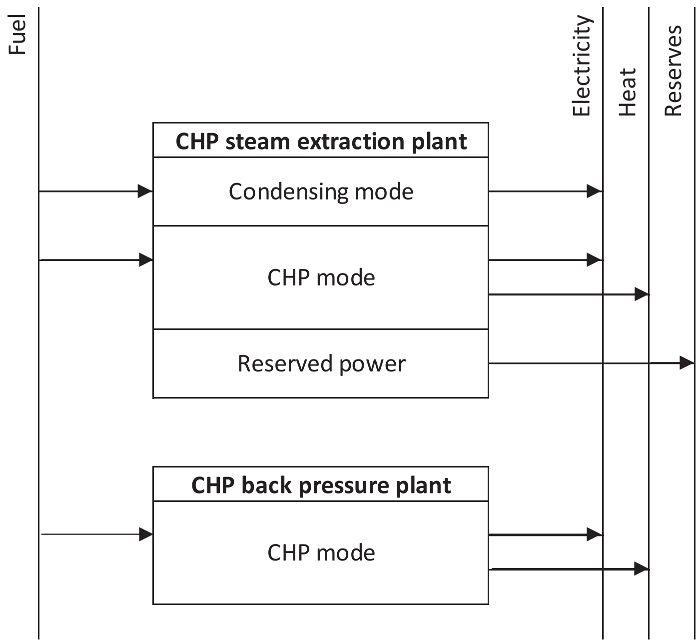


Figure 16. Steam extraction and backpressure CHP plants in the energy chain

Source: created by the author

Technical and economic parameter assumptions used when defining CHP plant technologies are given in Table A.2 and Table A.3. If construction time and investment costs are not given in the table, it means that constraints were placed to prohibit building new power plants of this type, and only already built ones can be used until the end of their lifetimes.

2.5.4. Heating plants

Heating plants were modelled relatively simply by technologies which consume fuel to produce heat (see Figure 17). The model includes biomass, natural gas and heat pump heating plants.

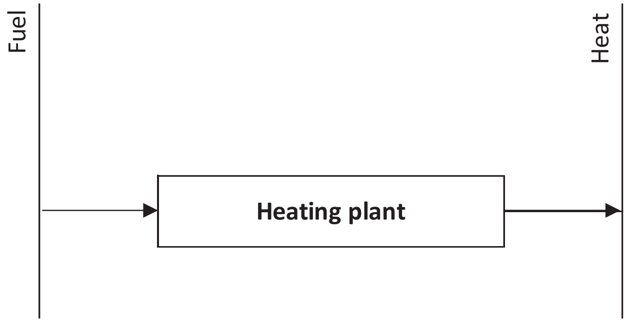


Figure 17. Heating plant in the energy chain

Source: created by the author

Techno-economic parameters of heating plants used in the model are given in Table A.4, installed capacities of biomass heating plants in Table A.5 and natural gas-fired heating plants in Table A.6. There are currently no district heating heat pumps in Lithuania.

2.5.5. Wind, solar and hydropower plants

2.5.5.1. Wind power plants

Four types of wind power plants were modelled:

- Large offshore wind power plants;
- Large onshore wind power plants connected to the transmission grid;
- Medium onshore wind power plants connected to the distribution grid;
- Small onshore prosumer wind power plants.

The modelling principles of all types are the same. Wind power plant technologies have a single operation mode with no inputs, only a single output – electricity. However, the level of outputted energy form differs between these technologies. Significant offshore and onshore wind power plant technologies produce electricity at the Secondary level. It means electricity has to pass through the transmission and distribution grid before reaching the consumers, considering both transmission and distribution grid losses and costs imposed by grid operators. Medium onshore wind power plants output electricity at the Tertiary level; thus, produced electricity has to pass only through the distribution grid. Prosumer wind power plants produce electricity at the place of consumption, i.e. electricity does not need to pass through the grid. Therefore additional grid costs do not apply. This technology outputs electricity at the Quaternary level. How these wind power plant technologies connect in the energy chain is given in Figure 18.

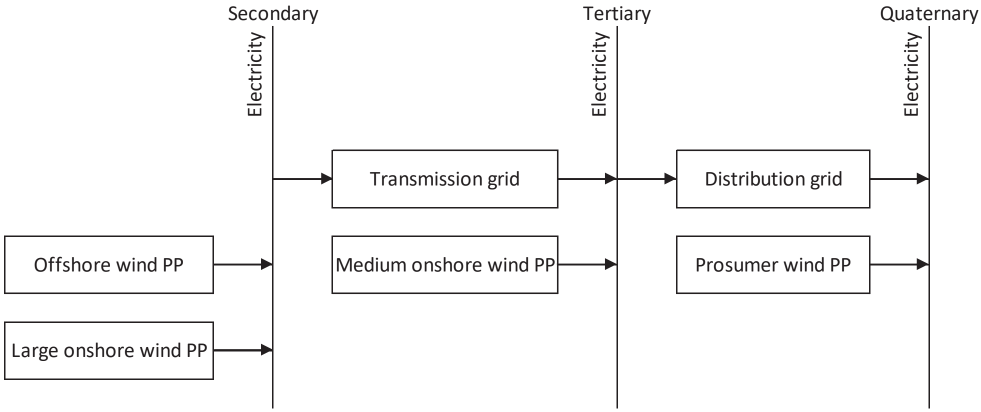


Figure 18. Wind power plants in the energy chain

Source: created by the author

The technologies of these four types of wind power plants differ not only by the energy level of outputted electricity but also by techno-economic parameters. In general, larger wind power plants have lower costs per kW, but smaller ones can be connected closer to the demand, i.e. to the distribution grid or, in the case of the prosumer, just beside the consumer, reducing grid losses. Furthermore, prosumers avoid costs imposed by grid operators when consuming their own generated electricity. The techno-economic parameters are given in Table A.7.

In 2019 Lithuania, the total installed wind power plant capacity was equal to 536.2 MW, of which 432.3 MW were connected to the transmission grid and 103.9 MW to the distribution grid. There were no offshore wind power plants. However, it is planned to build a 700 MW offshore wind farm by 2030 (*National energy and climate action plan of the Republic of Lithuania for 2021–2030*, 2019). Based on permits to generate electricity (State Energy Inspectorate under the Ministry of Energy of the Republic of Lithuania, 2019), no wind power plants were identified belonging to prosumers. However, investments in new prosumer wind power plants are enabled in the model. Installed wind power plant capacities by type and year are given in Table A.8.

The problem with representing wind power generation in aggregated time models lies in almost a total loss of variability when averaging. That can be seen in Figure 19. For this reason, a probabilistic wind speed modelling approach for generation in wind power plants was developed to properly represent fluctuations in wind power generation in an energy planning model with an aggregated temporal resolution. The approach was published in the paper *Incorporation of wind power probabilities into long-term energy system development analysis using bottom-up models* (Norvaiša, Galinis, & Neniškis, 2021). The main idea is to represent the possible wind power output variations using wind probability curves for each time slice. Each time slice is split into several sub-slices. Different wind speeds are used for each sub-slice, e.g. maximum, minimum and average. The length of sub-slices corresponds to the probabilities of these wind speeds. Such an approach enabled a better representation of wind power extremes and required balancing capacities. However, it increases the number of time slices several times.

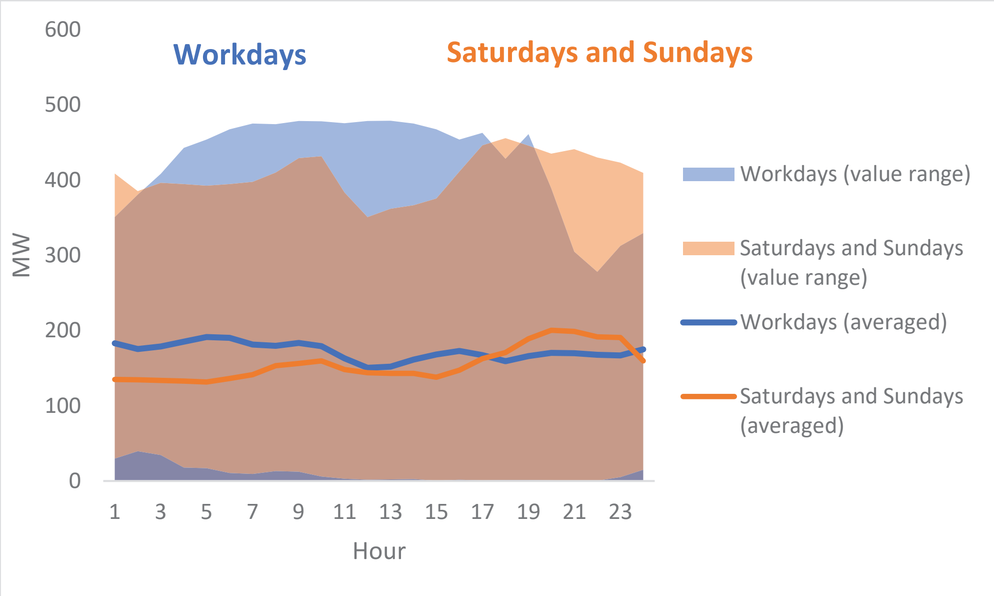


Figure 19. Lithuanian hourly averaged wind power plant generation in October 2020

Source: created by the author based on (Litgrid, 2021b) data

It was decided to adjust this approach during the model development as a high temporal resolution was deemed necessary to model sectoral interrelations adequately. Splitting each time slice into several ones to represent wind variability would substantially increase a high temporal resolution, resulting in increased model size and longer computational times. For this reason, wind speed probability curves were set not for each time slice but for each modelled day type. Wind speed distribution data (www.renewables.ninja[11] (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016) was used as a data source) of each modelled season and day type was approximated with 24 data points (see Figure 20). Each of these 24 data points represents wind speeds in integer values equal in probability. Integer wind speed values were used for the approximation to make it easier to convert wind speeds into energy generated in wind power plants. Typically, power curves for wind power plants are given in integer wind speed values. Twenty-four data points were used so that each data point could be assigned to one hourly time slice to represent seasonal wind speed probability distribution in a single typical day.

[11] Renewables.ninja provides hourly wind speeds, solar irradiance as well as output curves for wind and solar power plants based on geographical location. This platform uses NASA MERRA-2 dataset.

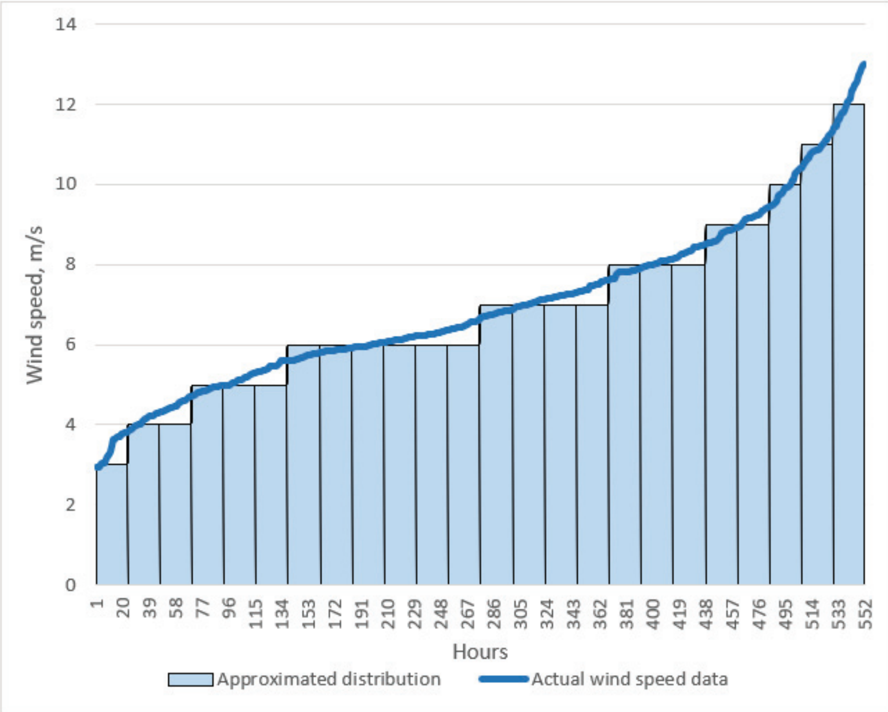


Figure 20. Approximated wind speed distribution of 2020 October workdays in Lithuania.

Source: created by the author based on www.renewables.ninja (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016) data

Such approximation was made for each modelled season and day type. Then, these approximated wind distributions were shuffled using a developed algorithm (the shuffling algorithm is explained in detail in the paper *Representation of wind power generation in economic models for long-term energy planning* (Neniškis & Galinis, 2018)[12] to mimic wind variability. Generated wind curves in this way were used with wind power plant power curves to create generation curves for wind power plants. Power curves for onshore wind power plants are given in Figure 21. This figure expresses the output in ratio to total installed capacity (power factor). As an example, generation curves for large and medium onshore wind power plants on October workdays are given in Figure 22. It was assumed that prosumer wind power plants would have the same generation curves as medium wind power plants. Different curves were generated for each modelled season and day type.

[12] Though the publication of adjusted approach (Neniškis & Galinis, 2018) is older than publication with sub-slices (Norvaiša, Galinis, & Neniškis, 2021), but actually it is based on the ideas in approach with sub-slices. Not the other way around.

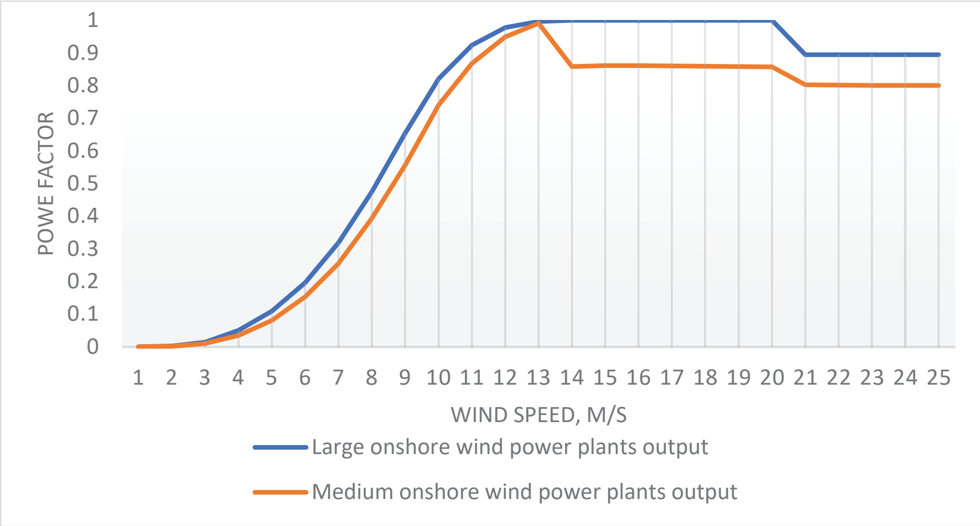


Figure 21. Weighted average power curves of large (connected to transmission grid) and medium (connected to distribution grid) onshore wind power plants

Source: created by the author

The output of wind power plants increases with wind speed. However, it starts to decrease at wind speeds higher than 13 m/s for medium and from 21 m/s in large wind power plants because some models stop the turbines to prevent damage at these wind speeds. All models in Lithuania stop producing electricity at speeds higher than 25 m/s.

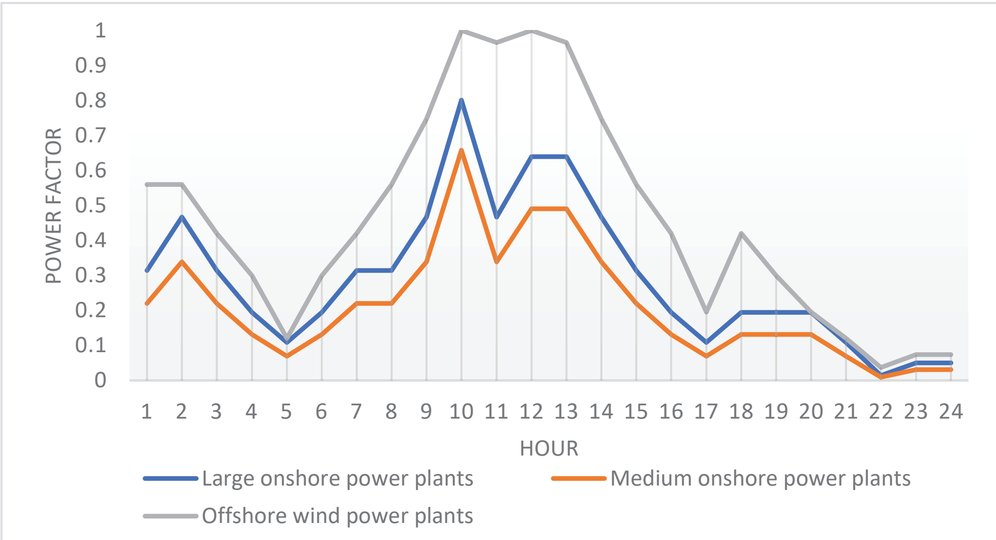


Figure 22. Generated wind generation curves for large and medium onshore as well as large offshore power plants on October workdays

Source: created by the author

Typically, offshore winds are higher compared to onshore winds. For this reason, a different wind speed dataset was used from renewables.ninja. A location in the Baltic sea near the Palanga coast was specified when downloading it. Wind speeds were aggregated the same way as with onshore wind power plants. However, the algorithm was not used to shuffle the values as it would mismatch the curves of onshore wind power plants. Curves for the offshore winds were created manually by following the principle that offshore winds follow the same pattern as onshore winds. A power curve of Siemens SWT-3.6-107 offshore turbine was used to determine the output of offshore wind power plants. THE Siemens SWT-3.6-107 model was chosen as a representative model as it is one of Europe's most commonly used models. The power curve of this offshore turbine model is given in Figure 23.

In MESSAGE, the generated wind curves can be set either on the technology's main output or plant factor (synonym for capacity factor and power factor). By setting it on main output, technology must produce precisely according to the set curve or not produce at all, while setting it on plant factor allows lower or equal production to the set curve. It was chosen to set it for plant factor to account for possible curtailment.

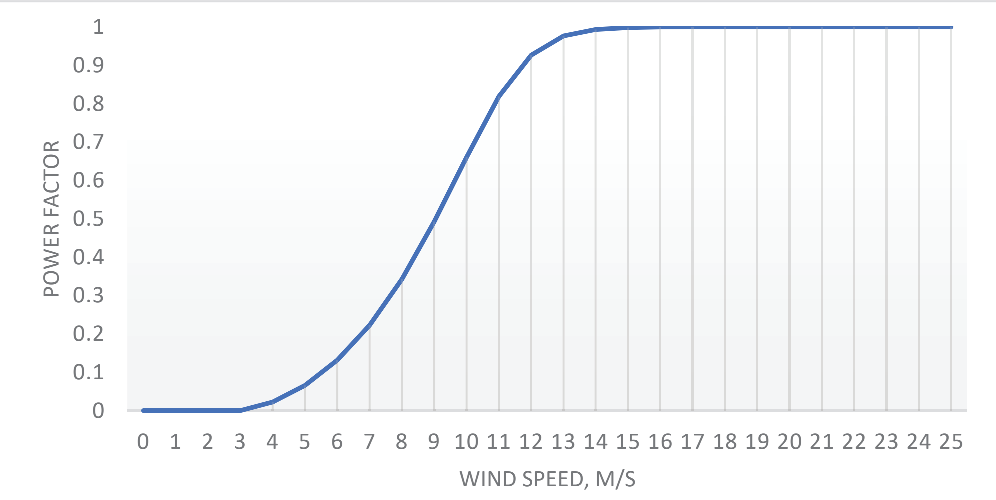


Figure 23. The power curve of Siemens SWT-3.6-107 offshore wind turbine

Source: created by the author based on (Pierrot, 2018) data

2.5.5.2. Solar power plants

Solar photovoltaic (PV) power plants were differentiated into three groups, similar to wind power plants: large solar PV farms, medium solar PV farms and prosumer PVs (See Figure 24). Large solar PV farms are the cheapest. However, since they are connected to the transmission grid, the generated electricity must flow through transmission and distribution grids to reach consumers. It means transmission and distribution grid losses and costs apply. Medium solar PV farms are connected to the distribution grid. Therefore, only losses and costs of the distribution grid apply. Prosumer PVs are the most expensive of these three groups. On the other hand, network losses and grid costs do not have to be calculated since they are connected on the consumer side. Techno-economic parameters of solar power plant groups are given in Table A.9.

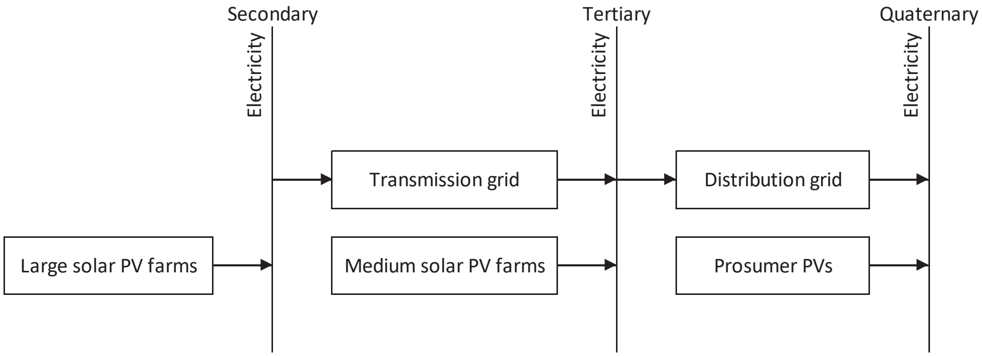


Figure 24. Solar PV power plants in the energy chain

Source: created by the author

In 2019, 87.08 MW of medium solar PV farms and 11.69 MW of prosumer PVs were installed in Lithuania. However, no large solar PV farms were connected to the transmission grid. Installed capacities by a year of instalment are given for each modelled PV group in Table A.10.

Solar power plants' seasonal and hourly variations were modelled by setting curves on capacity factors for PV technologies. These curves were generated based on www.renewables.ninja hourly data (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016). The model uses aggregated temporal resolutions, so hourly data was aggregated by averaging specific hours of workdays and off-work days for each season:

$$PF_{z,i,j} = \frac{\sum_{k \epsilon A_{z,i}} PF_{z,j}}{n(A_{z,i})}; \quad (7)$$

where: PF – power factor (dimensionless); z – modelled season; i – modelled day type; j – hour; k – date; $A_{s,t}$ – a set of dates that matches season z and day type i; $n(A_{z,i})$ – the number of elements in $A_{z,i}$ set.

Generated curves are given in Figure 25 for workdays. Curves for off-work days are almost identical, so it was deemed unnecessary to present them. The same curves were used for all three PV groups. However, additional multipliers were introduced for medium (0.9554) and prosumer solar power plants (0.9239) to account for different full-load hours.

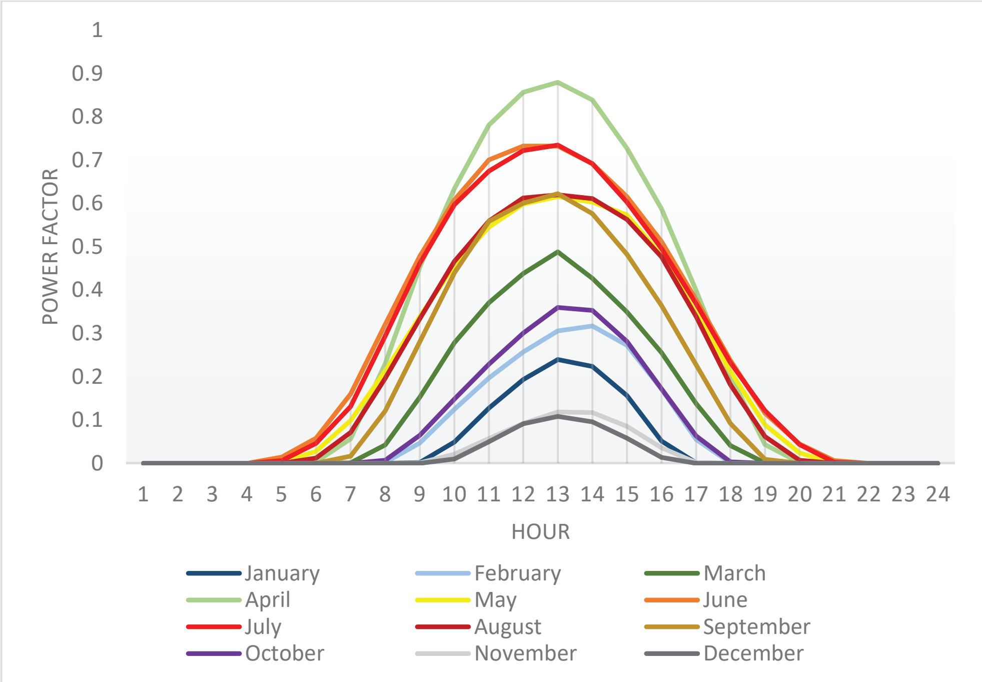


Figure 25. Aggregated power factor curves for solar power plant electricity generation during workdays.

Source: created by the author based on www.renewables.ninja (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016) data

In Figure 25, the highest power factor values are reached in April. It might seem like an error. However, this can be explained by very low cloud cover. Lithuanian Hydrometeorological Service (2021) data show that in 2019, April had a relatively high number of sunny hours – 313 (242 in 2020).

Unfortunately, by averaging PV generation curves, variability is reduced. See Figure 26. Unlike with the wind power plant generation curves, some variability is retained. The averaging approach was considered sufficient for solar power plants because, otherwise, every hour in a year should be modelled, or some other approach should be applied. For instance, each season could be split into low, medium and high irradiance days to reduce the loss of variability when averaging. However, this would increase the number of time slices three-fold, substantially increasing the model size and optimization time.

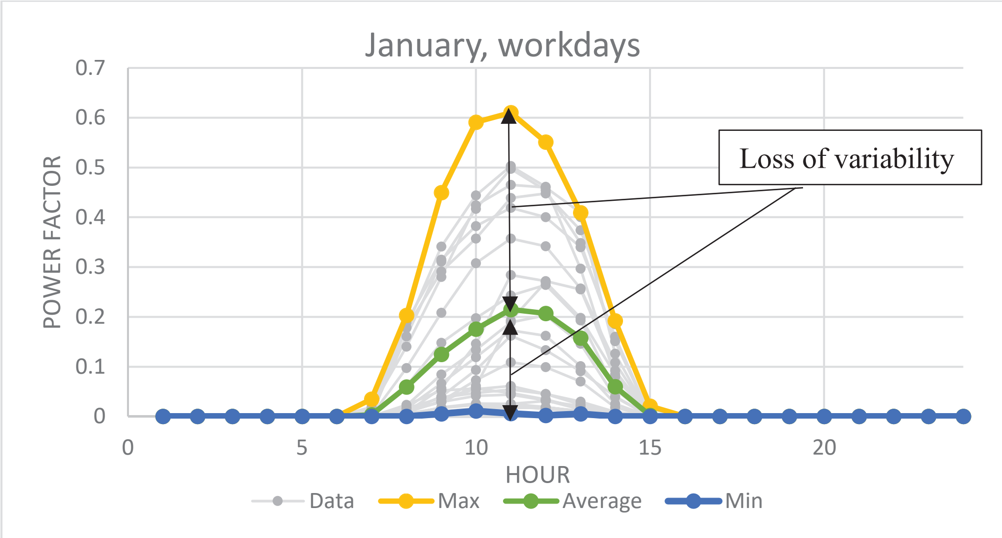


Figure 26. Loss of variability in solar power plant generation when averaging generation curves

Source: created by the author based on www.renewables.ninja (Pfenninger & Staffell, 2016; Staffell & Pfenninger, 2016) data

2.5.5.3. Hydropower plants

The developed model includes two types of hydropower plants (HPP): reservoir (RHPP) and run-of-river hydropower plants (RoR HPP). A pumped storage hydropower plant was also modelled. However, it is described in the section **Energy storage**. Reservoir hydropower plants use a dam to store water in a reservoir. For this reason, storage has to be modelled and linked with RHPP technology. This linkage is done through *linked storage constraints on activities*. The model reduces energy stored in the reservoir by one unit when one unit of electricity is produced. Hydropower plants do not consume any fuel, so representing technologies have no input. However, electricity generation by HPPs is limited by the river flow. The river flow was modelled through constraint, adding stored energy to the reservoir. In the described model, in 2020, it adds 0.242 TWh and 0.349 TWh in other modelled years. These numbers are based on statistical HPP electricity generation in Lithuania (Litgrid, 2021a; Statistics Lithuania, 2020a). A curve based on the BENTE project (Lindroos et al., 2018) data was added to the constraint to account for seasonalities. See Figure 27. There is a possibility that the reservoir will be filled quicker by the river than HPP can use up that water to generate electricity. In this case, once the reservoir limit is reached, the model will not be able to satisfy all equations and will return that solution is infeasible. This problem can be solved by adding overflow technology, which reduces stored energy in the reservoir by dumping part into the Dummy energy form. RHPP can also supply reserves to the system. Reserved power was modelled the same way as with electricity-only thermal power plants.

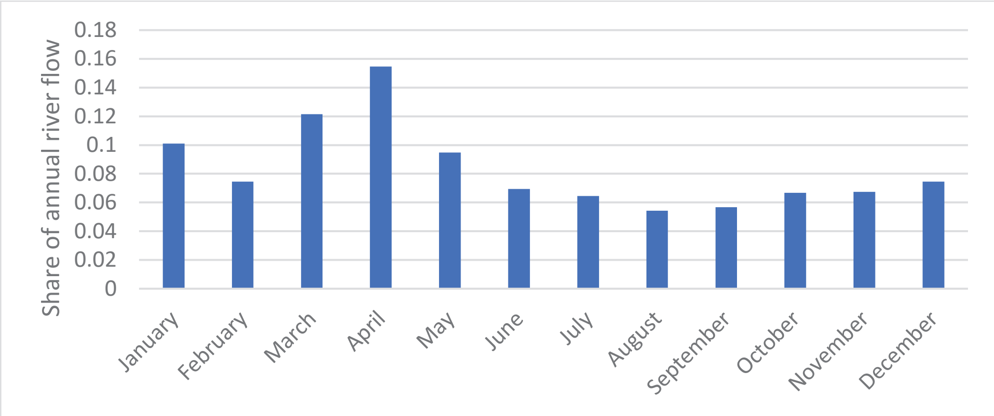


Figure 27. River flow in shares by month

Source: created by the author based on (Lindroos et al., 2018) data

Run-off-river hydropower plants do not have a reservoir, so they are modelled similarly to wind and solar power plants by technology with no input and electricity as an output (see Figure 28). Seasonal fluctuations are accounted for by adding the curve to the output. It was assumed that RoR HPPs do not provide the reserves because these power plants almost always produce the maximum they can. Reducing the electricity generation to provide reserves would be economically inefficient since there are no fuel costs, and electricity is a more valuable commodity than reserves. Techno-economic parameters of hydropower plants are given in Table A.11.

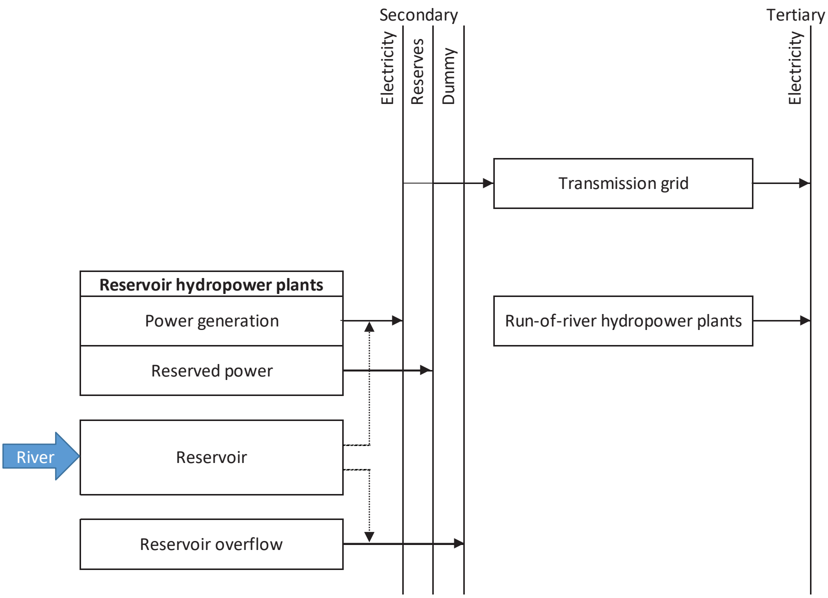


Figure 28. Hydropower plants in the energy chain

Source: created by the author

Lithuania has a single reservoir hydropower plant with a capacity of 100.8 MW and 27 MW of RoR HPPs.

2.5.6. Electricity imports and exports

Lithuania has power interconnections with five countries: Latvia, Belarus, Poland, Russia (Kaliningrad region) and Sweden (See Table 3). Net electricity imports cover more than 70% of the final electricity demand. For this reason, it is essential to adequately represent the imports and exports. Unfortunately, to fully represent the import/export possibilities and prices, the power sectors of neighbouring countries should be modelled. However, it would substantially increase the amount of data required and the model size. Also, gathering data on power systems in Belarus and Kaliningrad would be challenging. Furthermore, the such model size would likely exceed software limitations, requiring to decrease in detail in other parts of the model, e.g. temporal resolution, number of district heating systems or vehicle types modelled. Therefore, it was decided to use a single technology per interconnection.

Table 3. Lithuania's interconnections with neighbouring countries

Interconnection	Capacity
LT-LV	1300 MW
LT-PL	Litpol link: 500 MW + 200 MW (planned by 2025. However, from 2025, this line will be used for systemic needs and not commercial flows) Harmony link: 700 MW (planned to be built by 2025)
LT-SE	700 MW
LT-BY	1300 MW (planned to be decommissioned by 2025)
LT-Kaliningrad	680 MW (planned to be decommissioned by 2025)

Source: created by the author based on BENTE (Lindroos et al., 2018) and NECP (*National energy and climate action plan of the Republic of Lithuania for 2021–2030*, 2019) data.

Each representing technology has three alternative activities: import, reserved power and export (see Figure 29). As the name suggests, import activity represents electricity imports, reserved power cross-border reserve power supply, and export electricity exports. Favourable electricity prices are set for imports and negative for exports.

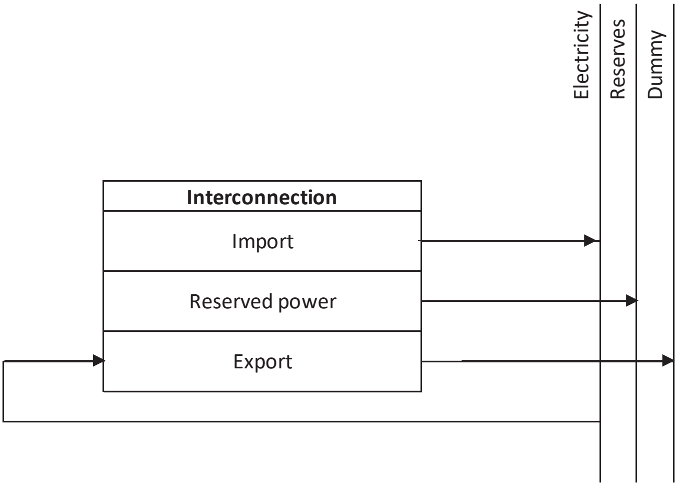


Figure 29. Power interconnection in the energy chain

Source: created by the author

Also, price curves were set for variable costs of import and export activities to represent electricity market price fluctuations in the neighbouring countries (see Figure 30)

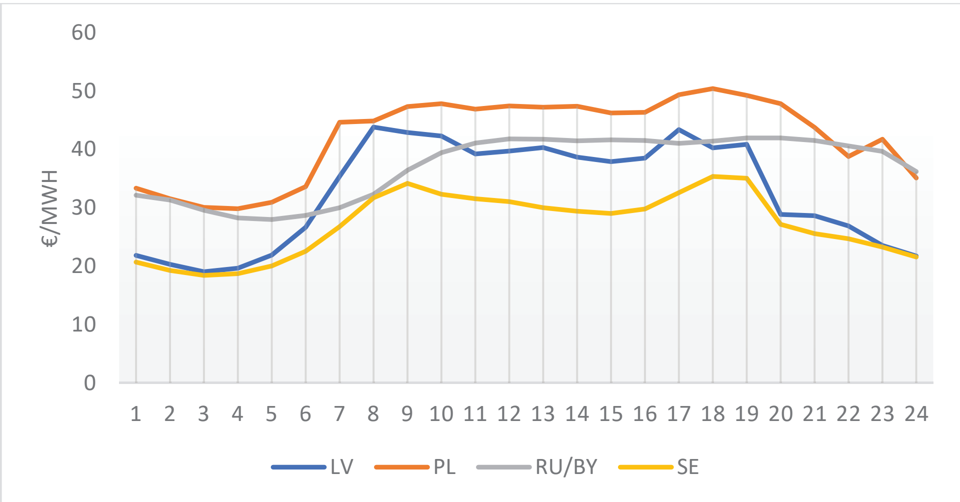


Figure 30. Hourly electricity market prices of countries interconnected with Lithuania on workdays in January 2020

Source: created by the author based on (Nordpool, 2020; PSE S.A., 2020; AO 'ATC', 2021) data

2.5.7. Energy storage

A pumped storage hydropower plant (PSHPP) is modelled somewhat similarly to RHPP. However, instead of the river filling the reservoir, the water is pumped to it by reversing the turbines, i.e. the same units are used for electricity generation and pumping water to the reservoir. It is modelled by adding another alternative activity corresponding to the pumping operation mode. In this operation mode, electricity from the secondary energy level is consumed to increase the energy stored in the reservoir. It produces a dummy energy form because each activity must have an output due to the MESSAGE requirement. This output is linked with the reservoir through the linked storage constraints on activities that specify how much energy stored in the reservoir changes depending on the output of this activity. The charge-discharge cycle efficiency is set by placing a coefficient for this relation. Another difference compared to RHPP is that overflow technology is unnecessary, as PSHPP technology in pumping mode can not overfill the reservoir. The schematic of PSHPP with storage in the energy chain is given in Figure 31. The techno-economic parameters are given in Table A.12.

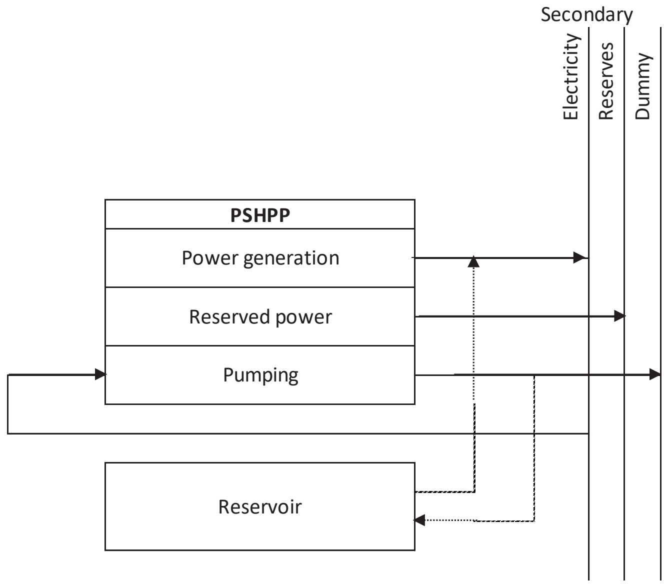


Figure 31. Pumped storage hydropower plant in the energy chain

Source: created by the author

Grid batteries were modelled as another energy storage option. The modelling principles are practically identical to PSHPP, as seen in Figure 32. The main difference is that the size of energy storage is not predetermined, i.e. investments can be made in both storage size and input/output capacity. However, modelling the possibility of investing in storage size is tricky in MESSAGE as there is no such default feature. Therefore a workaround has to be found. One possible way to do it is to use a different technology for investments in battery size. It produces a dummy energy form since the output is a mandatory parameter. A user-defined equation is set to limit the maximum energy stored in a grid battery based on the output of battery size technology, which depends on its capacity. Therefore, the model needs to invest in battery size technology to increase how much energy could be stored in battery storage.

$$E_{stored,\tau} \leq X_{battery\ size,\tau}; \quad (8)$$

where: $E_{stored,\tau}$ – energy stored (totally available) in battery storage in time slice τ in MWyr, $X_{battery\ size,\tau}$ – the output of battery size technology in time slice τ in MWyr.

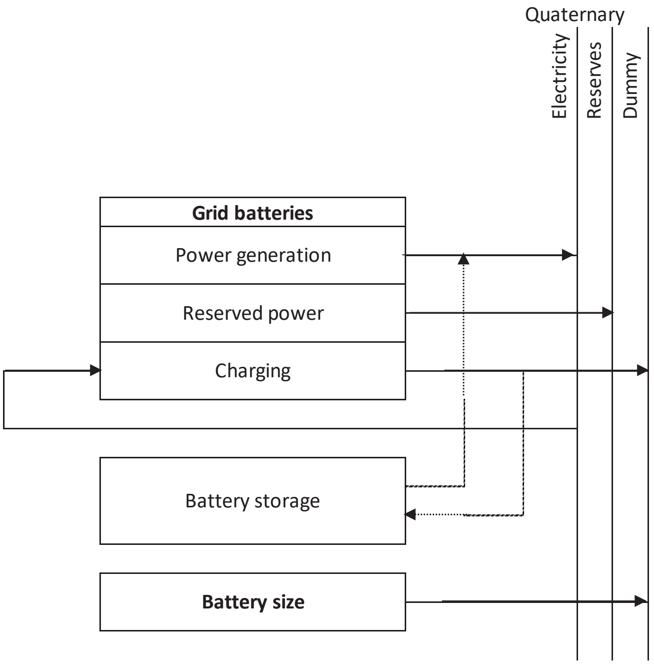


Figure 32. Grid batteries in the energy chain

Source: created by the author

The techno-economic parameters of grid batteries are given in Table A.13.

2.5.8. Reserves

In a power system, electricity generation has to be equal to consumption at any moment in time, i.e. equilibrium has to be ensured. Any disturbances in this equilibrium will affect the system frequency, a representative value of the rotational speed of generators connected to the synchronous system. (Entsoe, 2012) Deviations from standard frequency pose a risk to system stability and equipment safety. In case of frequency deviations, power reserves are utilized to maintain the balance between power generation and consumption. There are three types of reserves: (Entsoe, 2012)

- Frequency containment (Primary) – operating reserves for constant containment of frequency fluctuations. Typically, they activate within 30 seconds of the disturbance.
- Frequency restoration (Secondary) – operating reserves for restoring the frequency to nominal value after disturbance in the balance occurred. Frequency restoration reserves are activated within 15 minutes and free frequency containment reserves.

- Reserve replacement (Tertiary) – operating reserves for freeing up frequency containment and frequency restoration reserves to cope with the subsequent potential imbalance. They are activated within 15 minutes to several hours.

The power reserve activation scheme is given in Figure 33.

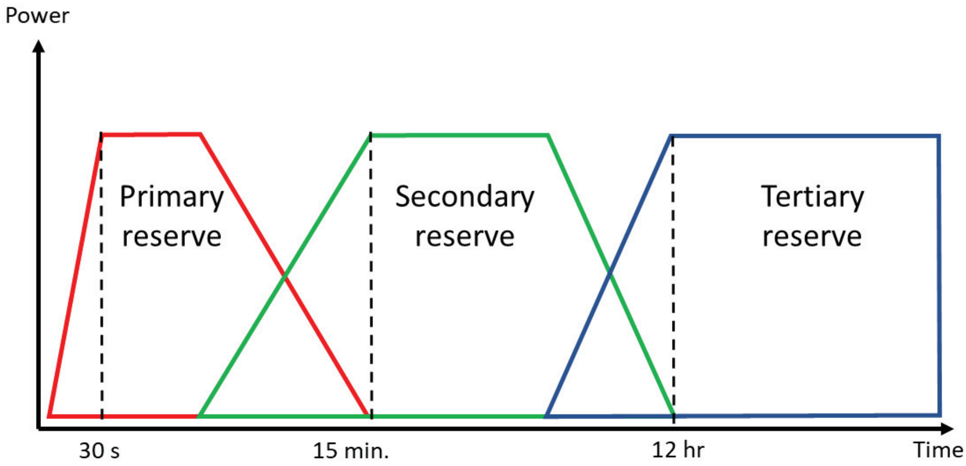


Figure 33. Power reserve activation scheme

Source: created by the author based on (Valstybinė kainų ir energetikos kontrolės komisija, 2019)

Each reserve type should be sized according to the N-1 rule, i.e. equal to or larger than the potential loss of the single biggest unit in operation.

Reserves are modelled as an energy form that has to be supplied by power plants. Except for VRES, all power plants can contribute to the power reserves. Unutilized capacity for power generation at any moment in time of these power plants can be used to provide reserves. For example, if a power plant with a nameplate capacity of 100 MW generates 40 MW of electricity, then the remaining 60 MW can be used to provide reserves. In MESSAGE, it is modelled through alternative activities. Since reserve demands depend on N-1 criteria, demands have to be calculated endogenously based on the biggest unit in operation for each moment in time. In this model, different types of reserves are not differentiated, and the assumption is made that the demand for reserves is equal to three times the potential loss of the largest unit in operation. A *Reserve demand* technology was added, which consumes reserves produced by power plant technologies to generate reserves at the tertiary level (See Figure 34) to set up these endogenous demands. Also, constraints were set to force *Reserve demand* technology to produce three times more than any other power plant generating electricity at any moment (see equation (9)). Therefore, this constraint has to be set for each power plant, whose generation loss can potentially cause significant disturbance in the system.

$$reserves_{\tau} \geq 3 \cdot X_{pp,\tau}; \quad (9)$$

where: $reserves_{\tau}$ is an output of the *Reserve demand* technology in time slice t in MW; $X_{pp,\tau}$ – the power output in MW of the power plant, which can potentially cause a significant disturbance in the system.

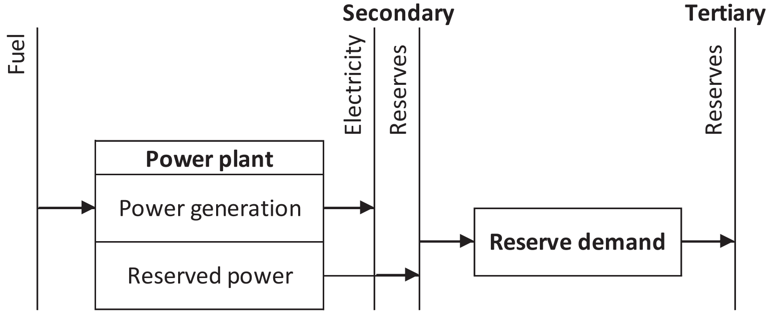


Figure 34. Power reserves in the energy chain

Source: created by the author

2.5.9. Fuel supply

Four fuel types are considered in the power and heat sector: natural gas, heating oil, biomass and municipal solid waste (MSW). Though hydrogen production here is under the power and heating sector, in this model, hydrogen is used as a fuel only for transport. The modelling principles of hydrogen production are given in the section **Hydrogen production**. The supply of the four fuel types mentioned is modelled relatively simply by adding technologies that produce the fuel energy form at a specified price (See Figure 35). The supply is assumed to be inexhaustible, except for waste supply, as it is assumed that annually 615 thousand tons of waste suitable for burning could be provided, equivalent to 175.51 MWyr of energy. In addition, it is assumed that fuel prices are not affected by the amount consumed. MSW has negative costs in the model, meaning the waste power plant earns money to dispose of it. Fuel prices for 2020 are given in Table 4, while their changes throughout the modelling years are in the section **Definition of the scenarios**.

Table 4. Prices of fuels used in power and district heating model for the year 2020

Fuel	Price, Eur/MWh
Natural gas	10.47
Oil	21.07
Biomass	10.06
Municipal solid waste	-12.74

Source: created by the author based on EU reference scenario (European Commission et al., 2021), BALTPOOL (BALTPOOL, 2022), Delfi (Vidūnaitė, 2019) data

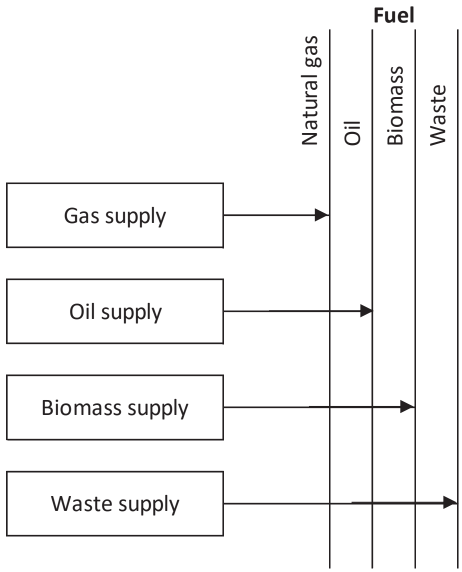


Figure 35. Fuel supply in the energy chain

Source: created by the author

2.5.10. Hydrogen production

Three different hydrogen production through electrolysis technologies were modelled: Alkaline electrolyzer (AE), Proton exchange membrane (PEM), and Solid-oxide electrolyzers (SOE). Modelling principles for all three technologies are the same – electricity is consumed to produce hydrogen (Figure 36). However, techno-economic parameters differ (Table A.14).

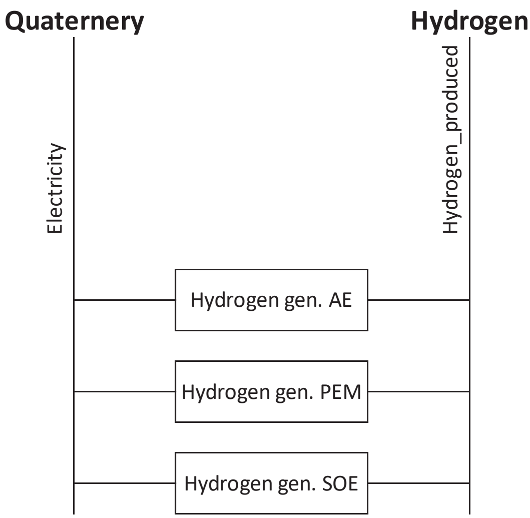


Figure 36. Hydrogen production in the energy chain

Source: created by the author

2.5.11. Carbon capture and storage

Three types of power plants with carbon capture and storage (CCS) are included in the model: CCGT CCS power plants, CCGT CHP plants and biomass CHP plants. The modelling principles for power plants with CCS are the same as for equivalent power plants without CCS. Only techno-economic parameters differ, and emission reductions are added in emission accounting based on fuel consumption in these power plants (see section **Emission** accounting). The technical parameters of CCS plants are given in Table A.15, and the economic parameters in Table A.16.

2.5.12. Emission accounting

CO_2 emissions are calculated based on total fuel consumption, emission factors and emission reduction in power plants with CCS:

$$m_{CO2} = \sum_{fuel} E_{fuel} \cdot EF_{fuel} - \sum_{CCS\ PP} E_{fuel,CCS\ PP} \cdot EF_{fuel,CCS\ PP} \cdot CR_{CO2}; \qquad (10)$$

where: m_{CO2} – CO_2 emissions in kt; E_{fuel} – fuel consumption in MWyr; EF_{fuel} – emission factor in kt CO2/MWyr; $E_{fuel,CCS\ PP}$ – fuel consumption in the CCS power plant in MWyr, $EF_{fuel,CCS\ PP}$ – emission factor of fuel used in CCS PP in kt CO2/MWyr, CR_{CO2} – CO_2 capture rate (dimensionless). Emission factors for different fuels are given in Table 5.

Table 5. CO_2 emission factors

Fuel		CO_2 emission factor	
		kg CO_2/TJ	kt CO_2/MWyr
Natural gas		56100	1.7692
Heating oil		79800	2.5166
Biomass[13]		0	0
Municipal solid waste[14]	Biodegradable	0	0
	Non-biodegradable	91700	2.8919

Source: created by the author based on (Eggleston, Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, & Chikyu Kankyo Senryaku Kenkyu Kikan, 2006) data

[13] Biomass is considered a carbon neutral fuel. Therefore, emissions in the case of biomass-fired power plants with CCS are negative. Emission factor ($EF_{fuel,CCS\ PP}$) of 3.532 kt CO_2/MWyr is used in equation (10) to calculate emission reduction due to operation of biomass-fired power plants with CCS.

[14] The share of biodegradable waste in MSW is assumed to be 49.92% in Lithuania based on (Aplinkos Apsaugos Agentūra, 2020) The share of biodegradable waste in MSW is assumed to be 49.92% in Lithuania based on (Aplinkos Apsaugos Agentūra, 2020)

2.5.13. Constraints

The energy system's development should align with the country's strategic goals. For this reason, three constraints were placed on accounting for national energy policy targets on:

1. Local electricity generation;
2. Electricity generation from RES;
3. Heat generation from RES.

These targets are given in the section **Definition of the scenarios.**

2.5.13.1. Local electricity generation

Constraints on local electricity generation set a minimum limit on the share of final electricity consumption generated within the country. The following equation is used for the constraint:

$$\sum_{pp} X_{pp,t} \geq T_{local\_gen,t} \cdot E_{final\_elec,t}; \tag{11}$$

where: $X_{pp,t}$ is electricity generation of a *pp* power plant in year *t* in MWyr; $T_{local\_gen,t}$ is a minimum share for local generation in year t (dimensionless); $E_{final\_elec,t}$ – final electricity consumption in year t in MWyr.

In MESSAGE, the right-hand side of equations for user constraints can not have any variables, so it must be transformed. Also, there is no direct way to use final electricity consumption in the constraint. However, the output of distribution grid technology can be used as a proxy, as this output must equal the final electricity consumption.

$$\sum_{pp} X_{pp,t} - T_{local\_gen,t} \cdot X_{Elec\_distr\_grid,t} \geq 0; \tag{12}$$

where: $X_{Elec\_distr\_grid,t}$ is the output of electricity distribution grid technology in year t in MWyr.

2.5.13.2. Electricity generation from renewable energy sources

A constraint on electricity generation from RES is formulated similarly to a constraint on local electricity generation. The sum of RES power plants' outputs has to be equal to or greater than the final electricity consumption multiplied by the set minimum share. The output of the electricity distribution grid is used as a proxy for final electricity consumption, as in the previous case.

$$\sum_{pp \in RES} X_{pp,t} - T_{RES\_E,t} \cdot X_{Elec\_distr\_grid,t} \geq 0; \tag{13}$$

where: $pp \in RES$ – power plants attributed to RES power plants; $T_{RES\_E,t}$ is a minimum share for electricity generation from RES in year t (dimensionless).

It should be noted that it is a simplified approach to set lower limits on electricity generation from RES, yielding a slightly lower bound than it should be. However, the precise constraint would be much more complicated, requiring tracking how much electricity is produced from RES and other sources and accounting for losses in the grid, which is complicated because wind and solar power plants can be connected to different parts of the power grid, resulting in different grid losses. Furthermore, the use of energy storage complicates calculations even more. As the differences between the outcomes of these two approaches are minor, a simplified approach was chosen.

2.5.13.3. Heat generation from renewable energy sources

The applied principle for constraint on heat generation from RES is analogous to a constraint on electricity generation from RES. However, there are several differences. First, heat is produced in heating plants and combined heat and power plants. The main output of CHP plants is electricity. Therefore, it has to be recalculated to the secondary output. It is done by multiplying the electricity output by the ratio of heat and electrical efficiencies. Also, seven district heating systems are represented in the model, so their outputs must be summed to get the value representing the final district heating consumption.

$$\sum_{hp\in RES} X_{hp,t} + \sum_{chp\in RES}\left(X_{chp,t}\cdot\frac{\eta_{chp,heat}}{\eta_{chp,elec}}\right) - T_{RES_H,t} \cdot \sum_{Heat\_distr\_grid,t} X_{Heat\_distr\_grid,t} \geq 0; \tag{14}$$

where: $hp \in RES$ – heating plants attributed to RES heating plants; $X_{hp,t}$ – the output of heating plant *hp* in year *t* in MWyr; $X_{CHP,t}$ – the output of the CHP plant *chp* in year t in MWyr; $\eta_{chp,heat}$ – heat efficiency of CHP plant *chp* (dimensionless); $\eta_{chp,elec}$ – electrical efficiency of CHP plant *chp* (dimensionless); $T_{RES\_H,t}$ – a minimum share for district heating generation from RES in year *t* (dimensionless); $X_{Heat\_distr\_grid,t}$ – the output of district heating grid *Heat_distr_grid* in year *t* in MWyr.

2.6. Modelling principles of the transport sector

The selected methodology for the modelling transport sector is based on Hannah E. Daly et al. (2014) approach. Though this approach is for modelling the transport sector within TIMES energy planning software, it can also be applied in the MESSAGE model since the core principles of how TIMES and MESSAGE work are very similar. The main idea of this approach is to have the travel needs (in pkm – passenger kilometres) set as demands and let different travel options compete. As previously mentioned, optimization models that minimise total discounted costs always prefer the cheapest option if not constrained. Thus, public transport would be preferred. For this reason, Hannah E. Daly et al. incorporated a travel time budget, which limits the use of slower modes of travel as time is a resource, and people are willing to spend a limited time travelling. The benefit of this approach is that it enables the modelling of the modal shift. This approach with a fixed travel time budget is already used in Irish, Californian (CA-TIMES) (Daly et al., 2014), Danish TIMES (TIMES-DKMS) (Tattini, Gargiulo, & Karlsson, 2018) and United Kingdoms ESME (Pye & Daly, 2015) models.

The developed transport model covers passenger and freight transport, including road and rail transport modes. For passenger transport, personal and public transport modes were considered. Personal transport includes only cars, while public transport includes city buses, trolleybuses, intercity buses and passenger trains. Modelled freight transport modes include trucks and freight trains. A visual representation of transport modes considered in the developed model is given in Figure 37.

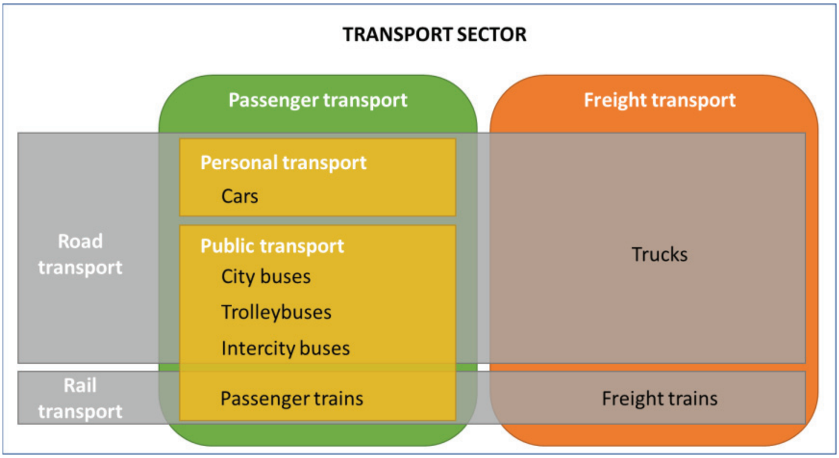


Figure 37. Transport modes considered in the model

Source: created by the author

Several improvements were implemented in the developed model compared to Daly's approach. First, freight transport was included. Second, cars were differentiated by size. Third, vehicles were differentiated by build year to represent fuel consumption and resulting emissions better. Fourth, vehicle age distribution constraints were applied to account for the import of used vehicles. Fifth, different electric vehicle charging strategies were implemented: uncontrolled, smart, and V2G.

The transport model developed includes:

- Petrol, hybrid, diesel, BEV and FCEV cars;
- Diesel, CNG, BEV and FCEV city and intercity buses, as well as trolleybuses and diesel and electric passenger trains;
- Diesel, CNG, BEV and FCEV trucks and diesel and electric freight trains;
- Travel time budget;
- Biofuel blending;
- CO_2 emissions accounting;
- Constraints on car class shares, vehicle age distributions, new capacity, total new capacity addition, new capacity addition by fuel, electric vehicle charger capacities, travel shares in short and long-distance travel modes, EV battery balance.

Figure 38 shows a simplified energy chain of the transport sector model.

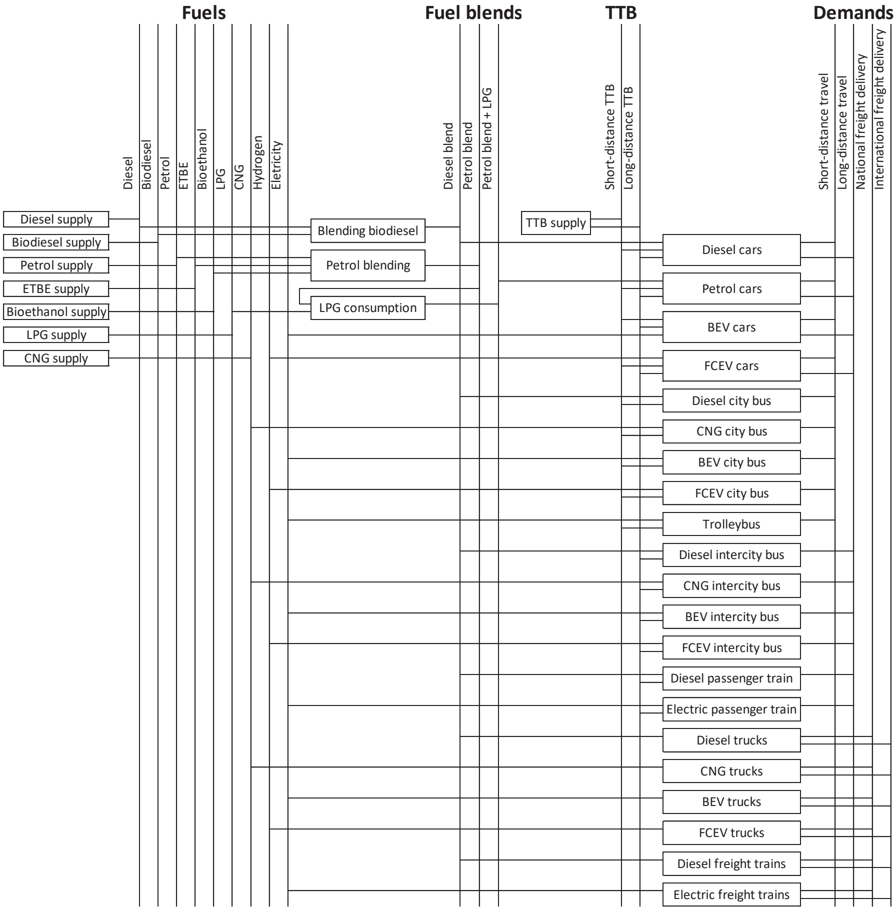


Figure 38. Simplified energy chain of power and district heating sectors in the model

Source: created by the author

2.6.1. Travel and freight delivery demands

In Lithuania, total passenger motorized travel volumes are declining, as shown in Figure 39. In 2006, around 45 billion passenger kilometres were travelled, but it dropped to around 36 billion by 2018. The most likely reason for this decline is the rapidly reducing population. Therefore, it is essential to look at pkm per capita. Another factor that might influence travel volumes is financial capabilities. It is expected that the citizens in more prosperous countries should travel more as they can afford higher travelling costs. However, based on statistical data, travel volumes in road transport saturate at around 11–14 thousand pkm per year (see Figure 40), and people do not travel more, even though they have the financial means to do so. Two factors can explain it: first, people are willing to spend a fixed amount of time travelling, and people exceeding a certain income already meet most of their travelling needs with a personal car, so a further increase in income does not lead to higher travel volumes; second, the overall travel demands might be increasing, but the increase is mainly in air travel, which is a substantially faster travel mode. However, this model does not consider air transport due to a lack of available data.

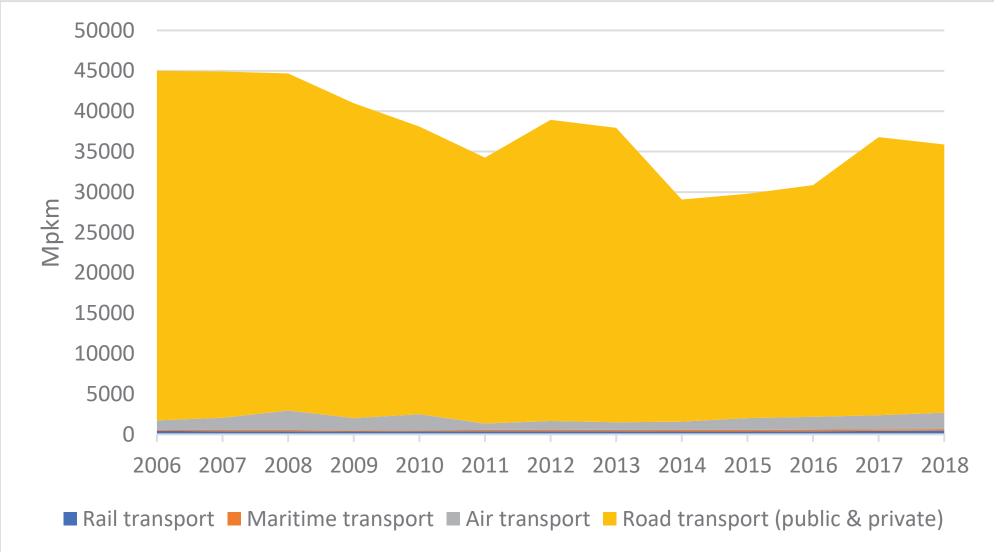


Figure 39. Passenger-kilometres by mode of transport in Lithuania

Source: created by the author based on (Eurostat, 2020a; Statistics Lithuania, 2022a) data

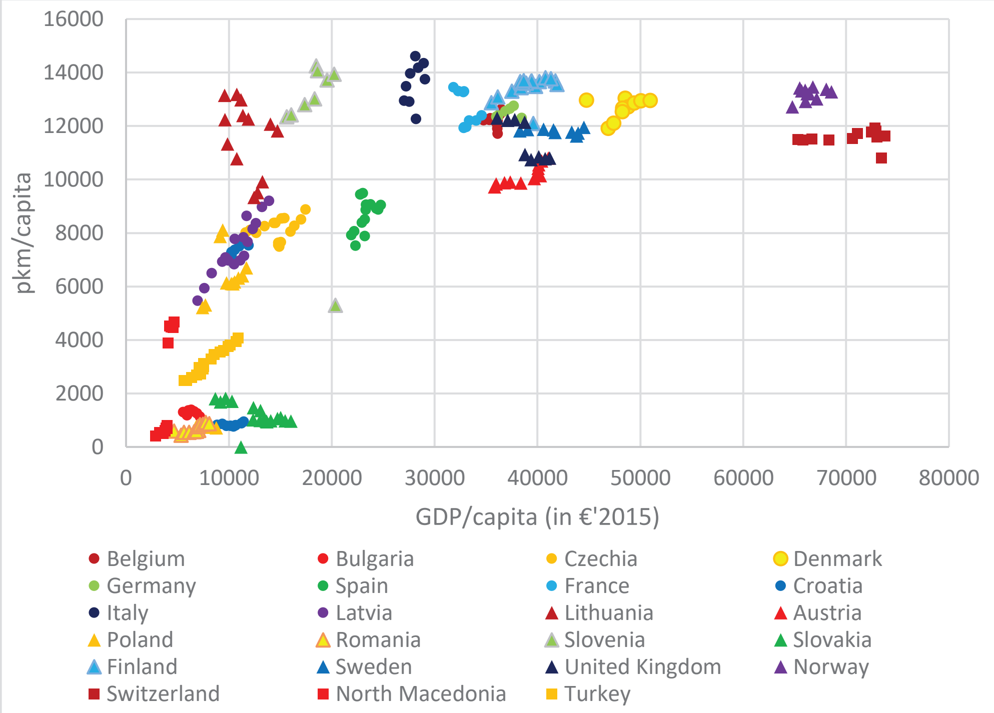


Figure 40. Road transport mobility and gross domestic product in 23 countries, 2002–2018

Source: created by the author based on (Eurostat, 2020a, 2020b, 2020c) data

When modelling electric vehicles, it is essential to know when the travel takes place as the vehicle battery has to be sufficiently charged before it. Furthermore, vehicles on the road can not be charged, and only part of vehicles parked can be charged due to limited charging infrastructure. For this reason, travel patterns were set for travel demands (see Figure 41).

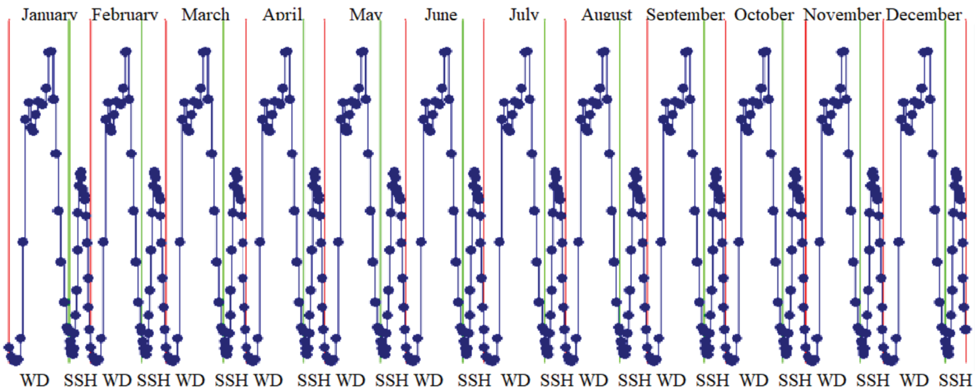


Figure 41. Travel patterns

Source: created by the author based on (SĮ 'Susisiekimo paslaugos', 2020) data

Constructed travel patterns are based on vehicle traffic data in Vilnius, as there are no available sources that provide detailed enough traffic data for Lithuania in general. Vilnius vehicle traffic data was provided by SĮ "Susisiekimo paslaugos" (SĮ 'Susisiekimo paslaugos', 2020) on request. However, acquired data covers only April to October 2020, and the coronavirus pandemic with lockdown measures substantially affected seasonal patterns. Therefore seasonal variations in travel were disregarded. Attempts were made to request data for the year 2021. Unfortunately, they were unanswered.

As mentioned before, freight transport is also included in the model. Since 1999 Lithuania has seen a sharp increase in freight delivery, especially in international delivery, including international transport links for goods loaded and unloaded in Lithuania and cabotage (see Figure 42). In 1999, 2.7 billion ton-kilometres (tkm) were delivered nationally and 4.9 Btkm internationally. The deliveries increased to 7.4 and 19.2 Btkm by 2019, almost three and four times as much as in 1999.

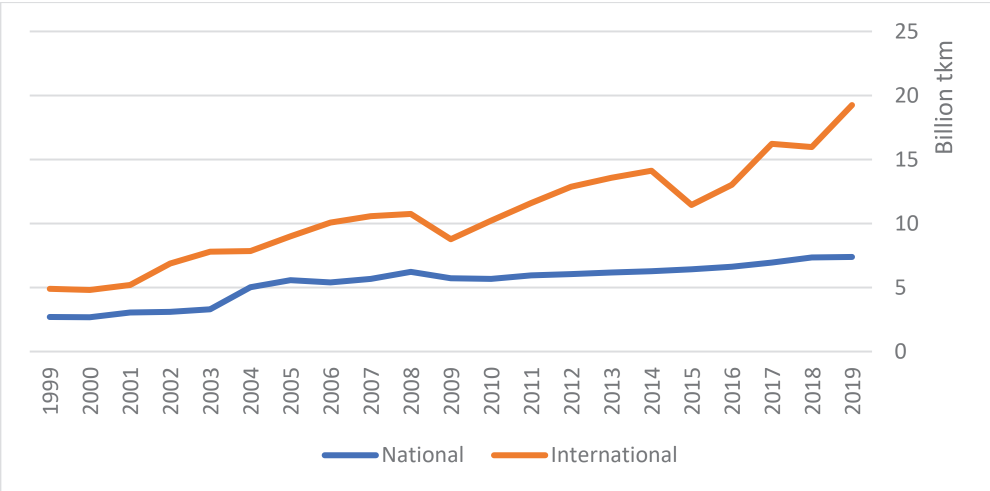


Figure 42. Freight transport demand

Source: created by the author based on (Statistics Lithuania, 2020b, 2020c) data

Since electric vehicles can be used for freight delivery, temporal delivery patterns have to be modelled as well. Patterns were taken from scientific literature (Roh, Datla, & Sharma, 2013), as data on patterns in Lithuania are unavailable (see Figure 43).

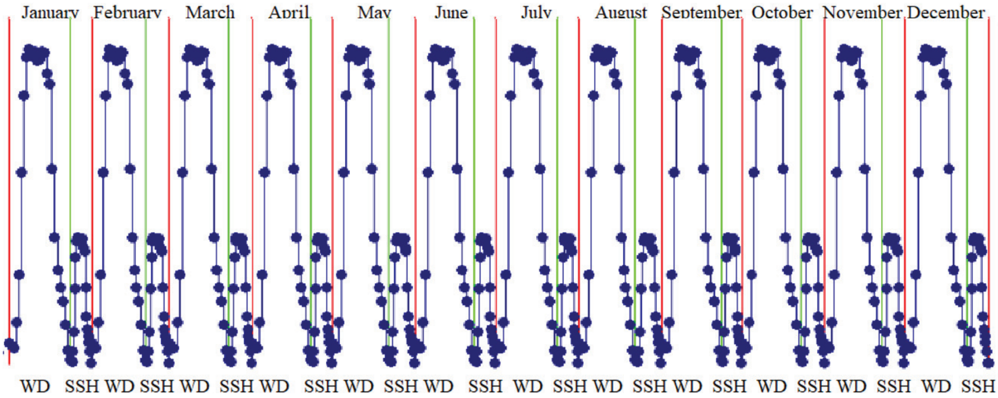


Figure 43. Freight delivery patterns

Source: created by the author based on (Roh et al., 2013). Data

In the section **Definition of the scenarios**, travel and freight delivery volume assumptions are given for future years**.**

2.6.2. Travel time budget

In 1980 Zahavi (Zahavi & Talvitie, 1980) proposed an idea of a fixed travel time budget (TTB). Even though there are significant variations in how much time different households/travellers spend on travelling, people spend a stable amount of time on average. Zahavi estimated TTB to be between 1 and 1.5 hours per day for the city residents of developed countries. Andreas Schafer (Schafer & Victor, 2000) developed this idea further and, based on statistical data, showed that people on average spend 1.1 hours travelling and that this TTB is stable over space and time. However, the stability of the travel time budget holds only if all travel modes are considered. He argues that as income increases, people use faster travel modes to satisfy growing travel demands with the same time budget. Data on time spent in motorized vehicles is sparse. Therefore Schafer describes how it can be derived from the relationship between TTB and mobility:

$$TTB_{mot} = a + \frac{b}{(TV - c)^d}; \tag{15}$$

where: TTB_{mot} – travel time budget in hours per capita per day; TV – traffic volume in person kilometres (pkm) per capita per day.

$$a = -\frac{b}{(-c)^d} \tag{16}$$

$$b = \frac{1.1}{\left(\frac{1}{(240000 - c)^d}\right) - \left(\frac{1}{(-c)^d}\right)} \tag{17}$$

here: c and d coefficients were manually iteratively changed so that the TTB curve would fit statistical data. The curve fits data best when c=-176 083 and d=20.

The travel time budget spent on motorized vehicles as a function of traffic volume is plotted in Figure 44.

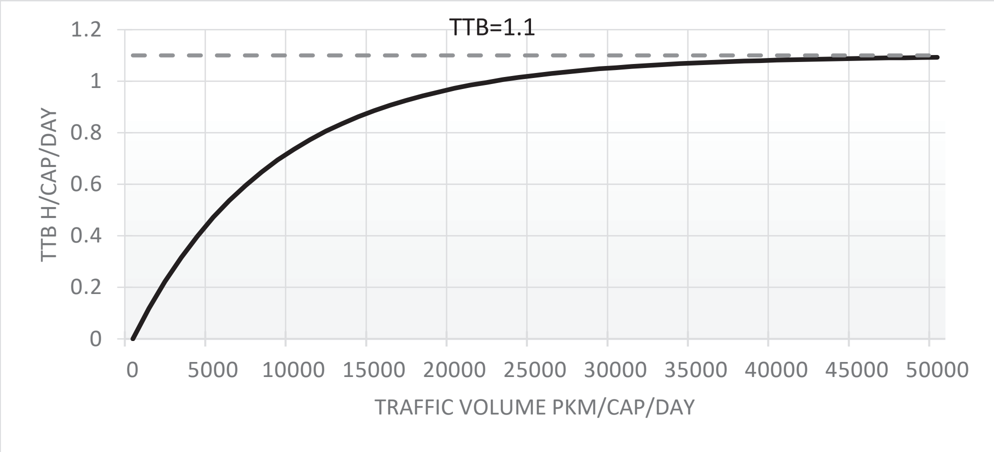


Figure 44. Travel time budget spent on motorized vehicles as a function of traffic volume

Source: created by the author based on (Schafer & Victor, 2000) data

If we assume that Lithuanians annually travel 12774 pkm per capita, by using equations (15), (16) and (17), it is possible to calculate the travel time budget for time spent in motorized vehicles in Lithuania. It is equal to 0.8289 h/cap/day. However, TTB values in the model have to be specified in a million hours. Thus, 0.8289 h/cap/day has to be multiplied by the population and the number of days in a year to estimate the total TTB for each modelled year. The United Nations population projection in the medium population change variant (United Nations, 2020) was used for these calculations. Furthermore, TTB was split into the budget for short-distance and long-distance travel. The main reason is that a single travel budget leads to high usage of public transport in long-distance travel and no usage in short-distance travel because inter-city travel is faster and an hour spent in inter-city public transport yields more pkm than city public transport, i.e. it is a more cost-efficient use of TTB in the eyes of the model. However, such results would be unreasonable. So, the TTB was split into the budget for short-distance and long-distance travel. The ratio was determined iteratively to match modelling results with statistical data. It was determined that 61% of TTB is spent on short-distance travel and 39% on long-distance travel.

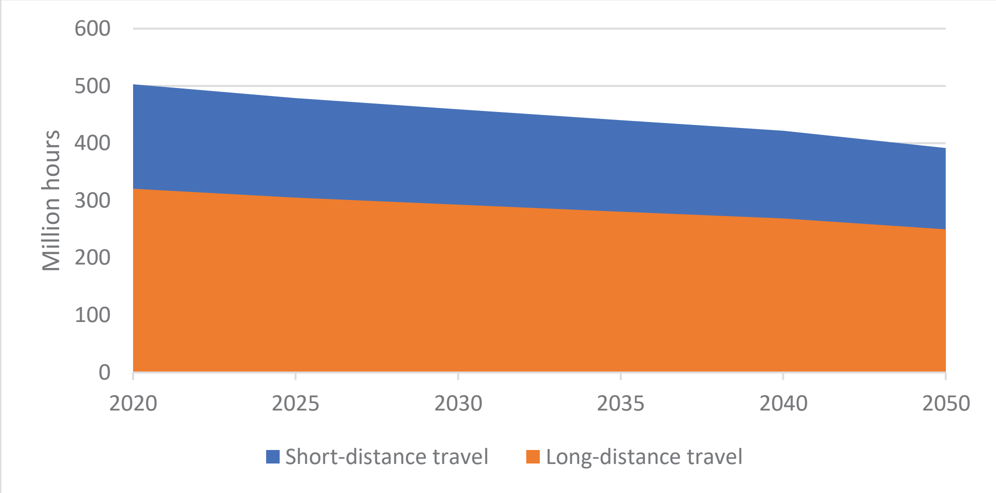


Figure 45. Travel time budget spent on motorized vehicles in Lithuania from 2020 to 2050.

Source: created by the author

2.6.3. Personal transport

2.6.3.1. Modelling approach

Cars are the only private transport mode represented in this model as it was deemed unnecessary to model other personal transport modes like motorcycles, bicycles, and walking because these transport modes' current and future effects on the energy sector are negligible.

Cars were modelled like in Ca-TIMES, Irish TIMES, TIMES-DKMS models. The model represents them by *technologies*, which have two inputs: time from a fixed travel time budget and fuel (see Figure 46). These technologies output travel in person-kilometres. Mathematically it can be expressed with the following equation:

$$\begin{cases} FC \cdot \eta = PKT \\ TC \cdot \bar{v} = PKT \end{cases}; \quad (18)$$

where: FC – fuel consumption in kg; η – vehicle fuel efficiency in pkm/kg; PKT – person kilometres travelled in pkm; TC – time consumption in ph; $\bar{v}$ – average speed in km/h.

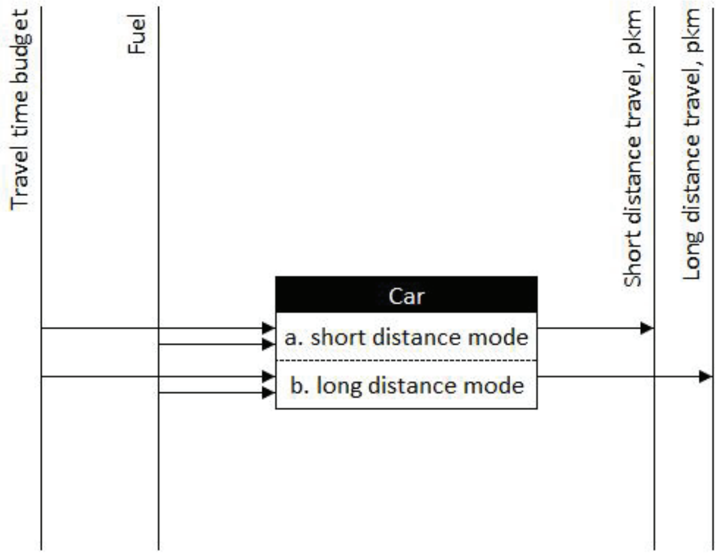


Figure 46. Car technology in the model energy chain

Source: created by the author

Each car technology has two operation modes, in MESSAGE called *alternative activities*. The first is for short-distance, and the second is for long-distance travel (see Figure 46). Both *alternative activities* use the same inputs, but outputs travel to different *energy forms*, enabling a representation of different fuel efficiencies and speeds in short-distance and long-distance travel modes.

Cars that use different fuels are modelled as separate *technologies*. Diesel, petrol, hybrid, electric and hydrogen fuel cell (FCEV) cars were considered in this model. Biofuel cars are not modelled as separate technologies because "biodiesel and conventional diesel vehicles are the same" (U.S. Department of Energy, 2018), and future petrol cars can be adapted to use up to 85% ethanol fuel blend (E85) without any extra cost to the vehicle. Furthermore, petrol vehicles worldwide are already compatible with 5 % and 10 % blends (E5 and E10). (Larsen, Johansen, & Schramm, 2009). In the **Biofuel blending** section, it is described how fuel blending was modelled in this transport model.

Cars were differentiated by fuel and class and vehicle age groups to represent better fuel consumption, emissions and changes in the transport sector (see Figure 47). Car classification was based on segmentation used by the European Commission (COMMISSION OF THE EUROPEAN COMMUNITIES, 1999):

- A-B – Mini and small cars;
- C-D – Medium and large cars;
- E-F – Executive and luxury cars;
- J-M – sport utility vehicles and multipurpose cars.

Vehicle age groups were constructed by the build year. These groups coincide with European emission standards up to 2020. Cars made in 2021 and further on were modelled in 5-year groups.

- 1992 and before (pre-Euro);
- 1993–1996 (Euro 1);
- 1997–2000 (Euro 2);
- 2001–2005 (Euro 3);
- 2006–2010 (Euro 4);
- 2011–2014 (Euro 5);
- 2015–2020 (Euro 6);
- 2021–2025;
- 2026–2030;
- 2031–2035;
- 2036–2040;
- 2041–2045;
- 2046–2050.

Two hundred eight car technologies were modelled – one technology per age group of each car class of each fuel type. Five fuel types, four classes and 13 age groups were modelled. Two hundred eight instead of two hundred sixty (5*4*13) *technologies* because, according to REGITRA data (REGITRA, 2020), there were no hybrid cars and electric vehicles built before 2001 and no hydrogen vehicles in Lithuania in 2020. Therefore, 52 redundant *technologies* were eliminated.

Each car *technology* has several parameters defined. These include:

- efficiency;
- time consumption rate;
- operation and maintenance cost;
- installed capacity;
- investment cost;
- plant factor.

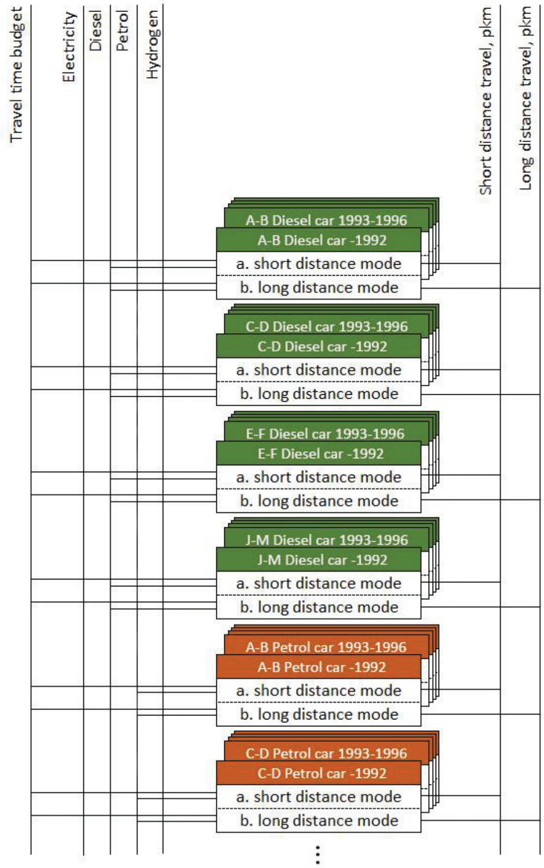


Figure 47. Car technologies by fuel, class and age group in the model energy chain

Source: created by the author

2.6.3.2. Efficiency

The efficiency of car *technology* in this transport model defines how many person kilometres can be travelled with one kilogram of fuel, except for electric vehicle *technologies*. They are modelled differently – more about it in the section Electric vehicles. Efficiency can be calculated from the fuel consumption rate and occupancy rate.

$$\eta = \frac{100 \cdot OR}{FCR} \tag{19}$$

where: η – efficiency of car *technology* in pkm/kg; FCR – fuel consumption rate in kg/100 km; *OR* – average car occupancy rate in passengers per vehicle, which is assumed to be 1.35.

2.6.3.3. Fuel consumption rates

Estimated car fuel consumption rates were based mainly on two data sources: spritmonitor.de (Fisch und Fischl GmbH, 2021) and U.S. Environmental Protection Agency's Automotive Trends Report (US EPA, 2018). Data was collected from the spritmonitor.de website on fuel consumption rates in each car class group's (A-B; C-D; E-F; J-M) most popular car models made between specified years. Weighted averages were calculated for cars by class and age group. Automotive Trends Report data was used to differentiate fuel consumption rates in short and long-distance travel modes. Car fuel consumption rates are given in Table A.17 and Table A.18, except for hydrogen fuel cell and electric vehicles. They are given in Table A.19.

2.6.3.4. Time consumption rate

Each car *technology* uses not only fuel but also time from TTB. The time consumption rate (TCR) is reciprocal to the average vehicle speed. It is assumed that cars travel at 31.37 km/h in short-distance mode and 69.72 km/h in long-distance travel mode. Initially, car travel speeds were estimated using Google Maps. However, these values were adjusted during the model calibration process.

$$TCR_o = \frac{1}{\bar{v}_o}; \tag{20}$$

where: TCR_o – time consumption rate in travel mode *o* in h/km; $\bar{v}_o$ – average speed in travel mode o in km/h.

However, TCR needs to be adjusted before using it in the model. Coefficients for each input and output are in relation to each other. In this model, all coefficients of inputs and outputs are expressed concerning the *main input*. The main input is fuel in car *technologies*, except for electric vehicles. They are modelled differently, as explained in the section **Electric vehicles.** For instance, in the case of diesel cars of A-B classes made up till 1992, the *technology* uses 1 kg of diesel fuel to produce 25.53 pkm in short-distance travel mode and 35.17 pkm in long-distance travel mode. 25.53 and 35.17 are the efficiencies in respective travel modes set as coefficients for the outputs. The coefficient for time consumption input should represent how many hours it takes to travel the pkm that can be travelled with 1 kg of fuel. Therefore, TCR has to be multiplied by efficiency.

$$TCR_o^* = TCR_o \cdot \eta_o; \tag{21}$$

where: TCR_o^* – adjusted time consumption rate in travel mode *o* in ph/kg; η_o – efficiency of car technology in travel mode *o* in pkm/kg.

2.6.3.5. Car fleet

In Lithuania in 2020, there were more than 1.5 million cars (REGITRA, 2020), of which 7.6% are A-B class cars, 48.4% C-D, 11% E-F, 32% J-M, 0.7% S (sport coupes), 0.2% not identified. S class and unidentified class cars were not considered in the model as their share in the car fleet is minuscule. Cars were classified by manually assigning a class to 2828 car models. Top 5 models in Lithuania for each car class:

A – Toyota Aygo, Fiat 500, Volkswagen Lupo, Fiat Panda, Volkswagen Fox
B – Toyota Yaris, Volkswagen Polo, Skoda Fabia, Nissan Almera, Opel Corsa
C – Volkswagen Golf, Opel Astra, Toyota Corolla, Skoda Oktavia, Renault Megane
D – Volkswagen Passat, Audi A4, Toyota Avensis, BMW 3 series, Opel Vectra
E – Audi A6, BMW 5 Series, Volvo V70, Mercedes-Benz E-class, Audi 100
F – Audi A8, Mercedes-Benz S-class, Lexus LS, Audi S8, Tesla Model S
J – Volvo XC, BMW X series, Toyota RAV4, Nissan Qashqai, Nissan X-Trail
M – Opel Zafira, Volkswagen Sharan, Volkswagen Touran, Ford Galaxy, Opel Meriva
S – BMW 6 Series, Mercedes-Benz CLK, Ford Mustang, Hyundai Coupe, Toyota Celica

69.2% of cars are diesel cars, 28.8% are petrol, 1.9% are hybrid, and 0.1% are electric vehicles. Car distribution by vehicle class and fuel is given in Figure 48.

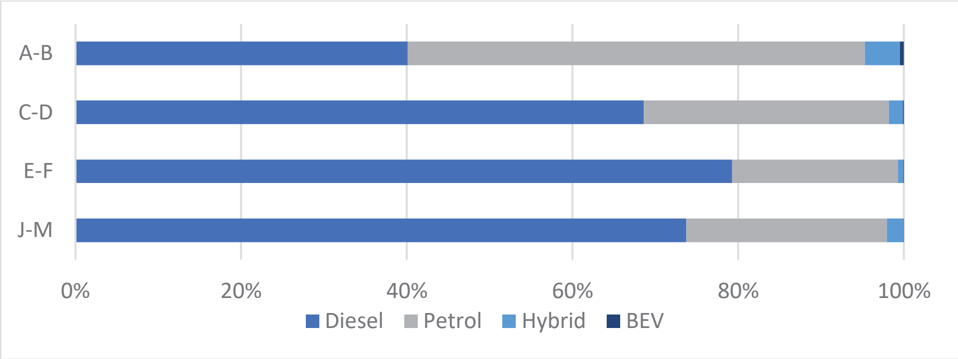


Figure 48. Cars by a class group and fuel in Lithuania in 2020

Source: created by the author based on (REGITRA, 2020) data

The average car age in Lithuania in 2020 was 15.4 years. 13.2 years for A-B class cars, 16.5 for C-D, 18.4 for E-F and 13.2 for J-M. Car age distribution by car class is given in Figure 49.

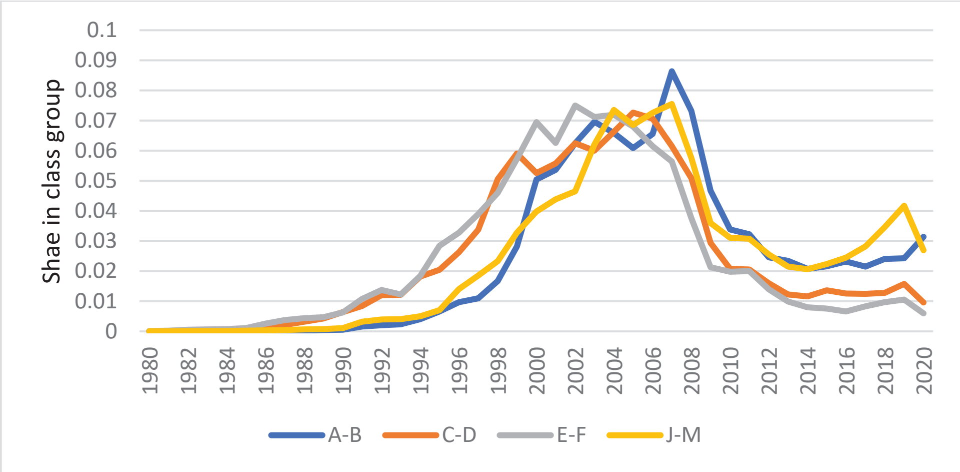


Figure 49. Car age distribution by a class group in Lithuania in 2020

Source: created by the author based on (REGITRA, 2020) data

The MESSAGE modelling software is designed for energy planning models. How many power plants are already installed in the system is irrelevant to the model. It matters what capacity is installed, where and when. So, even there is no option to model installed units by entering their count. Therefore, installed capacity has to be entered. For this reason, the vehicle count has to be recalculated to capacity before it can be entered into the model. The capacity (*P*) of the single car in the model is expressed in a million pkm that can be travelled in a year. It is calculated by multiplying an average travel speed by the number of hours in a year by the average occupancy rate and average operation time (*OT*). It is assumed that the average operation time is 0.04, which means that, on average, each car is used for 0.96 hours per day.

$$P_o = \frac{\bar{v}_o \cdot 365 \cdot 24 \cdot OR \cdot OT}{10^6}; \quad (22)$$

where: P_o – capacity of a single vehicle in Mpkm/yr; $\bar{v}_o$ – average speed in travel mode *o* in km/h; *OR* – occupancy rate in passengers per vehicle; *OT* – operation time (dimensionless).

In the model, cars have two operation modes short-distance and long-distance travel. The average travel speed differs between these two modes. Also, the occupancy rate might be different. Therefore, capacities differ as well. However, installed capacity can only be inputted into the model for one mode. So, short-distance travel is selected as the main mode. Capacities of all other operation modes are expressed through a *power relation* coefficient, by which the capacity of the main mode is multiplied. In the case of cars, this *power relation* coefficient for long-distance travel mode is equal to the ratio of average speeds multiplied by the occupancy rates in long and short-distance travel modes:

$$PR = \frac{\bar{v}_{long-distance} \cdot OR_{long-distance}}{\bar{v}_{short-distance} \cdot OR_{short-distance}}; \quad (23)$$

where: PR – power relation coefficient (dimensionless); $\bar{v}_{long-distance}$ – average speed in long-distance travel mode in km/h; $\bar{v}_{short-distance}$ – average speed in short-distance travel mode in km/h; $OR_{long-distance}$ – occupancy rate in long-distance travel mode in passengers per vehicle; $OR_{short-distance}$ – occupancy rate in short-distance travel mode in passengers per vehicle; Due to lack of available data, it was assumed that the occupancy rate is equal to 1.35 in both cases.

Short-distance travel capacity of a single car is equal to 0.014839 Mpkm/yr, and the power relation coefficient for long-distance travel mode is 2.2225. Total installed capacity can be calculated by multiplying the capacity of a single car by the number of cars. For example, if there are 3 A-B class electric vehicles built between 2006 and 2010, of which one in 2008 and two in 2009, in the model, the installed capacity for the *technology* of A-B class EVs built-in 2006-2010 has to be set to 0.014839 Mpkm/yr for 2008 and 0.029679 Mpkm/yr for 2009.

2.6.3.6. Purchase price and depreciation

Current purchase prices of new cars were derived based on data from car manufacturers and official retailers' websites. It was assumed that new cars in the past cost the same as now. Future prices were calculated based on car price changes in *A portfolio of power-trains for Europe: A fact-based analysis* (FCH JU, 2010) report.

As mentioned in Section **Car fleet** average car age in Lithuania is 15.4 years. Figure 49 shows that car age distribution in Lithuania has almost a bell curve. It means that most purchased cars are used cars from foreign markets. The average age of first-time registered cars in Lithuania is 11 years (AutoTyrimai, 2020). Major countries like the United States (EIA, 2018) or Germany (KraftfahrtBundesamt, 2020) have a declining curve (The older the car, the smaller the share in the car fleet). In these countries, almost all first-time registered cars are brand new. Therefore, only the initial purchase price of a new car has to be accounted for. However, this is not the case for countries like Lithuania, where most first-time registered cars in Lithuania are used cars from foreign countries. For this reason, it is essential to model cars by age and account for their declining purchase price with age

$$I_{used} = I_{new} \cdot (1 - \delta)^{\varepsilon} \quad (24)$$

where: I_{used} – used car price in Euros; I_{new} – new car price in Euros; δ – depreciation rate (dimensionless); ε – vehicle age in years.

Purchase prices of brand-new cars by age group are given in Table A.20.

The depreciation rate was estimated for each car class based on how the average prices of the most popular car models made in 2010 changed between 2010 and 2020. Data was used from Lithuania's biggest used car advertisement portal (DIGINET, 2020). The calculated average annual depreciation rate for A-B class cars is 9.95%, 11.11% for C-D, 12.98% for E-F and 10.05% for J-M.

Vehicle age for each modelling year is calculated by subtracting the average rounded-up year[15] of a specific car age group from that modelling year. For instance, the age of cars in the 2015–2020 age group in 2025 is calculated like this:

$$\varepsilon = 2025 - ceil\left(\frac{2015 + 2020}{2}\right) = 2025 - 2018 = 7\ years \quad (25)$$

Calculated used car price (I_{used}) has to be adjusted before it can be used in the model since *investment costs* in the model are expressed per unit of capacity, usually in euros per kW. Therefore, in the case of cars, it should be expressed in euros per thousand person-kilometres per year. Furthermore, an additional registration fee (F_{reg}) is added to the purchase price. It is mandatory to pay this fee in Lithuania when registering the vehicle. The size of the fee depends on the fuel and CO_2 emission rate. This fee applies only to cars that run on petrol, diesel or LPG cars (LPG cars are essentially modified petrol cars that can run either on petrol or LPG. LPG cars are not modelled explicitly, but LPG consumption is evaluated. See **LPG consumption** section). The sizes of the registration fee are given in Table 6. The recalculated registration fee by fuel, car age group and class, used as F_{reg} in further calculations, is given in Table 7. The investment cost for used cars is calculated as follows:

$$I_{used}^{*} = \left(I_{used} + F_{reg}\right) \cdot \frac{1000}{P_{o=short-distance}} \quad (26)$$

where: I_{used}^{*} – used car adjusted price in €/(kpkm/yr); I_{used} – used car price in Euros; F_{reg} – registration fee in Euros; $P_{o=short-distance}$ – capacity of a single car in short-distance travel mode in Mpkm/yr.

[15] In case of cars built till 1992, year 1992 was used as an average year.

Table 6. Car registration fee in Lithuania

CO_2 emissions, g/km		Registration fee, €	
From	To	Diesel	Petrol
0	115	0	0
116	130	0	0
131	140	30	15
141	150	60	30
151	160	90	45
161	170	120	60
171	180	150	75
181	190	180	90
191	200	210	105
201	210	240	120
211	220	270	135
221	230	300	150
231	240	330	165
241	250	360	180
251	260	390	195
261	270	420	210
271	280	450	225
281	290	480	240
291	300	510	255
301		540	270

Source: created by the author based on (Lietuvos Respublikos Seimas, 2019) data

Table 7. Car registration fee by fuel, car age group and class.

Vehicle age group		Registration fee, €											
		A-B			C-D			E-F			J-M		
From	To	Diesel	Petrol	Hybrid	Diesel	Petrol	Hybrid	Diesel	Petrol	Hybrid	Diesel	Petrol	Hybrid
	1992	60	135	0	240	195	30	480	270	105	480	270	105
1993	1996	60	120	0	240	180	15	480	270	105	480	270	105
1997	2000	30	120	0	240	180	15	480	270	90	480	270	90
2001	2005	30	120	0	240	180	15	450	270	90	450	270	90
2006	2010	0	105	0	180	150	0	390	270	75	390	270	75
2011	2014	0	75	0	120	120	0	300	225	45	300	225	45
2015	2020	0	60	0	120	105	0	210	165	15	210	165	15
2021	2025	0	45	0	90	90	0	120	105	0	120	105	0
2026	2030	0	30	0	60	75	0	90	90	0	90	90	0
2031	2035	0	15	0	30	45	0	60	60	0	60	60	0
2036	2040	0	0	0	0	30	0	30	45	0	30	45	0
2041	2045	0	0	0	0	15	0	0	30	0	0	30	0
2046	2050	0	0	0	0	0	0	0	0	0	0	0	0
2051	2060	0	0	0	0	0	0	0	0	0	0	0	0

Source: created by the author based on (European Environment Agency, 2019; Lietuvos Respublikos Seimas, 2019; US EPA, 2018) data

2.6.3.7. Operation and maintenance costs

Each car has to be maintained, and there are costs associated with it. For example, oils, filters, coolant, washer fluid and miscellaneous parts, like tires and windshield wipers, must be changed periodically. As the vehicle ages, more repairs must be performed due to wear and tear. U.S. data (Maddy, 2016) on car maintenance cost changes with car age were used since there is no reliable data for Lithuania. These costs recalculated in €/1000 pkm, based on assumptions that, on average, cars annually travel 13333 km and the average occupancy rate is 1.35, are given in Figure 50.

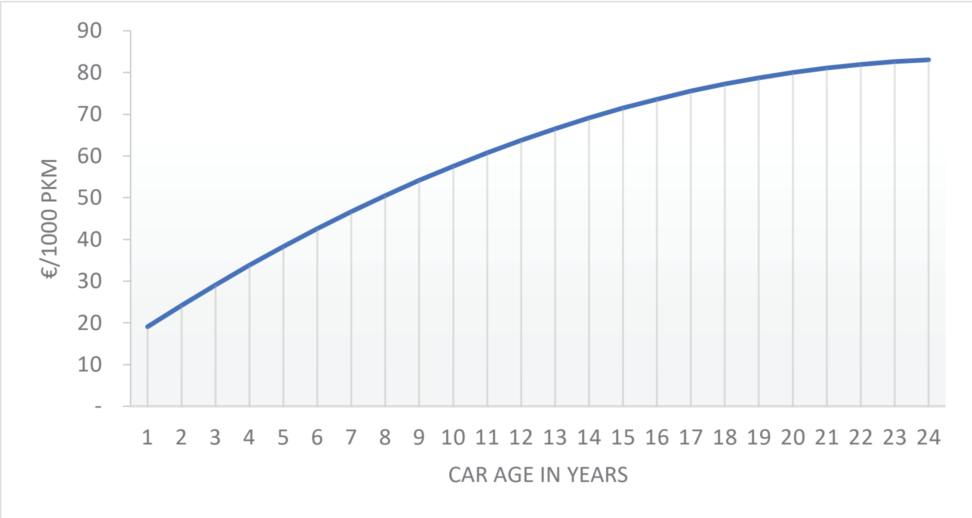


Figure 50. Car operation and maintenance costs

Source: created by the author based on (European Environment Agency, 2019; Lietuvos Respublikos Seimas, 2019; US EPA, 2018) data

2.6.3.8. Electric vehicles

Electric vehicles have to be modelled uniquely. Unlike fossil fuels or biofuels, it does matter at which hour electricity is consumed because electricity consumption and production have to be equal at any given time. Electricity consumption for electric vehicle charging timing affects required electricity generation capacities, and which power plants will produce this electricity. Wind and solar power plants cannot change the output freely depending on wind speed and solar irradiation. The previously described car modelling approach cannot be used for electric vehicles because fuel consumption occurs simultaneously as travel (person kilometres) is produced. There was no need to model fuel stored in car fuel tanks since it would not affect anything and would unnecessarily significantly increase the model size.

To adequately model electric vehicles, batteries and chargers have to be modelled. Chargers are modelled through additional charger technologies, which have two operation modes: charging and discharging (discharging is enabled only in the scenarios with V2G charging strategies), while batteries are modelled by adding *energy storage*.

Electric vehicle electricity consumption is set through *linked storage constraints on activities*, which define how much energy is stored in the *energy storage*, in this case, battery, changes concerning the technology's output. If the coefficient for *linked storage constraints on activities* is equal to 0.5, then it means that energy stored in the *energy storage* increases by 0.5 units for each outputted unit. Energy can be subtracted from energy stored by setting a negative coefficient. In MESSAGE, the stored energy is expressed in megawatt years (MWyr). Therefore, the coefficient for *linked storage constraints on activities* for electric vehicles needs to be negative and in MWyr/Mpkm.

$$consa = -\frac{1000}{FCR \cdot 365 \cdot 24 \cdot OR} \tag{27}$$

where: *consa* – the coefficient for *linked storage constraints on activities*; *FCR* – fuel (electricity) consumption rate in kWh/100km (see Table A.19); OR – occupancy rate (1.35) in passengers per vehicle.

As mentioned, an electric vehicle charger is modelled as a separate technology with two operation modes: charging and discharging. In MESSAGE, technologies can not output energy directly to *energy storage.* Instead, *linked storage constraints on activities* (consa) must be used. In the case of charging, the coefficient is positive since it increases stored energy, while a negative coefficient is used for discharging. The consa coefficient value for charging corresponds to the efficiency of the charger. It was assumed that average charging efficiency equals 83% (Apostolaki-Iosifidou, Codani, & Kempton, 2017), so consa=0.83, while -1 is used for discharging. In MESSAGE software, each technology's mode must have at least one output. For this reason, charger technology in charging mode produces a dummy *energy form*, which is not used by any technology. However, this output is linked to the battery and stored energy increases with each outputted unit (see Figure 51).

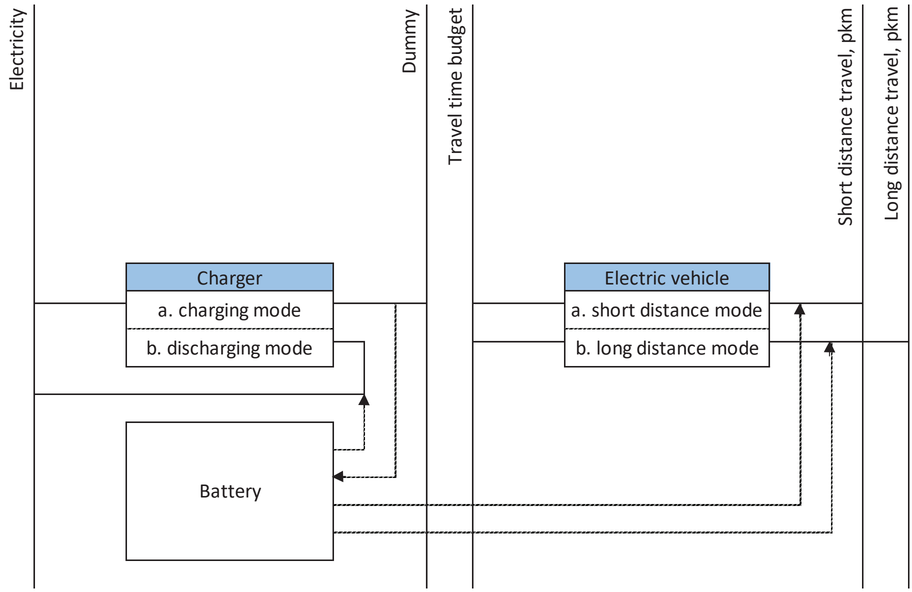


Figure 51. Electric vehicles in the model energy chain

Source: created by the author

Three different charging strategies were modelled: uncontrolled charging, smart charging and bidirectional vehicle-to-grid (V2G). Different charging strategies were used in separate scenarios (see section **Definition of the scenarios**). In the case of uncontrolled charging, a fixed charging pattern was set (see Figure 52). In scenarios with smart and V2G charging, the model is free to optimize the charging times according to the power supply as long as it is in line with the set charging availability curve (see Figure 55). The difference between smart and V2G charging strategies is that in V2G, electricity can be supplied back to the grid, i.e. discharging mode is enabled for the charging technology.

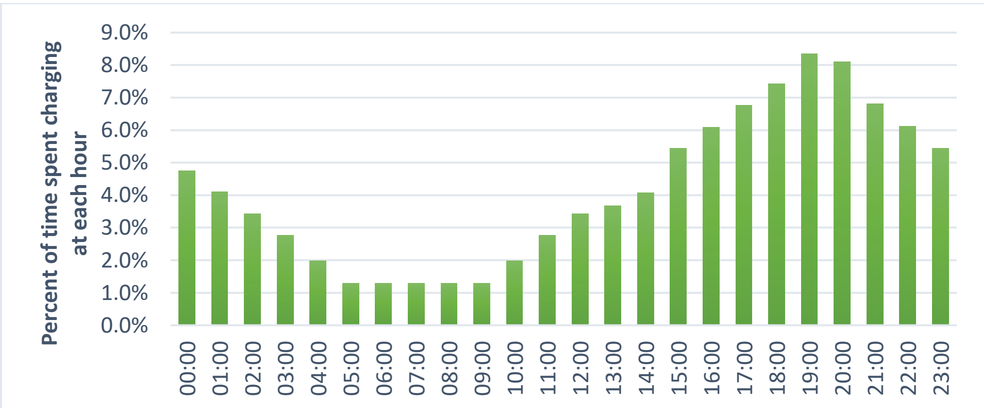
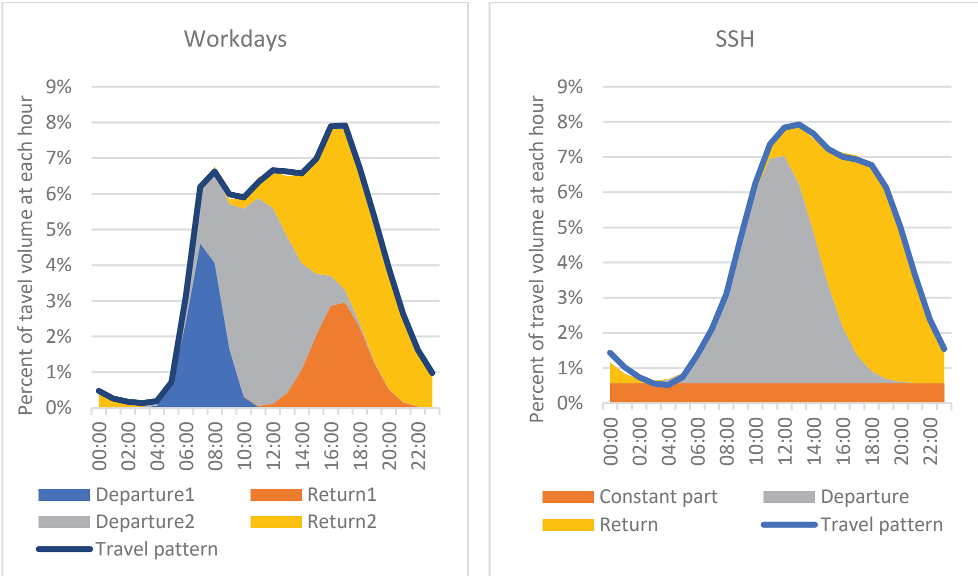


Figure 52. Uncontrolled EV charging pattern

Source: created by the author based on (Nelder & Fitzgerald, 2016) data

Charging availability depends on the vehicle states (parked at home, on the road, parked elsewhere), derived by approximating temporal travel patterns with normal distributions, using the methodology presented in the paper *Modelling electric vehicles and setting charging patterns endogenously in energy planning models* (Neniškis, 2019). The methodology relies on the assumption that departures and returns have a normal distribution. It was noticed that four natural distributions, two for departure and two for return, could reasonably well approximate workday travel patterns. It takes two natural distributions and a constant part to approximate SSH travel patterns (See Figure 53). Note: in the paper (Neniškis, 2019), travel patterns were based on Vilnius public transport data, while in this thesis, Vilnius vehicle traffic data (SĮ 'Susisiekimo paslaugos', 2020) was used instead as it represents much better car traffic patterns. At the time of the paper publishing, this data was unavailable.

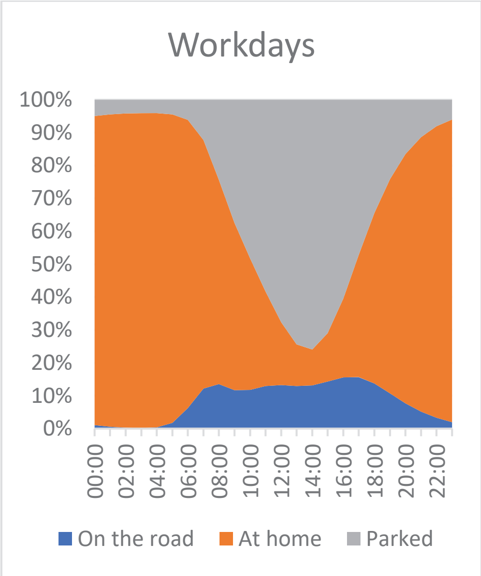


(a) (b)

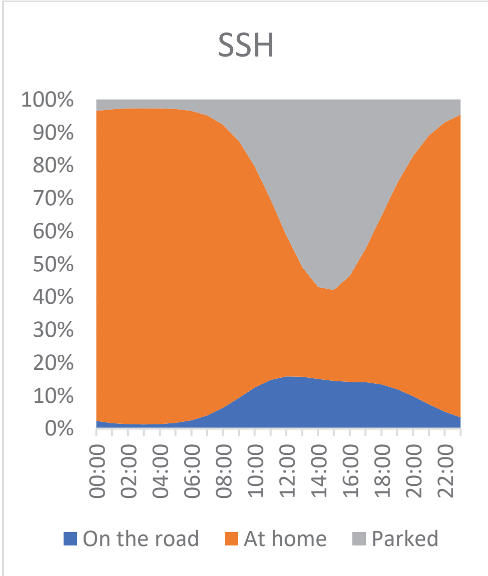
Figure 53. The approximation of travel patterns with natural distributions

Source: created by the author

The shares of vehicle states at each hour were derived as follows. First, the share of vehicles parked at home at each hour was calculated by subtracting the share of departing vehicles from the vehicle share at home in the previous hour and adding the share of arriving vehicles. In the case of the constant part, it was assumed that half are departing and half are returning. Second, the share of the vehicles on the road was calculated by summing the shares of departing and returning vehicles. Third, the share of vehicles parked elsewhere was calculated by subtracting the shares of vehicles at home and on the road from 1. Calculated hourly distributions of vehicle states at each hour during workdays and SSH are given in Figure 54.



(a)



(b)

Figure 54. Vehicle states at each hour during workdays and SSH

Source: created by the author

Charging availability curves were based on the assumption that 43% of EVs parked at home could be charged and 10% parked elsewhere to match the estimated charging availability curves in the scientific literature (Alvarez Guerrero, Bhattarai, Shrestha, Acker, & Castro, 2021). However, none of the EVs on the road can be charged. Charging availability curves are given in Figure 55.

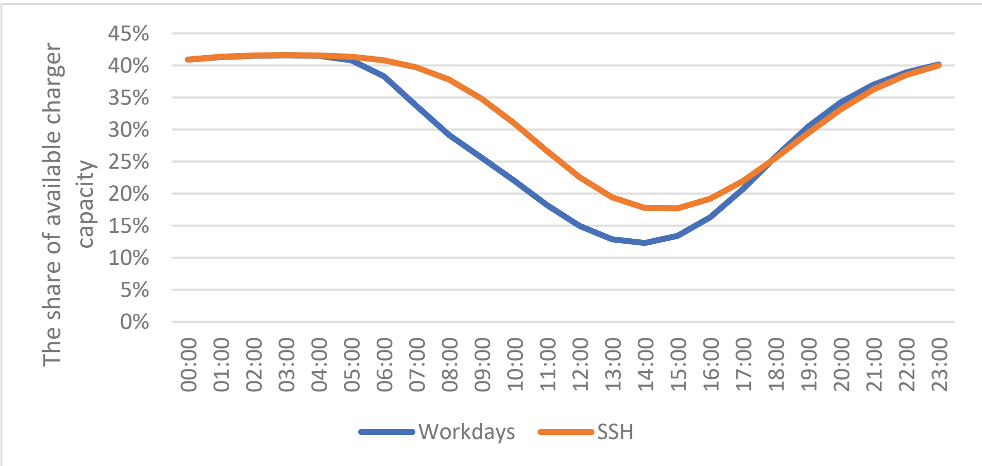


Figure 55. EV charging availability curves for workdays and SSH

Source: created by the author

Another essential aspect that is unique to EVs is range anxiety. J.Neubauer and E.Wood define it as “the fear of fully depleting a BEVs battery in the middle of a trip, leaving the driver stranded—can cause drivers to employ alternative (gasoline consuming) means of transportation even though their BEV is capable of adequately completing their required travel" (Neubauer & Wood, 2014). In this model, range anxiety was modelled as an additional cost for EVs. It was assumed that the owners of newer EVs would experience lower range anxiety because of larger batteries, and range anxiety should decrease with improving charging infrastructure. Also, range anxiety should be higher in long-distance travel. Estimated range anxiety costs for EVs in short-distance travel are given in Table 8. Values twice as large were used for long-distance travel.

Table 8. Range anxiety costs for EVs in short-distance travel, Eur/100 km

EVs built		**Modelling years**					
from	till	2020	2025	2030	2035	2040	2050
2001	2005	2.00	1.85	1.72	1.59	1.48	1.27
2006	2010	1.70	1.58	1.46	1.36	1.26	1.08
2011	2014	1.45	1.34	1.24	1.15	1.07	0.92
2015	2020	1.23	1.14	1.06	0.98	0.91	0.78
2021	2025	1.04	0.97	0.90	0.83	0.77	0.66
2026	2030	0.89	0.82	0.76	0.71	0.66	0.56
2031	2035	0.75	0.70	0.65	0.60	0.56	0.48
2036	2040	0.64	0.59	0.55	0.51	0.47	0.41
2041	2045	0.54	0.51	0.47	0.43	0.40	0.35
2046	2050	0.46	0.43	0.40	0.37	0.34	0.29
2051	2060	0.39	0.37	0.34	0.31	0.29	0.25

Source: created by the author

2.6.3.9. Additional constraints and bounds used for personal transport

Additional constraints were applied to ensure a realistic representation of car stock, its turnover and other aspects relevant to the model. Eight sets of constraints were applied:

- Car class constraints – to set the ratio of different car classes in the car stock.
- Vehicle age distribution – to constrain pkm travelled in cars by production year to match it with the actual vehicle age distribution in the car stock.
- Bounds on new capacity – to set an age limit after which cars cannot be added to the stock to prevent unrealistic fuel shifts in old vehicles.
- Constraints on new capacity addition – to limit how many cars can be added to the stock annually.
- Constraints on new capacity addition by fuel – to prevent too rapid fuel shifts.
- Constraints on electric vehicle charger capacities – to set a ratio of EV charger capacities and the number of electric vehicles.
- Minimum urban and rural travel shares for cars – to prevent using cars with certain fuels exclusively for short or long-distance travel.
- EV battery charging cycle constraints – to prevent interseasonal energy storage in EV batteries.

Car class constraints

Smaller cars are generally cheaper and more fuel-efficient, so the model would prefer them over bigger cars. However, in real life, people choose car class based not just on cost-effectiveness but also on other factors like comfort and looks. Vehicle stock data in Lithuania (REGITRA, 2020) shows that the most popular cars are medium and large (C-D), second by sports utility vehicles and multi-purpose vehicles (J-M). Car shares by class are given in Figure 56. Constraints have to be set to retain car class shares. Otherwise, the model would switch entirely to A-B class cars.

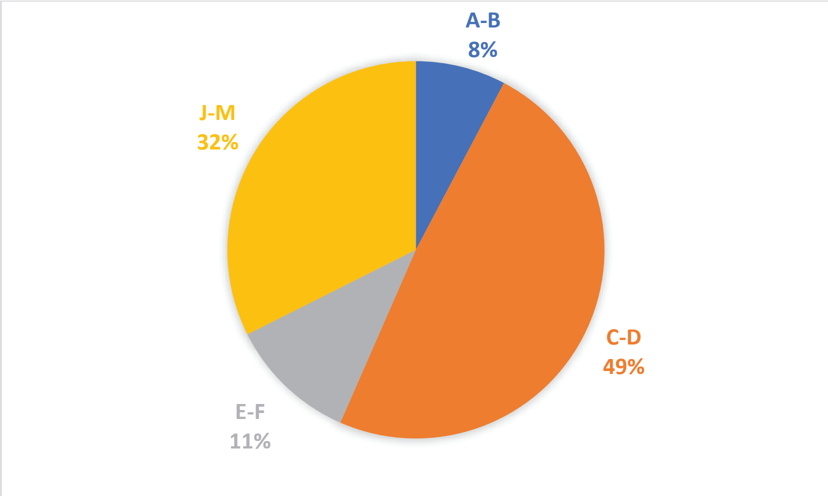


Figure 56. Car shares by class in Lithuanian car stock.

Source: created by the author based on (REGITRA, 2020) data

Car class shares are fixed with the following equation:

$$PKT_{l=s,t} = \alpha_{l=s,t} \cdot \sum_{l} PKT_{l,t}\,; \tag{28}$$

where: $PKT_{l,t}$ – passenger kilometres travelled by class l in year t in pkm; $\alpha_{l,t}$ – share of passenger kilometres travelled by class l in year t; s – selected car class.

The sum of shares in year t has to be equal to 1:

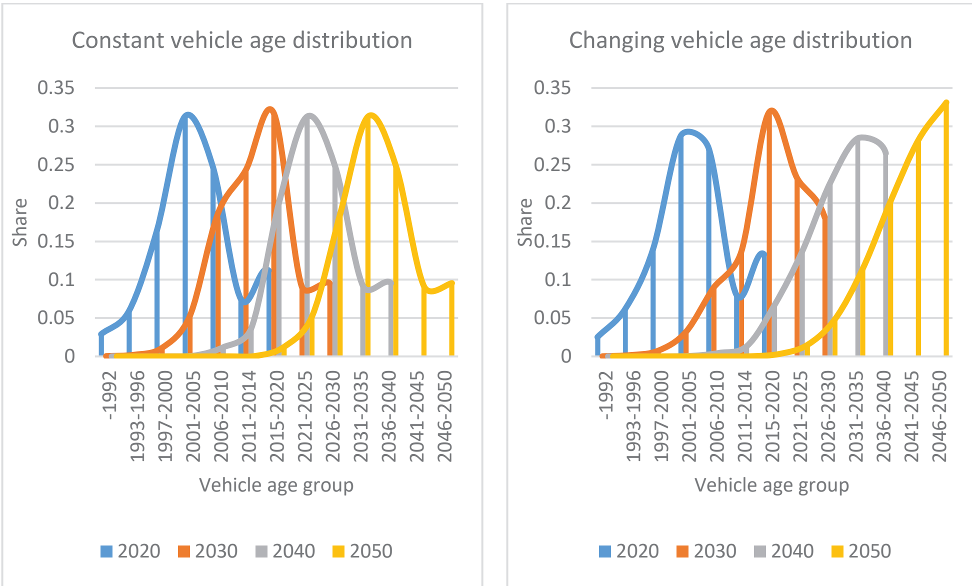
$$\sum_{l} \alpha_{l,t} = 1 \tag{29}$$

In linear programming models, the right-hand side of equations for user constraints can not have any variables, so it has to be transformed:

$$(1 - \alpha_{l=s,t}) \cdot PKT_{l=s,t} - \alpha_{l=s,t} \cdot \sum_{l \neq s} PKT_{l,t} = 0 \tag{30}$$

Vehicle age distribution

Vehicle age distribution constraints were applied to represent the actual vehicle age distribution and its assumed changes throughout the modelling years. In most scenarios, a constant/present vehicle age distribution was assumed. However, as income in Lithuania increases, it might be argued that vehicle age distribution should gradually change to similar ones, as seen in more prosperous countries. For this reason, additional scenarios that include changing vehicle age distribution were modelled (see section **Definition of the scenarios**). Assumptions for vehicle age distribution changes in modelling years are presented in Figure 57 for both cases.



(a) (b)

Figure 57. Car age distribution assumptions for 2020, 2030, 2040 and 2050

Source: created by the author

Vehicle age distribution constraints were set on the passenger kilometres travelled by vehicles of different age groups:

$$PKT_{y=e,t} = \beta_{y=e,t} \cdot \sum_{y} PKT_{y,t}\,; \tag{31}$$

where: $PKT_{y,t}$ – passenger kilometres travelled by age group y in year t in pkm; $\beta_{y,t}$ – share of passenger kilometres travelled by age group y in year t; e – selected age group.

The sum of shares in year t should be equal to 1:

$$\sum_{y} \beta_{y,t} = 1 \tag{32}$$

It was assumed that vehicle use does not depend on its age. Thus, if 30% of cars in the car stock were produced between 2005 and 2009, then these cars are used to travel 30% of the total pkm travelled by all cars.

As mentioned in the previous section, equations have to be set without any variables on the right-hand side in linear programming problems. Therefore, equation (31) has to be transformed:

$$\left(1-\alpha_{y=e,t}\right)\cdot PKT_{y=e,t}-\alpha_{y=e,t}\cdot\sum_{y\neq e}PKT_{y,t}=0 \qquad (33)$$

The approach is described in greater detail in the paper "Improving Transport Modeling in MESSAGE Energy Planning Model: Vehicle Age Distributions" (Neniškis, Galinis, & Norvaiša, 2021).

Bounds on new capacity in the transport model

In order to prohibit the installation of future technologies ahead of time and prevent unrealistic fuel shifts in used vehicles, an additional set of constraints was implemented. These constraints specify the modelling years in which the model is free to expand the installed capacity. In MESSAGE, it was done by setting upper bounds on new capacity addition (*bdc*) for each vehicle technology for each modelling year. An Upper bound of 0 prevents any capacity expansion, while a bound of 999999 allows to add up to 999999 Mpkm/yr, equivalent to almost 2.7 million cars. The Upper bound value depends on two conditions. If either of these conditions is true, then 0 bound is used, i.e. capacity can not be expanded. Otherwise, 999999 is used. The first condition: the age $\varepsilon_{h,t}$ (see equation (25)) of vehicle technology h, in model year t, is greater than 20. This condition was implemented to prevent unrealistic fuel shifts in used vehicles. A second condition: the first year of the vehicle age group q_h is greater than the model year *t*. A second condition is to prohibit the installation of future technologies.

$$bdc_{h,t}=\begin{cases}0, & \varepsilon_{h,t}>20\\ 0, & q_h>t\\ 999999, & otherwise\end{cases}; \qquad (34)$$

where: $bdc_{h,t}$ – bounds on new capacity addition for vehicle technology h in year *t* in Mpkm/yr; $\varepsilon_{h,t}$ – the age of vehicle technology *h* in model year *t* in years; q_h - the first year of the age group of vehicle technology h.

For instance, bdc in 2020, for A-B class diesel cars produced between 2021-2025, technology would be 0 because the second condition is true, 2021>2020, i.e. technology is not available yet. However, in the model year 2025, bdc would be 999999 as both conditions are false: $\varepsilon_{h,t}=2<20$; 2021<2025. With each subsequent modelling period, vehicle age increases; for this technology in 2045, it would exceed 20, fulfilling the first condition.

Constraints on total new capacity addition

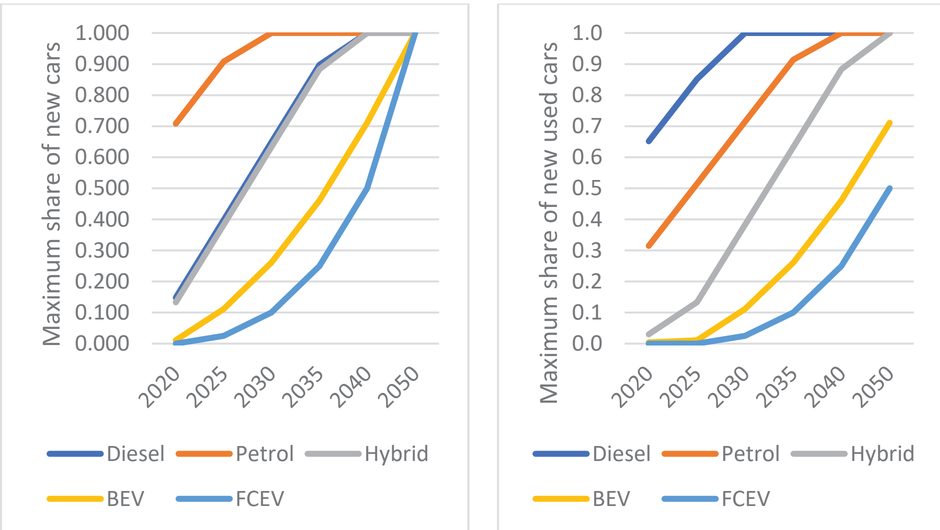
Constraints on total new capacity addition for cars were placed to limit how many cars could be added to the stock annually:

$$\sum_{h \in M1} CA_{h,t} \leq CA_{limit}; \quad (35)$$

where: $CA_{h,t}$ – h technology's capacity addition in year t in Mpkm/yr; $h \in M1$ denotes technologies that belong to the M1 vehicle category; CA_{limit} - the total capacity addition limit for cars in Mpkm/yr. Based on statistical data (REGITRA, 2021), it was estimated that, on average, 207697 cars are registered annually for the first time in Lithuania. Converting the number of cars to capacity gives 77051.8 Mpkm/yr, which was set as a limit (CA_{limit}).

Constraints on new capacity addition by fuel

The optimization algorithm constantly invests in the most cost-efficient option to satisfy the demands. It might result in unrealistically rapid fuel shifts, e.g. once electric vehicles become the cheapest private transport mode, all new cars added to the stock would be exclusively electric vehicles. Constraints on new capacity addition were applied to limit the maximum shares of cars by fuel in new and used vehicle additions to the stock. See Figure 58.



(a) (b)

Figure 58. Maximum shares of new and used car additions to the car stock by fuel and model year

Source: created by the author

$$CA_{u,f=p,t} \leq \gamma_{u,f,t} \sum_{f} CA_{u,f,t}\,; \tag{36}$$

where: $CA_{u,f,t}$ is capacity addition of new or used cars (u) that runs on fuel *f* in year *t*; p – selected fuel; $\gamma_{u,f,t}$ – maximum share in new or used car addition.

By moving all variables to the left-hand side, we get:

$$CA_{u,f=p,t} \cdot \left(1 - \gamma_{u,f,t}\right) - \gamma_{u,f,t} \sum_{f \neq p} CA_{u,f,t} \leq 0 \tag{37}$$

Which car age groups were considered as new or used cars are given in Table 9.

Table 9. New or used cars by each age group and modelling year

Age group	**Model years**					
	2020	2025	2030	2035	2040	2050
-1992						
1993–1996						
1997–2000						
2001–2005	used					
2006–2010	used	used				
2011–2014	used	used	used			
2015–2020	new	used	used	used		
2021–2025		new	used	used	used	
2026–2030			new	used	used	
2031–2035				new	used	used
2036–2040					new	used
2041–2045						used
2046–2050						new

Source: created by the author

Constraints on electric vehicle charger capacities

When buying an electric vehicle, it comes with a home charger (wall plug). It was assumed that the capacity of a single home charger is 2.3 kW. This assumption was implemented through a constraint that prohibits the installed home charging capacity $\left(C_{charger}\right)$ to exceed the number of electric cars $\left(\frac{C_{EV}}{P_{EV}}\right)$ multiplied by single-wall plug charger power $\left(P_{charger}\right)$ of 2.3 kW:

$$C_{charger,t} - C_{EV,t} \cdot \frac{P_{charger}}{P_{EV}} \leq 0; \tag{38}$$

where: $C_{charger}$ – total installed home EV charger capacity in year *t* in MW; C_{EV} – total installed EV capacity in year *t* in Mpkm/yr; P_{EV} – capacity of a single EV in Mpkm/yr (analogue of P_o in Section **Car fleet**); $P_{charger}$ – capacity of a single home EV charger. $C_{charger}$ and C_{EV} are internal model variables while $P_{charger}$ and P_{EV} are external values. For P_{EV} value see section **Car fleet**.

Minimum car travel shares in short and long-distance travel modes

One of the main advantages of personal cars is flexibility. Cars can be used for both short and long-distance travel, but the model decides which cars are used for short-distance and long-distance travel. For example, petrol cars are used exclusively for short-distance travel and diesel cars for long-distance travel. Though there might be fuel preferences for short and long-distance travel, such exclusivity is unrealistic. For this reason, an assumption is made that each car technology h has to operate at least 30% in either of the travel modes:

$$PKT_{h,o=short-distance,t} \geq 0.3 \cdot PKT_{h,t}; \quad (39)$$

$$PKT_{h,o=long-distance,t} \geq 0.3 \cdot PKT_{h,t}; \quad (40)$$

where: $PKT_{h,o,t}$ – person kilometres travelled by technology h in operation mode o and year t.

By moving all variables to the left-hand side and substituting PKT_h with ($PKT_{h,o=short-distance} + PKT_{h,o=long-distance}$) we get equations for constraints on minimal urban and rural travel shares for cars:

$$0.7 \cdot PKT_{h,o=short-distance} - 0.3 \cdot PKT_{h,o=long-distance} \geq 0 \quad (41)$$

$$0.7 \cdot PKT_{h,o=long-distance} - 0.3 \cdot PKT_{h,o=short-distance} \geq 0 \quad (42)$$

EV battery balance constraints

In the MESSAGE modelling framework, there is no predefined option for ensuring storage balance within season or daytype, i.e. by default, stored energy could be transferred to the next season. However, it is problematic for modelling electric vehicles as it might result in unrealistic seasonal charging patterns. For example, there might be a mismatch between EV use and charging in some seasons as batteries could be charged more during seasons with cheaper electricity, and surplus energy could be transferred to another season. Therefore, a workaround is needed to ensure storage balance within season or daytype.

Two technologies with 12 alternative activities were added, matching modelled seasons (months) (see Figure 59). Each activity was constrained to be operational only during the respective month by setting maximum bounds on activities. Additional constraint (43) was set to force the output of car charging constraint technology to match the output of EV charger technology (see Figure 51), and constraint (44) was used to match the output of car discharging constraint technology with the sum of EV electricity consumption and electricity supplied back to the grid (V2G). Basically, it forces these technologies to replicate charging and discharging volumes. However, different alternative activities account for only charging and discharging of respective seasons (months). This approach enables to set a constraint that forces the amount of energy charged to be equal to what is discharged for each season (45).

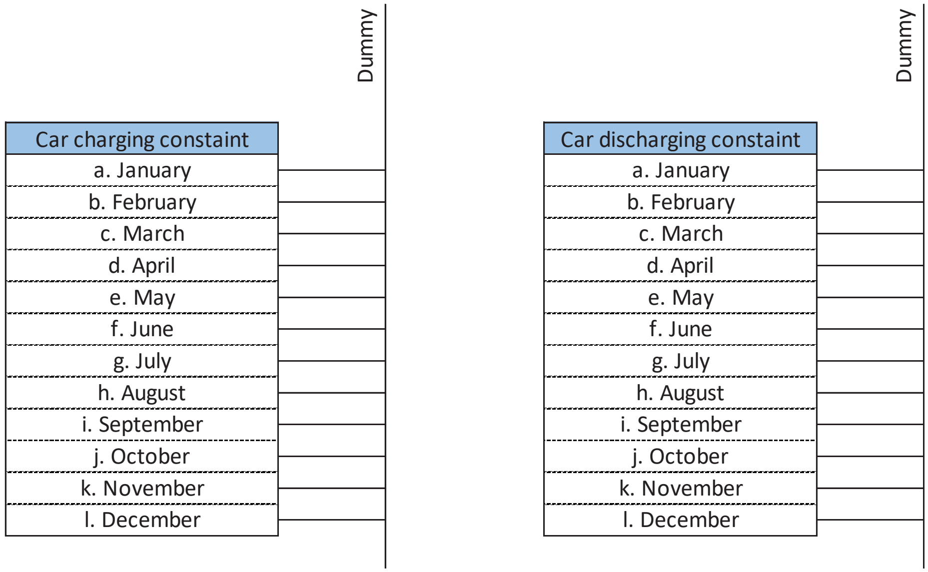


Figure 59. Car charging and discharging constraint technologies

Source: created by the author

$$consa_{charger} \cdot X_{charger,\tau} - \sum_{w} X_{charg\_constr,w,\tau} = 0; \tag{43}$$

where: $consa_{charger}$ – the coefficient for linked storage constraints on activities of charger technology; $X_{charger,\tau}$ – output of the charger in time slice τ in MWyr; $X_{charg\_constr,w,\tau}$ – the output of car charging constraint technology's alternative activity w in time slice τ in MWyr.

$$\sum_{l,y,o} \left(-consa_{EV,l,y,o,\tau} \cdot X_{EV,l,y,o,\tau}\right) + X_{V2G,\tau} - \sum_{w} X_{discharg\_constr,w,\tau} = 0; \tag{44}$$

where: $consa_{EV,l,y,o,\tau}$ – the coefficient for linked storage constraints on activities of EV of class l and build year y technology's operation mode o in time slice τ. There is a minus sign before the consa coefficient used for EV technologies as it has a negative value (see equation (27)). $X_{V2G,\tau}$ – electricity supplied back to the grid (V2G) in time slice τ in MWyr. $X_{discharg\_constr,w,\tau}$ – the output of car discharging constraint technology's alternative activity w in time slice τ in MWyr.

$$\sum_{\tau} X_{charg\_constr,w,\tau} - \sum_{\tau} X_{discharg\_constr,w,\tau} = 0 \tag{45}$$

2.6.4. Public transport

The modelling approach for public transportation is analogous to personal transport. The main difference is that different public transportation modes satisfy either short or long-distance travel demands, while personal transport can be used for both. Four types of public transportation modes were modelled: city buses, trolleybuses, intercity buses and passenger trains. City buses and trolleybuses can be used only for short-distance travel, and intercity buses and passenger trains only for long-distance travel. See Figure 60.

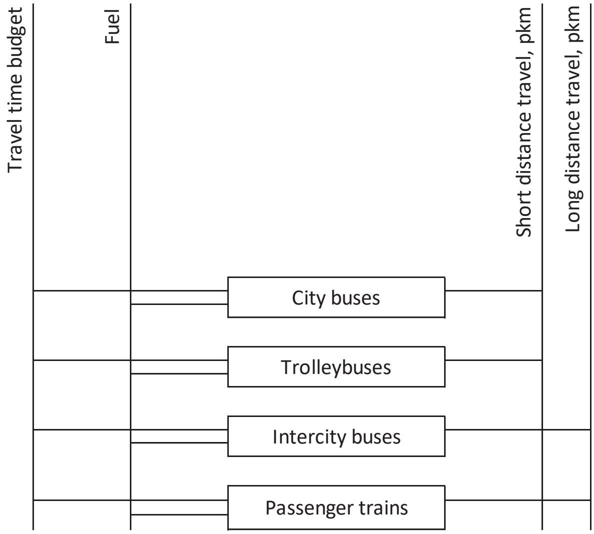


Figure 60. Public transport in the energy chain

Source: created by the author

For buses, four types of fuels were considered: diesel, compressed natural gas (CNG), electricity, and hydrogen. Trolleybuses use only electricity, and both diesel and electric trains were modelled. City buses, trolleybuses and intercity buses were also differentiated by production year:

- 1992 and before (pre-Euro);
- 1993–1996 (Euro 1);
- 1997–2000 (Euro 2);
- 2001–2005 (Euro 3);
- 2006–2008 (Euro 4);
- 2009–2012 (Euro 5);
- 2013–2020 (Euro 6);
- 2021–2025;
- 2026–2030;
- 2031–2035;
- 2036–2040;
- 2041–2045;
- 2046–2050;
- 2051–2060.

According to REGITRA data (REGITRA, 2020), in Lithuania, there were no CNG city buses built before 2001, no BEV city buses before 2013 and no city FCEV buses at all. Also, no CNG intercity buses were built before 2013 and no BEV and

FCEV intercity buses. Therefore, corresponding redundant technologies were eliminated. Also, unlike personal cars, it was assumed that only brand-new buses or other passenger transport vehicles could be added to the vehicle stock.

The efficiencies for public transport technologies were determined the same way as for car technologies, using the equation (19). Fuel consumption rates for road public transport are given in Table A.21. For diesel trains, 88.2 kg/100 km fuel consumption rate was used, while 345.4 kWh/100 km for electric trains, based on statistical data on rail travel (Statistics Lithuania, 2022b), final fuel and energy consumption in rail transport (Statistics Lithuania, 2022c) and fuel consumption rates in the scientific literature (García-Álvarez, Pérez-Martínez, & González-Franco, 2013). It was assumed that the average occupancy rate of city buses is 16.48 persons, trolleybuses – 12.74, intercity buses – 13.2 and passenger trains – 52.5 based on passenger and vehicles kilometres travelled in these modes of transport (Statistics Lithuania, 2022a, 2022d, 2022e).

Time consumption is also determined the same way as for car technologies (equations (20) and (21)). Assumed average speeds for public transportation modes, including waiting times, are as follows:

- 13.39 km/h – city buses and trolleybuses;
- 40.05 km/h – intercity buses;
- 63.57 km/h – passenger trains.

Initially, public transportation speeds were estimated by analyzing public transport timetables and accounting for the waiting times. Later, these values were adjusted during the model calibration process.

The purchase prices of public transport vehicles, except for trains, are given in Table A.22. Due to a lack of data on train and rail infrastructure investment, operation and maintenance costs is disabled, and O&M costs were not set. Also, the output of passenger train technology is limited to current passenger rail travel volumes (251.4 Mpkm/yr by diesel trains and 228.0 Mpkm/yr by electric trains), as it is unclear how they might change in the future. O&M costs for road passenger transport were used the same as for freight transport.

2.6.5. Freight transport

The modelling principles of freight transport are very similar to passenger transport. The main difference is that fuel is consumed to deliver freight instead of passengers. So, the output units are ton-kilometres. The efficiency is still calculated using equation (19), but it is in tkm/kg. It should be noted that the vehicle occupancy rate used in equation (19) is in tons. Another significant difference is that time budget constraints do not apply to freight transport, so each technology has only one input – fuel (see Figure 61). Freight delivery is differentiated into national and international delivery. It was assumed that all modelled freight technologies could provide nationwide and international delivery. Two types of freight transport were modelled – trucks and freight trains. Trucks were further differentiated by four types of fuels (diesel, CNG, hydrogen, and electricity), while trains were by two (diesel and electricity). Additionally, trucks were differentiated by build year:

- 1992 and before (pre-Euro);

- 1993–1996 (Euro 1);
- 1997–2000 (Euro 2);
- 2001–2005 (Euro 3);
- 2006–2010 (Euro 4);
- 2011–2014 (Euro 5);
- 2015–2020 (Euro 6);
- 2021–2025;
- 2026–2030;
- 2031–2035;
- 2036–2040;
- 2041–2045;
- 2046–2050.

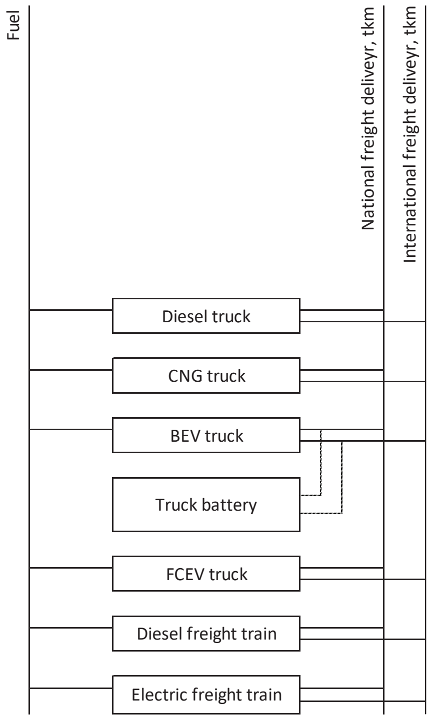


Figure 61. Freight transport in the energy chain

Source: created by the author

Fuel consumption rates, purchase costs and O&M costs for road freight transport are given in Table A.23, Table A.24 and Table A.25, respectively. 89.56 Mtkm/kt efficiency was assumed for diesel freight trains and 158.15 Mtkm/MWyr for electric trains. Investments in freight trains were disabled for the same reasons as for passenger trains. Also, freight delivery for trains was limited to 3833 Mtkm for nationwide delivery and 1150 Mtkm for international delivery.

Similarly to range anxiety costs for electric vehicles in passenger transport, inconvenience costs were applied for EV trucks. It is used to represent inconveniences from shorter driving ranges, longer fuelling times, and less accessible fuelling stations than ICE trucks. It could be argued that these inconveniences result in costs. For example, due to the shorter driving range, stops have to be made more often, also longer fuelling times, which means these stops are longer. Therefore, it takes more time to deliver cargo the same distance as with an ICE truck. So, assuming the drivers are paid per hour worked, the cost of driver per tkm is higher for BEV than for ICE trucks. This difference and other inconveniences are expressed as inconvenience costs in Table 10 and Table 11. It was assumed that inconvenience costs for international freight delivery are two to three times as high as national freight delivery as travel distances are more extended and necessary stops to charge the battery plays a more prominent role.

Table 10. Inconvenience costs for truck EVs in national freight delivery, Eur/100 km

EV trucks built		**Modelling years**					
from	**till**	2020	2025	2030	2035	2040	2050
2021	2025	15.00	13.56	12.26	11.08	10.01	8.18
2026	2030	12.00	10.85	9.80	8.86	8.01	6.55
2031	2035	9.60	8.68	7.84	7.09	6.41	5.24
2036	2040	7.68	6.94	6.28	5.67	5.13	4.19
2041	2045	6.14	5.55	5.02	4.54	4.10	3.35
2046	2050	4.92	4.44	4.02	3.63	3.28	2.68

Source: created by the author

Table 11. Inconvenience costs for truck EVs in international freight delivery, Eur/100 km

EV trucks built		**Modelling years**					
from	**till**	2020	2025	2030	2035	2040	2050
2021	2025	40.00	34.35	29.50	25.33	21.75	16.04
2026	2030	32.00	27.48	23.60	20.26	17.40	12.83
2031	2035	25.60	21.98	18.88	16.21	13.92	10.27
2036	2040	20.48	17.59	15.10	12.97	11.14	8.21
2041	2045	16.38	14.07	12.08	10.38	8.91	6.57
2046	2050	13.11	11.26	9.67	8.30	7.13	5.26

Source: created by the author

2.6.6. Biofuel blending

In Lithuania, from 2020, biofuel content in 95 Research Octane Number (RON) petrol is required to exceed 10% by volume and 7% in diesel (Ministry of Transport and Communications, 2010). However, it is reasonable to expect that the required biofuel content will increase in future to comply with emission abatement targets. Therefore, a dynamic approach was used to enable changing biofuel content.

Diesel and biodiesel blending is modelled through technology, with diesel and biodiesel as inputs and diesel-biodiesel blend as output (See Figure 62). The blend is later used by vehicles. Input ratios, i.e. biodiesel content, are assumed, while output efficiency is calculated based on assumed input ratios and heating values using equation (46) (see Table 12). Variable costs are calculated using equation (47). Note: Diesel gen and Biodiesel gen technologies do not have variable costs. All costs related to fuel are accounted for in technology blending biodiesel.

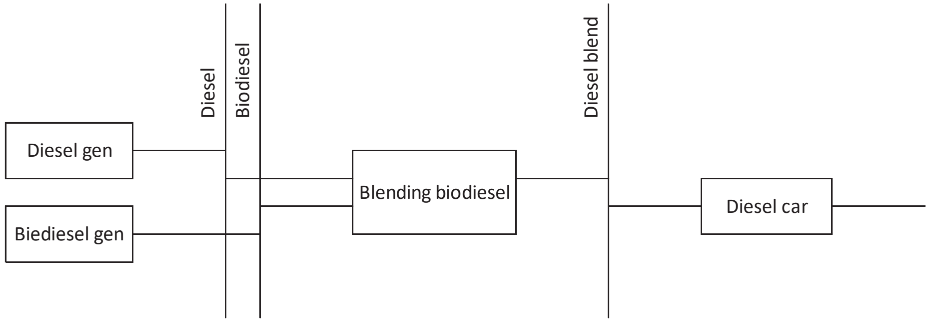


Figure 62. Diesel and biodiesel blending in the energy chain

Source: created by the author

Table 12. Biodiesel blend shares and the ratio of blend and diesel calorific values

	Diesel-biodiesel blend shares					
	2020	2025	2030	2035	2040	2050
Diesel	0.93	0.9	0.85	0.8	0.6	0
Biodiesel	0.07	0.1	0.15	0.2	0.4	1
The ratio of blend and diesel calorific values	0.990	0.986	0.979	0.971	0.943	0.863

Source: created by the author

$$\eta_{blending\ biodiesel,t} = \frac{\theta_{diesel,t} \cdot HV_{diesel} + \theta_{biodiesel,t} \cdot HV_{biodiesel}}{HV_{diesel}} \tag{46}$$

where: $\eta_{blending\ biodiesel,t}$ – efficiency of blending biodiesel technology in year t; HV – heating value, 42.86 GJ/t used for diesel and 37 GJ/t used for biodiesel; θ – a share of fuel in biodiesel blend in year *t*.

$$p_{biodiesel\ blend,t} = \left(\theta_{diesel,t} \cdot p_{diesel,t} + \theta_{biodiesel,t} \cdot p_{biodiesel,t} + RM_t + ED_t\right) \cdot \frac{1 + VAT}{\eta_{blending\ biodiesel,t}} \tag{47}$$

where: $p_{biodiesel\ blend,t}$ – the price of biodiesel blend in year *t*; $p_{diesel,t}$ and $p_{biodiesel,t}$ – diesel and biodiesel price in year *t*. RM_t – retail margin in year *t*, which was assumed to be €225.89/t; ED_t – excess duty (€443/t for diesel in 2020 and €555/t afterwards; €423/t for biodiesel); VAT – value-added tax (21% in Lithuania).

It was assumed that all diesel vehicles could use a blend with any biodiesel content. However, some modifications might be necessary for petrol cars to support fuels with higher biofuel content. Therefore, a somewhat different approach was taken. In this model, four petrol-biofuel blending technologies were used. The first is ETBE blending technology, producing a 10% ETBE-petrol blend. The second is E10 blending technology, which produces a 10% ethanol-petrol blend. The third and fourth technologies, E20 and E85, produce petrol blends with 20% and 85% ethanol content.

It was assumed that all petrol vehicles could use the ETBE blend, E10 by petrol vehicles produced since 2001, E20 by produced since 2031 and E85 by produced since 2041. Blend prices and efficiencies for these technologies were calculated similarly to the diesel-biodiesel blend. However, different retail margins (€128/t) and excess duties (€621/t for petrol and €575/t for ethanol) were used. The heating value for petrol is equal to 43.75 GJ/t, 27 GJ/t was used for ethanol and 36.2 GJ/t for ETBE. Calculated efficiencies for blending technologies are the following: 0.983 for ETBE blending; 0.959 for E10 blending; 0.917 for E20 blending; 0.649 for E85 blending.

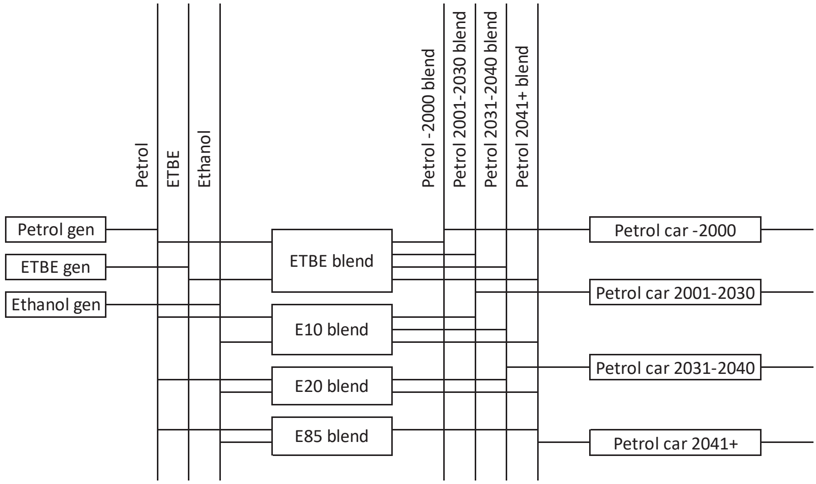
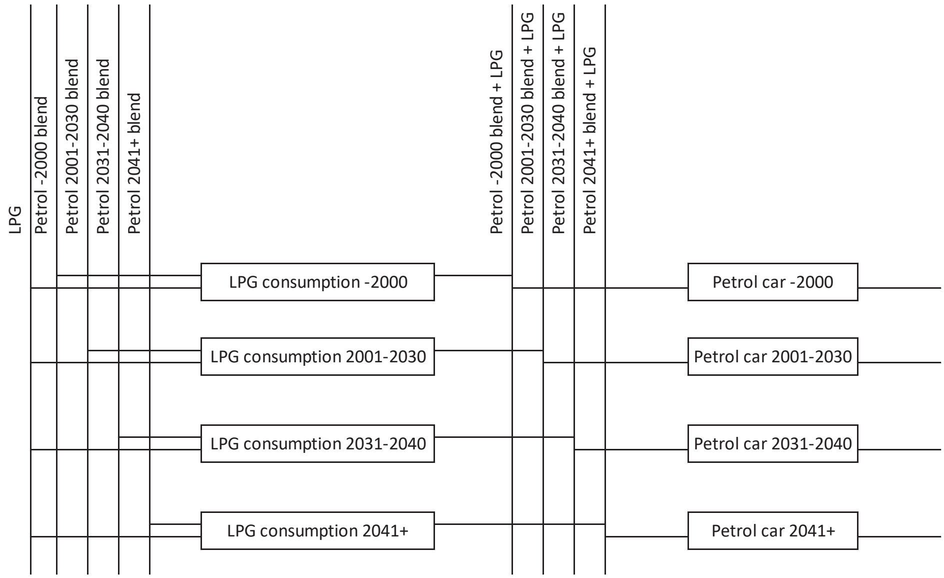


Figure 63. Petrol and ethanol or ETBE blending in the energy chain

Source: created by the author

2.6.7. LPG consumption

LPG-consuming vehicles are essentially modified petrol vehicles, and it is possible to model petrol cars retrofitting to be able to use LPG as fuel. However, it would add to the complexity of the model and require computational resources. As the developed model is at software limitations, it was decided to use a more straightforward approach – to link LPG and petrol blend consumption. These links are modelled by adding technologies that have LPG and a corresponding petrol blend as input (See Figure 64). Input ratios are fixed, and the LPG share is assumed to decrease gradually throughout the modelling years (See Table 13). The outputted energy forms by these technologies are used by petrol-fueled cars. It should be noted that the representation of part of the energy chain in Figure 63 is simplified as the LPG consumption part is skipped. However, such representation better explains the underlying modelling principles without presenting an overcomplicated graph.



Source: created by the author

Figure 64. LPG consumption in the energy chain

Table 13. LPG and petrol blend shares in LPG consumption technologies

	Modelled years					
	2020	2025	2030	2035	2040	2050
LPG share	26.3%	18.9%	13.6%	9.8%	7.0%	3.6%
Petrol blend share	73.7%	81.1%	86.4%	90.2%	93.0%	96.4%

Source: created by the author

2.6.8. Fuel emission factors

CO_2 emissions in the transport sector are calculated the same way as in the power and district heating sectors by multiplying fuel consumption by a corresponding emission factor. Tier 1 CO_2 emission factors for different road transport fossil fuels were used from EMEP/EEA air pollutant emission inventory guidebook 2019 (European Environment Agency, 2019).

Table 14. Transport fuel CO_2 emission factors

Fuel	**kg CO_2 per kg of fuel**
Petrol	3.169
Diesel	3.169
CNG	2.743
Hydrogen	0
Bioethanol	0
Biodiesel	0
ETBE	0

Source: created by the author based on (European Environment Agency, 2019) data

2.7. Model validation

Since the model was developed for the analysis of how power, district heating and transport sectors should develop in the future to reach near-zero carbon emissions, there is no direct way how to check the model's accuracy for future years, especially considering the uncertainty in various future values, like technology and fuel costs. However, the year 2020 was chosen as the first modelling year to be able to compare the modelling results of this year to statistical data to evaluate if the model gives reasonable results.

The power sector modelling results and statistical data on electricity generation by source (Litgrid, 2021a) and cross-border electricity flows (ENTSO-E, 2022) for 2020 are given in Table 15.

Table 15. The comparison of power sector modelling results and electricity generation by source and cross-border electricity flows in Lithuania in 2020, TWh

	Statistical data	Modelling results
Net electricity production	5.14	5.05
Thermal power plants	1.91	1.97
Kruonis PSHPP	0.77	0.63
Hydropower plants	0.30	0.29
Wind power plants	1.54	1.40
Wind power plants connected to the transmission grid	1.32	1.19
Wind power plants connected to the distribution grid	0.23	0.21
Other renewable sources	0.60	0.75
Biomass and biogas-fired power plants	0.39	0.48
Solar power plants	0.11	0.12
MSW-fired power plants	0.10	0.14
Cross-Border electricity flows, 2020		
BY->LT	2.25	3.06
LT->BY	0.07	0.00
LV->LT	1.45	1.45
LT->LV	0.48	0.48
PL->LT	0.38	0.01
LT->PL	2.16	2.16
KGD->LT	2.05	2.42
LT->KGD	0.00	0.08
SE->LT	4.74	4.19
LT->SE	0.09	0.09

Source: created by the author

As can be seen in Table 15, the differences between statistical data and modelling results are minor. However, the exact match should not be expected as the model has many simplifications, and the data on actual operation costs in specific power plants is unavailable. Instead, data from the Danish energy catalogue (Danish Energy Agency, 2020) and the BENTE project (Lindroos et al., 2018) were used. Also, the modelling approach has an inbuilt assumption of perfect markets. However, in reality, the power market is not perfect. As M. Fan stated, "The reason is that power production has a certain economy scale, which limits the number of investors. Besides, the number of buyers and sellers in a power market is not necessarily large because of security, stability, reliability, and financial requirements. Furthermore, power cannot be easily stored, and power production must be highly coordinated, with network loss and congestion. As a result, the goods offered by the various sellers are not necessarily the same." (Fan, Zhang, & Wang, 2019). Considering the abovementioned aspects and that differences between the modelling results and statistical data are minor, it can be concluded that the power sector model gives credible results.

Unfortunately, there is no publicly available data on district heat generated by sources in Lithuania in 2020. However, in their overview of the centralized heating sector in 2020 (Lietuvos šilumos tiekėjų asociacija, 2021b), the Lithuanian District Heating Association provides fuel consumption for district heat generation, which can be compared to the modelling results. See Table 16.

Table 16. The comparison of statistical fuel consumption in district heat generation in Lithuania in 2020 with fuel consumption in modelled district heating sector, TWh

	Statistical data	Modelling results
Natural gas	1.58	1.10
Heating oil	0.05	
MSW and other waste	0.33	0.41
Biomass and other biofuels	6.22	7.02
Other fuels	0.14	

Source: created by the author

The differences between statistical data and modelling results are somewhat higher for the district heating sector than for the power sector. It is likely due to a lack of available data on the actual techno-economic parameters of heat-producing plants and the aggregation of temporal and spatial resolutions. In the model, each month is represented by representative workdays and off-work days, resulting in averaged heat loads. Load averaging reduces centralized heating demand peaks, which gas-fired heating plants typically cover. Furthermore, only the district systems of the six biggest cities out of 60 cities and district municipalities where licensed heat suppliers operate were modelled separately. The remaining systems, with 29% of the country's heat demand, were modelled as a single one. Therefore, heat-generating plants with lower running costs can be utilised more in Lithuania's case of biomass-fired CHP and heating plants. Moreover, most district heating systems in Lithuania have only one or several suppliers, making it far from a perfect market. Also, it should be mentioned that heat production from coal, peat and oil products was not modelled due to model size restrictions and low share in overall heat production. Nevertheless, the model provides a reasonable centralized heat generation mix. However, the modelling results of the district heating sector should be treated with caution as heat generation from biomass could be slightly overestimated and from natural gas underestimated.

The reliability of the transport sector model was checked by comparing fuel consumption data with statistical data (Statistics Lithuania, 2022c), similar to the district heating sector, as there is no available data on passenger travel and freight delivery by fuel. Additionally, the travel volumes in busses, trolleybuses and trains were compared with statistical data (Statistics Lithuania, 2022a). See Table 17.

Table 17. The comparison of statistical fuel consumption in Lithuania's transport sector and travel volumes by public transport modes in 2019–2020 with the modelling results

	Statistical data		Modelling results
	2019	2020	2020
Diesel, kt	1595.7	1558.7	1510.9
Petrol, kt	231.0	225.9	234.0
CNG, kt	7.1	8.0	7.4
LPG, kt	96.2	88.6	90.1
Biodiesel, kt	72.0	95.9	113.7
Bioethanol and ETBE, kt	15.1	24.4	26.0
Electricity, TWh	0.1	0.1	0.1
Rail transport, Mpkm	479	260	479
Buses, Mpkm	2646	1486	3184
Trolleybuses, Mpkm	256	145	246

Source: created by the author

As can be seen in Table 17, the model modelling results are very close to the statistical data. It should be noted that the effects of the global coronavirus pandemic were not taken into account in the model, as the model is designed for long-term development analysis, while pandemic effects on travel are short-term. Therefore, the modelling results give significantly higher travel volumes with public transport for 2020. Instead, the modelling results can be compared to 2019 data. However, in 2020, the required biofuel content in diesel and petrol blends was increased. For these reasons, statistical data for the years 2019 and 2020 are given in Table 17.

The comparison of statistical data and modelling results shows that the integrated model represents power, district heating and transport sectors quite well and is suitable for long-term analysis. However, there is always uncertainty around the future values of costs and other parameters. Therefore, the input data should be updated in the model once newer data is available.

2.8. Model limitations

The main research limitations are related to data availability, selected modelling method and software limitations. The model needs a lot of techno-economical data to correctly represent modelled technologies (power plants, heating plants, electricity imports and exports, vehicles, and fuel supply). However, such data for specific power plants and heating plants, except for installed capacities and, in some cases, efficiencies, is not publicly available. Therefore, data from energy catalogues were used instead. Furthermore, acquired data on road travel patterns covers only April to October 2020, in which seasonal patterns were substantially affected by the coronavirus pandemic with lockdown measures. Attempts were made to acquire travel pattern data for the year 2021. Unfortunately, they were unsuccessful. Also, Lithuania's freight delivery pattern data, transport operation, and maintenance costs were unavailable, so data from the scientific literature was used instead. Though rail transport was modelled, its representation is limited to the current state due to a lack of data. Unfortunately, it is unclear how much rail electrification in Lithuania costs, how much electric trains cost, and how passenger rail travel and freight volumes could change in the future. Another limitation related to data availability is the lack of travel surveys in Lithuania, which could enable the inclusion of travellers' heterogeneity in the model. Finally, since the model was designed to analyse the decarbonization pathways, it is essential to emphasise the high uncertainty associated with future technology, fuel, emission, electricity import, and other costs.

Energy planning models have an embedded assumption of perfect markets and financial rationality, meaning that the cheapest options will always be chosen if not constrained. For the power and district heating sectors, these assumptions are reasonable. However, in the transport sector, especially in passenger transport, non-monetary factors like travel time, convenience, looks, and others play a significant role. For this reason, travel time budget and inconvenience penalties for EVs were implemented. Unfortunately, most of the behavioural aspects were not considered.

The MESSAGE modelling framework was developed in 32-bit architecture, meaning that the model size is limited to around 2 gigabytes (around 1 million equations and 1.4 million variables). Therefore, various simplifications had to be applied to fit the modelling limits. First, an aggregated temporal resolution was used, which hinders the representation of variability in RES. A probabilistic approach was developed for modelling wind power plants to mitigate some drawbacks of aggregated temporal resolution. However, the model does not consider possible prolonged periods with low wind speeds and low irradiance. As a result, the required energy storage size might be significantly underestimated. Second, an aggregated spatial resolution was used. The Lithuanian power grid was represented by a few technologies and energy forms (nodes), neglecting any grid limitations. Therefore, the model can not identify in which part of the country the power plants should be built. However, the six biggest district heating systems were represented, covering 71% of total district heating demand. The remaining district heating systems were grouped and represented as one. In the transport sector model, journeys were differentiated only into short and long-distance travel, national and international, during freight delivery. A more detailed representation of travel by distance could provide a better picture of different vehicle type roles in decarbonized future travel. Third, fuel supply was considered unlimited, i.e. each modelled year, an unlimited amount of fuel can be supplied at a fixed price. It is particularly problematic in the case of biomass and liquid biofuels, as increased production might require increased forest cutting and more land for energy crops. Consequently, the modelling results might yield unsustainable biomass and liquid biofuel production and consumption. Also, the energy systems of neighbouring countries were not modelled. Instead, interconnections were modelled as technologies that can import and export electricity at a set price and are limited only by throughput capacity. As neither electricity generation capabilities nor electricity demands of neighbouring countries are considered, the possibility of importing and exporting electricity might be overestimated.

3. RESULTS

3.1. Definition of the scenarios

Fifteen scenarios were analysed, which can be grouped by aspect analysed or applied EV charging strategy. Five aspects were investigated:

1. **Base** – the cross-sectoral effects of the development of transport, power, and district heating sectors. In other scenarios, the impacts of the aspects considered are assessed by comparing the modelling results with the results of the **Base** scenario;
2. **VehDistr** – the effects of gradually decreasing average vehicle age. With improving income, Lithuanians will likely afford newer cars, which could hasten the fuel transition in the transport sector, resulting in a sooner increased electricity demand compared to the base scenario (see section Vehicle age distribution).
3. **RedFlexi** – the effects of reduced reliance on interconnections to balance the electricity generation from variable renewable sources. Since neighbouring countries with which Lithuania has interconnections were not modelled explicitly, i.e. electricity imports from and exports to these countries are not limited by demand and generation in these countries; the model has more flexibility to utilize interconnections for VRES balancing than it would be possible in real life. For this reason, a scenario with reduced rates of how quickly the interconnections can change how much electricity is imported and exported was selected for the analysis.
4. **InterOff** – the effects of the need to fully balance electricity generation within the country from 2040. Neighbouring countries will likely transition to sustainable electricity generation based on VRES in the coming decades. Therefore, they will have the same issue of balancing intermittent electricity generation. Furthermore, as these countries are relatively in the same region, wind speeds and solar irradiance tend to be similar at any moment in time, meaning that generation peaks or valleys from VRES coincide. So, each country will have to be able to balance its electricity generation without relying on electricity imports and exports. In this scenario, interconnections are cut off after 2040.
5. **ZeroCO_2** – the effects of decarbonization of all three sectors modelled – transport, power and district heating. In previous scenarios, decarbonization is not directly enforced. Instead, it is modelled in a way that rising fossil fuel and CO_2 prices make the use of fossil fuels unattractive. However, it is valuable to investigate how these sectors could develop under strict CO_2 limitations that force them to reach carbon neutrality by 2050.

Additionally, three EV charging strategies were considered for each scenario mentioned above: uncontrolled EV charging, smart EV charging, and bidirectional vehicle-to-grid (V2G) (see section Electric vehicles). All fifteen scenarios are presented in the scenario matrix in Table 18. The magnitude of effects analysed with different scenarios is estimated by comparing the scenario modelling results with the Base scenario results.

Table 18. Scenario matrix

Aspects analysed	EV charging strategy		
	Uncontrolled	Smart	V2G
Cross-sectoral effects of the development of transport, power, and district heating	Base	Base+smart	Base+V2G
The effects of gradually decreasing average vehicle age	VehDistr	VehDistr+smart	VehDistr+V2G
The effects of reduced reliance on interconnections to balance the electricity generation from VRES	RedFlexi	RedFlexi+smart	RedFlexi+V2G
The effects of the need to fully balance electricity generation within the country from 2040	InterOff	InterOff+smart	InterOff+V2G
The effects of decarbonization of all three sectors modelled	ZeroCO_2	ZeroCO_2+smart	ZeroCO_2+V2G

Source: created by the author

As the model was developed to investigate how power, district heating and transport sectors should develop in the future to ensure near-zero carbon emissions, various assumptions are needed for the modelled years. These include assumptions on energy and travel demands, fuel prices, CO_2 price and techno-economic parameters. Also, different assumptions were applied for different scenarios.

Electricity demand assumptions were based on forecasts by (Løken, Brenden, & Berglund, 2020). As data on district heating demand forecasts are sparse, it was assumed that demands will decrease by 2% per year till 2030, 1% till 2040, and 0.5% till 2050. Electricity and district heating demand assumptions are given in Table 19.

Table 19. Electricity and district heating demand assumptions

	Modelled years					
	2020–2025	2025–2030	2030–2035	2035–2040	2040–2050	2050–2060
	Electricity demand, MWyr					
Integrated version	1229.5	1297.4	1349.4	1398.6	1443.8	1514.7
	District heating demand by district heating system, MWyr					
Vilnius	280.5	253.6	229.2	218.0	207.3	197.2
Kaunas	132.4	119.7	108.2	102.9	97.8	93.1
Klaipėda	87.4	79.0	71.4	67.9	64.6	61.4
Šiauliai	43.5	39.3	35.5	33.8	32.1	30.6
Panevėžys	35.8	32.4	29.3	27.8	26.5	25.2
Alytus	21.7	19.6	17.7	16.9	16.0	15.2
Other	241.5	218.3	197.3	187.6	178.4	169.7

Source: created by the author

Travel demands for future years were based on population forecast and average travel volume per capita, which seems to saturate at around 11–14 thousand pkm per year and does not increase further with GDP/capita. 12.774 thousand pkm per year was used to be exact and multiplied by the forecasted population by the United Nations (United Nations, 2020) for each modelled year. See Table 20.

Freight delivery demands for future years were estimated based on the growth rate in statistical data. However, Lithuania saw a substantial increase in freight delivery volumes over the last couple of decades and continuing the trend will lead to questionable volumes by 2050. Therefore, a declining growth rate was assumed, decreasing by 40% every five years.

Table 20. Travel and freight delivery demand assumptions

	Modelled years					
	2020–2025	2025–2030	2030–2035	2035–-2040	2040–-2050	2050–2060
Travel demands, Mpkm						
Short distance travel	13539	12888	12358	11846	11361	10551
Long distance travel	21234	20212	19382	18579	17818	16547
Freight delivery demands, Mtkm						
National delivery	7810	10305	12192	13496	14348	15218
International delivery	20751	30215	37985	43630	47434	51414

Source: created by the author

Fuel price assumptions are given in Table 21. Natural gas and heating oil price changes were based on EU reference scenario data (European Commission et al., 2021). Biomass price was relatively low in 2020, so it was assumed to reach the average value of 2014–2020 (BALTPOOL, 2022) in 2025 and increase by 1% annually. Due to a lack of available data, constant price values were used for MSW and a 1% annual increase for ETBE, ethanol, and biodiesel. Changes in petrol, diesel and LPG prices were linked to oil price changes and CNG prices to natural gas price changes.

Table 21. Fuel price assumptions in €/t

Fuel	Modelled years					
	2020–2025	2025–2030	2030–2035	2035–2040	2040–2050	2050–2060
Natural gas	91.8	139.2	186.6	204.6	240.2	263.9
Heating oil	184.5	278.4	372.2	420.1	452.6	548.0
Biomass	88.2	112.6	118.3	124.4	130.7	159.5
MSW	-111.6	-111.6	-111.6	-111.6	-111.6	-111.6
Petrol	482.7	728.0	973.4	1073.4	1183.7	1433.2
Diesel	357.1	538.7	720.3	794.3	875.9	1060.5
LPG	513.0	773.8	1034.6	1140.9	1258.1	1523.2
CNG	1117.6	1695.2	2272.8	2578.7	2925.8	3214.6
ETBE	810.8	852.2	895.6	941.3	989.3	1092.9
Ethanol	619.9	651.5	684.8	719.7	756.4	835.5
Biodiesel	817.8	859.5	903.3	949.4	997.7	1102.2

Source: created by the author. Prices for Petrol, Diesel, ETBE, Ethanol and Biodiesel are wholesale prices without taxes. Taxes, duties and retail margins are added when calculating fuel blend prices (See section Biofuel blending)

Electricity import prices are based on own estimations, considering the increasing average cost of gross electricity generation and price conversion between neighbouring countries. Electricity import price assumptions are given in Table 22. Note: electricity import prices from Belarus (BY) and the Kaliningrad region (RU) are given only for 2020, as interconnections are planned to be cut off after synchronising with the continental European power grid in 2025.

Table 22. Electricity import prices, €/kWyr

Interconnection	Modelled years					
	2020–2025	2025–2030	2030–2035	2035–2040	2040–2050	2050–2060
LT-LV	298.3	312.7	327.9	343.7	360.4	377.8
LT-PL1	376.2	382.2	388.3	394.5	400.8	407.2
LT-PL2	376.2	382.2	388.3	394.5	400.8	407.2
LT-SE	226.6	291.5	309.9	324.6	327.7	355.3
LT-BY	269.9					
LT-RU	268.1					

Source: created by the author

CO_2 prices for the power and district heating sectors were based on EU reference scenario data (European Commission et al., 2021). CO_2 price assumptions are given in Table 23

Table 23. Assumptions on CO_2 price for power and district heating sector

	Modelled years					
	2020–2025	2025–2030	2030–2035	2035–2040	2040–2050	2050–2060
CO_2 price, €/t	25	26.5	30	50	80	150

Source: created by the author based on (European Commission et al., 2021) data

For scenarios designed to investigate the effects of reduced reliance on interconnections to balance electricity generation from VRES (RedFlexi), the maximum electricity import and export change rate was reduced by half (see Table 24).

Table 24. Assumptions on the maximum rate of electricity import and export change

The maximum rate of electricity import/export change, MW/h		
Interconnection	RedFlexi scenarios	Other scenarios
LT-LV	37	74
LT-PL1	32	64
LT-PL2	50	100
LT-SE	45	90
LT-BY	31.5	63
LT-RU	10	20

Source: created by the author

Maximum CO_2 limits were set for ZeroCO_2 scenarios to ensure gradual emission reduction toward carbon neutrality by 2050. Assumptions on maximum CO_2 limits for each year modelled are given in Table 25.

Table 25. Yearly CO_2 limits in ZeroCO₂, ZeroCO₂+smart and ZeroCO₂+V2G scenarios

	Modelled years					
	2020–2025	2025–2030	2030–2035	2035–2040	2040–2050	2050–2060
CO_2 limit for power and DH sectors, kt	1076.6	897.16	717.72	538.3	358.86	0
CO_2 limit for transport sector, kt	5800	5800	4640	3480	2320	0

Source: created by the author

3.2. Comparative scenario analysis

The modelling results of the developed model include electricity generation by power plant type, electricity imports and exports by interconnection, operation of energy storage, electricity market prices (equilibrium prices, based on marginal costs of generation), heat generation by CHP and heating plant type and heat market prices for each modelled district heating system, travel and freight delivery volumes by type of transport means, fuel, age group, fuel consumptions, emissions, capacity expansions and total installed capacity for each modelled technology, fixed, variable and investment costs and even more (See Figure 65). The model provides all the abovementioned results for each of the six modelled periods (2020–2025; 2025–2030; 2030–2035; 2035–2040; 2040–2050; 2050–2060), and most of them for each time slice (576 time slices per modelled period). A summary of the modelling results is given in Table 26. Scenarios effects matrix. Modelling results of different scenarios are discussed in detail in the following sections.

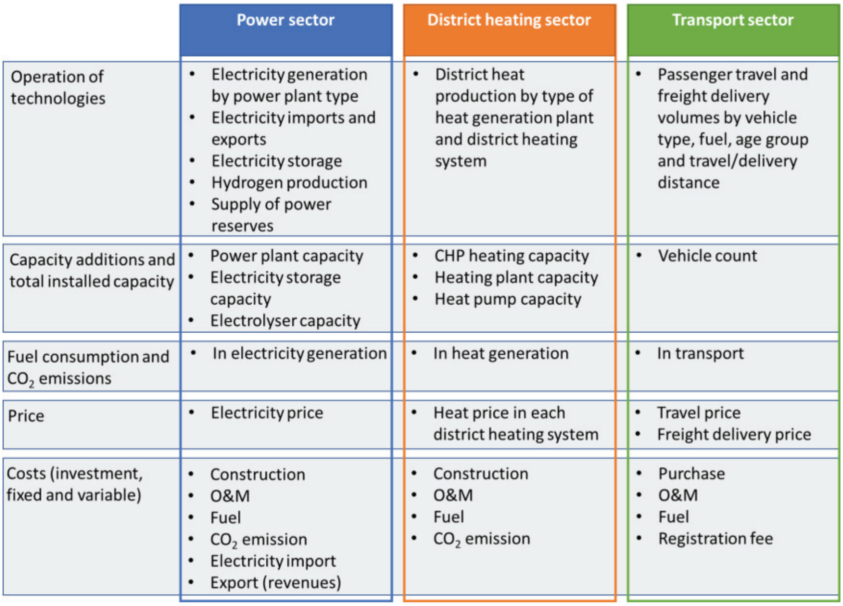


Figure 65. Results provided by the model

Source: created by the author

In this matrix, the key results of different scenarios were compared to the Base scenario with uncontrolled EV charging results, enabling the evaluation of the effects of aspects considered in different scenarios. The results that are higher by more than 10% (significant increase) compared to the Base scenario are marked by green. Ones that exceed 1% (slight increase) are marked by light green colour. Results lower than 10% (significant decrease) and 1% (slight decrease) are marked by red and orange colours. Since the model gives results for each modelled period, weighted average values were used to determine the differences, where weights are based on the number of years in the modelled period.

The comparison of **VehDistr**, **RedFlexi**, **InterOff** and **ZeroCO$_2$** scenarios results to Base scenario results reveals that:

1. The application of shifting vehicle age distributions substantially increases the use of BEVs in passenger transport but not in freight transport. On the contrary, it slightly reduces freight transport electrification rate due to increased electricity prices. It also significantly reduces the use of FCEVs in passenger transport, as BEVs are preferred instead. The overall passenger transport electrification happens faster; therefore, transport emissions are lower than in the Base scenario. Even though electricity consumption increases due to a faster electrification rate, local electricity generation is barely affected. Only electricity production in gas-fired and biomass CHP plants slightly increases. However, as BEVs have higher overall efficiency than FCEVs, the electricity demand is slightly lower after 2040 in the **VehDistr** scenario. In the case of uncontrolled EV charging (marked as Unc in Table 26), the additional electricity demand for charging EVs contribute to the evening demand peak, resulting in slightly higher average electricity prices but substantially higher price dispersion.
2. Reduced electricity import and export flexibility (**RedFlexi** scenario) decreases the local electricity generation, primarily from VRES, and slightly increases the use of energy storage. Reduced electricity generation in the wind and solar power plants, which have low marginal electricity generation costs and slightly increased imports and generation in CHP and gas-fired plants result in higher electricity prices and slightly higher electricity price dispersion. Also, the CO_2 emissions are slightly higher due to increased electricity generation in gas-fired power plants. In passenger transport, FCEV vehicles are used more in the **RedFlexi** scenario to utilize increased hydrogen produced via electrolysis, which contributes to balancing electricity generation from VRES. The FCEV share is increased for the most part at the expense of BEV vehicles. Therefore, transport emissions are at the same level as in the Base scenario.
3. The need to ensure a complete electricity generation balancing within the country after 2040 (**InterOff** scenario) significantly impacts all sectors modelled. It reduces the use of VRES and increases the curtailment of electricity generation in wind and solar power plants. The model chooses to produce more electricity in thermal power plants, including CHP plants and builds more grid batteries in the **InterOff** scenario to ensure the required

system flexibility to balance VRES generation within the country. However, it results in significantly higher electricity prices and price dispersion. Also, CO_2 emissions from power and district heating sectors are substantially higher. In the transport sector, the use of FCEV is increased, similarly to the **RedFlexi** scenario, but to a greater level as more hydrogen production through electrolysis plays a more significant role in balancing electricity generation.

4. Strict CO_2 emission reduction targets toward carbon neutrality by 2050 (**ZeroCO$_2$** scenario) increase electricity generation from VRES and the use of energy storage. Also, from all modelled scenarios, power plants with CCS were built only in the **ZeroCO$_2$** scenario. On average, electricity prices in the ZeroCO$_2$ scenario are only slightly higher, but the price spread substantially increases compared to the Base scenario. Emission constraints on the transport sector increase the use of BEVs and FCEVs in both passenger and freight transport.

The comparison of **Base**, **VehDistr**, **RedFlexi**, **InterOff**, **ZeroCO$_2$** scenarios with smart EV charging and V2G charging results to scenarios with uncontrolled EV charging results reveals that:

5. The application of smart charging for electric vehicles has substantial benefits. For example, it reduces the average electricity price and price spread as electric vehicle charging times are adjusted to match the cheaper power generation, mainly in wind and solar power plants. Therefore, in the modelling results of scenarios with smart charging applied, electricity generation from VRES is higher, and the use of energy storage is lower than in the equivalent scenarios with uncontrolled charging. Also, smart EV charging is a more cost-efficient way to provide VRES balancing capabilities compared to green hydrogen production and subsequent use in FCEVs. As a result, in scenarios, with smart charging applied, the share of BEVs is higher, and the share of FCEVs is lower.
6. The bidirectional EV charging (V2G) application has the same benefits as smart charging, but it provides even more flexibility as electricity can be temporarily stored in EV batteries and supplied back to the grid later. However, the differences between uncontrolled and smart charging scenarios are far greater than between smart and V2G charging scenarios.

Table 26. Scenarios effects matrix

	Base		VehDistr			RedFlexi			InterOff			$ZeroCO_2$		
	Smart	V2G	Unc	Smart	V2G	Unc	Smart	V2G	Unc	Smart	V2G	Unc	Smart	V2G
Local electricity generation	5%	6%	0%	7%	8%	-11%	0%	3%	1%	6%	6%	6%	12%	13%
Electricity from RES	6%	7%	-1%	7%	9%	-12%	1%	4%	-6%	3%	4%	6%	13%	14%
VRES curtailement	0%	0%	0%	0%	0%	0%	1%	1%	5%	3%	4%	0%	0%	0%
Electricity storage	-44%	-49%	1%	-46%	-50%	5%	-40%	-49%	7%	-35%	-44%	4%	-42%	-47%
CCS use	No	No	No	No	No	No	No	No	No	No	No	Yes	Yes	Yes
Electricity price	-12%	-12%	4%	-12%	-12%	4%	-8%	-9%	18%	0%	-2%	5%	-11%	-12%
Electricity price dispersion	-42%	-45%	22%	-43%	-45%	5%	-33%	-38%	61%	58%	42%	28%	-41%	-44%
District heating from RES	0%	0%	0%	0%	0%	0%	0%	0%	-3%	-2%	-1%	-1%	0%	0%
CO_2 emissions in power and DH	-10%	-10%	2%	-11%	-11%	2%	-8%	-8%	155%	60%	48%	-6%	-16%	-16%
BEV use in passenger transport	3%	3%	23%	27%	27%	-2%	3%	2%	-11%	-1%	-1%	7%	8%	8%
FCEV use in passenger transport	-20%	-20%	-81%	-92%	-92%	14%	-19%	-19%	103%	27%	23%	18%	-1%	0%
BEV use in freight transport	36%	36%	-7%	36%	36%	-7%	36%	36%	-15%	36%	36%	42%	92%	92%
FCEV use in freight transport	-14%	-14%	0%	-14%	-14%	0%	-14%	-14%	18%	0%	0%	28%	6%	6%
CO_2 emissions in transport	-1%	-1%	-7%	-10%	-10%	0%	-3%	-3%	1%	-4%	-4%	-10%	-10%	-10%

Source: created by the author

3.2.1. Base scenario modelling results

Base scenario modelling results show the pathway on how power, district heating and transport sectors should develop to satisfy future electricity, district heating and travel demands with the least costs. In this scenario, there are no strict restrictions on CO_2 emissions. However, constraints were placed on minimum shares of electricity and district heating generation from RES compared to final consumption.

3.2.1.1. Power and district heating sectors

In the modelling results of the Base scenario, Lithuania gradually transitions from an electricity net importing country to a net exporting country by 2050. This transition is based on a rapid expansion of electricity generation from variable renewable sources (See Figure 66). Annual electricity generation in onshore wind power plants more than triples in 2025–2030 compared to 2020–2025, reaching 532 MWyr (1 MWyr = 8.76 GWh). During 2025-2040 electricity production level in these power plants remains similar. However, a 700 MW offshore wind park will start operation in 2030. It should be noted that the construction of this park was forced on the model, considering plans for capacity expansion in the NECP, so it is not necessarily cost-optimal. No further investments in offshore wind power plants have been made in subsequent modelling years, but annual electricity generation in onshore wind power plants was expanded to 964 MWyr in 2040–2050 and 1965 MWyr in 2050–2060. Annual electricity generation using photovoltaics also rapidly develops, from 14 MWyr in 2020–2025 to 1059 MWyr in 2050–2060. The model sees the highest PV development potential at the prosumer level.

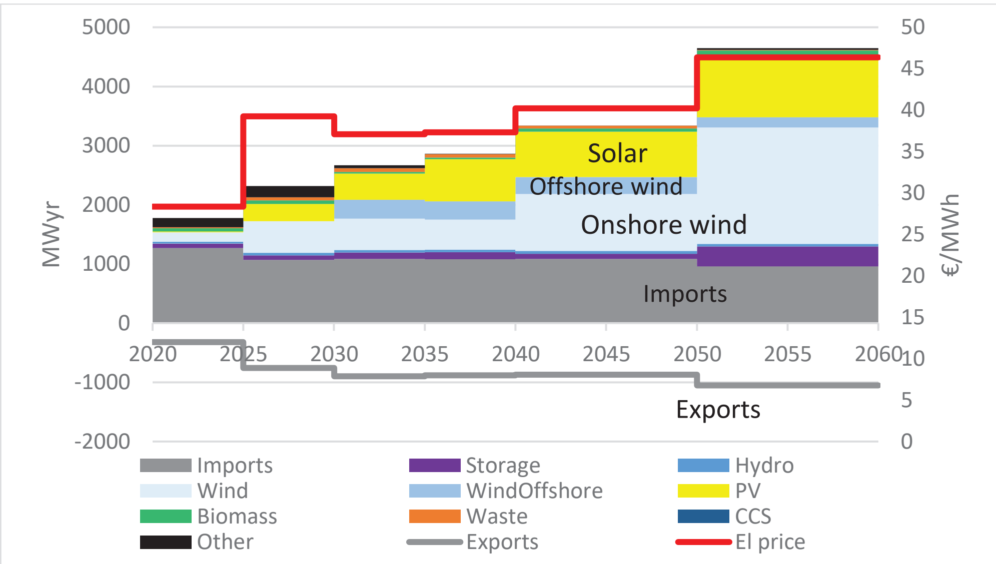


Figure 66. Electricity generation mix in the Base scenario

Source: created by the author

As electricity generation from variable renewable sources increases, the electricity generation from fossil fuel power plants is gradually phased out and reaches 0 by 2040. The balancing of variable electricity generation is primarily ensured by interconnections. For this reason, electricity imports remain relatively high throughout all modelling years, though they somewhat decrease after synchronization with the continental European grid in 2025 since interconnections with Belarus and Kaliningrad region are discontinued. However, exports rise with local generation and surpass imports in 2050–2060. Though the model primarily relies on interconnections to balance VRES electricity generation, other measures are also needed, including energy storage and electricity generation curtailment. For example, more than 1600 MW of grid storage batteries, with 43 GWh of energy storage, are built in 2050–2060. Also, VRES electricity generation is curtailed at peak moments for a smoother generation. The level of curtailment increases with VRES penetration, reaching 5% for PVs and 10% for wind power plants by 2050, as shown in Figure 67. However, it is important to mention that new grid batteries will reduce the curtailment of VRES in 2040–2050. Without the batteries, the curtailment should be even higher.

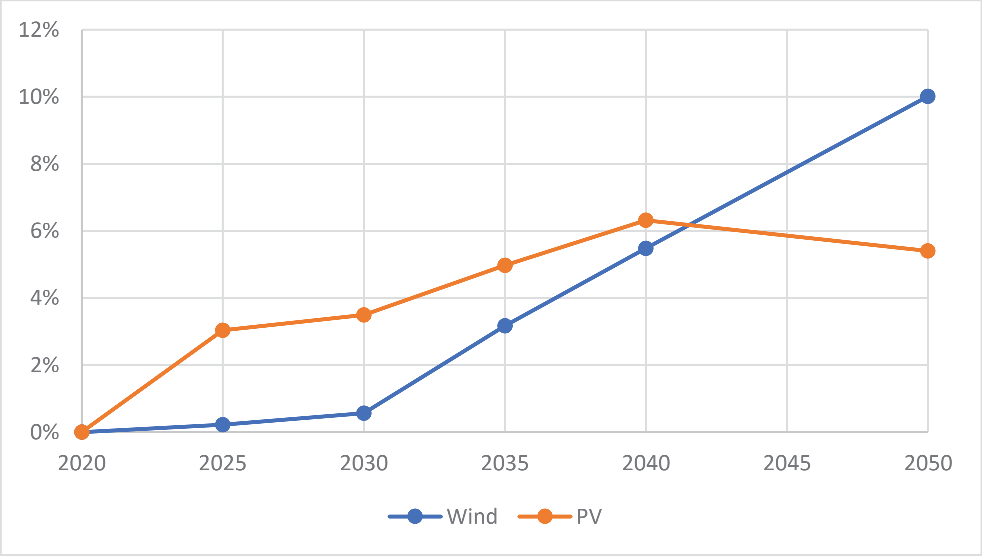


Figure 67. Curtailment of electricity generation in the wind and PV power plants in the Base scenario

Source: created by the author

The modelling results show that discontinuing interconnections with Belarus and Kaliningrad region could increase the electricity price in Lithuania by 40%. It is understood that even an increased electricity price seems very low compared to current market prices of €100-450/MWh (Nordpool, 2022) due to extremely high natural gas prices, as Russia substantially decreased natural gas supply in Europe in retaliation for the support of Ukraine in Russia-Ukraine conflict (Lu, 2022). However, the model was calibrated using pre gas price surge data, and general trends were considered and not shocks. In the case of long-lasting high fossil-fuel prices, the electricity market price would be accordingly higher, and the model would likely invest more heavily into VRES technologies in the near future as these technologies would be more profitable. Increased local electricity generation from VRES would reduce electricity imports and increase exports. However, the modelling results from 2040 should be the same as in the Base scenario because fossil fuel power plants are phased out by then.

Considering general trends, the electricity price will be positively affected (increased) by rising fuel and CO_2 prices and negatively (decreased) by electricity generation from VRES, as wind and solar power plants have meagre variable costs. These two opposite effects can result in increasing electricity price fluctuations. For example, at hours with high wind and solar electricity generation, electricity price would be low, while high at low VRES generation. The magnitude of fluctuations depends on VRES penetration and electricity costs from other sources. As a fuel, import, CO_2 prices and VRES penetration increase in the model with modelling years, price fluctuations substantially increase, especially at the bottom and top quarters, as shown in Figure 68.

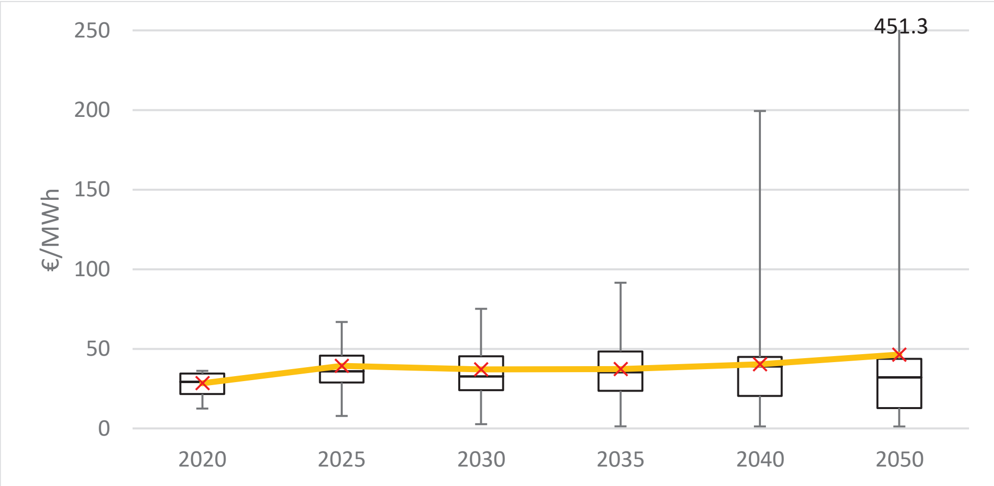


Figure 68. Electricity price in the Base scenario

Source: created by the author

In the district heating sector, already in 2020, more than 80% of heat is generated using renewable sources. Base heat generation is primarily supplied by biomass and waste CHP power plants, while biomass heating plants cover most of the additional heating demand during the heating season. The peaks are satisfied with heat production in gas-fired CHP and heating plants. See Figure 69. Generating only at peak demand times results in a low plant utilization rate. Therefore, cheap-to-build heat-generating technologies are preferred for this type of operation, even if operating costs are relatively high. Gas CHP and heating plants are substantially cheaper than biomass or waste-fired ones.

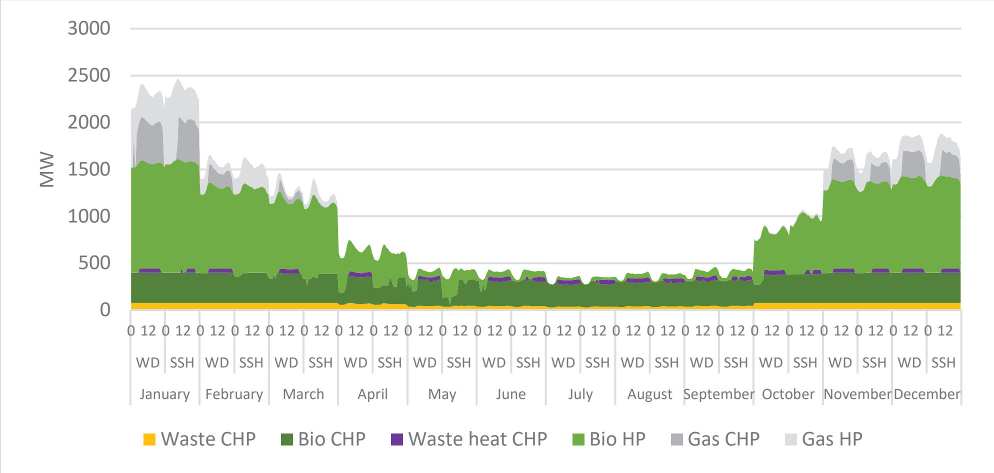


Figure 69. District heating generation by plant type in 2020 in the Base scenario

Source: created by the author

A similar district heating generation structure was observed throughout all modelling years. However, as centralized heat demand drops due to building renovation, biomass and waste-fired CHP plants push out other heat-producing plants since they are the cheapest sources of heat production (see Figure 70). For example, the share of heat generation in biomass and waste-fired CHP plants in total district heating generation increased from 34% in 2020 to 76% in 2050. Due to relatively high natural gas prices, including CO_2 prices, compared to biomass, no new gas CHP plants are built, and they will completely retire by 2030. Heat generation in gas-fired heating plants drops from 84 to 27 MWyr by 2050, and they operate only a small number of hours in a year, covering only the highest demand peaks. Heat generation in biomass heating plants also drops from 483 (49%) in 2020 to 140 MWyr (20%) in 2050.

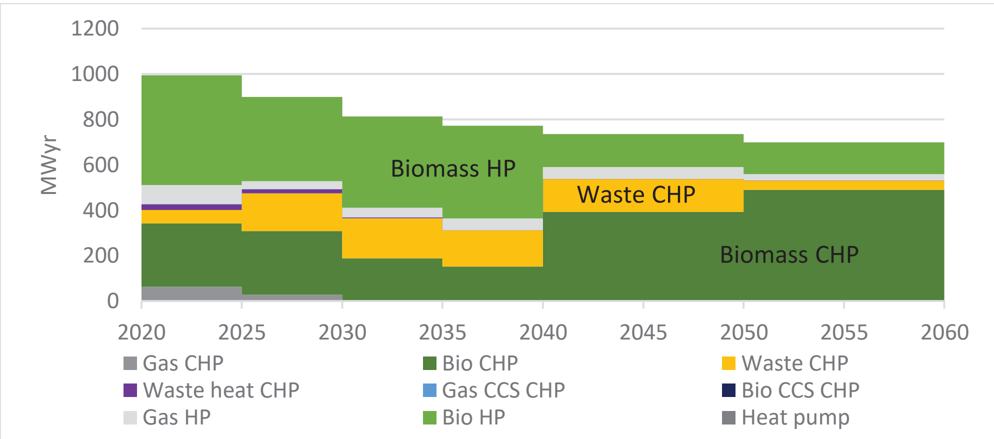


Figure 70. District heating generation mix in the Base scenario

Source: created by the author

The modelling results show that CO_2 emissions are likely to increase temporarily after the disconnection of interconnections with Belarus and the Kaliningrad region as electricity generation in gas-fired power plants will be increased, mainly in the CCGT unit of Elektrėnai complex. However, increasing electricity generation from renewable sources will decrease the need for generation in gas-fired power plants and the resulting emissions. In modelling results, emissions drop to 281 kt CO_2 in 2030–2035, 106 kt CO_2 in 2035–2040, 87 kt CO_2 in 2040–2050 but slightly rise to 133 kt CO_2 in 2050–2060 (See Figure 71). For comparison, CO_2 emissions from electricity and heat production in 1990 were 12003 kt, 3889 kt in 2000 and 3706 kt in 2010 (UNFCCC, 2020).

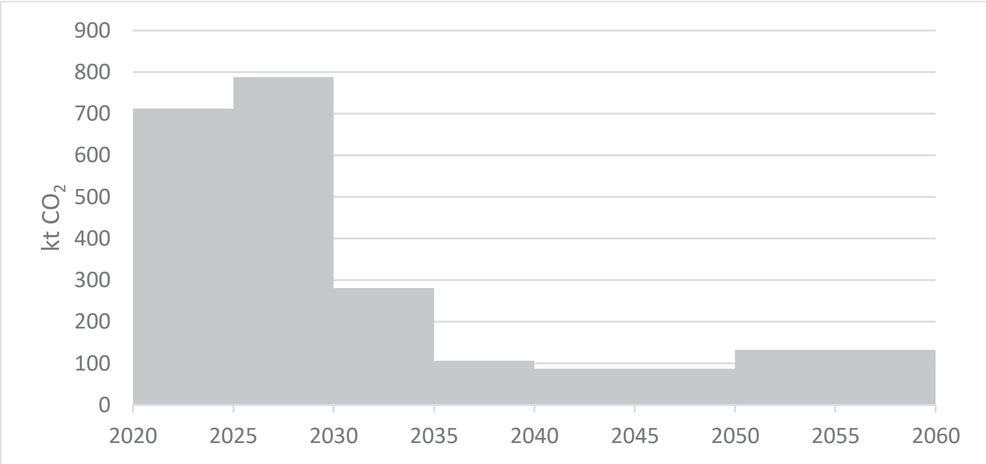


Figure 71. CO_2 emissions in power and district heating sectors in the Base scenario

Source: created by the author

Annual investment, fixed and variable costs in power and district heating sectors by modelled periods are given in Figure 72. The highest investments are foreseen for 2020–2025 and 2040–2050 at 1 billion euros per year. Most of it is in expanding the installed capacities of wind and solar power plants. In 2025–2030, a significant share of investments goes to constructing an offshore wind power farm. The lowest investments are in 2030–2035. Then, only new solar power plants are being built. Afterwards, in 2035–2040, investments go to building new onshore wind power plants and biomass-fired CHP plants and in 2040–2050 to wind, solar, biomass CHP plants and grid batteries. There are no investments in 2050–2060 as investments in MESSAGE are made in a period before the period of the beginning of the operation, and there are no modelled periods after 2050–2060.

Total annual expenditure on fixed costs stays between 125 and 204 million euros throughout the modelling years. Total fixed costs increase with new technologies added to the system and reduce with the retirement of old equipment.

Total annual variable costs change in the power and district heating sector are primarily determined by electricity imports and exports, local electricity and heat generation, fuel consumption, fuel prices, CO_2 emissions and prices. Increasing electricity generation from wind and solar power plants with low variable costs and decreasing electricity imports result in decreasing variable costs in 2025–2035. However, increasing local electricity generation due to increasing electricity demands as well as increasing fuel and CO_2 emission costs raises the variable costs in subsequent periods.

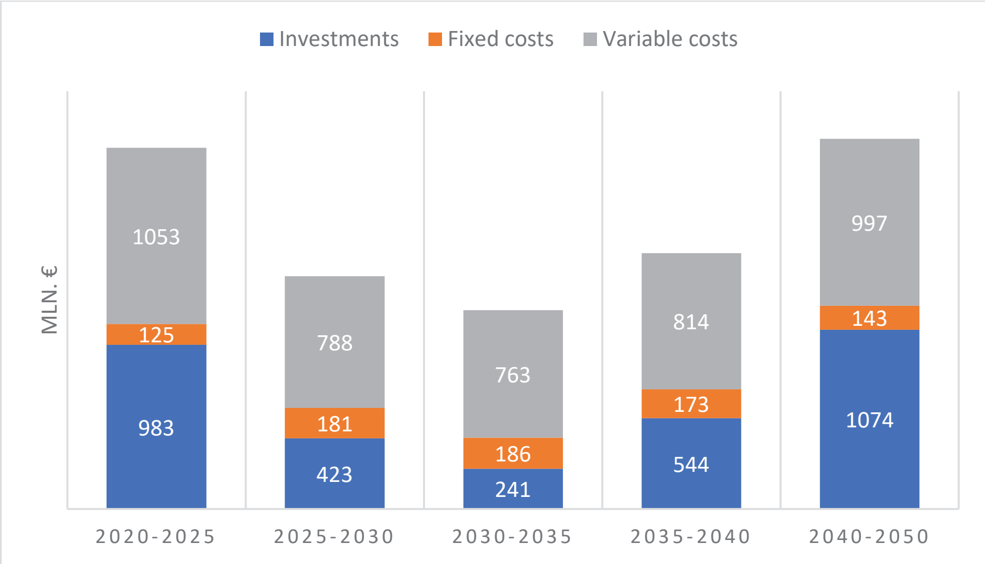


Figure 72. Annual investment, fixed and variable costs in power and district heating sectors by modelled periods in the Base scenario

Source: created by the author

3.2.1.2. Transport sector

The model estimates that the cost-optimal pathway for the development of personal travel is a gradual shift to electric and fuel-cell cars. Therefore, in 2025–2030, 8.6% of car travel demands should be covered by electric vehicles. In 2030–2035 this number should rise to 17.3%, in 2035–2040 to 30.7%, in 2040–2050 to 63.7%, and by 2050–2060 it should reach 89.4%. Fuel cell electric vehicle use is not expected before 2035, but in 2035–2040 it should rise to 0.5% and 9.1% in 2040–2050. However, the share of FCEV in car travel slightly reduces to 7.1% in 2050–2060 in the modelling results. As the shares of electric and fuel cell vehicles in car travel increase, the shares of petrol and diesel cars decrease, except for hybrid vehicles. Their popularity will likely increase towards 2050 as they have greater fuel efficiency and purchase costs are on par with diesel and petrol cars. However, after 2050 hybrid cars should be almost entirely replaced by electric and fuel-cell cars. Car travel volumes by car type in the Base scenario are given in Figure 73.

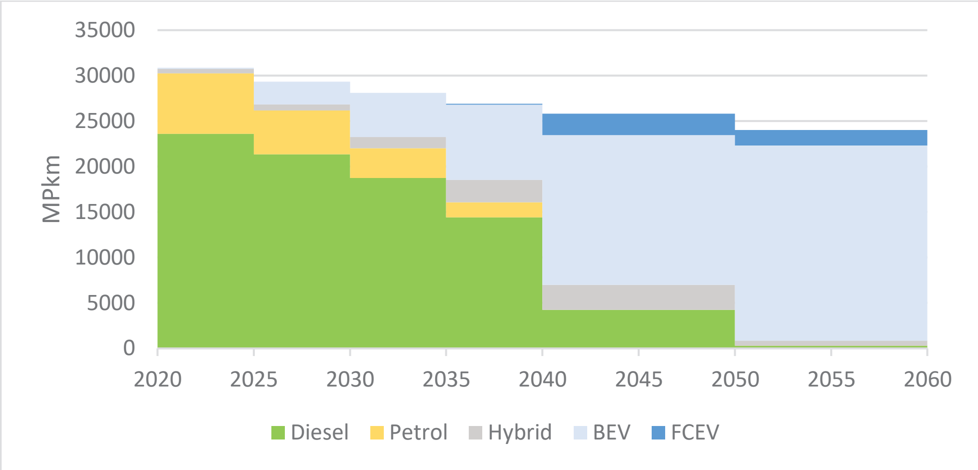


Figure 73. Car travel volumes by car type in the Base scenario

Source: created by the author

The modelling results for public transport show that it is beneficial to electrify it quicker than personal transport (see Figure 74). In 2025–2030, 13% of travel with public transport should be using vehicles run by electricity, but in 2030–2035 this number should rise to 82%, and by 2050–2060 it should reach 92%. Within the modelling time horizon, the use of hydrogen for public transport is rather limited. In 2050–2060, it reaches only 2%.

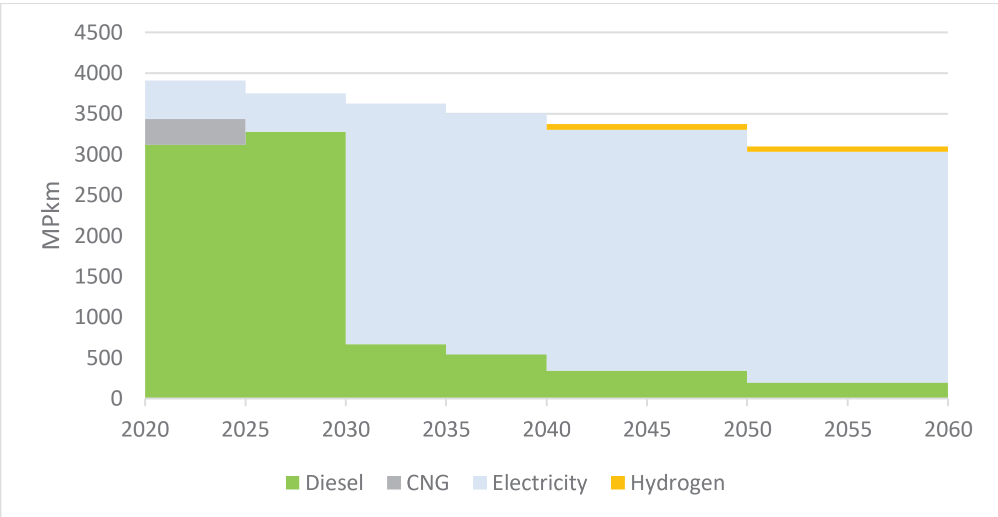


Figure 74. Public transport travel volumes by fuel in the Base scenario

Source: created by the author

According to the modelling results, freight transport is much more challenging to decarbonize than passenger transport as emission reduction till 2050 primarily relies on increasing the biodiesel content in diesel. In this model, it is assumed that by

2050, biodiesel content will reach 100% in diesel. However, there might be technical difficulties in applying high shares of biodiesel. Nevertheless, the model indicates that ICE vehicles will remain the most cost-efficient mean of freight delivery till 2050 (see Figure 75). Freight delivery share by hydrogen fuel cell trucks gradually increases from 2035, reaching only 15.4% by 2050–2060. However, in 2050–2060 the model foresees a rapid adoption of BEV trucks, reaching 66.5%. One of the possible solutions to reduce freight transport emissions sooner would be increasing the share of freight delivery using rail transport while electrifying rail transport. However, this option was not included in the model due to data limitations. Further investigation is necessary to determine the potential role of freight delivery using electric trains in decarbonizing freight transport.

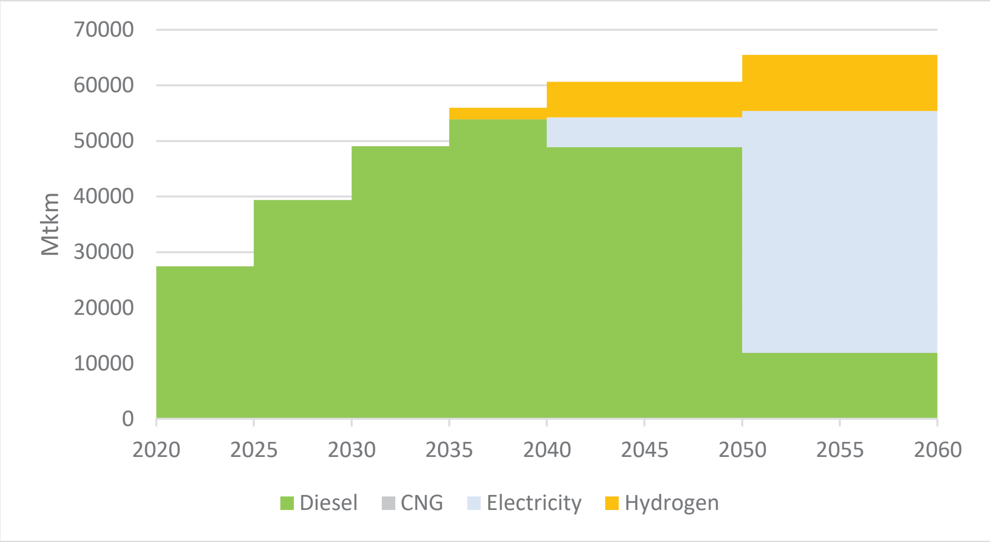


Figure 75. Freight transport delivery volumes by fuel in the Base scenario

Source: created by the author

In 2020–2025, total annual transport sector costs are around 6.1 billion euros, excluding electricity costs as they are accounted for in the power and district heating model. In 2025–2030, costs will increase by 21% to 7.3 billion euros, partly due to rapidly increasing freight delivery volumes and passenger transport electrification. In 2030–2035, costs increase to 7.6 billion and 8.7 billion in 2035–2040. However, annual transport costs will decrease to 8.2 billion euros in 2040–2050.

As can be seen in Figure 76, the annual transport investment costs increase throughout the modelling periods as the transport electrification rate increases. However, variable costs increase till 2035 and afterwards, they decrease. The observed variable cost increase is mainly due to significant growth in freight delivery volumes and increasing fuel prices. The decrease is because of reduced passenger travel demands (due to the shrinking population) and the transition to electric and fuel cell electric vehicles.

All operation and maintenance costs were considered to be variable costs. Therefore, this model has no fixed costs in the transport sector.

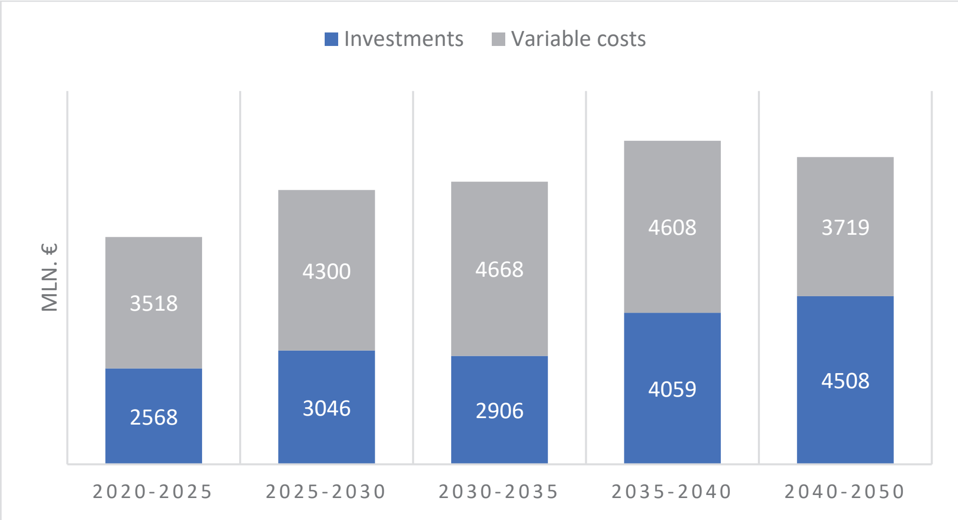


Figure 76. Annual investment and variable costs in the transport sector by modelled periods in the Base scenario

Source: created by the author

CO_2 emissions resulting from fuel combustion in the transport sector are given in Figure 77. Unfortunately, emissions in 2025–2030 are expected to rise slightly. Even though the shrinking population likely will reduce total travel demands, on average, newer, more efficient vehicles will be used, and the use of electric vehicles will increase to around 9% in personal and public transport travel volumes. However, the emission reduction effect will be offset by substantially increasing freight delivery volumes by diesel trucks. In modelled subsequent periods, the annual transport CO_2 emissions drop in 2030–2035 to 93%, 2035–2040 to 82%, 2040–2050 to 44% and 2050–2060 to 1% compared to the 2020 emission level. A rapid emission decrease in these periods is caused by the increasing rate of transport electrification and increasing biofuel content in petrol, especially diesel blends.

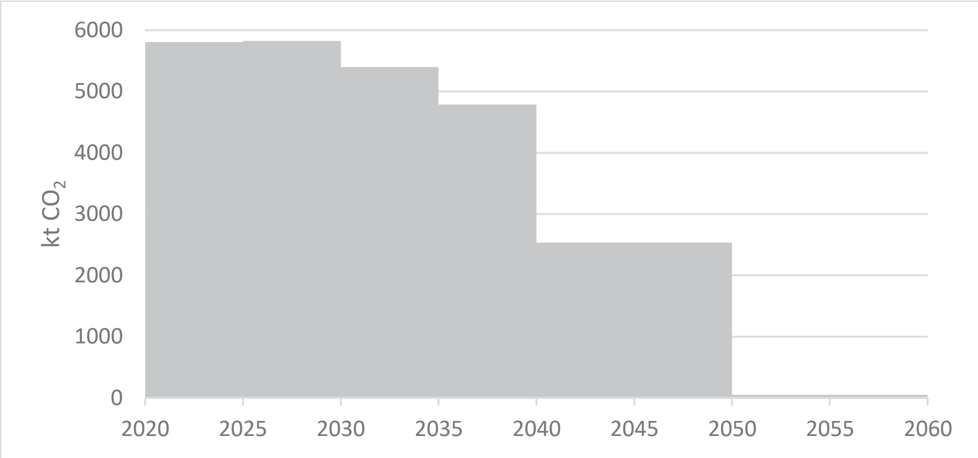


Figure 77. CO_2 emissions in the transport sector

Source: created by the author

3.2.2. VehDistr scenario modelling results

Lithuania has a non-declining vehicle age distribution, meaning that first-time registered vehicles in the country are used vehicles from foreign used car markets on average. Other countries with non-declining vehicle age distributions in Europe include Cyprus, the Czech Republic, Estonia, Latvia, Malta, Poland, Romania, and Slovakia. More prosperous countries, like Germany, the U.K. and France, typically have declining vehicle age distributions, i.e. almost all first-time registered vehicles in the country are new, and the share of vehicles built in a particular year drops with time due to wear and tear. A separate study should be carried out to identify what affects vehicle age distributions and how they might change. Therefore, a constant vehicle distribution was assumed for all scenarios except this one (VehDistr). This scenario was designed to investigate how a gradual vehicle age distribution shift in Lithuania toward a similar one to Germany's (see Figure 57) would affect the development of the transport, power and district heating sectors. The effects are analysed by comparing the modelling results of VehDistr and Base scenarios.

3.2.2.1. Power and district heating sectors

The result comparison of VehDistr and Base scenarios is given in Figure 78 for 2030, 2040 and 2050. The comparison figure shows that the effects of shifting vehicle age distribution on the power sector are not substantial. Most differences are within a few %. However, it can be seen that in 2030, there is a higher electricity demand for transport, resulting in higher local electricity generation and electricity imports as well as lower electricity exports. Also, electricity generation in thermal power plants is higher in the VehDistr scenario as higher penetration of electric vehicles requires greater balancing capabilities, resulting in higher electricity prices by 14% in 2040. Also, electricity demand primarily increases in the evening and night with EV penetration due to modelled EV overnight charging in this scenario, resulting in a slightly lower generation in PVs but higher in wind power plants. One of the more interesting differences is the 5% higher energy storage needs in 2040 because of the higher electricity price spread (see Figure 79). Furthermore, in this scenario, CO_2 emissions are higher by 14% in 2040 due to higher electricity generation in gas-fired power plants (4 MWyr vs 0 MWyr). However, the emission difference in absolute terms is minimal as emissions in the Base scenario are already very low.

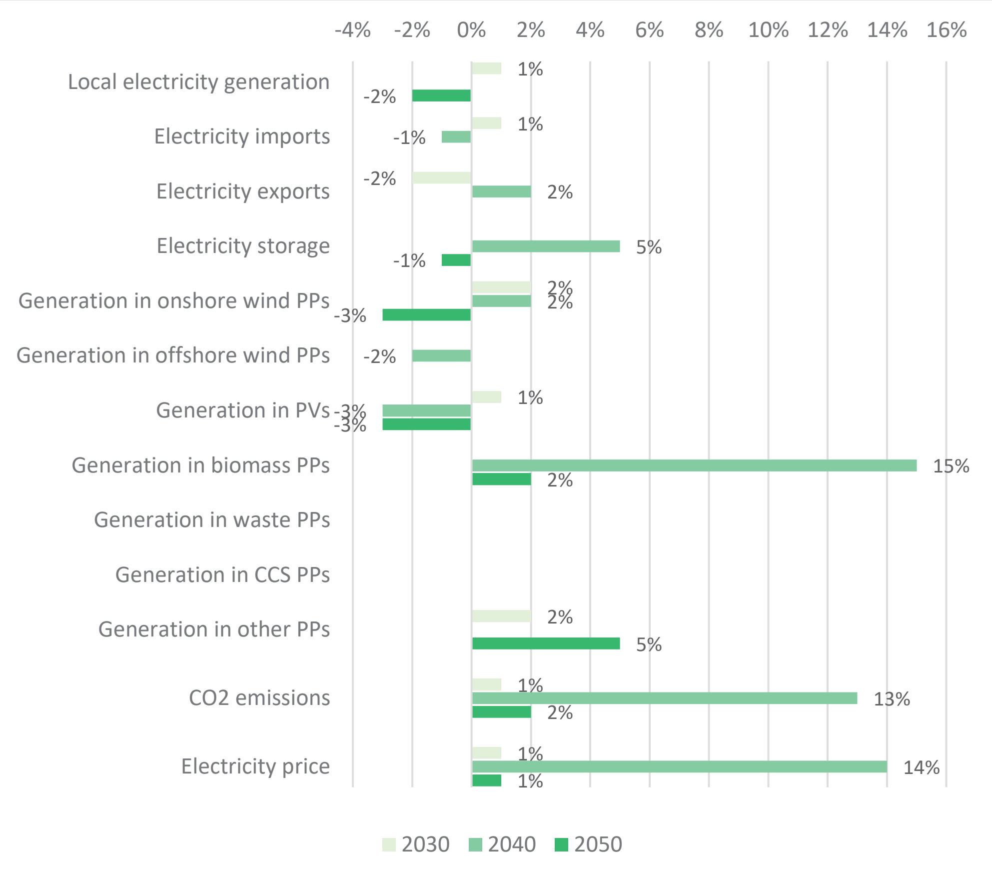


Figure 78. Electricity mix, CO_2 emission and electricity price differences between VehDistr and Base scenarios

Source: created by the author

The higher electricity price spread at the upper price quarter in the VehDistr scenario is caused by the contribution of electric vehicle charging to the electricity demand peak in the evening. Since electricity demand for EV charging is higher than in the Base scenario, the contribution to the peak is also more significant. The higher the peak demand is, the more expensive power plants have to supply electricity.

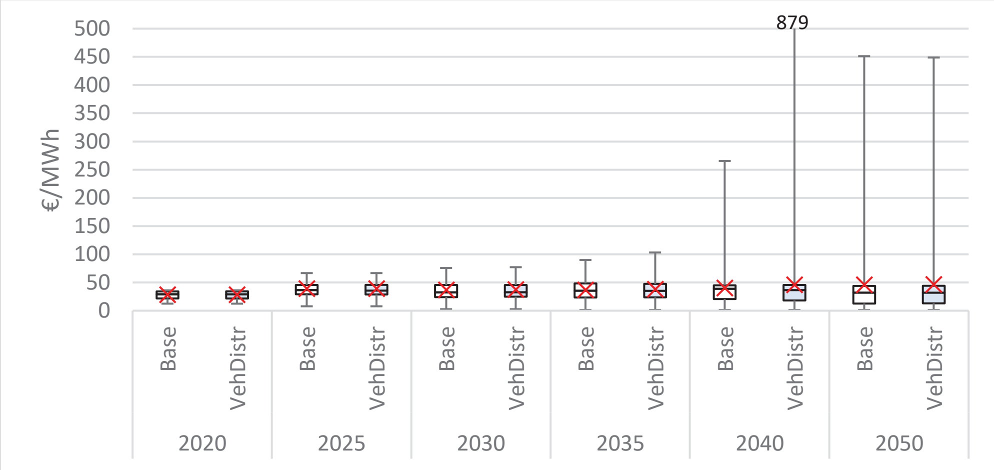


Figure 79. Electricity price in Base and VehDistr scenarios

Source: created by the author

In this scenario, generation in wind power plants is higher until 2050, leading to slightly higher output curtailment to ensure the power balance in the system. Also, PV output curtailment will be slightly higher in 2040. However, in other modelling years, it is almost identical. Curtailment of electricity generation in the wind and PV power plants in Base and VehDistr scenarios is given in Figure 80.

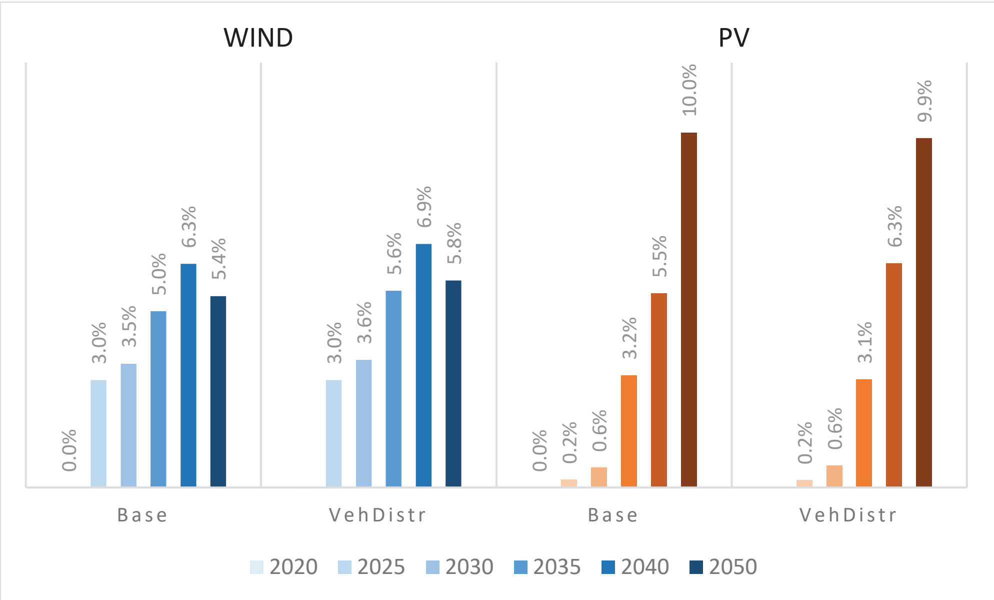


Figure 80. Curtailment of electricity generation in the wind and PV power plants in Base and VehDistr scenarios

Source: created by the author

In the district heating sector, Biomass CHP plants are utilized more in 2040 and 2050, at the expense of natural gas and biomass-fired heating plants, in the VehDistr scenario compared to the Base scenarios, as shown in Figure 81. Biomass CHP plants produce more heat in this scenario because these power plants produce more electricity to cover additional demand in the evening caused by higher penetration of EVs.

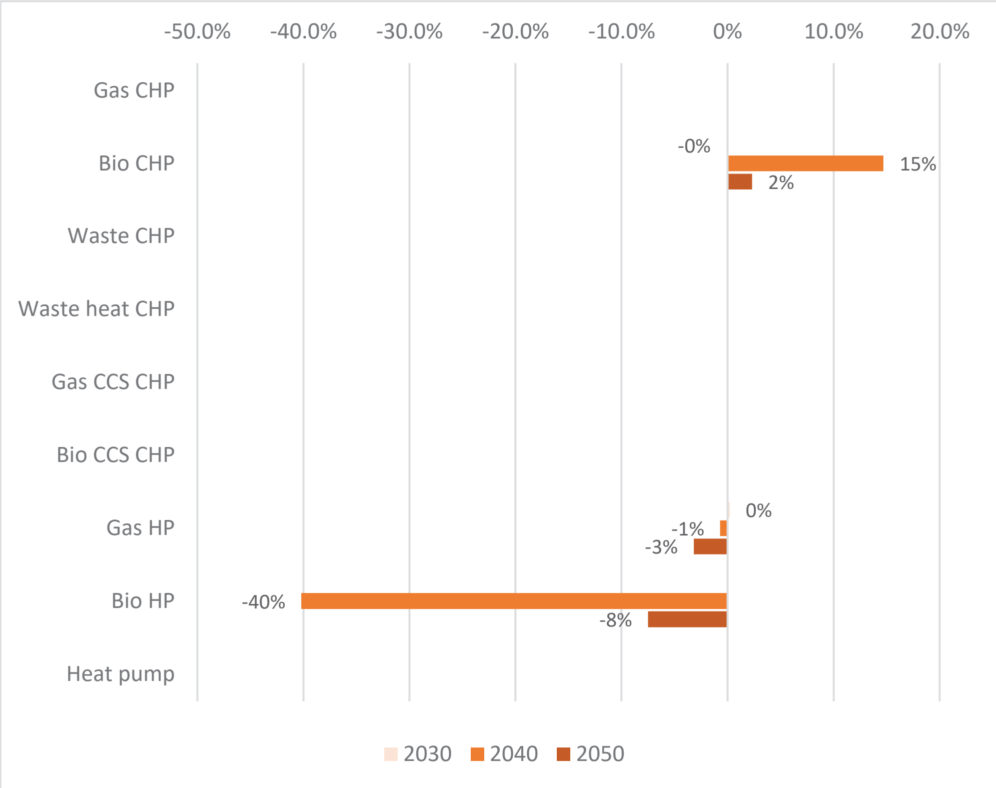


Figure 81. District heating generation differences between VehDistr and Base scenarios

Source: created by the author

The cost comparison of power and district heating sectors in VehDist and Base scenarios shows that shifting vehicle age distribution results in higher power sector costs till 2040, mainly because of the required additional capacity to satisfy increased evening electricity demand peak due to overnight charging of additional EVs. However, the annual cost difference is not that significant: €10m in 2020–2025; €16m in 2025–2030; €81m in 2030–2035; €54m in 2035–2040. However, the costs in 2040–2050 are lower by €31m and in 2050–2060 by €13m. It is lower because of the lower penetration of FCEVs, which have significantly lower overall electrical efficiency than BEVs, resulting in lower electricity demand in 2040–2060.

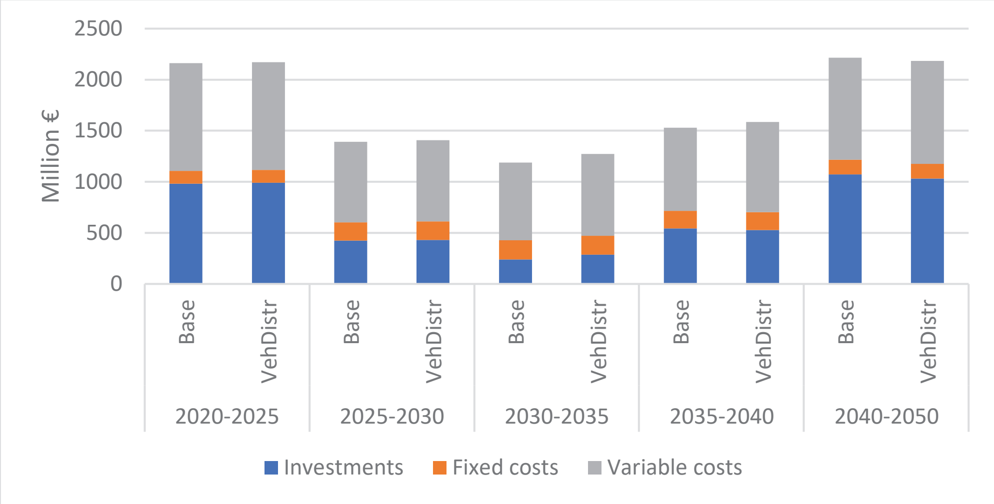


Figure 82. Annual investment, fixed and variable costs in power and district heating sectors by modelled time periods in Base and VehDistr scenarios

Source: created by the author

3.2.2.2. Transport sector

The most significant differences between VehDistr and Base scenario results are in the transport sector. A shifting vehicle age distribution applied in the VehDistr scenario results in the use of newer cars. Therefore, the transition to electric cars is substantially faster. For example, in 2030, electric vehicle travel is almost double compared to the Base scenario, 31% of total car travel versus 17%. In 2040 it is 88% vs 64%, and in 2050 99% vs 89%. A higher EV penetration rate leads to the faster phasing-out of fossil fuel cars. Interestingly, in the VehDistr scenario, the model does not see FCEV cars as an attractive option, possibly because electric cars are cheaper both to purchase and run. The use of FCEV cars in the Base scenario appears probably because the EV penetration rate is constrained (See **Constraints on new capacity addition by fuel**), though it is difficult to pinpoint the exact reason as the model chooses the cheapest option, taking into account the cross-sectoral effects. However, the electrification rate of public and freight transport is lower in the VehDistr scenario because of higher electricity prices.

Faster personal transport electrification in VehDistr results in lower CO_2 emissions by 7% in 2030, 11% in 2040 and 89% in 2050. However, it should be noted that emissions in 2050 are very low in both scenarios, 5.4 and 50.3 kt CO_2 (transport emissions in 2020 are equal to 5654 kt CO_2).

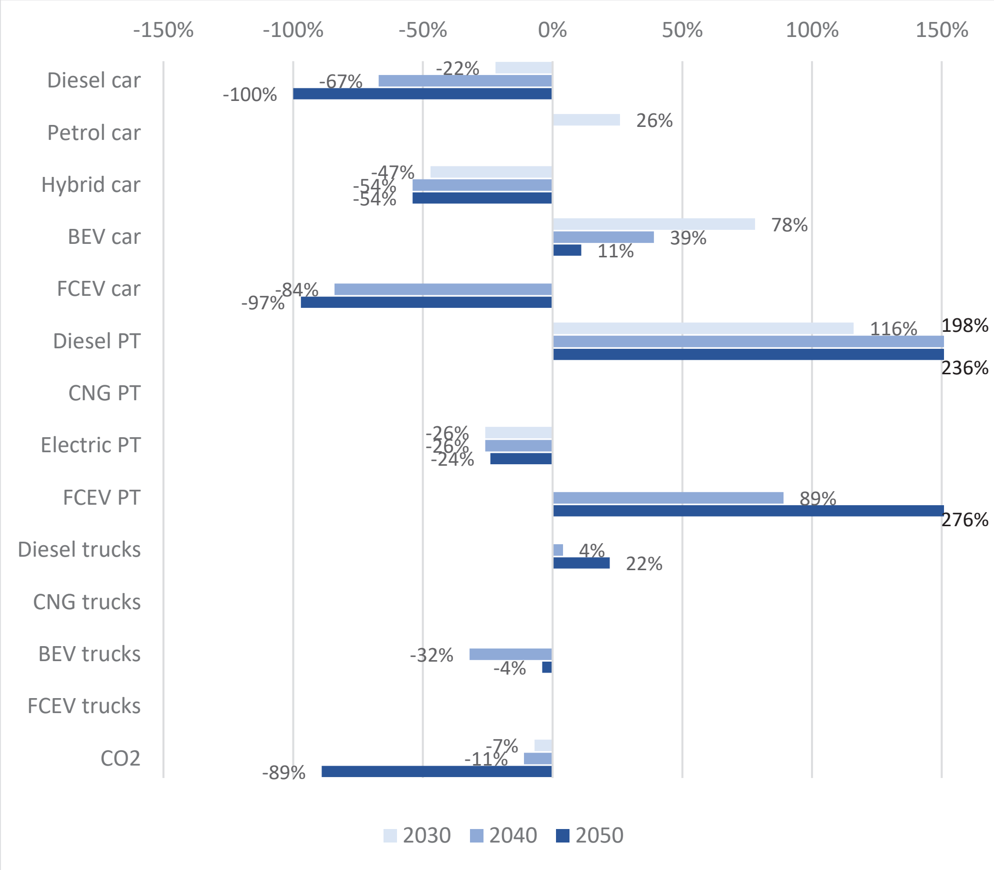


Figure 83. Travel, freight delivery and CO_2 emission differences between VehDistr and Base scenarios

Source: created by the author

To no surprise, annual transport costs are higher in the VehDistr scenario as, in general, newer cars are purchased that have higher investment costs. In the VehDistr scenario, annual investments are higher by €680-1164m. However, the variable costs are lower by €143-554m in 2025–2060 due to higher transport electrification rates and lower fuel costs for electric vehicles. Furthermore, costs to produce electricity that powers electric vehicles are accounted for in the power and district heating model. By looking at the total annual transport costs shown in Figure 84, it can be seen that in the VehDistr scenario, they are higher by €1027m in 2020–2025, by €827m in 2025–2030, by €842m in 2030–2035. In 2035–2040, the total annual costs are almost the same between these two scenarios, and in 2040–2050, costs are higher in the VehDist scenario by €443m.

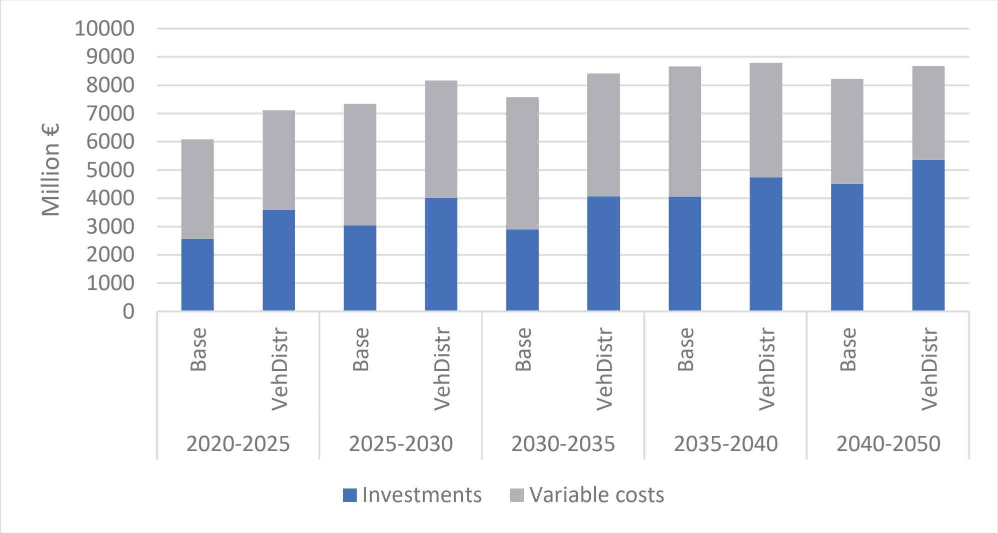


Figure 84. Annual investment and variable costs in the transport sector by modelled periods in Base and VehDistr scenarios

Source: created by the author

3.2.3. RedFlexi scenario modelling results

In the modelling results of Base and VehDist scenarios, electricity generation from variable renewable sources is balanced primarily with electricity imports and exports. However, the power systems of neighbouring were not modelled. Instead, they were represented by technologies, acting like power sources and sinks, allowing electricity imports and exports at set prices and limited by throughput capacities and how quickly imported and exported power can change. Thus, balancing capabilities using interconnections might be overestimated, especially considering that VRES penetration will likely increase in these countries. For this reason, the RedFlexi scenario was designed to investigate the effects of reduced reliance on interconnections to balance the electricity generation from variable renewable sources. In this scenario, the rate of how quickly the imported and exported power can change was reduced by half for each interconnection, decreasing the capabilities to react to generation fluctuations in PV and wind power plants.

3.2.3.1. Power and district heating sectors

The modelling results of the power sector in the RedFlexi scenario show that reduced electricity import and export flexibility decreases electricity exports and generation from variable renewable sources and increases imports compared to the Base scenario. PV generation is particularly affected. It is lower by 24% in 2030, 28% in 2040 and 13% in 2050. Electricity generation in onshore wind power plants is lower by 10% in 2030, 15% in 2040 and 7% in 2050, while in offshore wind power plants by 0%, 5% and 6%. However, electricity generation is increased in other power plants: by 15% in gas-fired power plants in 2030, by 9% in biomass CHP plants in 2040 and by 4% in 2050. Also, the use of energy storage in 2050 is 8% higher. Due to the higher use of gas-fired power plants in 2030, the emissions exceed ones in the Base scenario by 10%. Furthermore, lower electricity generation from cheap VRES results in slightly higher electricity prices.

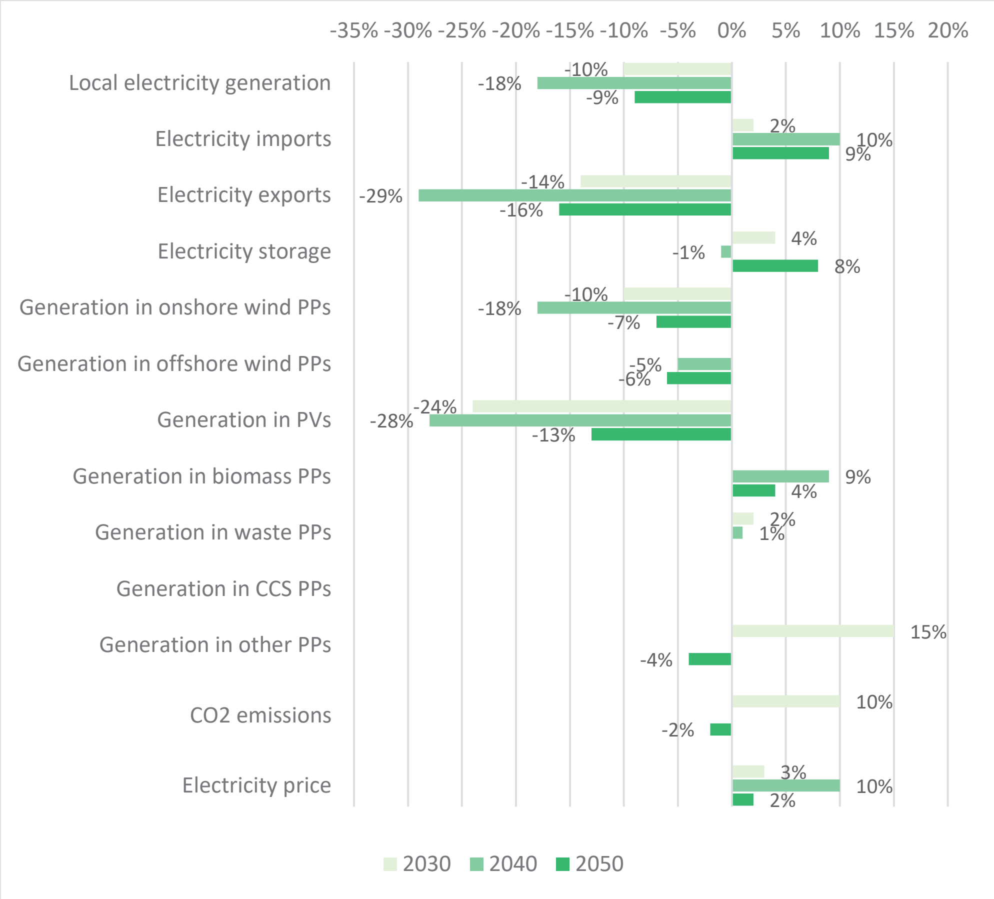


Figure 85. Electricity mix, CO_2 emission and electricity price differences between RedFlexi and Base scenarios

Source: created by the author

Reduced capabilities to use interconnections to balance VRES lead to higher generation curtailment in the wind and PV power plants (see Figure 86), even though total electricity generation from VRES is lower than in the Base scenario. For wind power plants, it increases from 3.5% to 4.4% in 2030, from 5% to 7% in 2035, from 6.3% to 8.5% in 2040 and from 5.4% to 7.8% in 2050. PV generation curtailment does not increase that much till 2040. However, in 2040 it will rise by 3% and in 2050, by 2.4%.

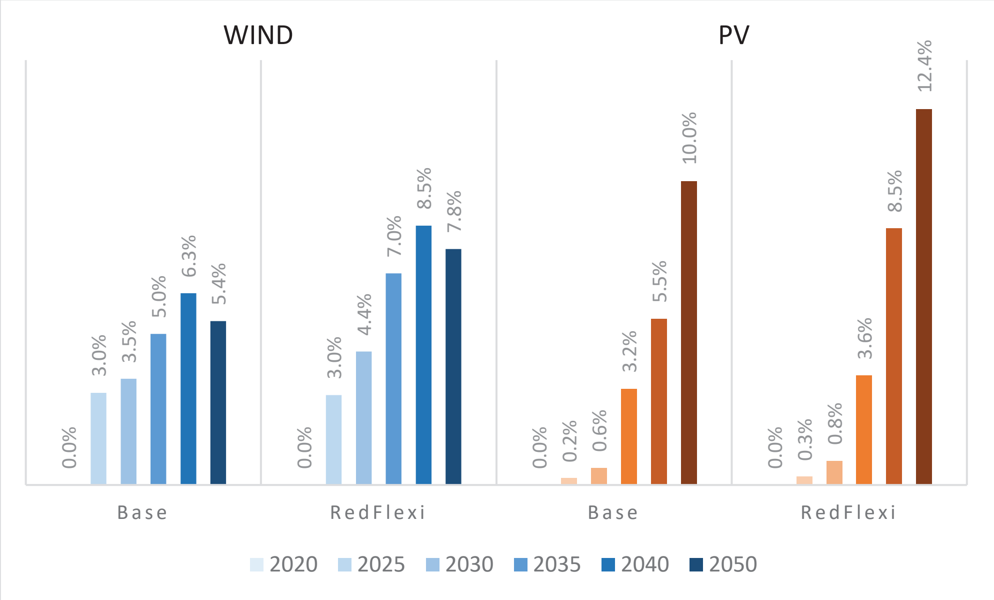


Figure 86. Curtailment of electricity generation in wind and PV power plants in Base and RedFlexi scenarios

Source: created by the author

As previously mentioned, reduced electricity generation from cheap VRES leads to slightly increased electricity prices. However, the price spread remains unchanged throughout all modelling periods (see Figure 87).

Figure 87. Electricity price in Base and RedFlexi scenarios

Source: created by the author

As can be seen in Figure 88, the main differences between the modelling results of the district heating sector in RedFlexi and Base scenarios are increased heat generation in biomass and waste CHP plants and decreased in heating plants. As interconnections have lower flexibility in this scenario, increased electricity and, in turn, heat generation in CHP plants provide some of the needed power-balancing flexibility.

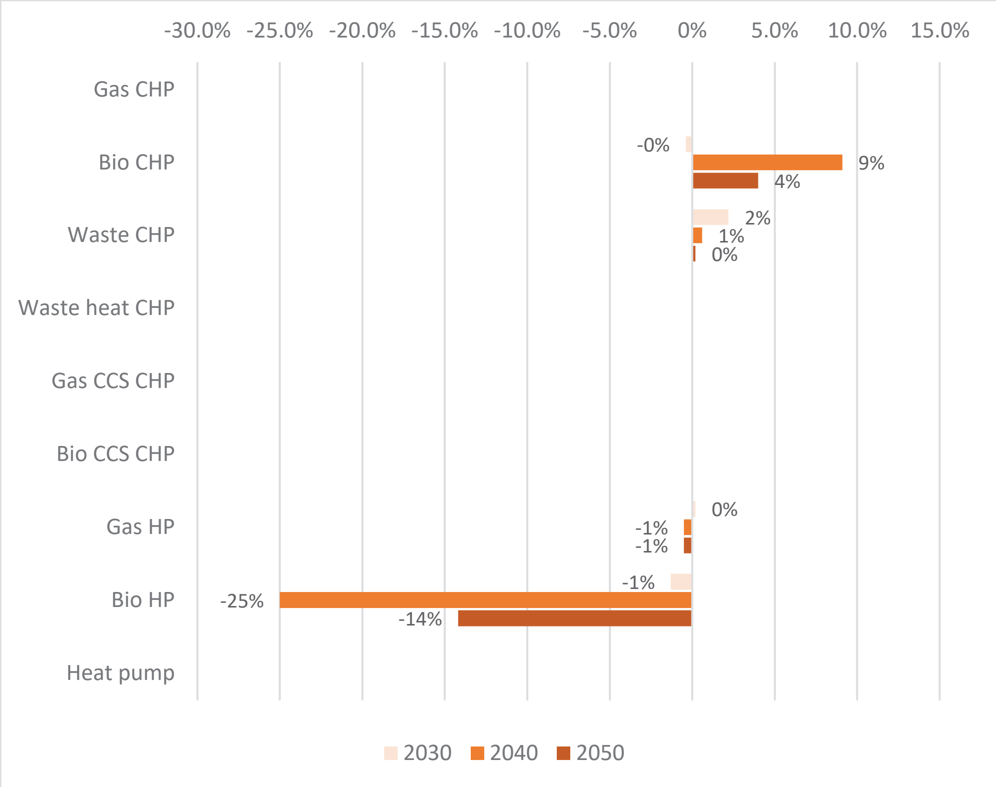


Figure 88. District heating generation differences between RedFlexi and Base scenarios

Source: created by the author

Calculated cost differences in power and district heating sectors between RedFlexi and Base scenarios are not that high (see Figure 89). In 2020–2030 they are slightly lower in the RedFlexi scenario as fewer investments are made into expanding power plant capacities. In 2030–2040 they are practically on the same level, but in 2040–2060 they are higher due to more investments in biomass CHP plants and grid batteries. Throughout all modelled years from 2025, variable costs are higher in the RedFlexi scenario due to more electricity being imported and less exported than in the Base scenario. Note: revenues from electricity exports are subtracted from the variable costs.

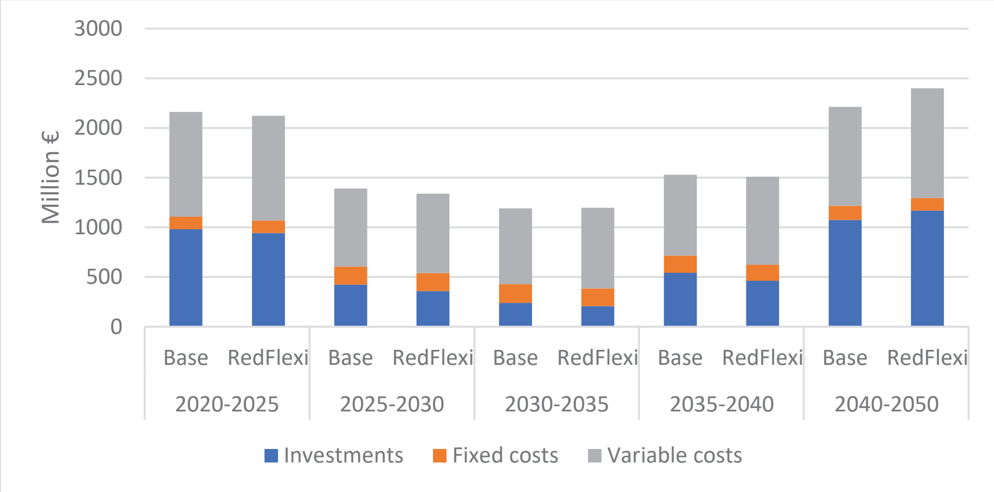


Figure 89. Annual investment, fixed and variable costs in power and district heating sectors by modelled periods in Base and RedFlexi scenarios

Source: created by the author

3.2.3.2. Transport sector

The modelling results of the transport sector in the RedFlexi scenario are similar to the ones in the Base scenario. The result comparison is given in Figure 90. In 2040, travel volumes in diesel cars are slightly higher, and in hybrid and electric vehicles are slightly lower. Also, the use of FCEV cars will increase by 23% in 2050. In 2040 and 2050, FCEV vehicles will also satisfy more travel demands in public transport. In 2040, 155% more, and in 2050, 144% more than in the Base scenario. However, it reaches only 0.4% and 1.7% of total travel volumes in public transport. This increase in FCEV use in passenger transport is due to increased VRES balancing needs, as this scenario has decreased flexibility in interconnections. Hydrogen production can contribute to balancing VRES by producing hydrogen through electrolysis during peak generation in the wind and solar power plants.

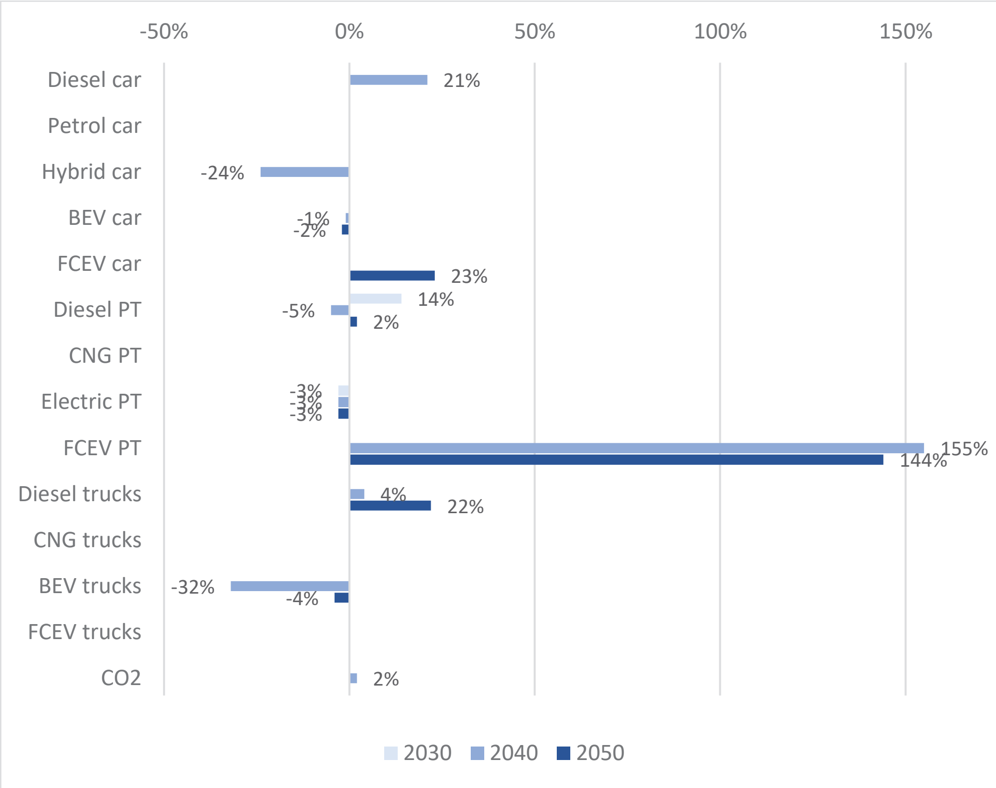


Figure 90. Travel, freight delivery and CO_2 emission differences between VehDistr and Base scenarios

Source: created by the author

The differences in annual transport costs between RedFlexi and Base scenarios are negligible till 2035. In 2035–2040 they are lower by €158m in the RedFlexi scenario but higher in 2040–2060 by €63m. Annual investment and variable costs in the transport sector in Base and RedFlexi scenarios are given in Figure 91.

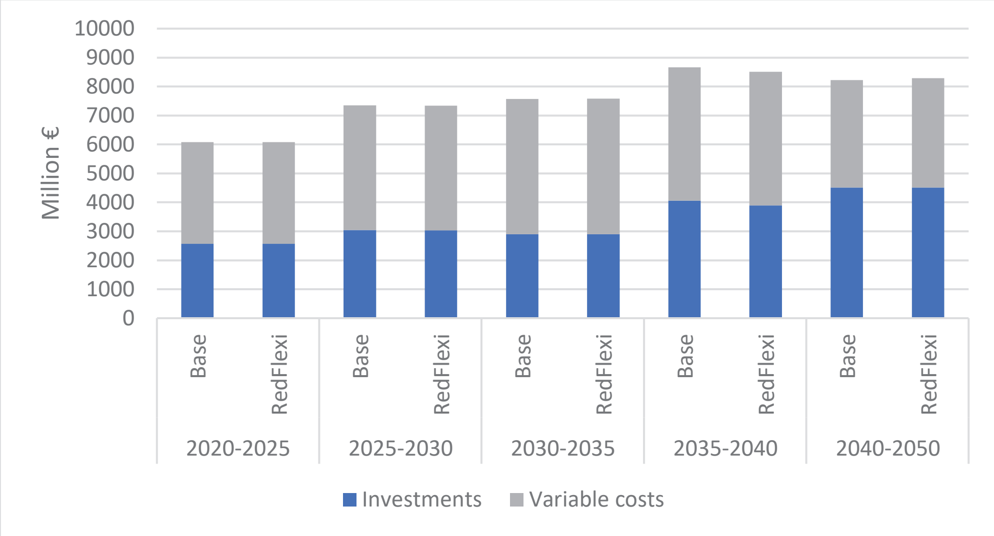


Figure 91. Annual investment and variable costs in the transport sector by modelled periods in Base and RedFlexi scenarios

Source: created by the author

3.2.4. InterOff scenario modelling results

In the RedFlexi scenario, even though the interconnections' flexibility is reduced, VRES electricity generation is primarily balanced by electricity imports and exports. However, VRES penetration will likely increase in the neighbouring countries towards 2050, and VRES electricity generation peaks and valleys will likely match between Lithuania and interconnected countries as they are approximately in the same region. Therefore, it can be argued whether relying on interconnections to balance variable electricity generation will be possible. For this reason, an InterOff scenario was modelled in which electricity imports and exports are prohibited from 2040 to test the effects of fully balancing variable electricity generation within the country.

3.2.4.1. Power and district heating sectors

The most apparent differences between InterOff and Base scenario modelling results are that in the InterOff scenario, there are no electricity imports and exports from 2040. The amount of electricity produced in Lithuania is barely affected as the annual electricity generation is just 9% lower in 2040–2050 than the consumption in the Base scenario. From 2050 in the Base scenario, local generation even exceeds the consumption. From 2040, electricity generation in PV and offshore wind power plants is significantly lower in the InterOff scenario than in the Base scenario due to the difficulty of balancing generation variability. In 2040, offshore wind power plants will produce 40% and PVs 27% less; in 2050, 46% and 17% less (see Figure 92). However, despite PV generation in the InterOff scenario being lower than the Base scenario, annually produced electricity increases throughout the modelling years, just at a lower rate. In offshore wind power plants, electricity generation will decrease from 323

MWyr in 2030 to 172 MWyr in 2040 and 95 MWyr in 2050. The model compensates for the lost flexibility caused by prohibited imports and exports after 2040 by increasing electricity generation in thermal power plants, most notably in gas-fired power plants, resulting in substantially higher CO_2 emissions. CO_2 emissions in 2040 jump to 1085 kt but from 2050 reduce to 812 kt. On the one hand, 812 kt of CO_2 emissions in 2050 seem high, considering net zero-emission targets. However, on the other, local electricity generation fully covers the country's electricity demand at a slightly higher level than the 2020 emission level (713 kt CO_2), when only around 30% of electricity consumed was produced locally.

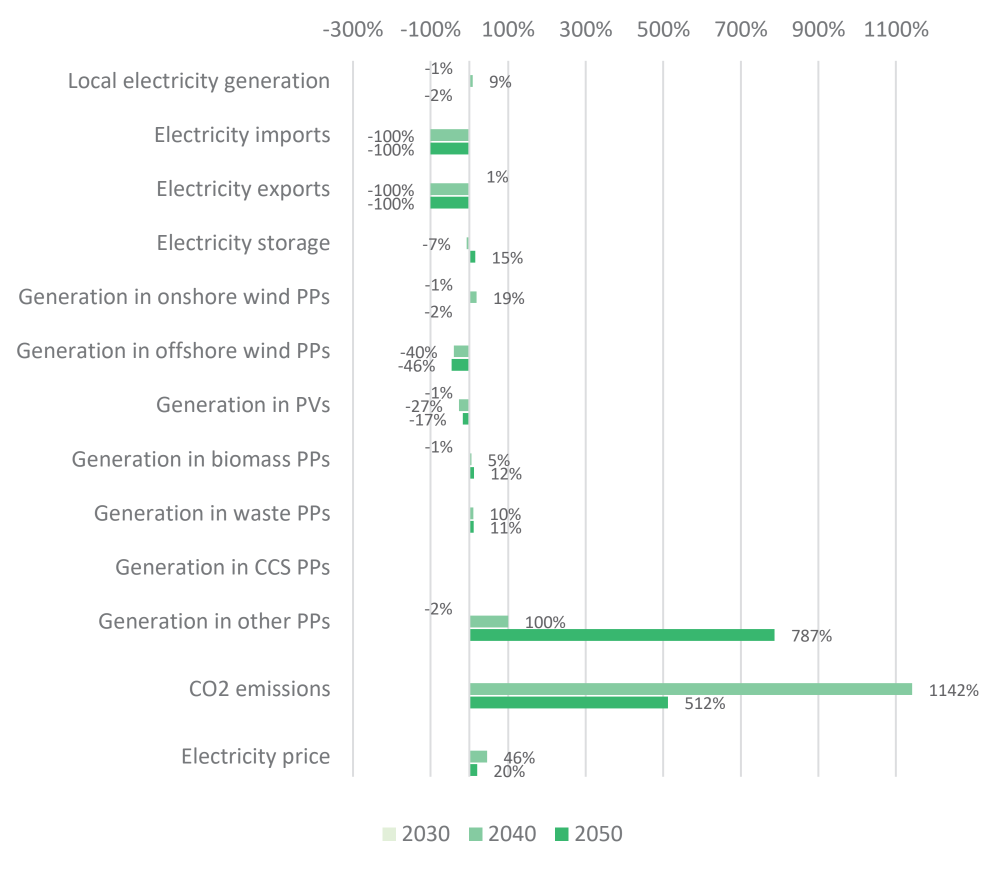


Figure 92. Electricity mix, CO_2 emission and electricity price differences between InterOff and Base scenarios

Source: created by the author

The flexibility loss caused by discontinuing electricity imports and exports from 2040 leads to high VRES electricity generation curtailment, especially for PVs (see Figure 93). PV generation curtailment in 2040 reaches 19.9% and 23.2% in 2050, while in the Base scenario, the curtailment values are 5.5% and 10%. Interestingly, PV generation curtailment in the InerOff scenario in 2035 is lower than in the Base scenario because of lower installed PV capacity and the fact that interconnection can still balance variable generation. In the InterOff scenario, the generation curtailment in wind power plants is also higher than in the Base scenario, though not as significantly as in the case of PVs. In 2040, it is higher by 2.4% and in 2050, by 3.5%. In 2035, it is higher by 2%. However, not because of discontinued interconnections, as in the InterOff scenario, they are cut off from 2050, but because of higher installed capacity.

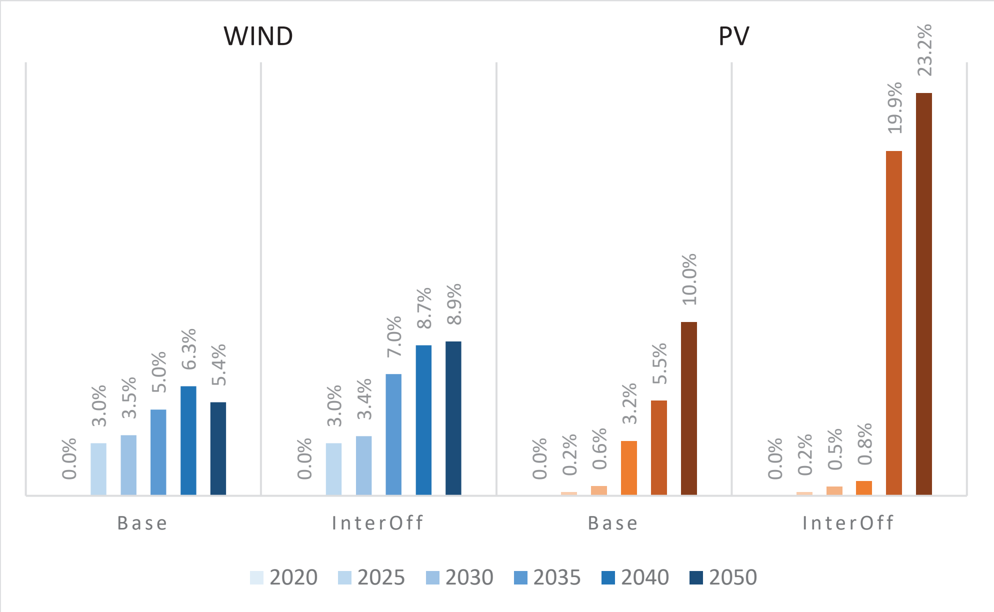


Figure 93. Curtailment of electricity generation in wind and PV power plants in Base and InterOff scenarios

Source: created by the author

There are practically no differences in electricity prices between InterOff and Base scenarios until 2040, but after the prohibition of electricity imports and exports, the average electricity price jumps from 38 to €59/MWh. In 2050, it will decrease to €56/MWh. It is a 46% and 20% increase from the Base scenario. In Figure 94, it can be seen that the price dispersion substantially increases in 2040 in the InterOff scenario. More than a quarter of the time in a year, electricity is produced solely from variable renewable sources keeping electricity prices near zero as their variable costs are negligible. On the other hand, the maximum electricity price reaches €895/MWh. However, as grid batteries cost decreases, the model chooses to add more grid batteries in 2050, reducing the price spread in the InterOff scenario. Nevertheless, these results show the importance of interconnections and other means that can increase the system's flexibility to support high penetration of variable renewable sources.

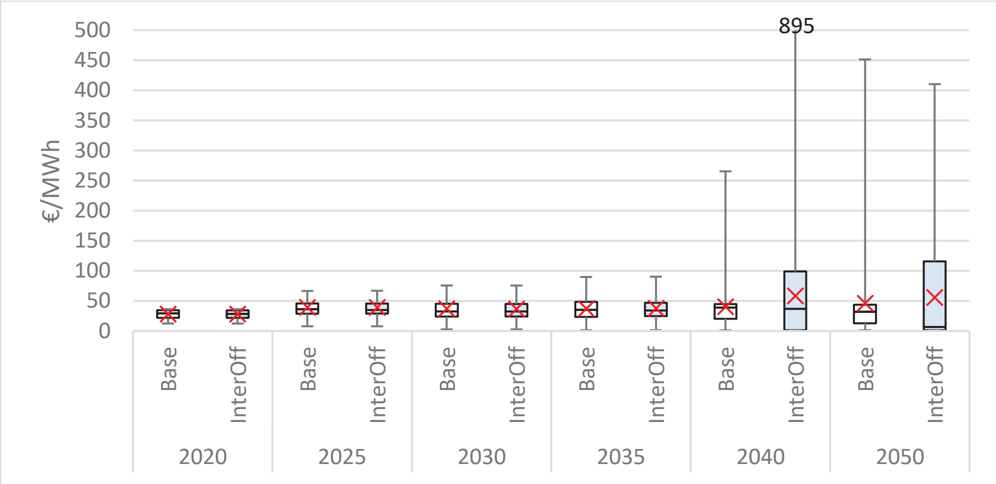


Figure 94. Electricity price in Base and InterOff scenarios

Source: created by the author

In the Base scenario, gas-fired CHP plants are phased out in the district heating sector by 2030. However, in the InterOff scenario, new CCGT CHP plants are built to generate electricity at times of low electricity generation in solar and wind power plants, in turn providing heat for the district heating, though heat production is not that high: 40 MWyr in 2040 and 13 MWyr in 2050. 5.5% and 2% of total district heating generation, respectively. In 2040 and 2050, most heat is generated in biomass and waste CHP plants. Biomass CHP plants will produce 56% in 2040 and 79% in 2050, while waste CHP plants 21% and 7%. Generation in biomass and waste CHP plants is 5–13% higher than in the Base scenario. Naturally, there might be a question of why the model invests in gas-fired CHP plants rather than building more biomass CHP plants. It is because biomass CHP plants were modelled to have backpressure turbines, meaning the ratio of electrical and heat outputs is fixed, but CCGT CHP plants were modelled to have steam extraction turbines, which can change the output ratio. The differences between district heating generation in InterOff and Base scenarios are given in Figure 95.

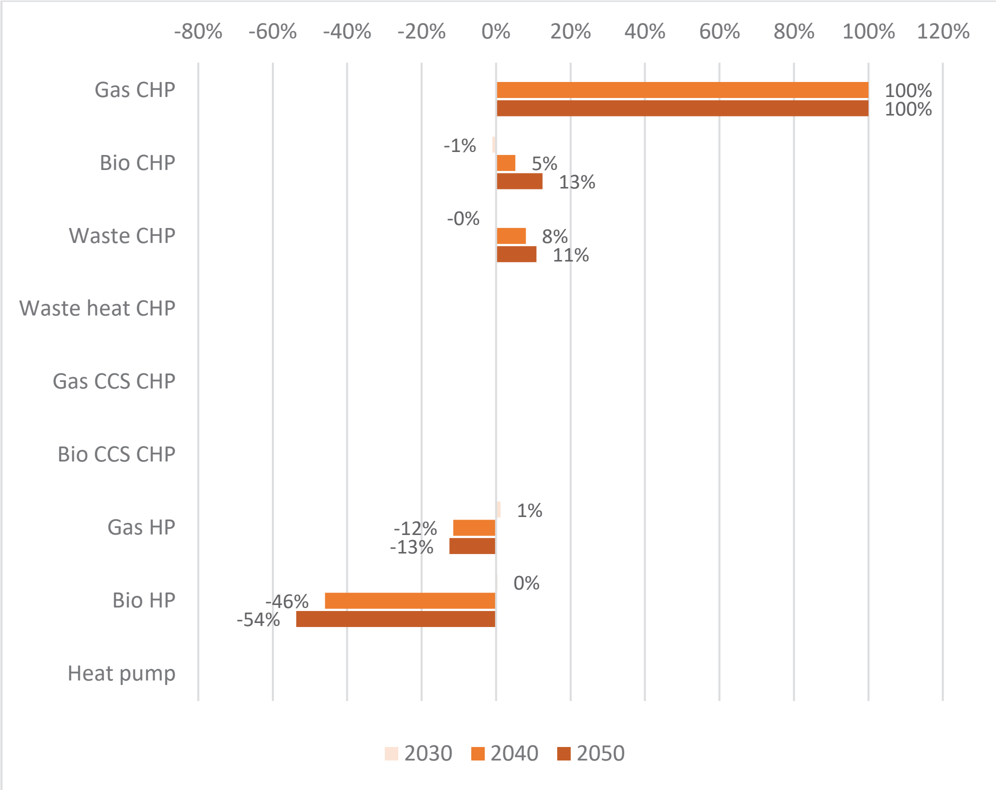


Figure 95. District heating generation differences between InterOff and Base scenarios

Source: created by the author

The annual costs in the power and district heating sectors, given in Figure 96, are practically identical between InterOff and Base scenarios in 2020–2035. However, the modelling results show that the InterOff scenario has substantially higher annual investment costs in 2035–2040 and 2040–2050, by 387 and €188m (investments in MESSAGE are made in a modelled period before the start of the operation). Also, compared to the Base scenario, annual variable costs are higher by 214 (2040–2050) and €255m (2050–2060) because of electricity and heat production in gas-fired CHP plants that use expensive natural resources gas as fuel and have to pay the CO_2 emission costs.

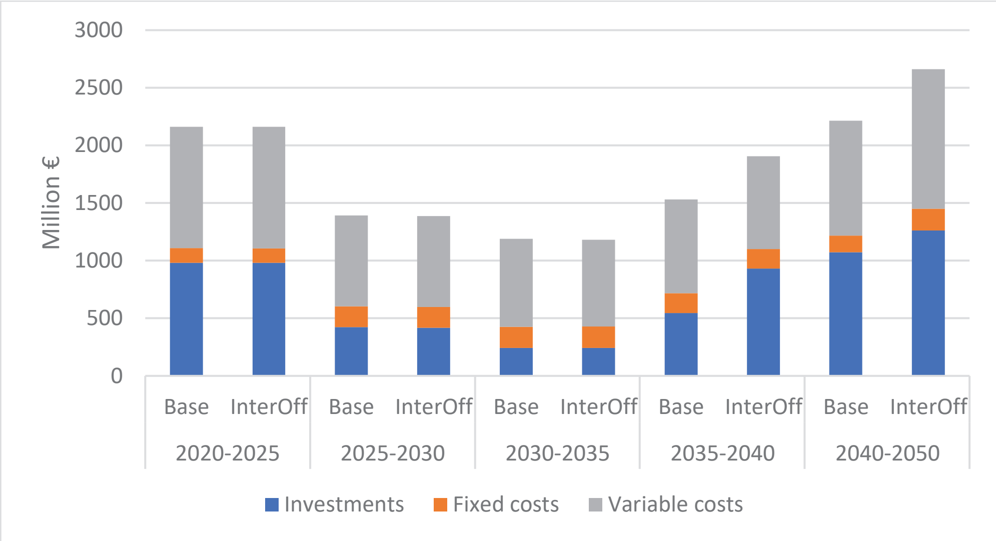


Figure 96. Annual investment, fixed and variable costs in power and district heating sectors by modelled periods in Base and RedFlexi scenarios

Source: created by the author

3.2.4.2. Transport sector

As shown in Figure 97, the use of electric vehicles in the InterOff scenario is lower in 2040 and 2050 compared to the Base scenario. In car travel by 2–13%, in public transport by 28–30% and in freight transport by 85% and 6%. However, the penetration of FCEV vehicles is significantly higher. FCEV use in car travel in 2050 is higher by 159%. In the Base scenario, there are practically no FCEVs in public transport. However, in the InterOff scenario, the share of FCEVs in public transport reaches 28% in 2040–2060. In freight transport, the penetration of FCEV trucks is 33% higher in 2040 and 11% in 2050 compared to the Base scenario. The overall transport electrification rate, including electric and fuel cell electric vehicles, is slightly lower in the InterOff scenario, resulting in 3% higher transport CO_2 emissions in 2040 and 17% higher in 2050.

The modelling results of RedFlexi and InterOff scenarios show the potential of green hydrogen production and its utilization in the transport sector as a VRES balancing measure, indicating the possible role in the future Lithuanian power system.

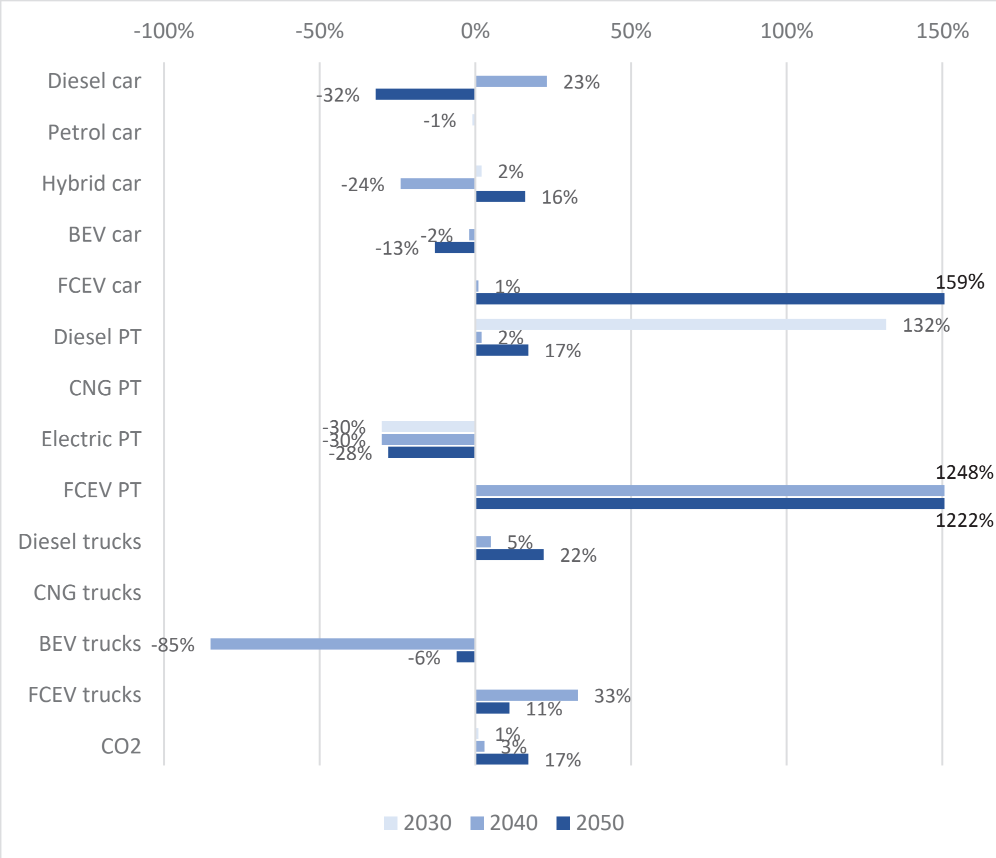


Figure 97. Travel, freight delivery and CO_2 emission differences between InterOff and Base scenarios

Source: created by the author

Annual costs in the transport sector are very similar in InterOff and Base scenarios (see Figure 98). In 2025–2030, they are slightly lower (0.9%) in the InterOff due to a slower electrification rate, and in 2040–2060 slightly higher (1.3–2.4%) due to investments into expensive FCEVs and higher shares of diesel vehicles and increasing fossil fuel prices.

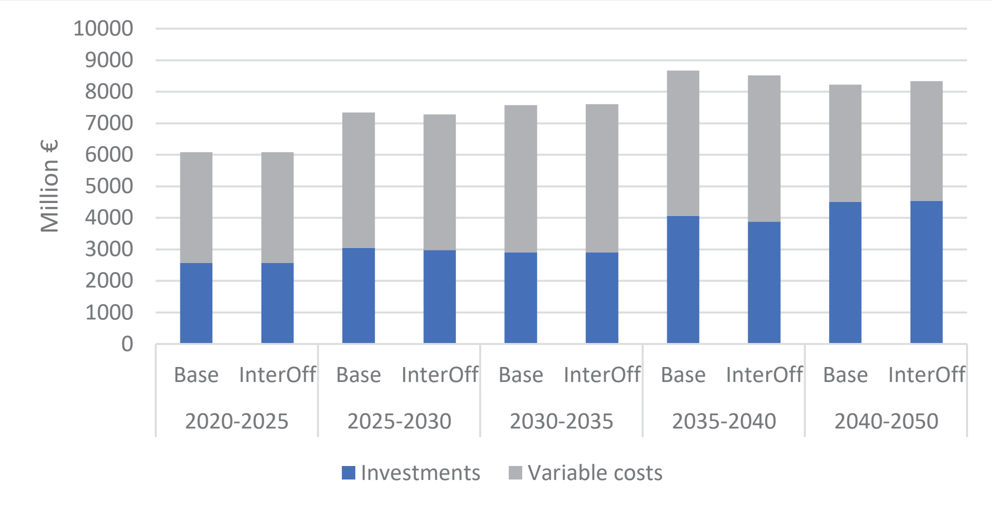


Figure 98. Annual investment and variable costs in the transport sector by modelled periods in Base and InterOff scenarios

Source: created by the author

3.2.5. ZeroCO_2 scenario modelling results

A scenario with strict CO_2 emission constraints for all three modelled sectors was created, considering the country's targets to reach a climate-neutral economy by 2050. In previous scenarios, there were no constraints on how much CO_2 could be emitted, but there were restrictions on the minimal use of RES in power and heat generation. Also, biofuel content was gradually increased in transport fuels with modelled years. The way how these scenarios were set up left the model some space to have non-zero CO_2 emissions. In the ZeroCO_2 scenario, it is investigated how power, district heating and transport sectors should develop to reach carbon neutrality by 2050.

3.2.5.1. Power and district heating sectors

In the modelling results of the ZeroCO_2 scenario, local electricity generation in 2030 is 8% higher than in the Base scenario, 11% higher in 2040, and 1% lower in 2050. Electricity imports in 2030 and 2040 are also higher, and exports are lower in 2030. Higher local generation with increased imports and decreased exports indicate increased electricity consumption due to faster transport electrification.

In electricity generation, the highest increase is observed in onshore wind power plants. It is higher by 12% in 2030 and 31% in 2040, compared to the Base scenario. However, in 2050, electricity generation from wind will be practically the same in both scenarios. PV generation in 2030 is higher by 11%, but in 2040 and 2050, it is on the same level. Electricity generation in biomass and waste power plants is also slightly higher. Interestingly, Gas-fired power plants in 2040 do not operate in the Base scenario but produce 22 MWyr of electricity (1% of total electricity production) in the ZeroCO_2 scenario. Therefore, CO_2 emissions are higher by 73% in the ZeroCO_2 scenario, but by 2050 emissions drop to 0, while in the Base scenario, they are around

133 kt CO_2. Despite emissions being 73% higher in 2040 in the ZeroCO_2 scenario, the absolute emission level is rather low (151 kt CO_2). This electricity generation in gas-fired power plants is caused by additional balancing needs to balance increased generation in wind power plants. The increased use of electricity storage supports this claim.

As a consequence of higher electricity production in more expensive power plants and greater use of energy storage, the electricity price in the ZeroCO_2 scenario is higher by 4% in 2030 and 15% in 2040 compared to the Base scenario.

Electricity mix, CO_2 emission and electricity price differences between ZeroCO_2 and Base scenarios are given in Figure 99.

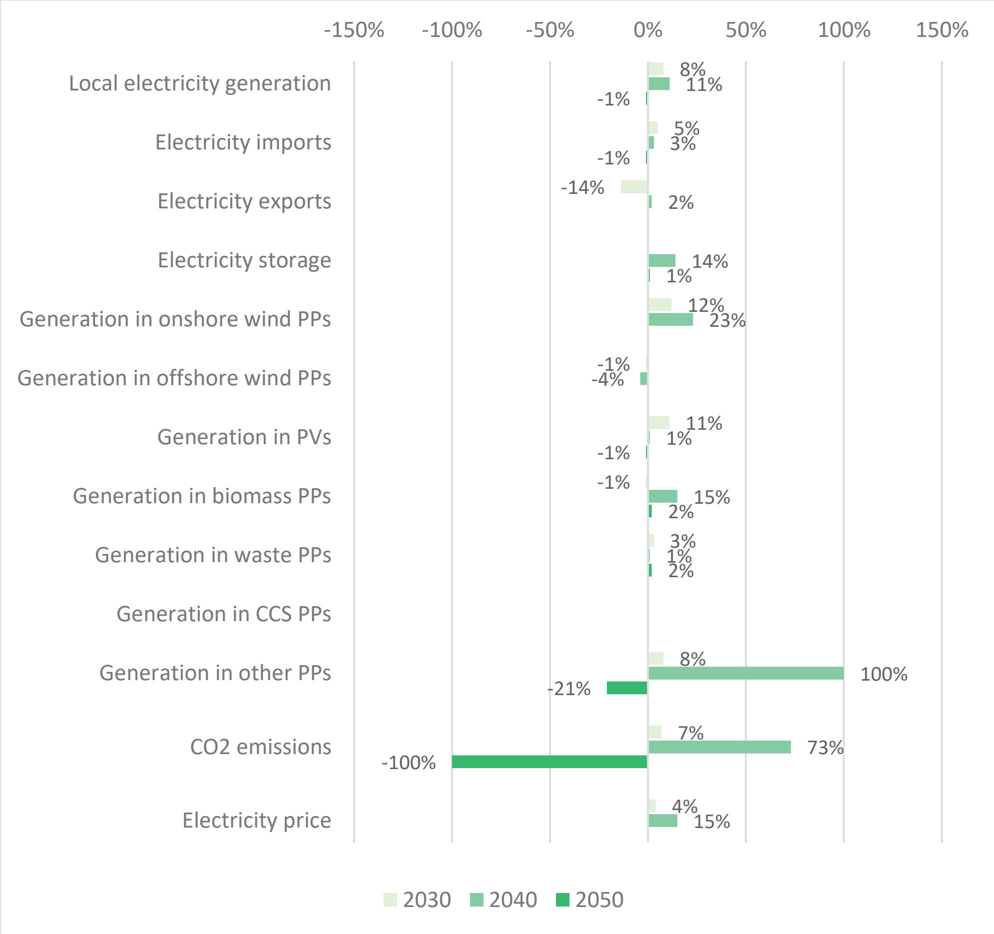


Figure 99. Electricity mix, CO_2 emission and electricity price differences between ZeroCO_2 and Base scenarios

Source: created by the author

VRES electricity generation curtailment is very similar between ZeroCO_2 and Base scenarios, as shown in Figure 100. Wind curtailment is slightly lower, and PV curtailment is slightly higher in the Zero CO_2 scenario.

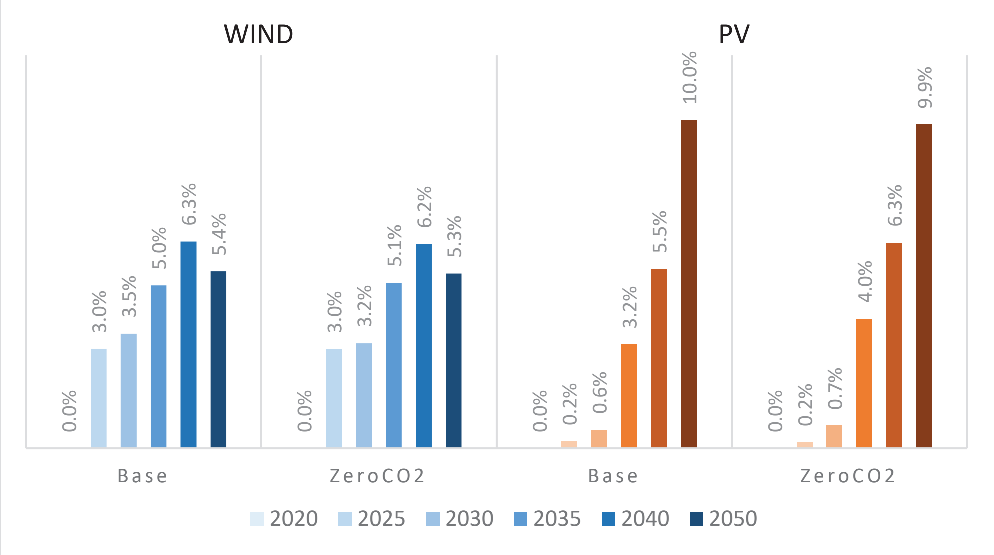


Figure 100. Curtailment of electricity generation in wind and PV power plants in Base and $ZeroCO_2$ scenarios

Source: created by the author

Till 2035 electricity price and price dispersion are almost identical between $ZeroCO_2$ and Base scenarios, but from 2035 both electricity price and dispersion are higher in the $ZeroCO_2$ scenario, especially in 2040 and 2050 (see Figure 101). The maximum electricity price reaches €940/MWh in 2040, but it only lasts one hour. The second most considerable price value in 2040 is €523/MWh, which is still substantially higher than the maximum value in the Base scenario. Interestingly, the price spread at the bottom 75% is similar between these two scenarios. The most significant differences are in the upper 25%.

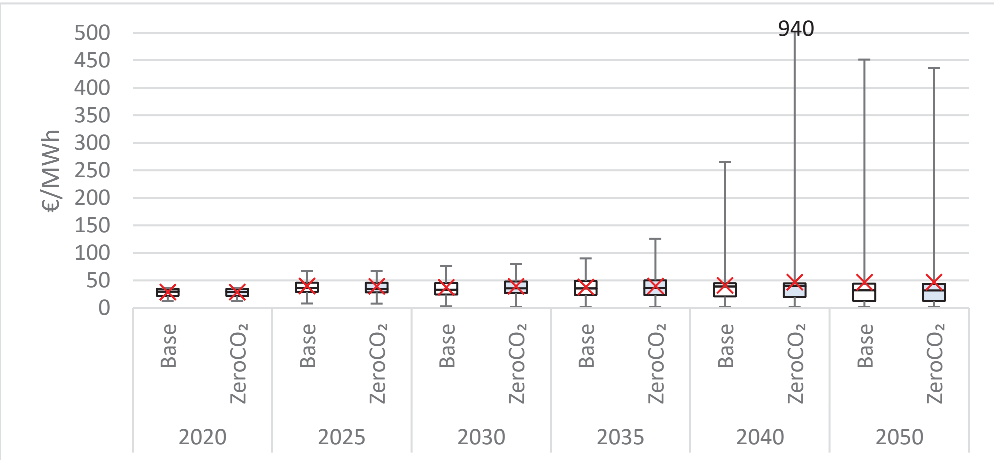


Figure 101. Electricity price in Base and $ZeroCO_2$ scenarios

Source: created by the author

In the ZeroCO$_2$ scenario, slightly higher heat generation can be seen in biomass and waste-fired CHP plants and lower in gas and biomass-fired heating plants compared to the Base scenario. It is worth mentioning that the model chooses to build a biomass CHP plant with CCS that has negative emissions to offset emissions in gas-fired power plants so that total emissions in 2050 would be equal to zero. However, heat generated in biomass CHP plant with CCS is only 5% of total heat generation. District heating generation differences between ZeroCO$_2$ and Base scenarios are given in Figure 102.

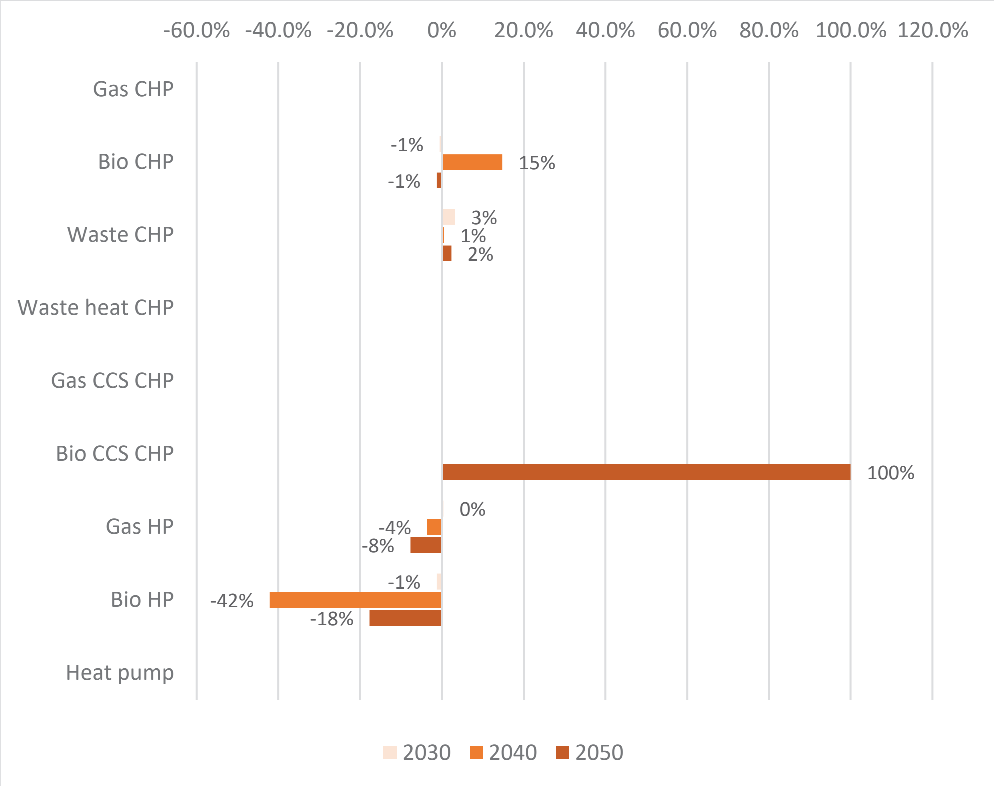


Figure 102. District heating generation differences between ZeroCO$_2$ and Base scenarios

Source: created by the author

Annual costs in the power and district heating sectors are higher by 24% in 2030–2035 and 14% in 2035–2040 in the ZeroCO$_2$ due to greater local electricity generation. However, annual costs are higher only by 1–2% in other modelled periods. The annual cost comparison between ZeroCO$_2$ and Base scenarios is given in Figure 103.

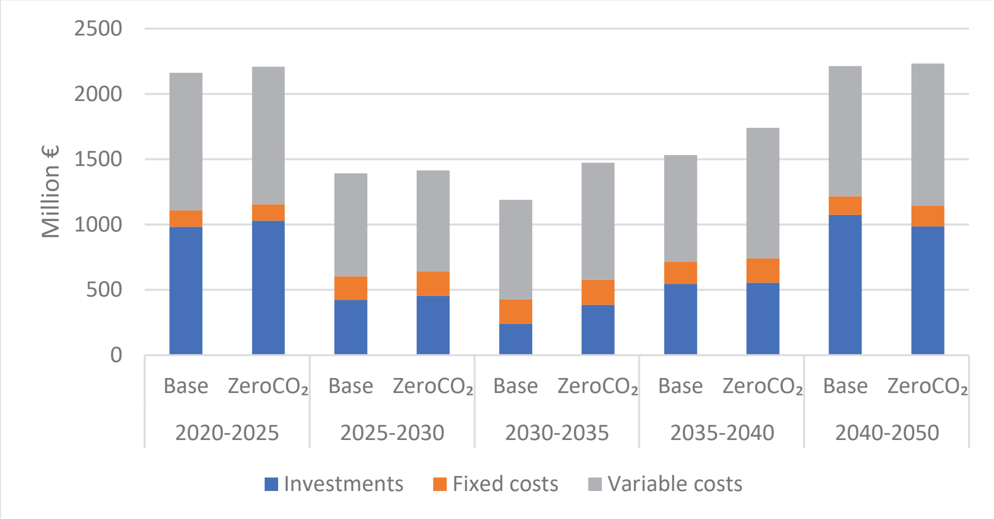


Figure 103. Annual investment, fixed and variable costs in power and district heating sectors by modelled periods in Base and $ZeroCO_2$ scenarios

Source: created by the author

3.2.5.2. Transport sector

In the modelling results of the transport sector in the $ZeroCO_2$ scenario, there is a more rapid switch to BEV and FCEV cars compared to the Base scenario, though by 2050, car electrification will reach a similar level in both scenarios. Also, as shown in Figure 104, the travel volumes in hybrid cars are lower and higher in diesel cars since the maximum bioethanol content in the petrol blend was assumed to be 85%, while 100% of biodiesel could be used in diesel cars. Thus, the model could not have any petrol consumption in 2050–2060 to ensure zero CO_2 emissions in the transport sector. In the Base scenario, public transport electrification is rapid, but in the $ZeroCO_2$ scenario, it is slightly faster. For example, in the Base scenario, travel volumes in electric and FCEV vehicles comprise 81.7% of total passenger travel volumes, while 91.3% in the $ZeroCO_2$ scenario. Freight transport electrification is also more rapid in the $ZeroCO_2$ scenario. Freight delivery volumes by electric and FCEV vehicles will reach 26.1% in 2030 and rise to 41.4% by 2035. However, in 2040 it decreases to 41% but afterwards increases again and reaches 84.2% in 2050. In the Base scenario, freight transport electrification starts only from 2035 when it reaches a 4% level. In 2040, freight delivery volumes by electric and FCEV vehicles will rise to 20.7% and 87% in 2050. Calculated CO_2 emissions in the $ZeroCO_2$ scenario are 14% lower in 2030 and 8% lower in 2040 than in the Base scenario. By 2050 transport emissions will reach zero.

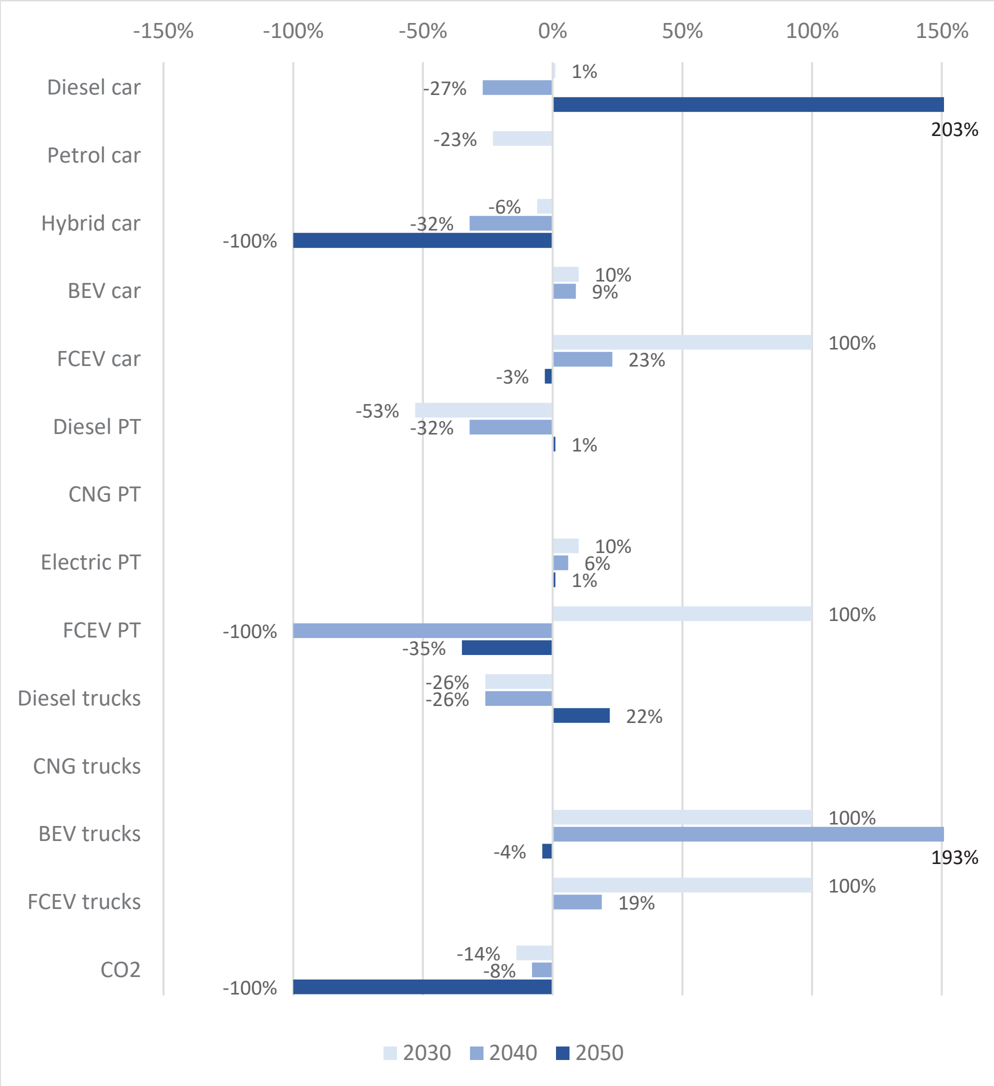


Figure 104. Travel, freight delivery and CO_2 emission differences between ZeroCO_2 and Base scenarios

Source: created by the author

The transport costs in the ZeroCO_2 scenario (see Figure 105), in general, are higher in 2025–2035 due to the required more significant investments for faster transport electrification. However, from 2035 investment costs decreased to below the level of the Base scenario. Also, variable costs in the ZeroCO_2 scenario throughout all modelling years are lower than in the Base scenario due to a higher electrification rate. Costs for electricity generation to power electric vehicles are accounted for in power and district heating costs.

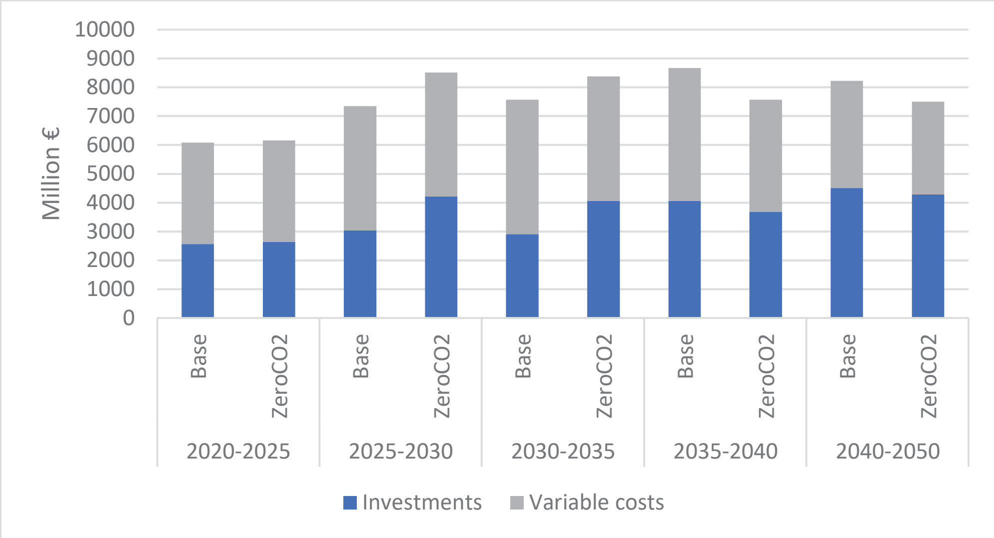


Figure 105. Annual investment and variable costs in the transport sector by modelled periods in Base and $ZeroCO_2$ scenarios

Source: created by the author

3.2.6. The effects of different electric vehicle charging strategies

Previous sections discussed the modelling results of five scenarios (Base, VehDistr, RedFlexi, InterOff and $ZeroCO_2$) of the power and district heating model and transport model. In all these cases, uncontrolled EV charging was applied. However, for each of the five scenarios, two additional were modelled to assess the effects of smart and V2G EV charging strategies. In this section, the modelling results of scenarios with smart and V2G EV charging applied are compared with counterpart scenarios with uncontrolled charging.

3.2.6.1. Power and district heating sectors

The graphical comparison of main power sector results of scenarios with smart and V2G EV charging applied with counterpart scenarios with uncontrolled charging is given in Figure 106, Figure 107 and Figure 108. The comparison shows that:

1. In most cases, smart and V2G charging effects are the same, but the magnitude of the effects is higher in the case of V2G.
2. Smart and V2G charging can contribute to the balancing of VRES, enabling higher electricity generation from these sources. Provided flexibility by smart and V2G charging can prove especially beneficial for electricity production in onshore wind power plants as scenarios with smart and V2G charging have a higher electricity generation in onshore wind power plants by 7–11% in 2030, 20–67% in 2040 and 8–27% in 2050 than scenarios with uncontrolled EV charging. Improvements are the highest in RedFlexi scenarios. Generally, scenarios with V2G have electricity generation in wind power plants higher by a few per cent than with smart EV charging. Smart and V2G charging also increased electricity generation in PV power plants, though not as significantly,

up to 4% in 2030, 13% in 2040 and 1% in 2050. Interestingly, in all scenarios, except VehDistr, smart charging and V2G had a negative impact on PV electricity generation in 2050, though only by several per cent. In all scenarios, except InterOff, smart and V2G charging had a negative impact on electricity generation in offshore wind power plants.

3. As a result of increased electricity generation in the wind and solar power plants, scenarios with smart or V2G charging applied have 4–17% higher local generation, 1–9% lower electricity imports and 2–18% higher exports. Though the local electricity generation is higher in these scenarios, the generation in non-VRES power plants is 18–51% lower than in scenarios with uncontrolled EV charging, resulting in 11–42% lower CO_2 emissions.
4. As EV smart and V2G charging can significantly contribute to balancing electricity generation from VRES, the need for energy storage could be substantially reduced by applying either of these charging strategies. The highest reductions were in the year 2050, in which energy storage needs were reduced by 61–77% in scenarios with smart charging and by 78–85% with V2G charging.
5. In scenarios with smart and V2G charging, average electricity prices are lower due to increased electricity generation from VRES, reduced imports and generation in thermal power plants, and decreased use of energy storage. The estimated effects on electricity prices before 2040 are relatively low. However, in 2040, smart and V2G EV charging can reduce electricity prices by around 13–25% and 25–34% in 2050.
6. Electricity price dispersion in scenarios with smart and V2G charging is lower, especially at the upper 25% price range. In previously discussed aspects, V2G provided only marginal benefits over smart charging. However, V2G reduces the price spread at the upper 25% price range substantially even compared to smart charging. It was also noticed that the effects of smart and V2G charging on the price spread increase with EV and VRES penetration.

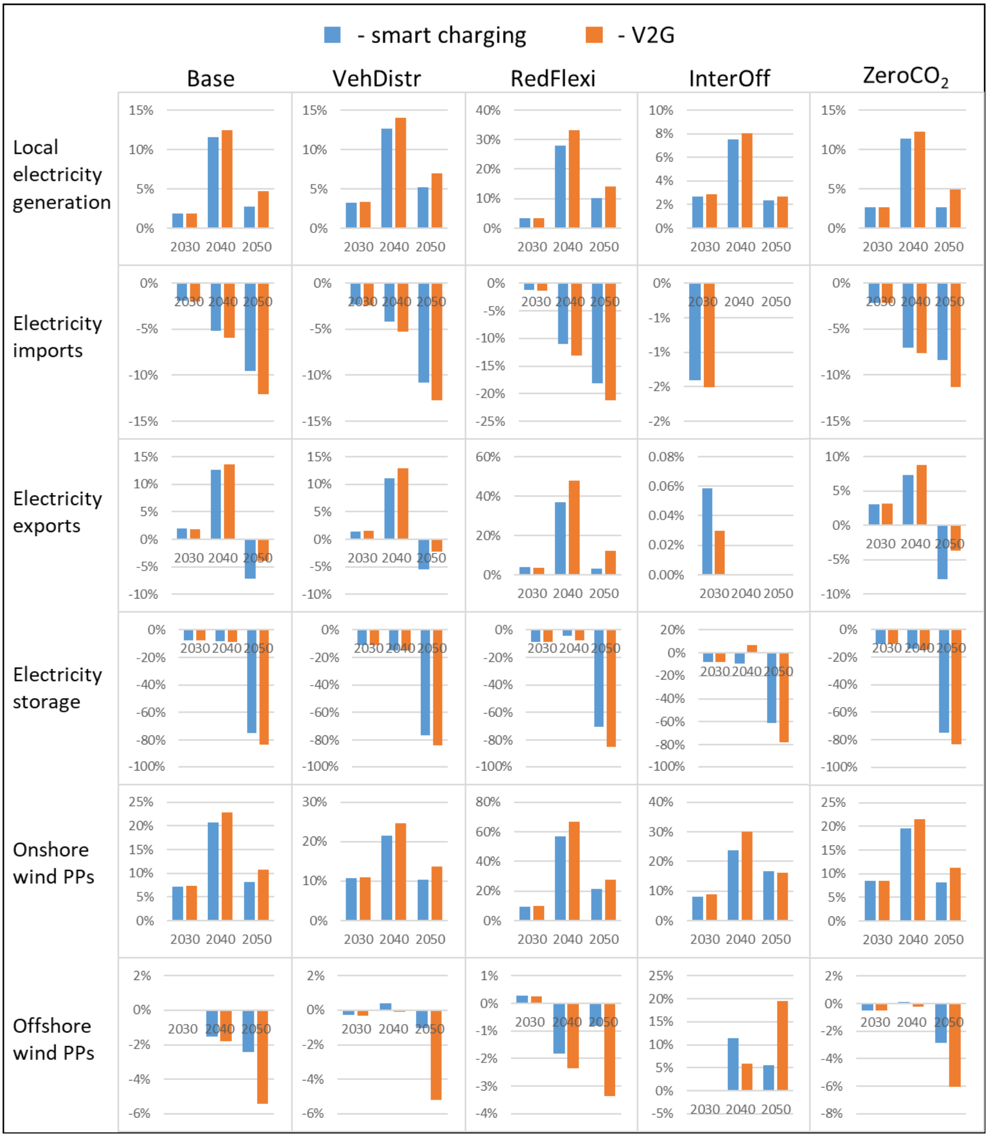


Figure 106. The power sector's main modelling results' differences between scenarios with smart charging and V2G compared to scenarios with uncontrolled charging (1st out of 2)

Source: created by the author

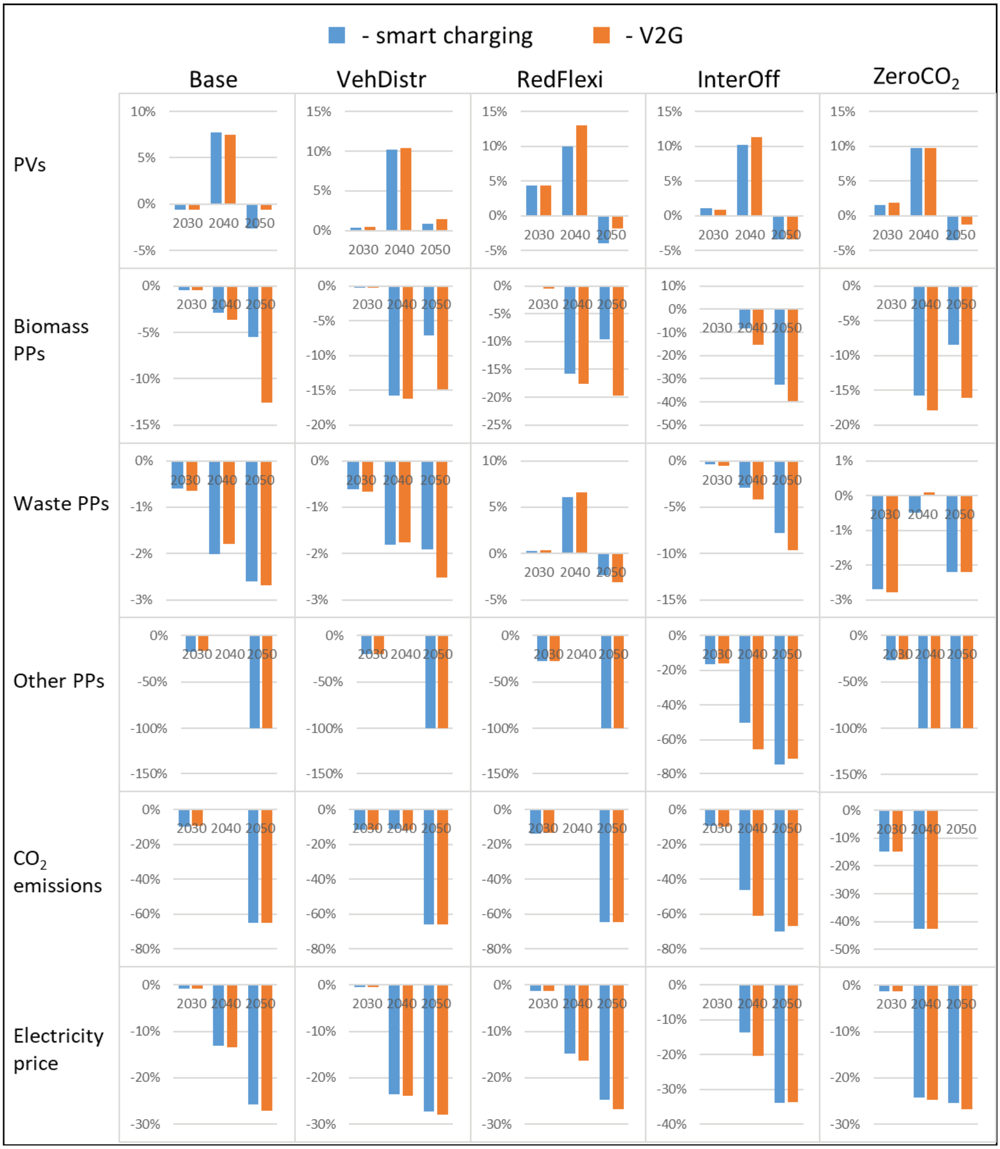


Figure 107. The power sector's main modelling results' differences between scenarios with smart charging and V2G compared to scenarios with uncontrolled charging (2nd out of 2)

Source: created by the author

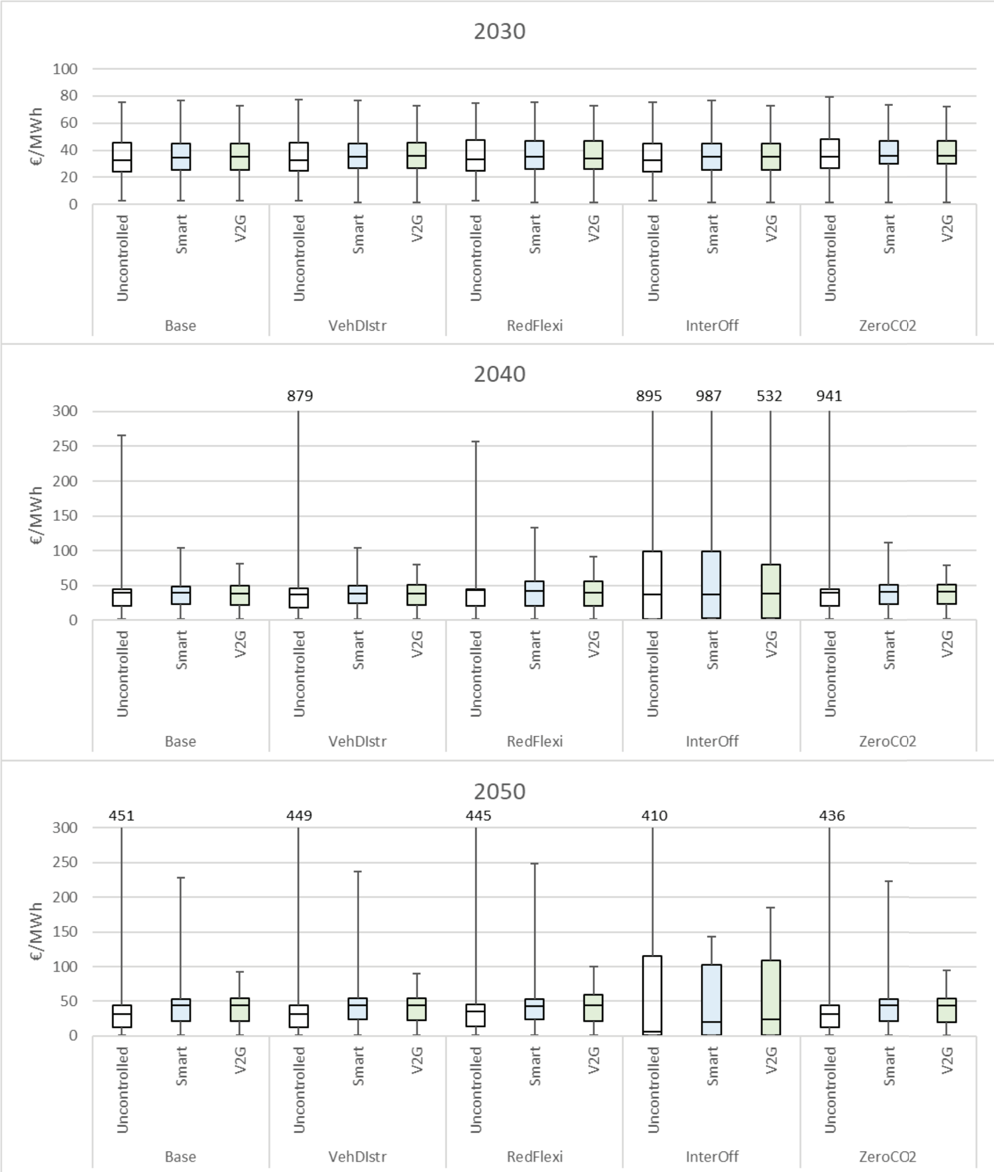


Figure 108. Electricity price in all 15 modelled scenarios for 2030, 2040 and 2050

Source: created by the author

A similar comparison of results between scenarios with smart charging and V2G compared to scenarios with uncontrolled charging was made for the district heating sector (see Figure 109). It can be summarized as follows: since smart and V2G EV charging can provide additional flexibility in balancing VRES, they reduce the need for variable electricity balancing with CHP plants, reducing both electricity and heat production in these plants and increasing generation in heating plants.

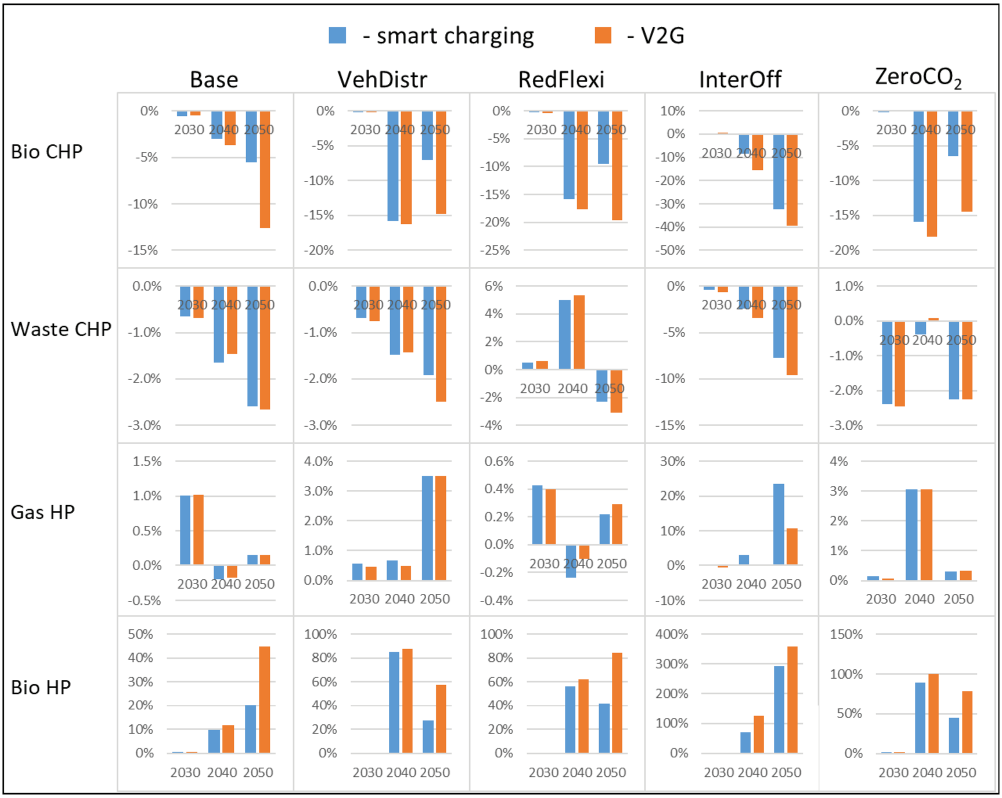


Figure 109. The district heating sector's main modelling results' differences between scenarios with smart charging and V2G compared to scenarios with uncontrolled charging

Source: created by the author

The total 2020–2060 cost comparison of power and district heating sectors, as shown in Figure 110, shows that costs in scenarios with smart EV charging are lower by 6.1–9.2% or €4–7 billion than uncontrolled charging. Scenarios with V2G charging do not show significant cost improvements over smart EV charging, except for InterOff scenarios (11.2% cost reduction, while smart charging provides 9.2%), as the requirement to fully balance electricity generation and consumption within the country after 2040 leads to high flexibility needs. V2G charging can provide more flexibility since it determines the best times to charge the electric vehicles and provides energy storage for the system. In other scenarios, most of the required balancing needs are ensured by interconnections. Adapting charging times according to the power supply showed significant cost reductions throughout all modelled scenarios, mainly because it reduces evening peak demand at times of low generation from renewable sources, resulting in lower required installed power plant or energy storage capacities.

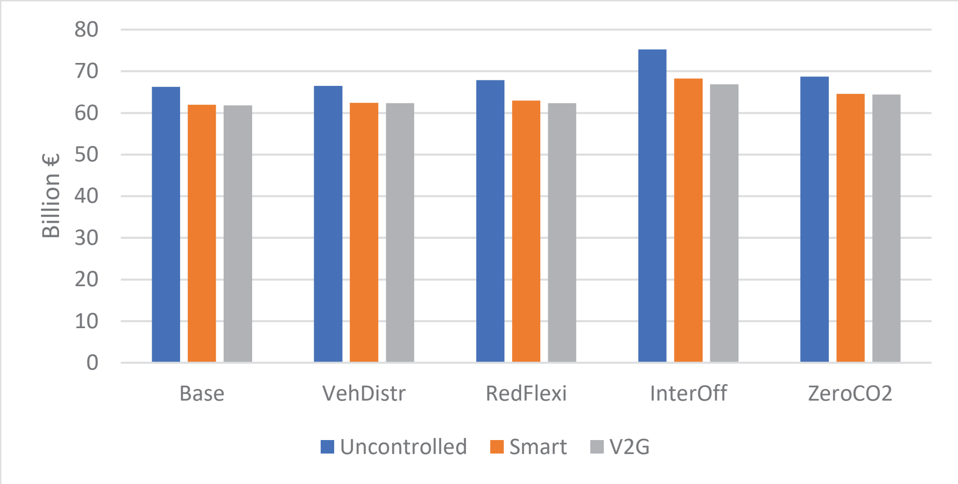


Figure 110. Total undiscounted costs of power and district heating sectors for 2020–2060 in modelled scenarios

Source: created by the author

3.2.6.2. Transport sector

In scenarios with smart and V2G charging, the use of BEV cars is higher at the expense of ICE and FCEV cars, as shown in Figure 111. At maximum, BEV use increased by 12% (InterOff+V2G scenario, the year 2050) compared to the Base scenario with uncontrolled EV charging. In the same scenario in 2050, the use of ICE cars is lower by 64% and FCEVs by 33%. The most significant reduction in FCEV use is in 2040 in VehDistr+smart and VehDistr+V2G scenarios, where it is lower by 68%.

The effects of smart and V2G charging in public and freight transport are similar to ones in personal transport. Electric vehicle use is higher in scenarios with smart and V2G charging than in scenarios with uncontrolled charging, while ICE vehicles and FCEV use are lower. In the case of public transport, passenger kilometres travelled by electric vehicles increase by up to 45% (in the InterOff scenarios). However, in the Base and ZeroCO$_2$ scenarios, the increase is negligible. Smart and V2G charging, in most cases, completely eliminate the need for FCEV in public transport, though it should be mentioned that FCEV share in public transport is very small (up to 8%), except for the InterOff scenario, in which it is around 28% in 2040–2060.

In freight transport, freight delivery volumes by BEV trucks increase substantially in scenarios with smart and V2G charging. However, interestingly, only in 2040. It is because BEV truck penetration in 2050 is very high in scenarios with uncontrolled EV charging (66–71%). As BEV's share in freight delivery volumes increases in 2040, the share of FCEV will decrease, though in 2050, it is on a similar level as in scenarios with uncontrolled charging. Also, the application of smart or V2G EV charging reduces the penetration of diesel trucks, especially in the year 2050 (from 12.5–15.8% to 2.2%)

Even though smart and V2G charging provides power balancing possibilities, it does not remove the need for green hydrogen production as a balancing measure since charging availability is limited during working hours.

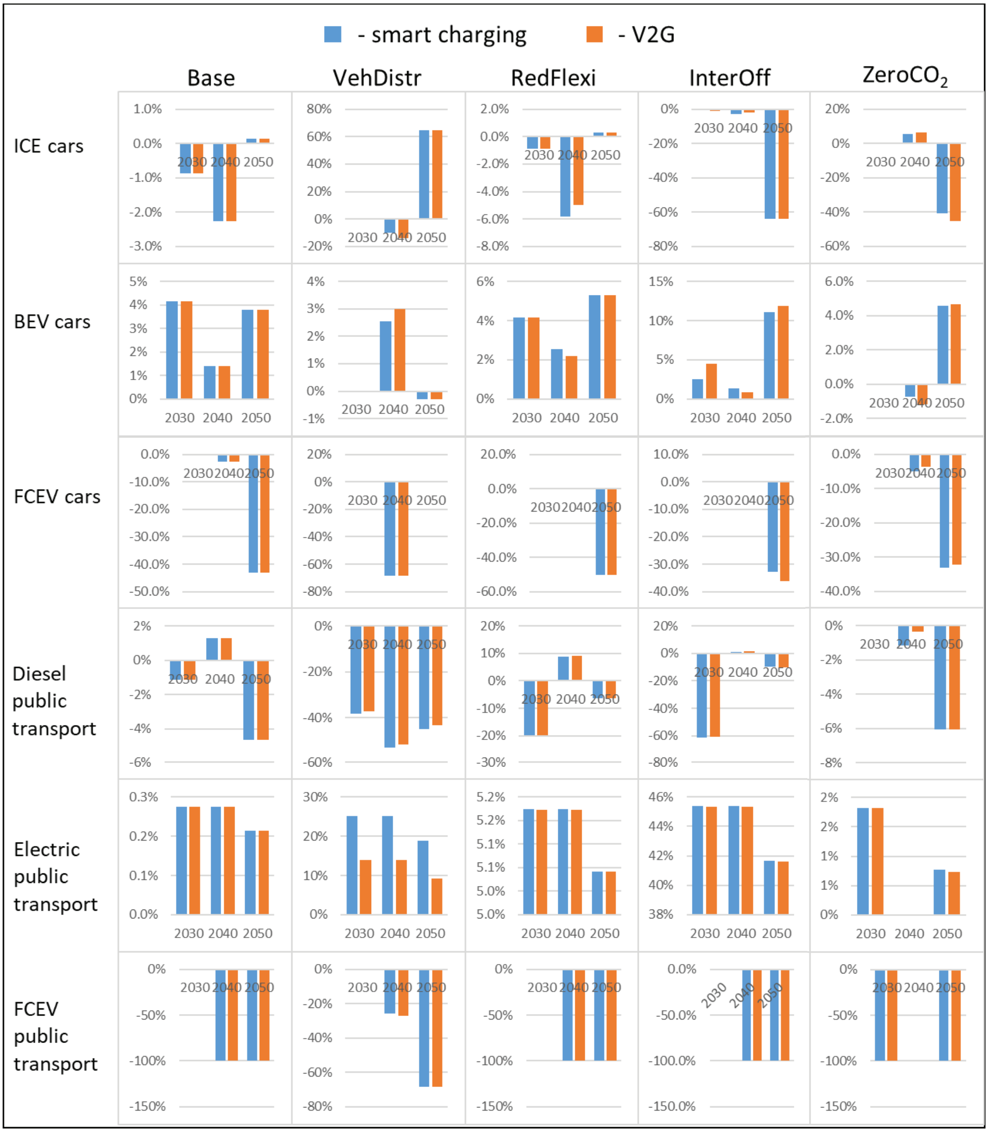


Figure 111. The transport sector's main modelling results' differences between scenarios with smart charging and V2G compared to scenarios with uncontrolled charging (1st out of 2)

Source: created by the author

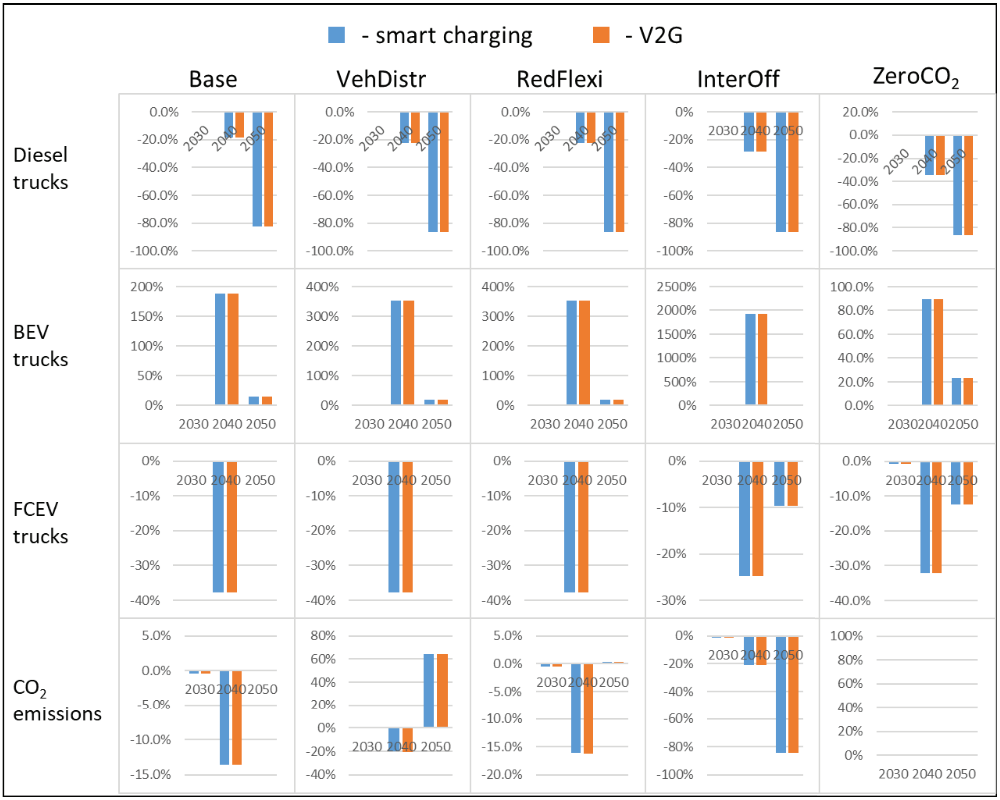


Figure 112. The transport sector's main modelling results' differences between scenarios with smart charging and V2G compared to scenarios with uncontrolled charging (2nd out of 2)

Source: created by the author

By comparing the modelling results of scenarios with smart and V2G charging to scenarios with uncontrolled charging, it was observed that smart and V2G charging similarly affects personal, public and freight transport. Electric vehicles use increased, while ICE and FCEV decreased. However, despite these changes, the effects of different charging strategies on the total undiscounted costs of the transport sector for the years 2020–2060 are negligible, as shown in Figure 113. Total costs are so similar between the scenarios with different charging strategies because, in essence, these scenarios yield very similar results for the transport sector, and the cost differences between vehicle fuel types are not that high, especially in 2050. Also, costs for electricity and hydrogen are not included in Figure 113 as they are calculated in the power and district heating sectors.

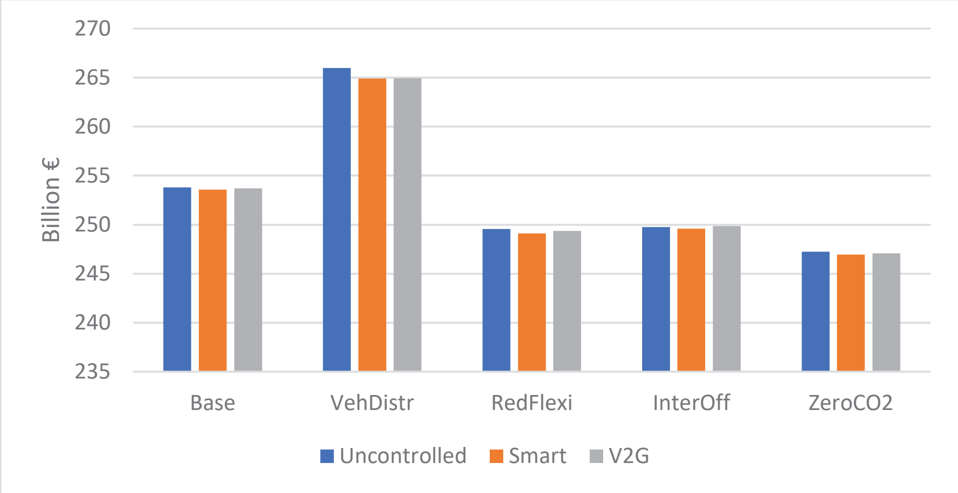


Figure 113. Total undiscounted costs of the transport sector for 2020–2060 in modelled scenarios

Source: created by the author

3.3. Application of results

The developed model calculates the least-cost long-term development pathways for the energy and transport sectors under certain assumptions to achieve strategic targets like decarbonization or ensuring energy security. Therefore, it is well-suited to provide valuable insights for developing energy strategies. In the EU, Member States are required to every ten years prepare national energy and climate plans (NECP) that set out national objectives for energy security, internal energy market, energy efficiency, decarbonization of the economy and research, innovation and competitiveness for the next ten year period (The European Parliament & Council of the European Union, 2018). Also, these plans have to be updated by 2024 and every ten years thereafter. Furthermore, each Member State every ten years has to prepare long-term strategies covering at least 30 years, in which action plants are set to achieve the overall climate targets. However, the developed modelling approach could prove beneficial not only for the EU countries but many other countries as well since, under the Paris Agreement, each country has to submit nationally determined contributions and update them every five years. Even though the model was developed for the Lithuanian case, the same modelling approach can be used to create a model for any country.

At the time of thesis preparation, a LIFE IP EnerLIT project has started and will last till the end of 2030 to support the implementation of Lithuania's NECP (Lietuvos Respublikos aplinkos ministerija, 2022). The project includes activity A1.2 Improving the modelling process. The developed integrated model of energy and transport sectors for Lithuania could be potentially used in this activity, contributing to already used models and models under development.

3.4. Policy recommendations

The modelling results show that electricity generation from VRES should be developed rapidly to achieve set emission abatement and energy security targets. In 2025–2030 installed PV capacity should reach almost 2.2 GW and wind power plant capacity 1.6 GW. According to the system operator Litgrid (2022a), at the beginning of 2022, the total installed capacity of solar and wind power plants was 259 MW and 671 MW, respectively. However, signed protocols of intent for connecting the producer's facilities to the transmission grid (Litgrid, 2022b) show that it is planned to build more than 3 GW of solar and 700 MW of wind power plants. Also, according to the Lithuanian Wind Power Association (2022), wind power projects currently in various stages of development exceed 2.7 GW. It is essential to mention that parts of solar farms are often sold as remote power plants. A consumer can become a prosumer by buying such a remote solar power plant and get a subsidy for prosumers in the form of a one-time payment of up to 3230 Eur (for 10kW). This support mechanism increases the demand for solar power plants, and it is likely that a significant share of planned solar farms will be sold as remote solar power plants. However, additional incentives are unnecessary, as companies are already willing to invest in such projects. Also, the XIV-1169 amendment to the Law on Energy from Renewable Sources (Lietuvos Respublikos Seimas, 2022) states that the total installed capacity of solar power plants cannot exceed 2 GW, but the capacity of prosumer solar power plants does not count towards this limited capacity. Though the limit set by the Law on Energy from Renewable Sources is in line with modelling results for 2025–2030, the limits should be loosened in the future to enable further development of solar power plants. In the meantime, the power grid should be upgraded to support even higher VRES penetration. In addition, it is necessary to look for flexibility measures that would utilize excess electricity during peak generation from VRES times or store it for low generation times.

Modelling results show a gradual shift from ICE cars to BEVs in personal transport. Even though the model shows that such a shift is a least-cost pathway from a societal point of view, several factors will likely slow down this transition. First, a significant share of households might not afford higher BEV purchase costs. Second, the size of the used BEV market is still relatively small, limiting the availability of cheaper but preowned BEVs. Third, BEVs are an inconvenient option for residents living in blocks of flats (In Lithuania, the vast majority of city residents live in them) as, in most cases, parking spaces near blocks of flats are public. Therefore, not many would be willing to invest in a charging station since parking space could be occupied by somebody's else car. Furthermore, building a charging station near a block of flats is more expensive than near a single-family house.

Currently, In Lithuania, BEV buyers can apply for compensation that reaches €5000 for new BEVs and €2500 for preowned (Lietuvos Respublikos susisiekimo ministerija, 2022). An ongoing compensation scheme addresses the first and second issues as, in principle, it reduces the purchase price difference between BEV and ICE cars, increasing the number of BEVs bought. In the long run, it also increases the number of BEVs available in the used car market. However, it is worth investigating the effectiveness of this compensation scheme since the price difference currently is significantly higher than €5000 (The price of a new VW ID.3 BEV starts at €42 660, while the equivalent ICE VW golf's at €25,791 (Volkswagen, 2022b)) and it is possible that buyers that are willing to buy BEVs, in any case, are the main beneficiaries of these compensations. The third issue could be addressed by subsidizing building charging stations near blocks of flats, designating parking spaces with chargers exclusively for BEV cars and penalizing those who park ICE cars in such parking spaces.

The modelling results reveal significant benefits that smart electric vehicle charging can provide. Adjusting charging times to match the variability in electricity generation from wind and solar power contributes to the system balancing, enabling higher electricity generation from variable renewable sources and reducing required electricity storage in the system. Furthermore, it reduces average electricity prices as well as price spread. In the developed model, in scenarios with smart charging enabled, it was considered that all electric vehicles participate in smart charging. However, without incentives, it is unlikely that significant participation in smart charging could be achieved in real life. Smart charging can be managed by the user, meaning that the user decides when to charge the vehicle based on electricity price and needs, or the electricity supplier, meaning that the user gives supplier charging control. In the case of user-managed charging, real-time electricity pricing could be used as an incentive. However, smart meters need to be installed to enable real-time pricing. Also, the supplier needs to provide the user with a convenient platform to check electricity prices for the day to be able to plan EV charging accordingly. Still, even with real-time electricity pricing and a convenient platform, it is unclear how effective such an incentive would be at changing EV charging patterns. In the case of supplier-managed charging, charging patterns are determined by the suppliers. However, supplier-determined charging patterns might not suit the users' needs. A possible solution could be to provide the capability of easy switching between two charging management modes but encourage keeping supplier-managed charging on by providing additional incentives such as payments for providing vehicle-to-grid service.

The modelling results of RedFlexi and InterOff scenarios show the potential of green hydrogen production and its utilization in the transport sector as a VRES balancing measure, indicating the possible role in the future Lithuanian power system. However, at the moment, the development of green hydrogen in Lithuania has not even started. First and foremost, Lithuania should set green hydrogen goals and prepare a hydrogen sector development strategy to lay the groundwork for developing hydrogen policies, infrastructure, market and principles of how hydrogen producers would participate in the power market and supply balancing services. Then, appropriate policies and subsidized pilot projects should follow to kickstart hydrogen sector development. These actions should be completed by 2030-2035, as the modelling results show hydrogen use in the transport sector from 2035. In the case of the ZeroCO_2 scenario, from 2030.

CONCLUSIONS

1. When considering the transport and energy sector's development pathways to reach carbon neutrality, it is of great importance to consider the sectoral interrelations. It was identified that the most critical connections between district heating and power sectors are CHP plants that simultaneously produce electricity and heat for the district heating system and heat pumps, which need electricity to extract ambient heat and supply it to the district heating grid. Transport and power sectors are connected by electric vehicles and FCEV if hydrogen is produced through electrolysis. Often heat pumps, electric vehicles and fuel cell electric vehicles are considered to have zero emissions, but the effectiveness of these technologies as emission reduction measures depend on the electricity generation mix. In the case of electricity generation from coal, the total emissions might even increase. Furthermore, the electrification of various sectors increases total electricity demand and affects the shape of the electricity consumption curve affecting the required total installed capacities and which power plants operate. On the other hand, electric vehicle charging, hydrogen generation through electrolysis and heat pump use can be utilized to shift electricity demand to match the variable electricity generation from wind and solar energy, contributing to the balancing of the power system, enabling higher penetration of VRES. Also, bidirectional V2G charging can be applied to electric vehicles, providing short-term electricity storage.
2. The scientific literature review revealed that optimization models, based on total discounted cost minimization, are commonly used to determine least-cost pathways on how analysed systems should develop to reach set emissions and other strategic targets. It was found that all such models that cover power, district heating and transport sectors consider specific flexibility measures through sectoral interrelations, like P2H, green hydrogen use in transport, and smart or V2G EV charging. However, some of them do not consider V2G charging or FCEVs. Also, some of these models do not optimize the investments in the transport sector, i.e. transport development is assumed. Optimization models are computationally heavy. Therefore, in some cases, a low temporal resolution is used to reduce the model size and computational times. However, it hinders the representation of power supply and demand variability, which is especially problematic when considering renewable source-based power systems. Other models use myopic foresight to reduce computational requirements, which means investments are optimized in time steps instead of the whole modelled time horizon. However, F. Fuso Nerini showed that myopic foresight might result in delayed investments and higher costs in a determined pathway to reach set decarbonization targets compared to the model with perfect foresight. None of the optimization models mentioned in the scientific literature covering power, district heating and transport sectors has these four features simultaneously: works by minimizing total discounted costs, optimizes transport investments, has a relatively high temporal resolution, and has perfect optimization foresight.

3. To fill a research gap in the scientific literature, the MESSAGE modelling framework developed an integrated transport and energy sectors model for assessing the least-cost pathways, which ensure near-zero carbon emissions. The model covers power, district heating and transport sectors. It optimizes the investments in all modelled sectors, has a relatively high temporal resolution, and optimization is performed using perfect foresight. The model was developed for Lithuania's case. Furthermore, considering the fact that most first-time registered vehicles in Lithuania are used vehicles from foreign used car markets, a unique approach was developed to account for vehicle age distributions. Additionally, a probabilistic approach was developed to improve the representation of variability in wind power generation. Although the model was developed for Lithuania within the MESSAGE modelling framework, it can be adapted for other countries, and described methodology can be applied in other modelling frameworks (like TIMES) with some modifications.
4. The modelling results show that the least-cost way to decarbonize Lithuania's power sector and, at the same time, ensure the power supply's security is to rapidly expand electricity generation in the wind and solar power plants. In 2025–2030, electricity generation from VRES should reach 56% of total electricity consumption and gradually increase to 98% in 2050–2060. The optimal ratio between electricity generation in wind and solar power plants is around 1.7. The model reveals that installing small decentralized solar power plants at the consumers' side, making them prosumers, is more cost-efficient than building large solar farms. However, the balancing needs increase with the rising share of electricity generation from VRES. It was estimated that it is cheaper to ensure the balancing with interconnections than by expanding the installed capacities of thermal power plants or energy storage. On the other hand, it should be noted that the developed model does not consider the power supply and demand in neighbouring countries. Therefore, the balancing capabilities through interconnections might be limited in the future as neighbouring countries will likely switch to electricity generation from VRES as well and face the same balancing issues.

   The modelling results for the district heating sector show that the role of biomass and MSW CHP plants gradually increases in the least-cost pathway from today's total district heat generation share of 34% to 76% in 2050–2060. However, till 2040, the share increases primarily because of decreasing district heat demand. As demand decreases, the gas-fired CHP plants are pushed out first and then the heating plants.

   The determined development pathway for the transport sector includes a gradual transition to battery-electric cars and fuel cell cars by 2050–2060, reaching 89.4% and 7.1% penetration, and rapid electrification of public transport (13% in 2025–2030, 82% in 2030–2035, 94% in 2050–2060). Freight transport electrification starts latest in the determined pathway as only 4% of total freight deliveries are by electric and FCEV vehicles till 2035; however, in 2035–2040, this number rises to 19% and in 2050 to 82%.

5. Fifteen scenarios were modelled, including a base scenario, a scenario with changing vehicle age distribution, another with reduced flexibility of interconnections, a scenario with interconnections cut-off after 2040 and a scenario with strict requirements to reach net-zero emissions by 2050. Two additional scenarios were modelled for each of these five scenarios: one with smart EV charging applied and the other with V2G. The comparison of the results of the scenarios showed that:
   - Changing vehicle age distribution, i.e. reduction in average vehicle age, results in a faster switch to BEVs, which increases overall electricity demand and demand peak in the evening, leading to higher average electricity prices and wider electricity price spread.
   - Reduced flexibility of interconnections decreases the electricity generation from VRES and electricity produced within the country in general, resulting in higher average electricity prices. Also, it increases the need for energy storage and other flexibility measures, like hydrogen production through electrolysis.
   - The requirement to fully balance VRES generation within the country decreases the electricity generation from VRES, especially in offshore wind power plants, but increases electricity generation in thermal power plants and the need for energy storage. As a result, the average electricity price, price spread and CO_2 emissions increase. Also, the role of hydrogen production through electrolysis as a balancing measure becomes more prominent.
   - Strict requirements to reach net-zero CO_2 emissions in all sectors considered result in increased generation from renewable sources and higher needs for energy storage. Also, CCS technology is used only in ZeroCO_2 scenarios. As a result, the average electricity price and price spread are higher in the ZeroCO_2 scenario than in the Base scenario. Furthermore, the FCEV use in both passenger and freight transport is more significant.
   - Smart and V2G charging provide clear benefits over uncontrolled EV charging. They enable the adaptation of charging times to match the variability in electricity generation from wind and solar power, contributing to the balancing of VRES and resulting in higher electricity generation in the wind and solar power plants, lower average electricity price and price spread as well as decreased needs for energy storage. However, the benefits of V2G charging over smart charging in the modelling results are marginal.

SUMMARY

ĮVADAS

Tyrimo aktualumas

Nuo pramonės revoliucijos laikų atmosferoje sparčiai didėja šiltnamio efektą sukeliančių dujų (toliau – ŠESD) koncentracija, lemianti didėjančią vidutinę pasaulinę temperatūra, kuri jau dabar yra 0,99 °C aukštesnė, lyginant su priešindustriniu laikotarpiu (Masson - Delmotte et al., 2021). Neigiamas dabartinės klimato kaitos poveikis pasireiškia vandens prieinamumo bei tam tikrų gyvūnų ir augalų rūšių buveinių pokyčiais, sumažėjusiu derliumi, padidėjusiu ekstremalių klimato reiškinių ir su karščiu susijusių mirčių skaičiumi (Field et al., 2014). Toliau kylant pasaulinei temperatūrai neigiamas poveikis sustiprėtų ir dar labiau paplistų.

Siekiant sušvelninti klimato kaitą ir jos padarinius buvo pasirašytos įvairios tarptautinės sutartys, iš kurių bene svarbiausias yra Paryžiaus klimato susitarimas. Paryžiaus susitarime nustatytas visuotinis tikslas – stabilizuoti vidutinės pasaulinės temperatūros kilimą iki 2 °C, lyginant su priešindustriniu laikotarpiu, ir siekti, kad jis neviršytų 1,5 °C. Pagal šį susitarimą kiekviena šalis turi parengti ir kas penkerius metus atnaujinti emisijų mažinimo ir prisitaikymo prie klimato kaitos poveikio veiksmų planus (Kuyper et al., 2018). Tęsdamos Paryžiaus susitarimą, 137 šalys užsibrėžė dekarbonizuoti savo ekonomikas XXI a. antroje pusėje arba anksčiau. Tačiau ekonomikos dekarbonizacijai reikia radikalių ir didžiulių investicijų reikalaujančių pokyčių visuose ekonomikos sektoriuose. Todėl nacionaliniai veiksmų planai turėtų būti grindžiami išsamiomis įvairių sektorių perspektyvinės raidos ir emisijų mažinimo priemonių ekonominio efektyvumo analizėmis.

91 % pasaulyje išmetamo CO_2 kiekio susidaro deginant kurą, o likusius 9 % sudaro neorganizuoti išmetimai, daugiausia susiję su iškastinio kuro gavyba, perdirbimu ir transportavimu (IEA, 2021a). Didžioji dalis kuro deginimo metu išmetamo CO_2 kiekio susidaro gaminant elektros energiją ir šilumą (44 %), transporto sektoriuje (22 %), o likusi dalis – pramonės (20 %), pastatų (9 %) ir kituose (2 %) sektoriuose (IEA, 2021a). Nuo 2010 m. elektros ir šilumos gamybos sektoriuje bei transporto sektoriuje emisijų kiekis per metus augo labiausiai, 1,3 % ir 1,8 % atitinkamai. Pramonės sektoriuje išmetamo CO_2 kiekis didėjo 0,3 %, pastatų sektoriuje 0,35 %, o kituose sektoriuose sumažėjo 0,6 %. Atsižvelgiant į tai, kad didžiausi emisijų kiekiai ir jų didėjimo tempai yra elektros ir šilumos gamybos bei transporto sektoriuose, rengiant dekarbonizacijos veiksmų planus didžiausias dėmesys turėtų būti atitinkamai skiriamas šiems sektoriams.

Elektrifikavimas bei elektros energijos gamyba iš atsinaujinančiųjų energijos išteklių (toliau – AEI) dažnai įvardijami kaip pagrindiniai ekonomikos dekarbonizacijos būdai. Tačiau nepastovi elektros gamyba vėjo ir saulės elektrinėse riboja šių šaltinių panaudojimą elektrai gaminti, nes kiekvienu momentu gamyba ir vartojimas elektros sistemoje turi būti lygūs. Siekiant įgalinti elektros gamybą, grįstą iš esmės vėjo ir saulės energija, reikalingos įvairios elektros sistemos lankstumo priemonės. Įprastai sistemos lankstumą užtikrina generuojamą galią, priklausomai nuo elektros poreikių, galinčios keisti šiluminės elektrinės ir hidroelektrinės. Kadangi atsinaujinančiaisiais šaltiniais grįstoje elektros sistemoje lankstumo galimybės elektros pasiūlos pusėje yra ribotos, todėl lankstumas turi būti užtikrinamas paklausos pusėje, o tai reikštų paradigmos pasikeitimą iš gamybos prisitaikymo prie vartojimo grafikų į vartojimo prisitaikymą prie gamybos grafikų. Sistemos lankstumas paklausos pusėje gali būti didinamas išnaudojant įvairius tarpsektorinius ryšius, iš kurių svarbiausi yra elektromobilių vienkryptis ir dvikryptis išmanusis įkrovimas, išmanioji vandenilio gamyba elektrolizės būdu bei šilumos gamyba iš elektros energijos.

Šioje daktaro disertacijoje pristatomas sukurtas modelis, skirtas integruotai elektros, centralizuoto šilumos tiekimo ir transporto sektorių dekarbonizacijos mažiausiais kaštais analizei, įvertinant galimą tarpsektorinių ryšių panaudojimą elektros sistemos lankstumui didinti.

Mokslinė problema ir jos ištyrimo lygis

Tikėtina, kad transporto elektrifikavimas atliks esminį vaidmenį mažinant ŠESD emisijas transporto sektoriuje. Nors elektra ar vandeniliu varomos transporto priemonės neišmeta CO_2, tačiau elektra, reikalinga elektromobiliams įkrauti ar vandeniliui gaminti, dažnu atveju yra generuojama deginant iškastinį kurą ir išmetant CO_2. Todėl transporto elektrifikavimo, kaip emisijų mažinimo priemonės, veiksmingumas priklauso nuo to, kokius šaltinius naudojant yra generuojama elektros energija.

Be to, transporto elektrifikavimas gerokai padidintų elektros energijos poreikį. Taip pat elektromobiliai dažniausiai įkraunami vakare, todėl padidėja elektros poreikis vakarinio piko metu, o tai yra itin problemiška elektros energetikos sistemoms, kuriose ženklią gamybos dalį sudaro saulės elektrinės (Muratori & Mai, 2021). Tokiose sistemose saulei leidžiantis generuojamas elektros kiekis sparčiai mažėja, o poreikiai išauga (Krietemeyer et al., 2021). Todėl reikalingos elektrinės, kurios galėtų greitai keisti generuojamą galią, tokios kaip dujomis kūrenamos elektrinės, arba didelių investicijų reikalaujančios elektros akumuliavimo technologijos, kad būtų galima kompensuoti gamybos saulės elektrinėse sumažėjimą. Kita vertus, taikant išmanųjį elektromobilių įkrovimą galima prisidėti prie elektros energijos sistemos balansavimo (Muratori & Mai, 2021), taip sumažinant balansavimo įrenginių ar energijos akumuliavimo poreikį. Tokie tarpsektoriniai ryšiai gali turėti ženklią įtaką, kaip energetikos sistema veiks ateityje, todėl jie turėtų būti įvertinami rengiant emisijų mažinimo veiksmų planus.

Energetikos planavimo modeliai, grįsti diskontuotų kaštų minimizavimu, dažnai yra naudojami siekiant nustatyti, kaip turėtų vystytis energetikos sektorius, kad būtų pasiekti įvairūs strateginiai tikslai, įskaitant emisijų mažinimą, mažiausiomis sąnaudomis. Tačiau dažnai yra neatsižvelgiama į energetikos ir transporto sektorių tarpusavio ryšius, nors jie gali turėti ženklų poveikį. Mokslinėje literatūroje yra atlikta tyrimų, pasitelkiant energetikos planavimo modelius, siekiant nustatyti, kokį poveikį transporto ir energetikos sektorių tarpusavio ryšiai gali turėti energetikos sistemos raidai (T. Brown et al., 2018; Gea-Bermúdez et al., 2021; Gunkel et al., 2020; Juul & Meibom, 2012; Kiviluoma & Meibom, 2010, 2011). Visuose šiuose modeliuose, išskyrus (Juul & Meibom, 2012), transporto sektoriaus raida buvo modeliui užduota išoriškai, vietoje raidos nustatymo modeliu, taikant optimizaciją. Tačiau transporto raidos optimizavimas gali suteikti vertingų įžvalgų, nes juo ne tik nustatoma transporto sektoriaus raida mažiausiais kaštais, bet ir sudaromos sąlygos modeliui įvertinti ar tikslingiau būtų išnaudoti tarpsektorinius ryšius, ar kitas elektros sistemos lankstumo priemones. Be to, šie modeliai arba atlieka optimizavimą vieniems metams (T. Brown et al., 2018; Juul & Meibom, 2012; Kiviluoma & Meibom, 2010, 2011), arba taiko trumparegišką optimizavimą (Gea-Bermúdez et al., 2021; Gunkel et al., 2020). Jei optimizavimas atliekamas vieniems metams, tokiu atveju modelis nepateikia optimalaus dekarbonizacijos kelio, o apskaičiuojama, kokia galėtų būti optimali sistema kaštų atžvilgiu, esant tam tikriems emisijų apribojimams. Taikant trumparegišką optimizavimą galima nustatyti dekarbonizacijos kelius. Tačiau Fuso Nerini ir kiti (2017) parodė, kad trumparegiškas optimizavimas gali lemti vėluojančias investicijas ir gerokai didesnes sąnaudas emisijų mažinimo tikslams pasiekti nei optimizavimas su tobulu numatymu. Mokslinėje literatūroje kai kurie modeliai apima energetikos ir transporto sektorius bei taiko optimizavimą su tobulu numatymu (Balyk et al., 2019; C. Butler et al., 2020; Daly & Fais, 2014; Dodds, 2021; European Commission. Joint Research Centre. Institute for Energy and Transport., 2013; Kannan & Turton, 2014; McCollum et al., 2012). Tačiau optimizavimas su tobulu numatymu reikalauja ženkliai didesnių kompiuterinių pajėgumų, todėl paprastai tokiuose modeliuose naudojama žemesnė laiko rezoliucija, kuri apriboja tarpsektorinių ryšių atvaizdavimą modelyje.

Nei vienas iš mokslinėje literatūroje aptiktų modelių, apimančių elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektorius, nepasižymi visais šiais aspektais: optimizuojamos investicijos į transportą, taikomas optimizavimas tobulu numatymu bei aukšta laiko rezoliucija, reikalinga tinkamai atspindėti tarpsektorinius ryšius. Todėl, remiantis atlikta literatūros analize, buvo suformuluota mokslinė problema: **kaip ekonomiškai optimizuoti elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektorių dekarbonizavimą, atsižvelgiant į tarpsektorinius ryšius?**

Tyrimo objektas

Elektros energetikos, centralizuotos šilumos tiekimo ir transporto sektorių dekarbonizacija

Tyrimo tikslas

Sukurti integruotą modelį, skirtą nagrinėti elektros, centralizuotos šilumos tiekimo ir transporto sektorių dekarbonizacijos mažiausiais kaštais kelius, užtikrinančius artimas nuliui anglies dioksido emisijas.

Tyrimo uždaviniai

1. Nustatyti elektros, centralizuotos šilumos tiekimo ir transporto sektorių tarpsektorinius ryšius ekonomikos dekarbonizacijos kontekste;
2. Atlikti metodų ir modelių, taikomų elektros, centralizuotos šilumos tiekimo ir transporto sektorių plėtros, tarpsektorinių ryšių bei sektorinių klimato kaitos mažinimo priemonėms vertinti, analizę;

3. Sukurti metodiką ir modelį integruotai elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektorių dekarbonizacijos mažiausiais kaštais analizei;
4. Atlikti transporto ir energetikos sektorių dekarbonizacijos mažiausiais kaštais analizę Lietuvos atvejui, taikant sukurtą modelį;
5. Atlikti lyginamąją scenarijų analizę, siekiant patikrinti modeliavimo rezultatų jautrumą skirtingoms technologinėms galimybėms ir apribojimams.

Tyrimo metodai

Siekiant nustatyti elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektorių CO_2 emisijų mažinimo galimybes bei tarpsektorinius ryšius, atlikta sisteminė mokslinės literatūros analizė. Taip pat atlikta kitų mokslininkų taikomų metodų ir modelių, skirtų transporto ir energetikos sektorių plėtrai, tarpsektoriniams ryšiams ir sektorinėms emisijų mažinimo priemonėms vertinti, lyginamoji analizė. Remiantis atlikta analize, nustatyta, kad tinkamiausias metodas integruotai elektros, šilumos ir transporto sektorių dekarbonizacijos mažiausiais kaštais analizei atlikti yra energetikos planavimo modelis, grįstas optimizavimu minimizuojant suminius diskontuotus kaštus. Modeliavimo sistema MESSAGE buvo pasirinkta siekiant sukurti integruotą šių sektorių dekarbonizacijos mažiausiais kaštais modelį. Modelis sudarytas Lietuvos atvejui, tačiau sukurti modeliavimo metodiniai sprendimai su tam tikrais pakeitimais gali būti pritaikyti bet kuriai kitai valstybei. Siekiant palengvinti modelio naudojimą, programoje „Microsoft Excel“ buvo sukurtos dvi duomenų bazės, į kurias buvo įtraukti visi modeliui reikalingi duomenys: viena – elektros energetikos ir centralizuoto šilumos tiekimo sektoriams, kita – transporto sektoriui. Duomenų bazėse yra integruoti programiniai kodai, kurie duomenų lenteles konvertuoja į tekstinį formatą, naudojamą modeliavimo programinės įrangos. Atsižvelgiant į skirtingas technologines galimybes ir apribojimus, atlikta lyginamoji scenarijų analizė modeliavimo rezultatų patikimumui patikrinti.

Darbo mokslinis naujumas

Disertacijos metu sukurtas integruotas transporto ir energetikos sektorių modelis, skirtas dekarbonizacijos mažiausiais kaštais įvertinimui. Modelis apima elektros energetikos, centralizuotos šilumos tiekimo sektorius, keleivinį ir krovininį transportą. Veikla ir investicijos visuose modeliuojamuose sektoriuose optimizuojamos taikant tobulo numatymo optimizavimą. Modeliuojamas laikotarpis apima keturis penkerių metų laikotarpius nuo 2020 m. iki 2040 m. ir du dešimties metų laikotarpius nuo 2040 m. iki 2060 m. Kiekvienas modeliuojamas laikotarpis yra atvaizduojamas 12 sezonų, o kiekvienas jų dviem tipinėmis dienomis (darbo ir nedarbo). Tipinės dienos išskaidytos į 24 laiko pjūvius. Iš viso kiekvienas laiko periodas atvaizduojamas 576 laiko pjūviais. Santykinai didelė laiko rezoliucija pasirinkta siekiant tinkamai atvaizduoti elektros energijos gamybą iš AEI bei tarpsektorinius ryšius. Toks integruotas transporto ir energetikos sektorių modelis sudarytas ir pritaikytas Lietuvos atvejui pirmą kartą. Taip pat sudarytas modelis pasižymi dviem išskirtinėmis savybėmis: tikimybiniu vėjo greičių modeliavimu vėjo elektrinėms bei transporto priemonių amžiaus skirstiniais.

Elektros gamybos vėjo elektrinėse atvaizdavimas agreguoto laiko modeliuose yra problematiškas dėl beveik visiško elektros gamybos kintamumo praradimo vidurkinant duomenis. Dėl šios priežasties buvo sukurtas tikimybinis modeliavimo metodas, leidžiantis atspindėti elektros gamybos vėjo elektrinėse svyravimus modeliuose su agreguota laiko rezoliucija. Šis metodas yra grįstas elektros gamybos vėjo elektrinėse atvaizdavimu, remiantis vėjo greičių tikimybiniu pasiskirstymu. Vėjo greičių skirstiniai sudaromi kiekvieno modeliuojamo sezono darbo ir nedarbo dienoms ir aproksimuojami 24 taškais, kad kiekvieną duomenų tašką būtų galima priskirti vienam valandiniam laiko pjūviui ir taip atspindėti sezoninį vėjo greičio tikimybinį pasiskirstymą kiekvienai modeliuojamai tipinei dienai. Šie aproksimuoti vėjo greičių skirstiniai sumaišomi sukurtu algoritmu, siekiant imituoti vėjo nepastovumą.

Energetikos planavimo modeliuose modeliuojamos technologijos nustoja veikti praėjus nustatytam eksploatavimo laikotarpiui. Tačiau realybėje tam tikrais metais pagamintos transporto priemonės yra palaipsniui atiduodamos į metalo laužą. Tattini ir Gargiulo (2018) mėgino išspręsti šią problemą pasitelkdami naują modeliavimo sistemos TIMES funkciją – išlikimo tikimybės kreivę. Tačiau taikant šį metodą galima atvaizduoti tik besileidžiančios formos transporto priemonių amžiaus skirstinius, t.y. tokius, kuriuose naujesnių transporto priemonių yra daugiau nei senesnių. Čekijoje, Estijoje, Kipre, Latvijoje, Lenkijoje, Lietuvoje, Maltoje, Rumunijoje ir Slovakijoje (Held et al., 2021) yra importuojama daug naudotų transporto priemonių, dėl to amžiaus skirstinys įgauna iškreiptą varpo formą. Neatsižvelgus į tokį transporto priemonių amžiaus pasiskirstymą, modelio rezultatuose galima gauti pernelyg optimistiškus transporto sektoriaus pokyčius bei per didelius emisijų sumažinimus. Dėl šios priežasties buvo sukurtas unikalus modeliavimo metodas, leidžiantis modelyje atvaizduoti skirtingų formų transporto priemonių amžiaus skirstinius bei jų pokyčius laike. Taikant šį metodą, transporto priemonės diferencijuojamos pagal pagaminimo metus ir nustatomi apribojimai, kuriais užduodama, kokią dalį kelionių apimčių turi patenkinti tam tikrais metais pagamintos transporto priemonės.

Siekiant įvertinti kai kuriuos keleivių elgsenos aspektus, buvo modeliuotas kelionių laiko biudžetas bei nepatogumo naudojantis elektromobiliais kaštai. Kelionių laiko biudžetas nustato, kiek iš viso laiko gali būti skiriama kelionėms, taigi modelis, parinkdamas, kuriomis transporto priemonėmis tenkinami kelionių poreikiai, atsižvelgia ne tik į transporto priemonių kaštus, bet ir į jų greičius. Kelionių laiko biudžetas neleidžia modelyje tenkinti visų kelionių poreikių pigiu, bet lėtesniu viešuoju transportu. Nepatogumo naudojantis elektromobiliais kaštai modeliuoti siekiant įvertinti nepatogumus, atsirandančius dėl elektromobilių trumpesnio maksimalaus nuvažiuojamo atstumo, ilgiau trunkančio įkrovimo bei mažesnės prieigos prie įkrovimo stotelių lyginant su dyzelinu ar benzinu varomomis transporto priemonėmis.

Autorius žinias ir duomenis apie Lietuvos energetikos sistemą kaupė dirbdamas Lietuvos energetikos institute, todėl modelis kurtas Lietuvos atvejui. Tačiau atlikus tam tikrus pakeitimus, modelis gali būti pritaikytas ir kitoms šalims.

Tyrimo apribojimai

Modelyje siekiant tinkamai atvaizduoti įvairias technologijas (elektrines, katilines, transporto priemones, kuro tiekimą ir kt.) yra reikalingas didelis kiekis techninių ir ekonominių duomenų. Tačiau tokie duomenys konkrečioms elektrinėms ir katilinėms, išskyrus įrengtąją galią ir naudingumo koeficientą, nėra viešai prieinami, todėl pasitelkta energetikos katalogų duomenimis. Modeliuojant transporto sektorių susidurta su duomenų trūkumu apie kelionių ir krovinių pervežimo apimčių kaitą dienos ir sezonų metu Lietuvoje bei transporto priemonių eksploatacinius kaštus, todėl remtasi prieinamais ribotais arba kitų šalių duomenimis. Duomenų ypač trūko apie geležinkelių transportą, todėl modelyje priimta, kad kelionių ir krovinių pervežimų geležinkeliais apimtys ateityje išliks panašios kaip ir dabar. Dėl duomenų trūkumo nevertintas Lietuvos keliautojų heterogeniškumas. Taip pat svarbu yra pabrėžti ir neapibrėžtumus, susijusius su būsimomis technologijų, kuro, emisijų, elektros energijos importo ir kitomis kainomis.

Energetikos planavimo modeliai yra grįsti tobulų rinkų bei finansinio racionalumo prielaidomis. Elektros energetikos ir centralizuoto šilumos tiekimo sektoriuose šios prielaidos yra logiškos. Tačiau transporto sektoriuje yra itin svarbūs ir nepiniginiai veiksniai, tokie kaip kelionės laikas, patogumas, išvaizda. Dėl šios priežasties modelyje taikytas kelionių laiko biudžetas bei nepatogumo naudojantis elektromobiliais kaštai. Vis dėlto į daugumą elgsenos aspektų nebuvo atsižvelgta.

Modeliavimo sistema MESSAGE sukurtų modelių dydis yra ribotas, todėl taikyti įvairūs supaprastinimai. Naudota agreguota laiko rezoliucija, kuri apsunkina elektros gamybos iš AEI nepastovumo atvaizdavimą. Siekiant sumažinti agreguotos laiko rezoliucijos trūkumus, sukurtas ir pritaikytas tikimybinis elektros gamybos vėjo elektrinėse modeliavimo metodas. Tačiau modelyje neatsižvelgiama į galimus ilgai trunkančius mažo vėjo greičio ir žemos saulės apšvietos laikotarpius, todėl modeliu įvertinama reikalinga elektros kaupiklių galia bei talpa gali būti per mažos. Elektros tinklai modeliuoti tik visai šaliai, o ne regionams, taigi, remiantis modeliu, nėra galimybės nustatyti, kurioje šalies dalyje turėtų būti statomos elektrinės. Tačiau modeliuotos šešios didžiausios centralizuoto šilumos tiekimo sistemos, o likusios sugrupuotos ir pateiktos kaip viena. Kelionės transporto sektoriuje skirstomos tik į trumpų ir ilgų atstumų keliones, o krovinių pervežimai – į šalies viduje ir tarptautinius. Kuro tiekimas laikomas neribotu, dėl to modeliavimo rezultatuose galima gauti netvarią biomasės ir biodegalų gamybą ir vartojimą. Taip pat, modeliuojant elektros importą ir eksportą, neatsižvelgiama nei į kaimyninių šalių elektros energijos gamybos pajėgumus, nei į elektros poreikius, todėl elektros importo ir eksporto galimybės gali būti pervertintos.

Galimas praktinis sudaryto modelio ir modeliavimo rezultatų pritaikymas

Sukurtame modelyje apskaičiuojamos mažiausiai sąnaudų reikalaujančios ilgalaikės elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektorių plėtros kryptys, kuriomis būtų pasiekiami strateginiai tikslai, tokie kaip dekarbonizacija ar energetinio saugumo užtikrinimas. Todėl sudarytas modelis gali pasitarnauti rengiant energetikos strategijas. ES valstybės narės kas dešimt metų turi parengti nacionalinius energetikos ir klimato srities veiksmų (NEKS) planus, kuriuose nustatomi nacionaliniai energetinio saugumo, energijos vidaus rinkos, energijos vartojimo efektyvumo, ekonomikos dekarbonizavimo, mokslinių tyrimų, inovacijų ir konkurencingumo tikslai kitam dešimties metų laikotarpiui (The European Parliament & Council of the European Union, 2018). Taip pat kiekviena valstybė narė kas dešimt metų turi parengti ilgalaikes strategijas, apimančias ne mažiau kaip 30 metų, kuriose numatomi veiksmai bendriems klimato kaitos tikslams pasiekti. Tačiau sukurti modeliavimo metodiniai sprendimai gali būti naudingi ne tik ES šalims, bet ir daugeliui kitų šalių, nes pagal Paryžiaus susitarimą kiekviena šalis nacionaliniu lygmeniu turi pateikti nustatytus įpareigojančius veiksmus ir kas penkerius metus juos atnaujinti. Nors modelis buvo sukurtas Lietuvos atvejui, tie patys modeliavimo metodiniai sprendimai gali būti pritaikyti kuriant bet kurios kitos šalies modelį.

Disertacijos rengimo metu pradėtas projektas „Energijos efektyvumo didinimas Lietuvoje“ (*LIFE IP EnerLIT*), kuris truks iki 2030 m. pabaigos ir kuriuo siekiama paremti Nacionalinio energetikos ir klimato srities (toliau – NEKS) veiksmų plano įgyvendinimą energijos vartojimo efektyvumo srityje (Lietuvos Respublikos aplinkos ministerija, 2022). Į projektą įtraukta veikla „A1.2 Modeliavimo proceso tobulinimas“, kurioje dalyvauja disertacijos autorius. Šioje veikloje potencialiai galėtų būti panaudojamas darbe sukurtas integruotas Lietuvos elektros energetikos, centralizuoto šilumos tiekimo bei transporto sektorių modelis, taip prisidedant prie jau naudojamų ir kuriamų modelių.

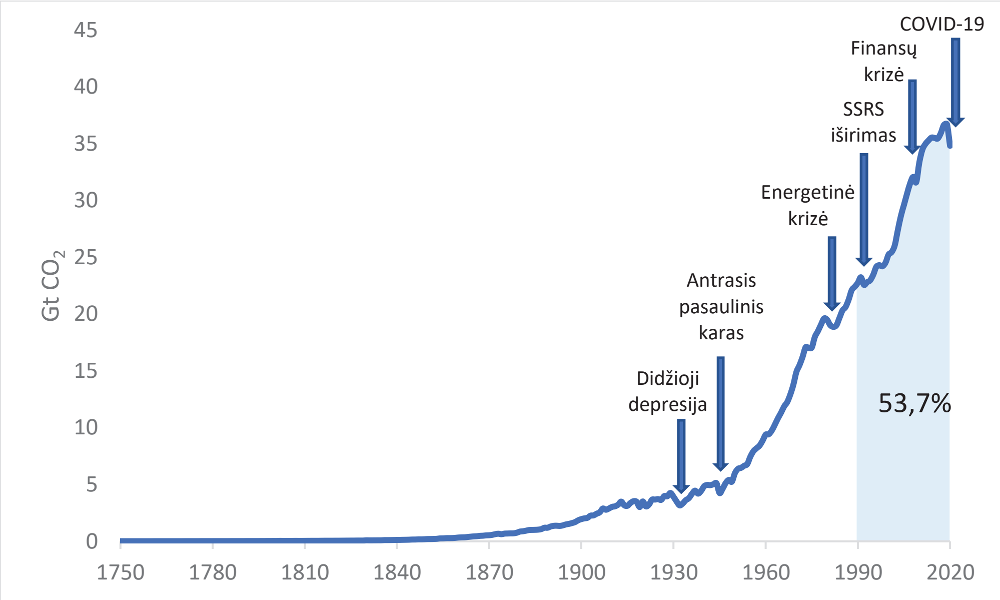
Disertacijos struktūra ir apimtis

Disertaciją sudaro 261 puslapiai (be priedų), 113 paveikslų, 51 lentelių, iš kurių 25 yra pateiktos A priede. Iš viso remtasi 317 literatūros šaltinių. Disertacijos struktūrą sudaro trys pagrindinės dalys: 1. Literatūros apžvalga; 2. Tarpsektorinis elektros energetikos, centralizuotos šilumos tiekimo ir transporto sektorių MESSAGE modelis; 3. Rezultatai. Pirmoje dalyje apžvelgiama klimato kaita, išmetami CO_2 kiekiai ir tarptautinės pastangos sumažinti ŠESD emisijas, taip pat analizuojamos dekarbonizacijos galimybės, poveikiai ir tarpsektoriniai ryšiai. Be to, palyginami transporto ir energetikos sektorių dekarbonizavimo mažiausiais kaštais tyrimai. Antroje disertacijos dalyje aprašoma pasirinkta modeliavimo sistema ir sukurti modeliavimo metodiniai sprendimai. Trečioje dalyje pateikiami modeliuojami scenarijai ir modeliavimo rezultatai.

1. LITERATŪROS APŽVALGA

1.1. Klimato kaita, CO_2 emisijos ir tarptautiniai susitarimai mažinti išmetamų šiltnamio efektą sukeliančių dujų kiekį

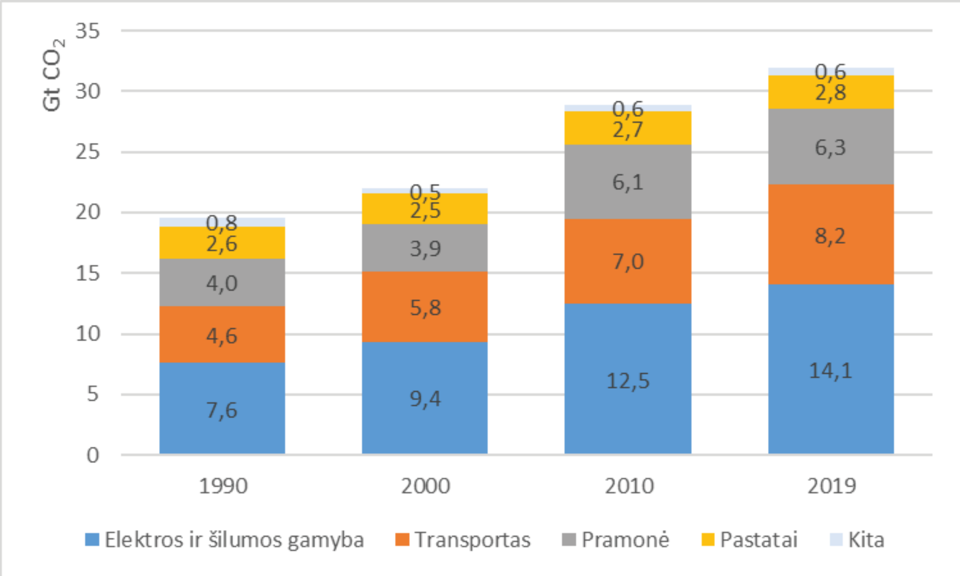
Nuo 1750 m. ŠESD koncentracijos padidėjimui ir dėl to įvykusiam atmosferos, vandenynų ir sausumos atšilimui neabejotinai turėjo įtakos žmogaus veikla. (Masson - Delmotte et al., 2021). Pasaulyje per metus išmetama 48,9 Gt CO_{2eqv} antropogeninių ŠESD emisijų, kurių didžiąją dalį (36,4 Gt CO_{2eqv}) sudaro CO_2 emisijos (World Resources Institute, 2021). Nuo pramonės revoliucijos laikų išmetamų emisijų lygis nuolat didėjo, tačiau ypač spartus augimas pastebimas nuo praėjusio amžiaus šeštojo dešimtmečio. Daugiau nei pusė nuo pramonės revoliucijos laikų išmesto į atmosferą CO_2 kiekio buvo išmesta per pastaruosius tris dešimtmečius, o beveik ketvirtadalis – nuo 2010 m. (žr. 1 pav.) (Global Carbon Project, 2021).



1 pav. Pasaulinės CO2 emisijų tendencijos

(sudaryta autoriaus, remiantis (Global Carbon Project, 2021) duomenimis)

Vertinant kuro deginimo metu išmetamą CO_2 pagal sektorius (žr. 2 pav.), matyti, kad daugiausia CO_2 išmetama gaminant elektros energiją ir šilumą (44 %) ir transporto sektoriuje (22 %) (IEA, 2021a). Šie du sektoriai sudaro du trečdalius bendrų emisijų. Likusią dalį sudaro pramonės (20 %), pastatų (9 %) ir kiti (2 %) sektoriai. 91 % visų CO_2 emisijų susidaro deginant kurą, o likę 9 % – neorganizuotai išmetami teršalai, daugiausia dėl gamtinių dujų deginimo naftos gavybos vietose ir naftos perdirbimo gamyklose, dujų nuotėkio vamzdynuose ir metano išsiskyrimo išgaunant ir transportuojant anglis.



2 pav. Pasaulinės CO2 emisijos dėl kuro deginimo pagal sektorių, 1990–2019 m.

(sudaryta autoriaus, remiantis (IEA, 2021a) duomenimis)

Nuo 1990 iki 2019 m. emisijų kiekis sparčiausiai augo elektros ir šilumos gamybos bei transporto sektoriuose – atitinkamai 85 % ir 78 %. Emisijos pramonėje išaugo 58 %, tačiau daugiausiai 2000–2010 m. Nuo 2010 m. emisijos elektros ir šilumos gamybos sektoriuose vidutiniškai per metus augo 1,3 %, o transporto sektoriuje 1,8 %, tuo tarpu pramonėje tik 0,3 %, pastatų sektoriuje 0,35 %, o kituose sektoriuose mažėjo 0,6 %.

Apskaičiuota, kad likęs anglies dioksido emisijų biudžetas, kuris leistų apriboti pasaulinį atšilimą iki 1,5 °C, su 50 % tikimybe, yra 420 Gt CO_2, o iki 2 °C – 1270 Gt CO_2, kas atitinka 11 ir 32 metus 2021 m. emisijų lygiu (Friedlingstein et al., 2021). Todėl, norint apriboti klimato kaitą iki 1,5 ar 2 °C, yra reikalingi drastiški pokyčiai visuose ekonomikos sektoriuose, tačiau ypatingas dėmesys turėtų būti skiriamas transportui bei elektros ir šilumos gamybai, nes šiuose sektoriuose emisijų mažinimo potencialas yra didžiausias.

Pripažįstant klimato kaitos keliamą pavojų, 1992 m. priimta Jungtinių Tautų Bendroji klimato kaitos konvencija, kuria nustatytas procesas, kuriuo siekiama apriboti šiltnamio efektą sukeliančių dujų koncentraciją atmosferoje iki tokio lygio, kad būtų išvengta žalingo žmogaus kišimosi į klimato sistemą per pakankamą laikotarpį, kad ekosistemos natūraliai prisitaikytų prie klimato kaitos (Kuyper et al., 2018; United Nations, 1992). Konvencijoje buvo sutarta, kad išsivysčiusios šalys turėtų pirmosios imtis emisijų mažinimo veiksmų, o besivystančios šalys turėtų pasekti pavyzdžiu kiek vėliau. Šį susitarimą vainikavo 1997 m. pasirašytas Kioto protokolas – tarptautinė sutartis, kurioje nustatyti teisiškai įpareigojantys tikslai, pagal kuriuos išsivysčiusiose šalyse ŠESD emisijų kiekis turėjo būti sumažintas vidutiniškai 5,2 %, lyginant su 1990 m. lygiu, iki 2012 m. (Maamoun, 2019). Tačiau, prieš ratifikuodamas dokumentą, JAV Senatas pareikalavo, kad emisijų mažinimo galimybės būtų kuo lankstesnės ir kad prie jų mažinimo prisidėtų ir besivystančios šalys. Kadangi pastaroji sąlyga nebuvo įvykdyta, JAV, kuri tuo metu buvo daugiausiai ŠESD emisijų išmetanti šalis, susitarimo neratifikavo. 2011 m. Kanada taip pat pasitraukė iš susitarimo (Kuyper et al., 2018).

Tolesnės derybos dėl klimato kaitos švelninimo priemonių, neapsiribojant Kioto protokolu, prasidėjo dar 2007 m., tačiau šalims pavyko susitarti tik 2015 m. Paryžiuje (Hirst, 2020). Paryžiaus susitarime nustatytas visuotinis tikslas stabilizuoti vidutinės pasaulinės temperatūros kilimą, kad jis neviršytų 2 °C, palyginti su ikipramoniniu laikotarpiu, ir siekti, kad jis neviršytų 1,5 °C. Pagal susitarimą kiekviena valstybė turi parengti, paviešinti bei įvykdyti nacionaliniu lygmeniu nustatytus įpareigojančius veiksmus. Kas penkerius metus šie planai turi būti atnaujinami, kaskart keliant vis ambicingesnius tikslus (Kuyper et al., 2018). Tačiau svarbu paminėti, kad Paryžiaus susitarime nenumatyti veiksmų įvykdymo užtikrinimo mechanizmai, t. y. įsipareigojimų nevykdančioms šalims nebūtų taikomos jokios nuobaudos. Vis dėlto, tęsdamos Paryžiaus susitarimą, 137 šalys užsibrėžė dekarbonizuoti savo ekonomikas XXI a. antroje pusėje ar anksčiau.

1.2. Elektros, šilumos ir transporto sektorių dekarbonizavimo galimybės, poveikiai ir tarpsektoriniai ryšiai

Elektros energetikos sektorius yra laikomas pirmuoju, kurį galima dekarbonizuoti (Papadis & Tsatsaronis, 2020). Iš pirmos pažiūros, tam reikiamos technologijos jau yra, tokios kaip hidroelektrinės, vėjo, saulės ir atominės elektrinės, bioenergetika, anglies dioksido sugavimas ir saugojimas. Taip pat gana nemažai šalių pavyko užsitikrinti elektros energijos gamybą, išmetančią santykinai nedidelius CO_2 emisijų kiekius. Remiantis leidiniu „Our World in Data" (Ritchie & Roser, 2020), yra 20 šalių, kuriose daugiau nei 90 % elektros energijos yra pagaminama iš netaršių šaltinių, bei 33, kuriose pagaminama daugiau nei 80 %. Pavyzdžiui: Paragvajuje 98 % elektros energijos pagaminama hidroelektrinėse; Norvegijoje 92 % hidroelektrinėse ir 7 % vėjo elektrinėse; Prancūzijoje 69 % atominėse elektrinėse, 11 % hidroelektrinėse, 7 % vėjo elektrinėse ir 3 % saulės elektrinėse; Švedijoje 44 % hidroelektrinėse, 31 % atominėse ir 16 % vėjo elektrinėse. Tačiau daugumoje valstybių didžioji dalis elektros energijos ir šilumos vis dar gamina deginant iškastinį kurą. Vis dėlto kiekviena šalis turi skirtingus poreikius, išteklius bei finansines galimybes. Todėl nėra vieno universalaus energetikos dekarbonizavimo būdo, kuris tiktų visoms šalims.

Kita vertus, atsižvelgiant į tai, kad vėjo ir saulės energija yra prieinama praktiškai visuose kraštuose, tikėtina, kad šie šaltiniai atliks svarbų vaidmenį daugumoje valstybių. Tačiau, kaip ir visi, šie energijos šaltiniai taip pat turi trūkumų, kurių pagrindinis yra elektros gamybos nepastovumas. Šie nepastovumai gali būti balansuojami energijos kaupimo technologijomis, tačiau jos reikalauja itin didelių investicijų. Todėl turėtų būti išnaudojamos ir kitos lankstumo priemonės, siekiant sumažinti elektros gamybos iš atsinaujinančiųjų šaltinių balansavimui reikiamas energijos saugyklų galias bei talpas.

Elektros energijos ir centralizuoto šilumos tiekimo sistemų susiejimas gali padidinti sistemos lankstumą bei balansavimo galimybes, būtinus atsinaujinančiaisiais energijos ištekliais grindžiamai elektros sistemai. Pavyzdžiui, perteklinė elektros gamyba vėjo ir saulės elektrinėse gali būti panaudota šilumos gamybai elektriniais katilais ar šilumos siurbliais ir tiekimui į centralizuotus šilumos tinklus (Averfalk et al., 2017). Tačiau tokiu atveju reikalingi ir kiti šilumos šaltiniai, kad būtų galima užtikrinti šilumos poreikių patenkinimą, kai elektros gamyba vėjo ir saulės elektrinėse yra nedidelė. Tarptautinės energetikos agentūros bioenergetikos studijoje (Arasto et al., 2017) autoriai pabrėžia, kad biomase kūrenamos kogeneracinės elektrinės turi gerą sinergiją su šilumos siurbliais, atsinaujinančiųjų energijos šaltinių balansavimo kontekste, kadangi elektros gamybos apimtys saulės elektrinėse, ypač šiauriniuose regionuose, ženkliai sumažėja šaltuoju metų laikotarpiu, kai tuo tarpu šilumos poreikiai išauga.

Transporto sektoriuje yra trys pagrindinės anglies dioksido emisijų mažinimo galimybės: biodegalų naudojimas, elektrinės transporto priemonės ir vandeniliu varomos transporto priemonės. Iš šių priemonių plačiausiai yra panaudojami biodegalai, kurie sudaro 3 % transporto sektoriuje sunaudojamos energijos (IEA, 2021d). Palyginimui, elektros energijos transporto sektoriuje sunaudojama dvigubai mažiau nei biodegalų (IEA, 2022). Tačiau, transporto dekarbonizavimo grindimas biodegalais ženkliai paveiktų miškų kirtimus, bioįvairovę bei maisto pasiūlą (de Blas et al., 2020). Elektromobiliai yra dažnai laikomi labiausiai tikėtina transporto dekarbonizavimo priemone. Tačiau, nors patys elektromobiliai neišmeta jokių emisijų, bet elektromobilių, kaip emisijų mažinimo priemonės, efektyvumas priklauso nuo to, iš kokių šaltinių yra pagaminama elektros energija (Franzò & Nasca, 2021). Vandeniliu varomos transporto priemonės, iš esmės, yra elektromobiliai, nes jie yra varomi elektriniais motorais. Tačiau jie unikalūs tuo, kad juose vietoje didelės baterijų talpos yra įmontuoti kuro elementai, skirti elektrai gaminti iš vandenilio. Todėl, priešingai nei elektromobilių, vandeniliu varomų transporto priemonių nereikia krauti, o pripildyti vandenilio baką užtrunka tik kelias minutes. Tačiau vandeniliu varomos transporto priemonės yra brangesnės, o vandenilio tiekimo infrastruktūra dar nėra pakankamai išvystyta. Beje, šiuo metu didžioji dalis vandenilio yra pagaminama naudojant metano riformingą vandens garais arba anglies dujofikavimą, kurių metų išsiskiria CO_2.

Elektros energetikos ir transporto sektorių susiejimas gali teikti papildomą elektros sistemos lankstumą, kadangi vandenilis transportui gali būti gaminamas elektrolizės būdu elektros gamybos vėjo ir saulės elektrinėse piko metu, taip prisidedant prie nepastovios gamybos iš atsinaujinančiųjų šaltinių balansavimo. Be to, galima pritaikyti elektromobilių įkrovimo laiką, atsižvelgiant į vėjo ir saulės elektrinių gamybos svyravimus. Taip pat galima išnaudoti elektromobilių akumuliatoriuose sukauptą elektros energiją, prireikus ją tiekti atgal į tinklą.

1.3. Transporto ir energetikos sektorių dekarbonizavimo mažiausiais kaštais tyrimai

Mokslinėje literatūroje siūlomi įvairūs sprendimai, kaip būtų galima mažinti transporto, elektros ir šilumos sektorių anglies dioksido išmetimus, įskaitant sektorių susiejimą. Tačiau mažai tikėtina, kad siekiant dekarbonizacijos pakaktų kokios nors vienos priemonės. Todėl yra svarbu ieškoti vienas kitą papildančių priemonių derinių. Be to, net jei tam tikras priemonių derinys gali sudaryti sąlygas dekarbonizacijai, tai nereiškia, kad jis yra optimalus pasirinkimas. Jis taip pat turėtų būti ekonomiškai efektyviausias.

Apžvelgus mokslinėje literatūroje atliktus tyrimus, kuriais įvertinama, kaip pasiekti transporto ir energetikos sektorių dekarbonizaciją mažiausiais kaštais, padarytos šios išvados:

- Tinkamiausia priemonė nustatyti, kaip sektoriai turėtų vystytis norint pasiekti dekarbonizacijos tikslų mažiausiais kaštais, yra energetikos planavimo modeliai, grįsti **optimizavimu minimizuojant suminius diskontuotus kaštus**. Tokiems modeliams kurti yra prieinama nemažai skirtingų modeliavimo sistemų, pavyzdžiui, Balmorel, Markal, MESSAGE, TIMES, OSeMOSYS, PyPSA ir kt.
- **Modelis su tobulu numatymu**, t. y., kai optimizavimas atliekamas visam modeliavimo laikotarpiui, yra geriausias pasirinkimas, siekiant nustatyti mažiausiai sąnaudų reikalaujančius raidos būdus, nes taikant trumparegišką optimizaciją modeliavimo rezultatuose galima gauti vėluojančias strategines investicijas ir didesnes sąnaudos emisijų mažinimo tikslams pasiekti.
- Analizuojant dekarbonizavimo būdus yra itin svarbu atsižvelgti į potencialias sektorių sąsajas, nes jos gali padidinti elektros sistemos lankstumą, kuris leistų integruoti atsinaujinančiuosius šaltinius mažesnėmis sąnaudomis. Tačiau modeliuose turėtų būti **naudojama palyginti didelė laiko rezoliucija**, kad būtų galima tinkamai atspindėti lankstumo poreikius.
- **Investicijų į transportą optimizavimas** galėtų suteikti vertingų įžvalgų, nes taip nustatoma ne tik mažiausiai sąnaudų reikalaujanti transporto sektoriaus raida, bet ir sudaromos sąlygos modeliui rinktis tarp papildomo elektros sistemos lankstumo dėl sektorių susiejimo ir kitų lankstumo priemonių.

Nė vienas iš mokslinėje literatūroje aptinkamų modelių, apimančių elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektorius, nepasižymi visais šiais keturiais bruožais: skaičiavimai grįsti diskontuotų suminių kaštų minimizavimu; optimizavimui taikomas tobulas numatymas; taikoma palyginti didelė laiko rezoliucija; optimizuojamos investicijos transporto sektoriuje. Todėl, siekiant užpildyti mokslinių tyrimų spragą, buvo sukurtas integruotas transporto ir energetikos sektorių modelis, skirtas įvertinti mažiausiai sąnaudų reikalaujančius kelius, kurie užtikrintų artimas nuliui anglies dioksido emisijas. Modelis apima elektros energetiką, centralizuotą šildymą, keleivinį ir krovininį kelių transportą bei pasižymi visais keturiais prieš tai minėtais bruožais. Modelis sukurtas Lietuvos atvejui, tačiau atlikus tam tikrus pakeitimus gali būti pritaikytas ir kitoms šalims.

2. TARPSEKTORINIS ELEKTROS, CENTRALIZUOTOS ŠILUMOS TIEKIMO IR TRANSPORTO SEKTORIŲ MESSAGE MODELIS

Modeliui, skirtam integruotai transporto ir energetikos sektorių dekarbonizacijos mažiausiais kaštais analizei, sukurti pasirinkta modeliavimo sistema MESSAGE dėl keleto priežasčių:

1. Modeliuose, sudarytuose šia modeliavimo sistema, apskaičiuojama, kaip sektoriai turėtų vystytis, kad būtų pasiekti užsibrėžti tikslai mažiausiai kaštais, o skaičiavimai yra grįsti suminių diskontuotų kaštų minimizavimu;
2. Optimizacija atliekama su tobulu numatymu;
3. Modeliavimo sistema yra labai lanksti, t. y. modeliuotojas gali laisvai nustatyti laiko ir erdvinę rezoliucijas, technologijas (procesus), išteklius, energijos formas bei įvairius apribojimus;
4. Ši sistema yra plačiai naudojama nagrinėjant energijos tiekimo galimybes, energetikos perspektyvinę raidą, energetikos dekarbonizacijos būdus bei branduolinio kuro ciklą. Jungtinės Karalystės akademinės ir politinės literatūros apžvalga (Hall & Buckley, 2016) parodė, kad modeliavimo sistema MESSAGE yra antra pagal naudojimo mastą Jungtinėje Karalystėje po MARKAL šeimos sistemų, įskaitant TIMES;
5. Modeliavimo sistemą MESSAGE galima įsigyti nemokamai.

2.1. Modeliavimo sistema MESSAGE

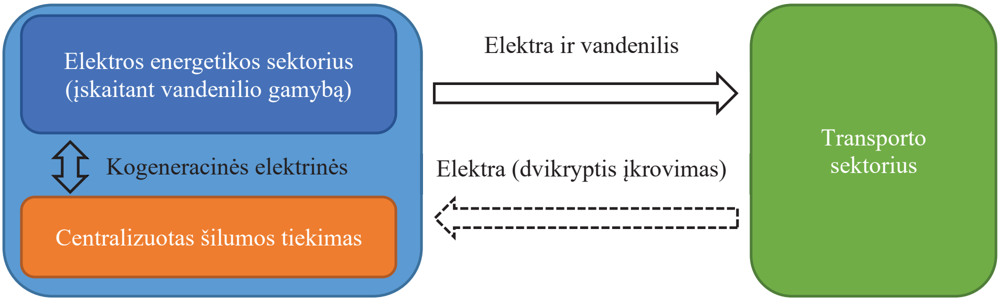
MESSAGE (pavadinimo „Model for Energy Supply Strategy Alternatives and their General Environmental Impact" akronimas) – modeliavimo sistema, skirta kurti energetikos sistemos modelius vidutinės trukmės ir ilgalaikiam energetikos planavimui, scenarijų kūrimui ir energetikos politinių priemonių analizei.

Pagrindinis sistemos MESSAGE veikimo principas yra grįstas tikslo funkcijos optimizavimu, atsižvelgiant į nustatytus apribojimus. Paprastai suminiai diskontuoti kaštai yra naudojami kaip tikslo funkcija (International Atomic Energy Agency, 2007). Šie kaštai apima pastovius ir kintamus kaštus, investicijas, išlaidas, susijusias su emisijomis, bei kitus modeliuotojo įvedamus kaštus. Modeliuojamos sistemos suminių diskontuotų kaštų minimizavimas užtikrina, kad išoriškai užduodami poreikiai, vertinant visą modeliavimo laikotarpį, būtų patenkinti mažiausiomis sąnaudomis, kiekviename laiko pjūvyje sudarant dalinę pusiausvyrą.

Sukurtą integruotos analizės modelį sudaro du tarpusavyje sujungti modeliai: pirmasis apima elektros energetikos ir centralizuoto šilumos tiekimo sektorius, o antrasis transporto sektorių.

Sukurtas elektros energetikos ir centralizuoto šilumos tiekimo sektorių modelis apima aštuonias rinkas: elektros energijos ir 7 centralizuoto šilumos tiekimo rinkas (šešių didžiausių Lietuvos miestų ir vieną, kuria atspindimos visų kitų centralizuoto šilumos tiekimo sistemų rinkos). Šie du sektoriai buvo įtraukti į vieną modelį dėl esamų stiprių tarpsektorinių ryšių per kogeneracines elektrines, kurios tiekia elektros energiją ir šilumą į centralizuotus šilumos tinklus. Taip pat ateityje gali būti naudojami šilumos siurbliai, kuriais elektra ir aplinkos energija verčiamos šilumine energija.

Transporto sektoriaus modelis apima keleivių ir krovinių vežimą keliais ir geležinkeliais. Transporto sektorius su energetikos sektoriumi yra susietas per elektros energijos ir vandenilio sunaudojimus. Dvikrypčio elektromobilių krovimo atveju, elektros energija sukaupta elektromobilių baterijose potencialiai gali būti tiekiama atgal į elektros tinklus 3 pav.



3 pav. Tarpsektoriniai ryšiai

(sudaryta autoriaus)

Atsižvelgiant į ES poveikio vertinimo gairėse (ang. „The Impact Assessment Guidelines“) (Hermelink & de Jager, 2015; Van Bossuyt, 2015) pateiktas rekomendacijas, taikyta 4 % socialinė diskonto norma. Modeliuojamas laikotarpis apima keturis penkerių metų laikotarpius nuo 2020 m. iki 2040 m. ir du dešimties metų laikotarpius nuo 2040 m. iki 2060 m. Kiekvienas modeliuojamas laiko periodas yra atvaizduojamas 12 sezonų, atitinkančių kalendorinius mėnesius. Kiekvienas iš sezonų atvaizduojamas dviem tipinėmis dienomis: tipinėmis darbo ir nedarbo dienomis. Kiekvienam iš šių tipinių dienų modeliuojami 24 laiko pjūviai. Taigi, iš viso yra naudojami 576 laiko pjūviai. Tokia, santykinai aukšta laiko rezoliucija, pasirinkta siekiant tinkamai atvaizduoti elektros gamybos nepastovumus iš AEI.

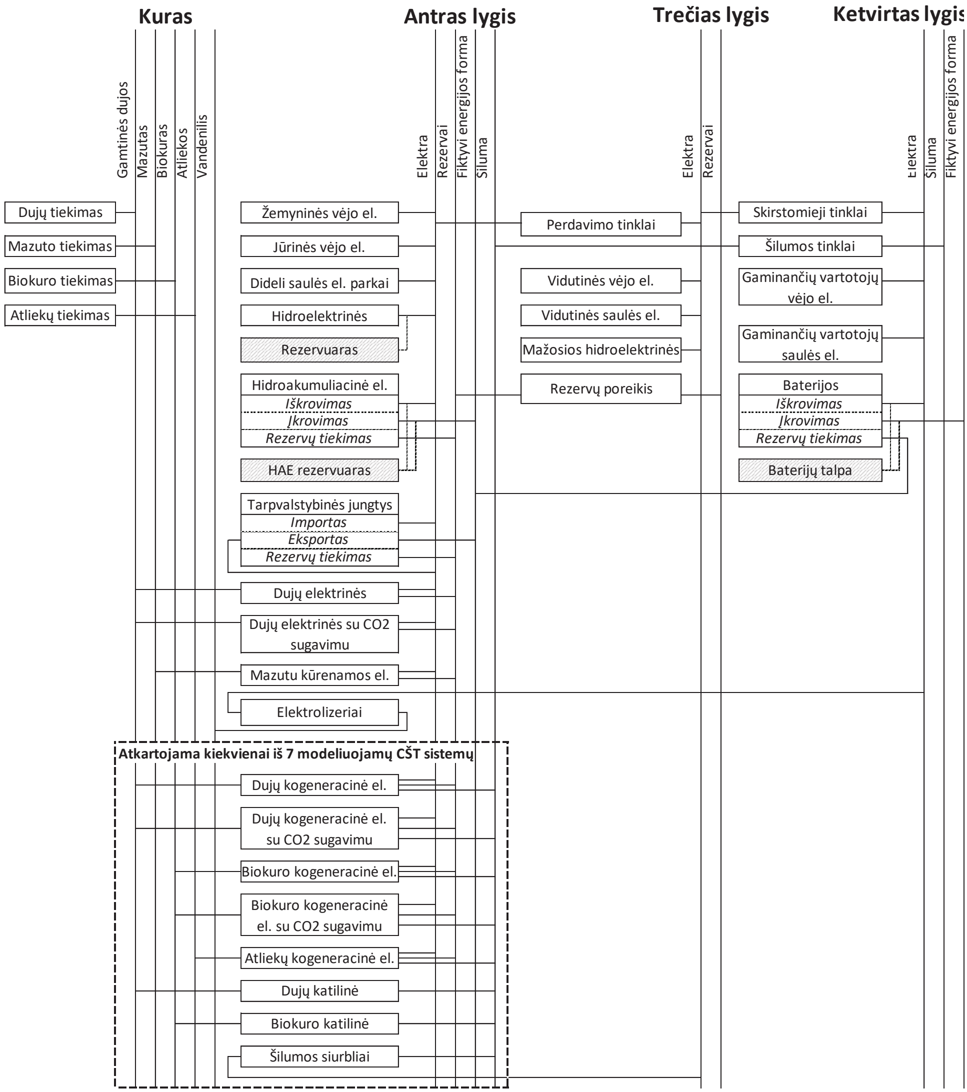
2.2. Elektros energetikos ir centralizuotos šilumos tiekimo sektorių modeliavimo principai

Kaip minėta anksčiau, elektros energetikos ir centralizuotos šilumos tiekimo modelis apima vieną elektros energijos ir septynias centralizuotos šilumos rinkas, iš kurių šešios yra Lietuvos didžiausių miestų, o septintąja atvaizduojamos likusios centralizuotos šilumos rinkos. Modeliu yra nustatoma pasiūla šiose rinkose, tuo tarpu energijos poreikiai modeliui yra užduodami išoriškai. Sukurtas modelis apima:

- Dujomis ir mazutu kūrenamas šilumines elektrines;
- Dujomis, biokuru ir atliekomis kūrenamas kogeneracines elektrines;
- Biokuru kūrenamas katilines;
- Vėjo žemynines ir jūrines elektrines;
- Saulės elektrines;
- Hidroelektrines;
- Elektros energijos importą ir eksportą;
- Elektros kaupimo įrenginius;
- Galios rezervus;

- Kuro tiekimą (gamtinių dujų, mazuto, biokuro, atliekų);
- Vandenilio gamybą elektrolizės būdu;
- Anglies dioksido sugavimą ir saugojimą;
- CO_2 emisijų apskaitą;
- Vietinės elektros gamybos, elektros ir šilumos gamybos iš atsinaujinančiųjų šaltinių ribojimus.

Supaprastinta elektros energetikos ir centralizuotos šilumos tiekimo modelio schema pateikta 4 pav.



4 pav. Supaprastinta elektros energetikos ir centralizuotos šilumos tiekimo modelio schema

(sudaryta autoriaus)

Kuriant modelį buvo skirtas ypatingas dėmesys nepastovios elektros gamybos iš atsinaujinančiųjų šaltinių pavaizdavimui. Agreguoto laiko modeliuose elektros gamybos duomenys įprastai yra vidurkinami, todėl praktiškai visiškai prarandama informacija apie gamybos nepastovumus. Dėl šios priežasties buvo sudarytas tikimybinis elektros gamybos vėjo elektrinėse atvaizdavimo metodas.

Sudarytame metode vėjo greičių tikimybinis pasiskirstymas yra užduodamas kiekvienam modeliuojamam dienos tipui. Vėjo greičių skirstiniai yra aproksimuojami 24 taškais, kad kiekvieną jų būtų galima priskirti kiekvienam modeliuojamam laiko pjūviui, taip vaizduojant sezono vėjo greičių pasiskirstymą modeliuojamoje tipinėje dienoje. Tada šių vėjo greičių skirstinių reikšmės išmaišomos naudojant sukurtą algoritmą, kad būtų imituojamas vėjo nepastovumas. Tokiu būdu sudarytos vėjo greičių kreivės kartu su vėjo elektrinių galių kreivėmis naudojamos modelyje užduoti elektros gamybos kreives vėjo elektrinėms.

2.3. Transporto sektoriaus modeliavimo principai

Pasirinkta transporto sektoriaus modeliavimo metodika yra grįsta Hannah E. Daly ir kt. (2014) sudarytais metodiniai sprendimais. Pagrindinė jų idėja yra ta, kad modelyje yra užduodami kelionių poreikiai (keleivių kilometrais), o skirtingos transporto priemonės tarpusavyje konkuruoja, kurios tenkins šiuos poreikius. Tačiau modeliuose, kurių veikimas grįstas diskontuotų kaštų minimizavimu, visada renkamasi pigiausius variantus poreikiams tenkinti, jei tik pasirinkimas nėra apribotas. Transporto sektoriaus atveju, būtų renkamasi tenkinti kelionių poreikius viešuoju transportu. Todėl Hannah E. Daly ir kt. į modelį įtraukė laiko biudžetą, kuris riboja lėtesnių transporto priemonių naudojimą. Laiko biudžetas grįstas tuo, kad laikas yra ribotas išteklius ir keliautojai yra pasiryžę skirti tik tam tikrą laiką kelionėms. Šio metodo privalumas yra tas, kad jis leidžia modeliuoti modalinius pokyčius. Šis metodas su kelionės laiko biudžetu jau taikytas Airijos, Kalifornijos (CA-TIMES) (Daly et al., 2014), Danijos TIMES (TIMES-DKMS) (Tattini et al., 2018) ir Jungtinės Karalystės ESME (Pye & Daly, 2015) modeliuose.

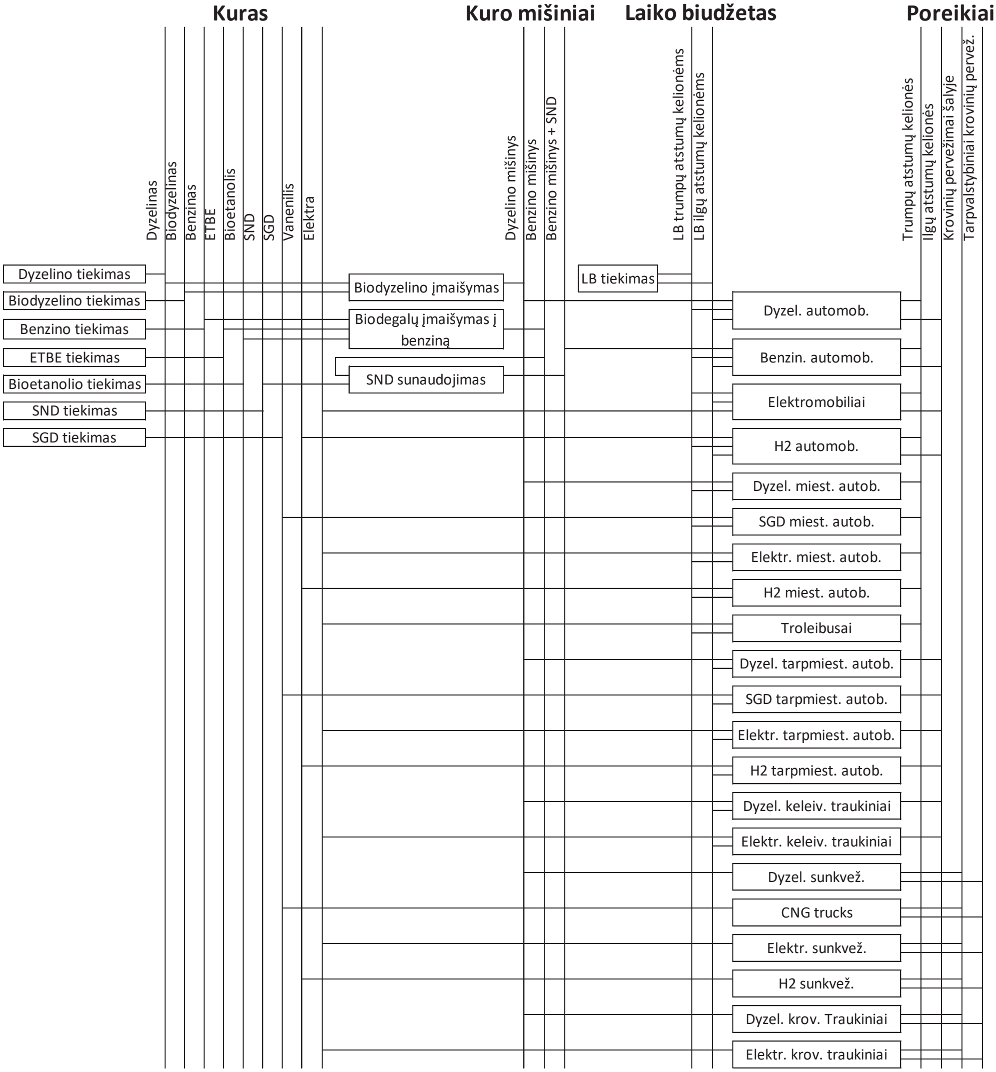
Tačiau sukurtame modelyje buvo padaryta keletas papildomų patobulinimų. Pirma, į modelį įtrauktas krovininis transportas. Antra, automobiliai išskirstyti pagal dydį į A–B, C–D, E–F ir J–M klases. Trečia, transporto priemonės diferencijuotos pagal pagaminimo metus, kad būtų galima tiksliau atspindėti degalų sąnaudas ir CO_2 emisijas. Ketvirta, siekiant atsižvelgti į naudotų transporto priemonių importą, buvo taikomi transporto priemonių amžiaus pasiskirstymo ribojimai. Penkta, modeliuoti trys skirtingi elektromobilių įkrovimo būdai: nevaldomas įkrovimas, vienkryptis ir dvikryptis išmanusis įkrovimas.

Sukurtas transporto modelis apima:

- Benzininius, hibridinius, dyzelinius automobilius, elektromobilius bei vandeniliu varomus automobilius;
- Dyzelinius, suslėgtomis gamtinėmis dujomis (SGD) varomus, elektrinius ir vandeniliu varomus miesto ir tarpmiestinius autobusus, taip pat troleibusus bei dyzelinius ir elektrinius keleivinius traukinius;
- Dyzelinius, SGD varomus, elektrinius ir vandeniliu varomus sunkvežimius bei dyzelinius ir elektrinius krovininius traukinius;

- Kelionių laiko biudžetą;
- Biodegalų įmaišymą;
- CO_2 emisijų apskaitą;
- Ribojimus automobilių klasių dalims, transporto priemonių amžiaus skirstiniams, naujai įdiegiamai galiai, naujai įdiegiamai galiai pagal kurą, elektromobilių įkroviklių galiai, elektromobilių baterijų energijos balansui, minimalioms automobilių trumpų ir ilgų atstumų kelionių dalims.

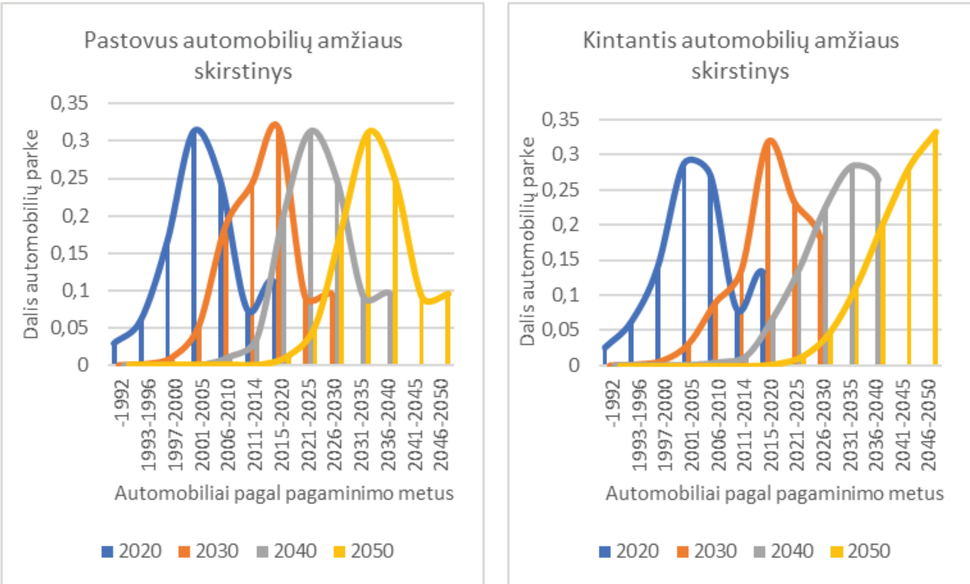
Supaprastinta transporto sektoriaus modelio schema pateikta 5 pav.



5 pav. Supaprastinta transporto sektoriaus modelio schema

(sudaryta autoriaus)

Sukurtas transporto modelis pasižymi išskirtiniu bruožu – modeliuojamais transporto priemonių amžiaus skirstiniais, kuriais siekiama tiksliau įvertinti kuro sąnaudas, emisijas bei galimus pokyčius transporto sektoriuje. Transporto priemonių amžiaus skirstiniai modeliuoti diferencijuojant transporto priemones pagal pagaminimo metus bei užduodant ribojimus, kokią dalį kiekvienais modeliuojamais metais kelionių apimčių turi sudaryti kelionės transporto priemonėmis, pagamintomis tam tikrais metais. Daugumoje scenarijų buvo daroma prielaida, kad transporto priemonių amžiaus pasiskirstymas ateityje išliks pastovus. Tačiau, didėjant gyventojų pajamoms, tikėtina, kad ir Lietuvoje transporto priemonių pasiskirstymas pagal amžių palaipsniui turėtų darytis panašesnis į tą, kuris pastebimas labiau pasiturinčiose šalyse. Dėl šios priežasties buvo sumodeliuoti papildomi scenarijai, įvertinantys galimus pokyčius automobilių amžiaus pasiskirstyme. Automobilių amžiaus skirstino kitimo pagal modeliuojamus metus prielaidos yra pateiktos 6 pav. abiem atvejams.



(a) (b)

6 pav. Automobilių amžiaus skirstinių prielaidos 2020, 2030, 2040 ir 2050 metams

(sudaryta autoriaus)

3. REZULTATAI

3.1. Modeliuoti scenarijai

Iš viso modeliuota penkiolika scenarijų, kuriuos galima sugrupuoti pagal analizuojamą aspektą arba taikomą elektromobilių įkrovimo būdą:

1. **Base** (baziniame) scenarijuje nagrinėjami transporto, elektros energetikos ir centralizuotos šilumos tiekimo tarpsektorinių ryšių poveikiai šių sektorių raidai. Kituose scenarijuose nagrinėjamų aspektų poveikiai įvertinami lyginant skaičiavimų rezultatus su bazinio scenarijaus rezultatais;
2. **VehDistr** scenarijuje nagrinėjami laipsniškai mažėjančio vidutinio transporto priemonių amžiaus poveikiai. Tikėtina, kad didėjant pajamoms gyventojai galės įsigyti naujesnius automobilius, o tai turėtų lemti spartesnį transporto elektrifikavimą;
3. **RedFlexi** scenarijuje vertinama, kokį poveikį turėtų sumažintos balansavimo galimybės tarpvalstybinėmis elektros jungtimis. Kadangi kaimyninių šalių, su kuriomis Lietuva turi tarpvalstybines elektros jungtis, elektros sistemos nebuvo modeliuojamos, t. y. elektros energijos importas iš šių šalių ir eksportas į jas nėra apribotas elektros pasiūlos ir paklausos jose, todėl modelis gali lanksčiau išnaudoti tarpvalstybines jungtis atsinaujinančiųjų šaltinių balansavimui, nei tai būtų iš tiesų įmanoma. Dėl šios priežasties buvo pasirinkta analizuoti scenarijų, kuriame yra sumažintas maksimalus importuojamos ir eksportuojamos galios kitimo greitis.
4. **InterOff** scenarijuje analizuojami poreikio nuo 2040 m. visiškai subalansuoti elektros energijos gamybą šalyje poveikiai. Tikėtina, kad artimiausiais dešimtmečiais kaimyninės šalys pereis prie tvarios elektros energijos gamybos, grįstos atsinaujinančiaisiais šaltiniais. Tokiu atveju būtų susiduriama su balansavimo tarpvalstybinėmis elektros jungtimis problema. Lietuvoje esant elektros gamybos vėjo ir saulės elektrinėse pertekliui, kaimyninėse šalyse toks perteklius irgi tikėtinas. Atitinkamai sutaptų ir gamybos iš šių šaltinių sumažėjimai. Taigi, kiekviena šalis turėtų sugebėti subalansuoti elektros energijos gamybą ir suvartojimą šalies viduje, nesikliaujant elektros energijos importu ir eksportu. Šiame scenarijuje tarpvalstybinės elektros energijos jungtys nutraukiamos po 2040 m.
5. **ZeroCO_2** scenarijuje nagrinėjami visų trijų modeliuojamų sektorių (transporto, elektros energetikos ir centralizuoto šilumos tiekimo) visiškos dekarbonizacijos poveikiai. Ankstesniuose scenarijuose nėra užduotų griežtų reikalavimų pasiekti nulines CO_2 emisijas. Todėl vertinga yra ištirti, kaip šie sektoriai galėtų vystytis esant griežtiems CO_2 emisijų apribojimams, kurie priverstų iki 2050 m. visiškai dekarbonizuoti šiuos sektorius.

Kiekvienam iš prieš tai minėtų penkių scenarijų modelyje taikyti trys skirtingi elektromobilių įkrovimo būdai (nevaldomas, išmanusis ir išmanusis dvikryptis) taip sudarant penkiolika scenarijų. Visi penkiolika scenarijų yra pateikti 1 lentelėje.

1 lentelė. Scenarijų matrica

Nagrinėjamas aspektas	Elektromobilių įkrovimo būdas		
	Nevaldomas	Išmanusis	Išmanusis dvikryptis
Transporto, elektros energetikos ir centralizuotos šilumos tiekimo tarpsektorinių ryšių poveikiai	Base	Base+smart	Base+V2G
Laipsniškai mažėjančio vidutinio transporto priemonių amžiaus poveikiai	VehDistr	VehDistr+smart	VehDistr+V2G
Sumažintų elektros balansavimo galimybių tarpvalstybinėmis elektros jungtimis poveikiai	RedFlexi	RedFlexi+smart	RedFlexi+V2G
Poreikio nuo 2040 m. visiškai subalansuoti elektros energijos gamybą šalyje poveikiai	InterOff	InterOff+smart	InterOff+V2G
Visų trijų modeliuojamų sektorių visiškos dekarbonizacijos poveikiai	ZeroCO_2	ZeroCO_2+smart	ZeroCO_2+V2G

(sudaryta autoriaus)

Nagrinėjamų aspektų poveikių dydžiai nustatyti palyginant scenarijų modeliavimo rezultatus su bazinio scenarijaus (**Base**) rezultatais.

3.2. Palyginamoji scenarijų analizė

Sukurtas modelis nustato, kokia galia ir kada kiekviena technologija turėtų veikti, kokia galia turėtų būti diegiama, kiek sunaudojama kuro bei kokios CO_2 emisijos, taip pat apskaičiuoja gaminamos energijos rinkos kainas ir kaštus (žr. 7 pav.). Modeliavimo rezultatai pateikiami kiekvienam iš šešių modeliuojamų laikotarpių (2020–2025; 2025–2030; 2030–2035; 2035–2040; 2040–2050; 2050–2060), o dalis jų ir kiekvienam laiko pjūviui (vienas laiko periodas turi 576 laiko pjūvius). Modeliavimo rezultatų santrauka pateikta 2 lentelėje.

	Elektros energetikos sektorius	Centralizuotos šilumos tiekimo sektorius	Transporto sektorius
Technologijų veikimas	• Elektros gamyba pagal elektrinės tipą • Elektros importas ir eksportas • Elektros kaupimo įrenginių veikimas • Vandenilio gamyba • Rezervų tiekimas	• Centralizuotos šilumos gamyba pagal šilumos gamybos įrenginių tipus ir centralizuotos šilumos tiekimo sistemą	• Kelionių ir krovinių pervežimo apimtys pagal transporto priemonės tipą, kurą, amžiaus grupę bei kelionių ir krovinių pervežimų atstumus
Naujai įdiegiama ir įdiegta technologijų galia	• Elektrinių galia • Elektros kaupimo įrenginių galia • Elektrolizerių galia	• Kogeneracinių elektrinių šiluminė galia • Katilinių galia • Šilumos siurblių galia	• Transporto priemonių skaičius
Kuro sąnaudos ir CO_2 emisijos	• Elektros gamyboje	• Šilumos gamyboje	• Transporte
Kaina	• Elektros energijos	• Šilumos kiekvienoje CŠT sistemoje	• Kelionių • Krovinių pervežimų
Kaštai (investicijos, pastovūs ir kintami)	• Elektrinių statybos • Eksploataciniai • Kuro • Taršos leidimų • Elektros importo • Eksporto (pajamos)	• Šilumo įrenginių statybos • Eksploataciniai • Kuro • Taršos leidimų	• Transporto priemonių įsigijimo • Eksploataciniai • Kurui • Registracijos mokesčiui

7 pav. Modeliavimo rezultatai

(sudaryta autoriaus)

Šioje scenarijų rezultatų palyginimo matricoje pateikti pagrindiniai skirtingų scenarijų rezultatų procentiniai pokyčiai lyginant su bazinio (**Base**) scenarijaus su nevaldomu elektromobilių įkrovimu rezultatais siekiant įvertinti skirtinguose scenarijuose nagrinėjamų aspektų poveikį. Visos prielaidos, išskyrus susijusias su nagrinėjamais aspektais, tarp nagrinėjamų scenarijų sutampa. Kadangi modelis pateikia rezultatus kiekvienam laikotarpiui, o jų ilgiai yra nevienodi, todėl palyginimui naudotos vidutinės svertinės vertės. Laikotarpio svorio vertė atitinka metų skaičių tame laikotarpyje. Scenarijų rezultatų palyginimo matricoje scenarijai su nevaldomu elektromobilių įkrovimo pažymėti „**Unc**.“ („uncontrolled charging“ trumpinys), su išmaniuoju įkrovimu „**Smart**“, o su išmaniuoju dvikrypčiu „**V2G**“.

2 lentelė. Scenarijų rezultatų palyginimo matrica

	Base		VehDistr			RedFlexi			InterOff			$ZeroCO_2$		
	Smart	V2G	Unc.	Smart	V2G	Unc.	Smart	V2G	Unc.	Smart	V2G	Unc.	Smart	V2G
Elektros gamyba šalyje	5%	6%	0%	7%	8%	-11%	0%	3%	1%	6%	6%	6%	12%	13%
Elektra iš AEI	6%	7%	-1%	7%	9%	-12%	1%	4%	-6%	3%	4%	6%	13%	14%
Gamybos iš AEI sumažinimas	0%	0%	0%	0%	0%	0%	1%	1%	5%	3%	4%	0%	0%	0%
Elektros saugojimas	-44%	-49%	1%	-46%	-50%	5%	-40%	-49%	7%	-35%	-44%	4%	-42%	-47%
Anglies sugavimas ir saugojimas	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Ne	Taip	Taip	Taip
Elektros kaina	-12%	-12%	4%	-12%	-12%	4%	-8%	-9%	18%	0%	-2%	5%	-11%	-12%
Elektros kainos dispersija	-42%	-45%	22%	-43%	-45%	5%	-33%	-38%	61%	58%	42%	28%	-41%	-44%
Šilumos gamyba iš AEI	0%	0%	0%	0%	0%	0%	0%	0%	-3%	-2%	-1%	-1%	0%	0%
CO_2 emisijos elektros ir šilumos gamyboje	-10%	-10%	2%	-11%	-11%	2%	-8%	-8%	155%	60%	48%	-6%	-16%	-16%
Elektromobiliai keleiviniame transporte	3%	3%	23%	27%	27%	-2%	3%	2%	-11%	-1%	-1%	7%	8%	8%
Vandeniliu varomos transporto priemonės keleiviniame transporte	-20%	-20%	-81%	-92%	-92%	14%	-19%	-19%	103%	27%	23%	18%	-1%	0%
Elektriniai sunkvežimiai	36%	36%	-7%	36%	36%	-7%	36%	36%	-15%	36%	36%	42%	92%	92%
Vandeniliu varomi sunkvežimių	-14%	-14%	0%	-14%	-14%	0%	-14%	-14%	18%	0%	0%	28%	6%	6%
CO_2 emisijos transporto sektoriuje	-1%	-1%	-7%	-10%	-10%	0%	-3%	-3%	1%	-4%	-4%	-10%	-10%	-10%

(sudaryta autoriaus)

Palyginus **VehDistr**, **RedFlexi**, **InterOff** ir **ZeroCO$_2$** scenarijų rezultatus su **Base** scenarijaus rezultatais nustatyta, kad:

1. Taikant kintantį transporto priemonių amžiaus skirstinį (**VehDistr** scenarijus) gerokai padidėja elektromobilių naudojimas keleiviniame transporte, bet sumažėja vandeniliu varomų transporto priemonių naudojimas. Kadangi keleivinis transportas elektrifikuojamas sparčiau, todėl transporto emisijų kiekis yra mažesnis lyginant su baziniu scenarijumi. Nors elektros energijos suvartojimas dėl spartesnio elektrifikavimo padidėja, bet įtaka vietinei elektros gamybai yra nežymi. Šiek tiek padidėja elektros energijos gamyba dujomis ir biomase kūrenamose kogeneracinėse elektrinėse. Tačiau, kadangi elektromobilių bendrasis efektyvumas yra didesnis nei vandeniliu varomų transporto priemonių, elektros energijos poreikis po 2040 m. **VehDistr** scenarijuje yra kiek mažesnis. Nevaldomo elektromobilių įkrovimo atveju, papildomas elektros energijos poreikis elektromobilių įkrovimui prisideda prie vakarinio elektros paklausos piko, todėl vidutinės elektros energijos kainos yra šiek tiek didesnės, bet kainų sklaida yra gerokai didesnė.
2. Sumažinus elektros importo ir eksporto lankstumą (**RedFlexi** scenarijus), sumažėja vietinės elektros energijos gamyba, daugiausia iš saulės ir vėjo, taip pat kiek daugiau naudojamas energijos akumuliavimas. Sumažėjus elektros energijos gamybai vėjo ir saulės elektrinėse ir padidėjus importui bei gamybai kogeneracinėse ir dujomis kūrenamose elektrinėse, išauga elektros energijos kainos ir kainų sklaida. Be to, dėl padidėjusios elektros energijos gamybos dujomis kūrenamose elektrinėse išmetama kiek daugiau CO_2. Šiame scenarijuje keleiviniame transporte daugiau naudojamos vandeniliu varomos transporto priemonės, kadangi sumažėjusios galimybės balansuoti elektros gamybą iš AEI elektros importu ir eksportu yra iš dalies kompensuojamos intensyvesne vandenilio gamyba. Vandeniliu varomų transporto priemonių dalis padidėja elektromobilių sąskaita. Todėl transporto sektoriuje CO_2 emisijų kiekis yra toks pat, kaip ir baziniame scenarijuje.
3. Poreikis užtikrinti visišką elektros energijos gamybos subalansavimą šalies viduje po 2040 m. (**InterOff** scenarijus) daro didelį poveikį visiems modeliuojamiems sektoriams. Šiame scenarijuje yra mažesnės elektros gamybos apimtys vėjo ir saulės elektrinėse, taip pat didesnis gamybos šiose elektrinėse techninis sumažinimas. Siekiant užtikrinti reikiamą sistemos lankstumą gamybai iš AEI šalyje subalansuoti, modelyje daugiau elektros energijos yra pagaminama šiluminėse elektrinėse, įskaitant kogeneracines elektrines, bei statoma daugiau tinklo baterijų. Tačiau tai lemia gerokai didesnes elektros energijos kainas ir kainų sklaidą. Be to, elektros energijos ir centralizuoto šilumos tiekimo sektoriuose išmetamas gerokai didesnis CO_2 kiekis. Transporto sektoriuje yra pastebimas didesnis vandeniliu varomų transporto priemonių naudojimas, kaip ir **RedFlexi** scenarijuje, bet didesniu mastu, kadangi vandenilio gamyba elektrolizės būdu, kaip AEI balansavimo priemonė, atlieka svarbesnį vaidmenį **InterOff** scenarijuje.
4. Griežti CO_2 emisijų mažinimo tikslai, siekiant iki 2050 m. užtikrinti poveikio klimatui neutralumą (**ZeroCO$_2$** scenarijus), didina elektros energijos gamybą iš

AEI ir energijos akumuliavimo įrenginių naudojimą. Be to, iš visų sumodeliuotų scenarijų elektrinės su CO_2 sugavimu ir saugojimu buvo statomos tik **ZeroCO₂** scenarijuje. Vidutiniškai elektros energijos kainos **ZeroCO₂** scenarijuje yra tik šiek tiek didesnės, tačiau kainų sklaida yra ženkliai didesnė, lyginant su baziniu (**Base**) scenarijumi. Dėl transporto sektoriuje taikomų emisijų apribojimų pastebimas didesnis elektromobilių ir vandeniliu varomų transporto priemonių naudojimas tiek keleiviniame, tiek kroviniame transporte.

Palyginus **Base**, **VehDistr**, **RedFlexi**, **InterOff** ir **ZeroCO₂** scenarijų, kuriuose taikytas išmanusis (**Smart**) ir išmanusis dvikryptis (**V2G**) elektromobilių įkrovimas, rezultatus su scenarijų, kuriuose taikytas nevaldomas elektromobilių įkrovimas (**Unc.**), rezultatais nustatyta, kad:

1. Išmaniojo įkrovimo (**Smart**) taikymas elektromobiliams modelyje parodė ženklią naudą elektros energetikos sistemai. Jis sumažina vidutinę elektros energijos kainą ir kainų sklaidą, kadangi elektromobilių įkrovimo laikas yra parenkamas taip, kad atitiktų pigios elektros energijos gamybą vėjo ir saulės elektrinėse. Todėl scenarijų su taikomu išmaniuoju elektromobilių įkrovimu modeliavimo rezultatuose elektros energijos gamyba iš AEI yra didesnė, o energijos akumuliavimo įrenginių naudojimas mažesnis nei analogiškuose scenarijuose su nevaldomu įkrovimu. Be to, išmanusis elektromobilių įkrovimas yra ekonomiškai efektyvesnis būdas užtikrinti AEI balansavimo galimybės, palyginus su žaliojo vandenilio gamyba ir tokio vandenilio panaudojimu transporte. Todėl scenarijuose, kuriuose taikomas išmanusis įkrovimas, elektromobilių dalis yra didesnė, o vandeniliu varomų mažesnė.
2. Dvikrypčio elektromobilių įkrovimo (**V2G**) taikymas turi tuos pačius privalumus kaip ir išmanusis įkrovimas, tačiau sistemai suteikia dar daugiau lankstumo, nes elektra gali būti laikinai kaupiama elektromobilių baterijose, o vėliau, esant poreikiui, patiekiama atgal į tinklą. Tačiau skirtumai tarp nevaldomo ir išmaniojo įkrovimo scenarijų yra daug didesni nei tarp išmaniojo ir V2G įkrovimo scenarijų.

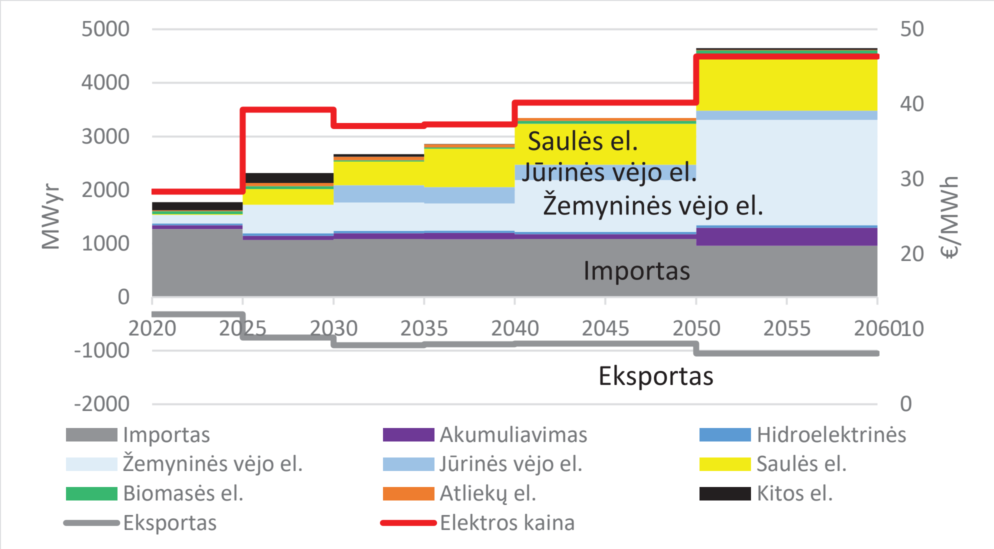
3.3. Bazinio scenarijaus modeliavimo rezultatai

Bazinio scenarijaus modeliavimo rezultatai rodo, kaip turėtų vystytis elektros energetikos, centralizuoto šilumos tiekimo ir transporto sektoriai, kad ateityje elektros energijos, centralizuotos šilumos ir transporto poreikiai būtų patenkinti mažiausiais kaštais. Šiame scenarijuje nėra griežtų apribojimų išmetamam CO_2 kiekiui. Tačiau buvo nustatyti apribojimai minimalioms elektros energijos ir centralizuotai tiekiamos šilumos dalims iš AEI, palyginus su galutiniu suvartojimu.

3.3.1. Bazinio scenarijaus modeliavimo rezultatai elektros energetikos ir centralizuotos šilumos tiekimo sektoriams

Remiantis bazinio scenarijaus modeliavimo rezultatais, Lietuva iki 2050 m. palaipsniui pereina iš neto elektros importuotojos į eksportuotoją. Šis perėjimas grindžiamas sparčia elektros energijos gamybos iš atsinaujinančiųjų šaltinių plėtra, daugiausiai iš saulės ir vėjo energijos (žr. 8 pav.). Metinės elektros gamybos apimtys žemyninėse vėjo elektrinėse daugiau nei trigubai padidėja 2025–2030 m. lyginant su

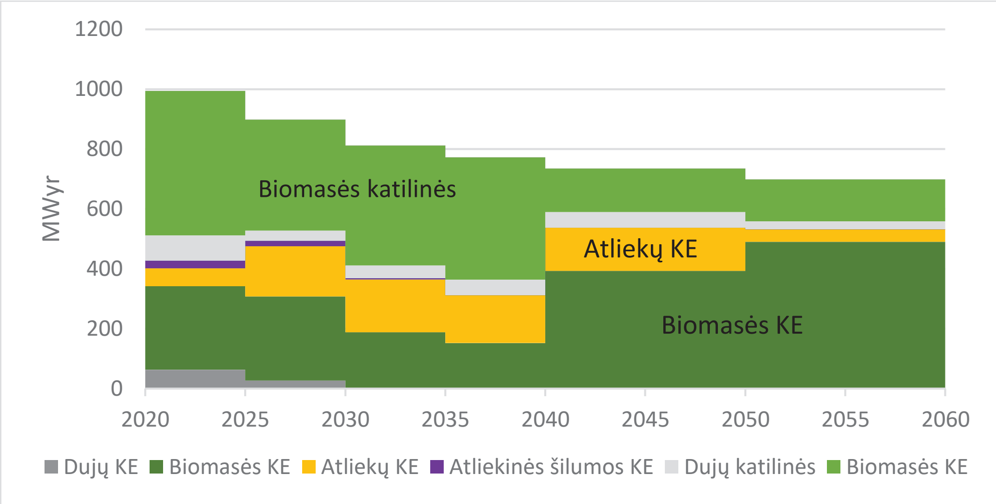
2020–2025 m. ir pasiekia 532 MWyr (1 MWyr = 8,76 GWh). 2025–2040 m. elektros gamybos apimtys šiose elektrinėse išlieka panašiame lygyje. Tačiau 2030 m. pradedamas eksploatuoti 700 MW jūrinių vėjo jėgainių parkas. Vėlesniais modeliavimo metais jūrines vėjo elektrines daugiau nėra plėtojamos, tačiau metinė elektros energijos gamyba sausumos vėjo elektrinėse 2040–2050 m. padidėja iki 964 MWyr, o 2050–2060 m. iki 1965 MWyr. Taip pat sparčiai didėja metinė elektros energijos gamyba saulės elektrinėse – nuo 14 MWyr per metus 2020–2025 m. iki 1059 MWyr 2050–2060 m. Pagal modeliavimo rezultatus didžiausias saulės elektrinių potencialas yra gaminančių vartotojų lygmenyje.



8 pav. Elektros energijos gamybos struktūra baziniame scenarijuje

(sudaryta autoriaus)

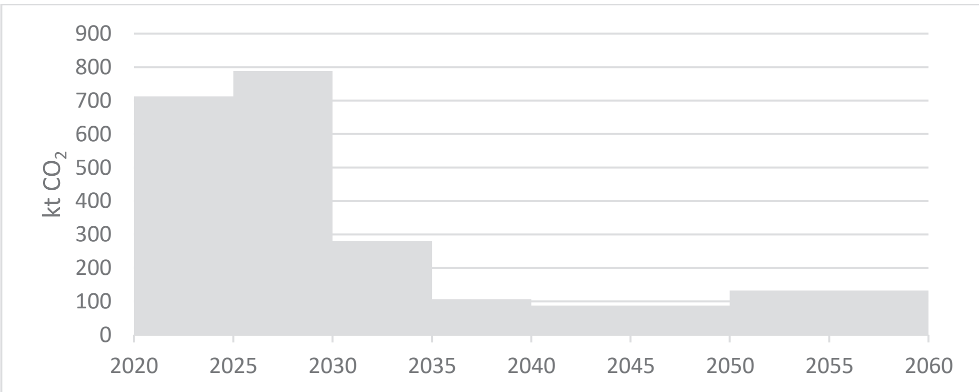
Modeliavimo rezultatuose pastebima, kad dėl pastatų renovacijos mažėjant centralizuotos šilumos poreikiui, biomasės ir atliekų kogeneracinės jėgainės, būdamos pigiausi šilumos gamybos šaltiniai, išstumia kitas, šilumą gaminančias jėgaines (žr. 9 pav.). Biomase ir atliekomis kūrenamose kogeneracinėse elektrinėse gaminamos šilumos dalis bendroje centralizuotai tiekiamos šilumos gamyboje padidėja nuo 34 % 2020 m., iki 76 % 2050 m. Dėl palyginti aukštų gamtinių dujų kainų, įskaitant CO_2 taršos leidimų kainas, palyginti su biomasės kainomis, naujos dujinės kogeneracinės elektrinės nėra statomos, o esamose gamyba nutraukiama nuo 2030 m. Iki 2050 m. šilumos gamyba dujomis kūrenamose katilinėse sumažėja nuo 84 iki 27 MWyr, padengiant tik didžiausius paklausos pikus šaltuoju laikotarpiu. Šilumos gamyba biomasės katilinėse taip pat sumažėja – nuo 483 MWyr (49 %) 2020 m. iki 140 MWyr (20 %) 2050 m.



9 pav. Centralizuotos šilumos gamybos struktūra baziniame scenarijuje

(sudaryta autoriaus)

Modeliavimo rezultatai rodo, kad, atjungus tarpvalstybines elektros jungtis su Baltarusija ir Kaliningrado sritimi, išmetamas CO_2 kiekis laikinai padidėja dėl padidėjusios elektros energijos gamyba dujomis kūrenamose elektrinėse. Tačiau didėjant elektros energijos gamybai iš atsinaujinančiųjų išteklių, mažėja poreikis gaminti elektrą dujomis kūrenamose elektrinėse, dėl to sumažėja CO_2 emisijų kiekis. Modeliavimo rezultatuose emisijos sumažėja iki 281 kt CO_2 2030–2035 m., 106 kt CO_2 2035–2040 m., 87 kt CO_2 2040–2050 m., tačiau nežymiai padidėja iki 133 kt CO_2 2050–2060 m. Palyginimui, CO_2 emisijos elektros ir šilumos gamyboje 1990 m. buvo 12003 kt, 3889 kt 2000 m. ir 3706 kt 2010 m. (UNFCCC, 2020). Modeliu apskaičiuotų CO_2 emisijų kaita elektros energetikos ir centralizuotos šilumos tiekimo sektoriuose yra pateikta 10 pav.

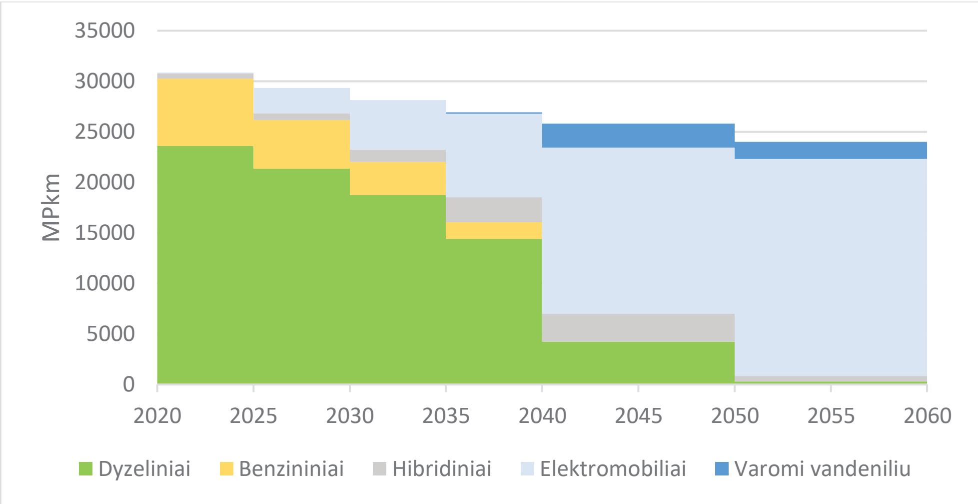


10 pav. CO2 emisijos elektros energetikos iš centralizuotos šilumos tiekimo sektoriuose baziniame scenarijuje

(sudaryta autoriaus)

3.3.2. Bazinio scenarijaus modeliavimo rezultatai transporto sektoriui

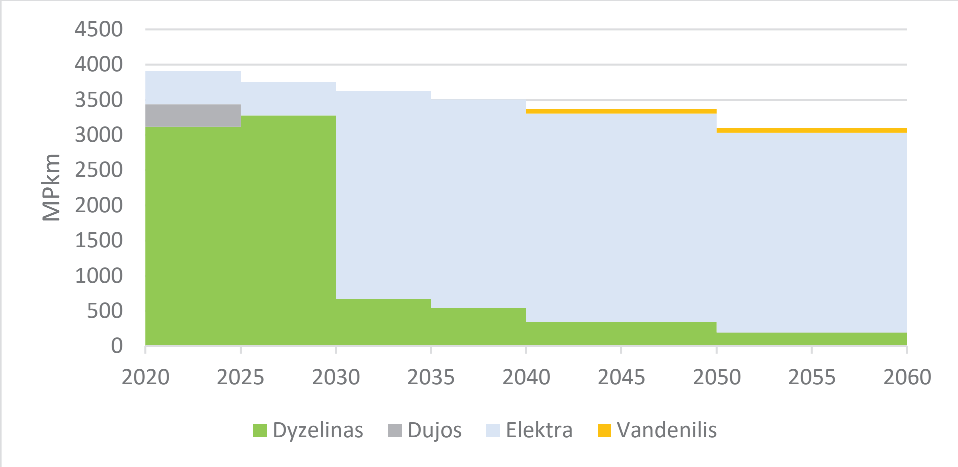
Sudarytu modeliu apskaičiuota, kad ekonomiškai optimalus asmeninių kelionių plėtros būdas yra laipsniškas perėjimas prie elektromobilių ir vandeniliu varomų automobilių (žr. 11 pav.). Numatoma, kad 2025–2030 m. 8,6 % kelionių apimčių automobiliu turėtų sudaryti kelionės elektromobiliais. 2030–2035 m. ši dalis turėtų padidėti iki 17,3 %, 2035–2040 m. iki 30,7 %, 2040–2050 m. iki 63,7 %, o 2050–2060 m. turėtų pasiekti 89,4 %. Vandeniliu varomų automobilių plėtra nėra numatoma iki 2035 m., tačiau 2035–2040 m. jų dalis kelionėse turėtų sudaryti 0,5 % ir 9,1 % 2040–2050 m. Tačiau modeliavimo rezultatuose kelionių vandeniliu varomais automobiliais 2050–2060 m. sumažėja iki 7,1 %. Didėjant elektra ir vandeniliu varomų transporto priemonių daliai, mažėja benzinu ir dyzelinu varomų automobilių dalis, išskyrus hibridines transporto priemones, kadangi jos pasižymi didesniu kuro efektyvumu, o įsigijimo kaštai yra panašūs į benzininių ir dyzelinių automobilių. Tačiau po 2050 m. hibridiniai automobiliai turėtų būti praktiškai visiškai pakeisti elektromobiliais ir vandeniliu varomais automobiliais.



11 pav. Kelionių automobiliu apimtys pagal automobilio tipą baziniame scenarijuje

(sudaryta autoriaus)

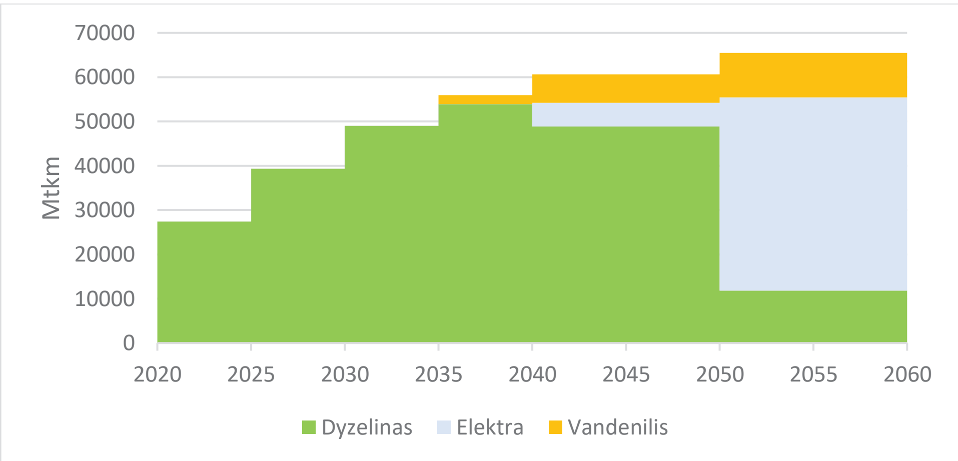
Modeliavimo rezultatai rodo, kad viešąjį transportą yra naudinga elektrifikuoti sparčiau nei asmeninį transportą. 2025–2030 m. 13 % kelionių viešuoju transportu turėtų būti atliekama elektra varomomis transporto priemonėmis, 2030–2035 m. šis skaičius turėtų išaugti iki 82 %, o 2050–2060 m. – iki 92 %. Modeliuojamu laikotarpiu vandenilio panaudojimas viešajame transporte yra gana ribotas. 2050–2060 m. jis pasiekia tik apie 2 %. Kelionių viešuoju transportu apimtys pagal kurą pateiktos 12 pav.



12 pav. Kelionių viešuoju transportu apimtys pagal kurą baziniame scenarijuje

(sudaryta autoriaus)

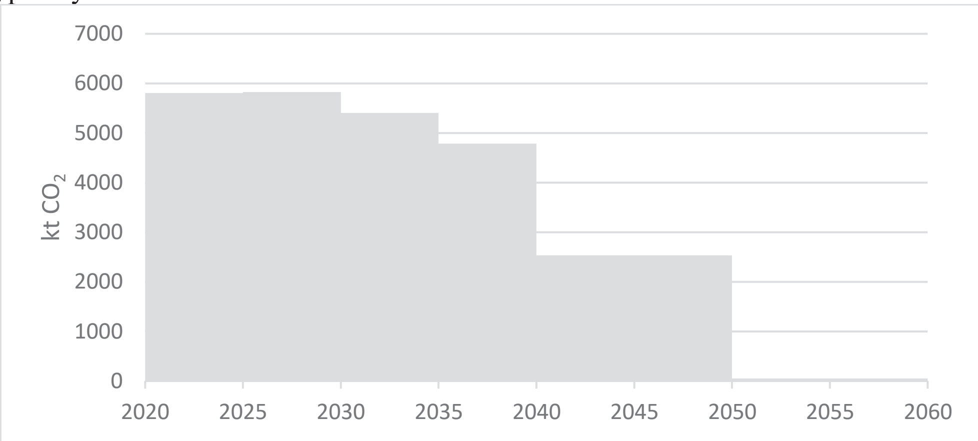
Remiantis modeliavimo rezultatais, krovininį transportą yra gerokai sunkiau elektrifikuoti nei keleivinį transportą. Todėl CO_2 emisijų mažinimas iki 2050 m. krovininiame transporte yra iš esmės grindžiamas įmaišomų biodegalų kiekio dyzeline didinimu. Šiame modelyje daroma prielaida, kad iki 2050 m. biodyzelino kiekis dyzeline pasieks 100 %. Nuo 2035 m. vandeniliu varomų sunkvežimių krovinių pervežimų dalis palaipsniui didėja, tačiau 2050–2060 m. pasieks tik 15,4 % (žr. 13 pav.). 2050–2060 m. modelyje numatoma itin sparti elektrinių sunkvežimių plėtra. Numatoma pasiekti net 66,5 % krovinių pervežimų.



13 pav. Krovinių pervežimo apimtys pagal kurą baziniame scenarijuje

(sudaryta autoriaus)

CO_2 emisijos, susidarančios transporto sektoriuje, pateiktos 14 pav. Numatoma, kad 2025–2030 m. emisijos transporte šiek tiek padidės. Nors tikėtina, kad dėl mažėjančio gyventojų skaičiaus sumažės bendras kelionių poreikis, vidutiniškai bus naudojamos naujesnės, efektyvesnės transporto priemonės, o elektra varomų transporto priemonių panaudojimas padidės iki maždaug 9 % asmeninio ir viešojo transporto kelionių apimčių, tačiau šių veiksnių emisijų sumažinimus atsvers ženkliai padidėjusios krovinių pervežimo dyzeliniais sunkvežimiais apimtys. Vėlesniais modeliuojamais laikotarpiais metinės CO_2 emisijos transporto sektoriuje mažėja. 2030–2035 m. siekia 93 % 2020 m. emisijų lygio, 2035–2040 m. 82 %, 2040–2050 m. 44 %, o 2050–2060 m. 1 %. Spartų emisijų mažėjimą šiais laikotarpiais lemia didėjantis transporto elektrifikavimo lygis ir didėjantis biodegalų kiekis benzino ir ypač dyzelino mišiniuose.



14 pav. CO2 emisijos transporto sektoriuje baziniame scenarijuje

(sudaryta autoriaus)

IŠVADOS

1. Siekiant transporto ir energetikos sektorių dekarbonizacijos tikslų yra itin svarbu atsižvelgti į sektorių tarpusavio ryšius. Nustatyta, kad svarbiausi ryšiai tarp centralizuoto šilumos tiekimo ir elektros energetikos sektorių yra per kogeneracines elektrines, kurios vienu metu gamina elektros energiją ir šilumą, bei per šilumos siurblius, kurie naudoja elektros energiją šilumai iš aplinkos paimti ir patiekti į centralizuoto šilumos tiekimo tinklus. Transporto ir energetikos sektorius jungia elektra ir vandeniliu varomos transporto priemonės, jei vandenilis gaminamas elektrolizės būdu. Dažnai laikoma, kad šilumos siurbliai bei elektra ar vandeniliu varomos transporto priemonės turi nulines ŠESD emisijas, tačiau šių technologijų, kaip emisijų mažinimo priemonių, veiksmingumas priklauso nuo to, iš kokių šaltinių yra gaminama elektros energija. Jei elektros energija iš esmės generuojama iš iškastinio kuro, tokiu atveju bendras emisijų kiekis gali net padidėti. Be to, įvairių sektorių elektrifikavimas didina bendrą elektros energijos poreikį ir daro įtaką elektros energijos vartojimo kreivės formai, lemiančiai elektrinių veikimą bei reikalingas įdiegtąsias galias. Kita vertus, elektromobilių įkrovimo, vandenilio gamybos elektrolizės būdu ir šilumos siurblių veikimo laikai gali būti valdomi taip, kad jie labiau atitiktų kintamą elektros energijos gamybą vėjo ir saulės elektrinėse, taip prisidedant prie elektros energijos sistemos balansavimo ir sudarant sąlygas didesnei atsinaujinančiųjų šaltinių skvarbai. Taikant dvikryptį išmanųjį elektromobilių įkrovimą (V2G) elektromobilių baterijos taip pat gali būti išnaudojamos trumpalaikiam elektros energijos akumuliavimui.
2. Mokslinės literatūros apžvalga atskleidė, kad optimizavimo modeliai, pagrįsti bendrų diskontuotų kaštų minimizavimu, yra dažnai naudojami siekiant nustatyti mažiausiai sąnaudų reikalaujančius būdus kaip analizuojamos sistemos turėtų vystytis, kad būtų pasiekti nustatyti emisijų mažinimo ir kiti strateginiai tikslai. Nustatyta, kad visuose tokiuose modeliuose, apimančiuose energetikos, centralizuoto šilumos tiekimo ir transporto sektorius, atsižvelgiama į tam tikras sistemos lankstumo priemones per tarpsektorinius ryšius, pavyzdžiui, elektros energijos panaudojimą šilumos gamyboje, žaliojo vandenilio naudojimą transporte, išmanųjį vienkryptį arba dvikryptį elektromobilių įkrovimą. Tačiau kai kuriuose iš jų neatsižvelgiama į išmanųjį dvikryptį elektromobilių įkrovimą arba vandenilio panaudojimą transporte. Be to, kai kuriuose iš šių modelių investicijos į transporto sektorių nėra optimizuojamos, t. y. modelyje transporto sektoriaus raida yra užduodama išoriškai. Optimizaciniai modeliai reikalauja didelių kompiuterinių išteklių. Todėl kai kuriais atvejais, siekiant sumažinti modelio dydį ir skaičiavimo laiką, naudojama žema laiko rezoliucija, kuri apsunkina tinkamą energijos gamybos ir sunaudojimo nepastovumo vaizdavimą. Tai yra ypač problemiška, kai nagrinėjamos atsinaujinančiaisiais šaltiniais grįstos elektros energetikos sistemos. Kituose modeliuose, siekiant sumažinti modelio dydį, yra naudojamas trumparegiškas optimizavimas. Tai reiškia, kad investicijos optimizuojamos tam tikriems laikotarpiams, o ne visam modeliuojamam laikotarpiui. F. Fuso Nerini parodė, kad, siekiant

dekarbonizacijos tikslų, trumparegiško optimizavimo atveju rezultatuose gali vėluoti strateginės investicijos ir gali būti didesnės suminės sąnaudos, lyginant su modeliu, kuriame taikomas optimizavimas su tobulu numatymu. Nė vienas iš mokslinėje literatūroje aptiktų optimizacinių modelių, apimančių energetikos, centralizuoto šilumos tiekimo ir transporto sektorius, nepasižymi šiomis keturiomis savybėmis: veikimas, grįstas suminių diskontuotų kaštų minimizavimu; optimizuojamos investicijos transporto sektoriuje turi palyginti didelę laiko rezoliuciją; optimizavimas atliekamas su tobulu numatymu.

3. Naudojant modeliavimo sistemą MESSAGE, buvo sukurtas integruotas transporto ir energetikos sektorių modelis, skirtas įvertinti mažiausiai sąnaudų reikalaujančius raidos kelius, užtikrinančius beveik nulinius anglies dioksido išmetimus. Modelis apima elektros ir centralizuotos šilumos tiekimą, keleivinį ir krovininį kelių transportą. Sudarytame modelyje optimizuojamos investicijos visuose modeliuojamuose sektoriuose. Modelis pasižymi palyginti didele laiko rezoliucija, o optimizavimas atliekamas taikant tobulą numatymą. Modelis sukurtas Lietuvos atvejui. Atsižvelgiant į tai, kad Lietuvoje dauguma pirmą kartą registruotų transporto priemonių yra naudotos transporto priemonės iš užsienio, buvo sukurtas unikalus metodas, kuriuo įvertinamas transporto priemonių amžiaus pasiskirstymas. Taip pat, siekiant geriau atvaizduoti gamybos vėjo elektrinėse nepastovumą, buvo sukurtas tikimybinis elektros gamybos šiose elektrinėse atvaizdavimo metodas. Nors su modeliavimo sistema MESSAGE sukurtas modelis pritaikytas Lietuvos atvejui, tačiau jis gali būti pritaikytas ir kitoms šalims, o aprašytą metodiką su tam tikrais pakeitimais galima pritaikyti ir kitose modeliavimo sistemose (pvz., TIMES).
4. Modeliavimo rezultatai rodo, kad pigiausias būdas dekarbonizuoti Lietuvos elektros energetikos sektorių ir kartu užtikrinti energetinį saugumą yra sparčiai plėsti elektros energijos gamybą vėjo ir saulės elektrinėse. 2025–2030 m. elektros energijos gamyba šiose elektrinėse turėtų sudaryti 56 % visos suvartojamos elektros energijos šalyje, o iki 2050–2060 m. palaipsniui didėti iki 98 %. Optimalus elektros energijos gamybos vėjo ir saulės elektrinėse santykis yra apie 1,7. Modelis atskleidžia, kad mažų decentralizuotų saulės elektrinių įrengimas vartotojų pusėje, paverčiant juos gaminančiais vartotojais, yra ekonomiškai efektyvesnis nei didelių saulės elektrinių parkų statyba. Tačiau didėjant elektros energijos gamybos iš atsinaujinančiųjų šaltinių daliai, didėja balansavimo poreikis. Apskaičiuota, kad balansavimą yra pigiau užtikrinti tarpvalstybinėmis elektros jungtimis, nei plečiant šiluminių elektrinių įrengtąją galią ar energijos akumuliavimą. Kita vertus, reikėtų pažymėti, kad sukurtame modelyje neatsižvelgta į kaimyninių šalių elektros energijos pasiūlą ir paklausą. Balansavimo galimybės elektros importu ir eksportu ateityje gali būti ribotos, nes kaimyninės šalys elektros energijos gamybą greičiausiai taip pat grįs atsinaujinančiaisiais šaltiniais ir susidurs su tomis pačiomis balansavimo problemomis.

   Centralizuoto šilumos tiekimo sektoriaus modeliavimo rezultatai rodo, kad biomasės ir atliekomis kūrenamų kogeneracinių elektrinių vaidmuo palaipsniui didėja – nuo 34 % visos centralizuotai tiekiamos šilumos iki 76 % 2050–2060 m.

Tačiau iki 2040 m. ši dalis didėja daugiausiai dėl mažėjančio centralizuotai tiekiamos šilumos poreikio. Mažėjant paklausai, pirmiausia išstumiamos dujomis kūrenamos kogeneracinės elektrinės, o po to – katilinės.

Modeliu nustatyta transporto sektoriaus raida remiasi laipsnišku elektrifikavimu pereinant prie elektra ir vandeniliu varomų transporto priemonių. 2050–2060 m. elektromobiliais nukeliaujama 89,4% visų kelionių automobiliais, o vandeniliu varomais automobiliais – 7,1%. Pastebima itin sparti viešojo transporto elektrifikacija (13% 2025–2030 m., 82% 2030–2035 m., 94% 2050–2060 m.). Krovininio transporto elektrifikacija yra lėčiausia. Krovinių pervežimo apimtys elektra ir vandeniliu varomomis transporto priemonėmis iki 2040 m. sudaro tik 4 %. Tačiau 2040–2050 m. ši dalis išauga iki 19 %, o 2050–2060 m. pasiekia 82 %.

5. Modeliuota penkiolika scenarijų, tarp jų: bazinis (Base), scenarijus su kintančiu transporto priemonių amžiaus skirstiniu (VehDistr), sumažintų balansavimo galimybių tarpvalstybinėmis jungtimis scenarijus (RedFlexi), scenarijus, kuriame po 2040 m. nutraukiamos tarpvalstybinės elektros jungtys (InterOff), bei scenarijus, kuriame užduodami griežti reikalavimai iki 2050 m. pasiekti nulines CO_2 emisijas (ZeroCO_2). Kiekvienam iš šių penkių scenarijų modeliuota dar po du papildomus scenarijus, kuriuose taikytas išmanusis ir išmanusis dvikryptis elektromobilių įkrovimas. Scenarijų rezultatų palyginamoji analizė parodė, kad:
   - Kintantis transporto priemonių amžiaus skirstinys, t. y. mažėjantis vidutinis automobilių amžius, lemia spartesnį perėjimą prie elektra varomų transporto priemonių. Tai padidina bendrus elektros poreikius bei vakarinį poreikių piką, o tai lemia didesnes elektros kainas bei didesnę kainų sklaidą.
   - Sumažintos elektros balansavimo tarpvalstybinėmis elektros jungtimis galimybės lemia mažesnę elektros gamybą vėjo ir saulės elektrinėse bei bendrai mažesnes elektros gamybos apimtis šalyje, dėl ko gaunamos aukštesnės vidutinės elektros kainos. Mažesnės balansavimo tarpvalstybinėmis jungtimis galimybės dalinai kompensuojamos kitomis brangesnėmis sistemos lankstumo priemonėmis, kaip elektros akumuliavimas bei vandenilio gamyba elektrolizės būdu.
   - Poreikis nuo 2040 m. visiškai subalansuoti elektros energijos gamybą šalies viduje sumažina gaminamus elektros energijos kiekius saulės ir vėjo elektrinėse, tačiau padidina elektros gamybą šiluminėse elektrinėse bei energijos akumuliavimo poreikius. Dėl to išauga vidutinės elektros kainos, kainų sklaida bei CO_2 emisijos. Vandenilio išgavimas elektrolizės būdu, kaip balansavimo priemonė, atlieka svarbesnį vaidmenį.
   - Griežti reikalavimai iki 2050 m. pasiekti nulines CO_2 emisijas visuose modeliuotuose sektoriuose pasireiškia didesnėmis elektros gamybos apimtimis saulės ir vėjo elektrinėse bei didesnių elektros akumuliavimo galimybių poreikiu. Be to, CO_2 sugavimo ir saugojimo technologija yra panaudojama tik ZeroCO_2 scenarijuose. Visa tai lemia didesnes vidutines elektros energijos kainas bei kainų sklaidą, lyginant su baziniu scenarijumi.

Taip pat vandenilio panaudojimas tiek keleiviniame, tiek krovininiame transporte yra ženklesnis.

- Išmanusis vienkryptis ir išmanusis dvikryptis elektromobilių įkrovimo būdai turi ženklius privalumus lyginant su nevaldomu įkrovimu. Jie įgalina geriau pritaikyti įkrovimo laikus prie nepastovios elektros gamybos vėjo ir saulės elektrinėse, taip prisidedant prie atsinaujinančiųjų šaltinių balansavimo. Dėl to scenarijuose su išmaniuoju vienkrypčiu ir išmaniuoju dvikrypčiu įkrovimo būdais gaunamos didesnės elektros energijos gamybos apimtys saulės ir vėjo elektrinėse, mažesnės vidutinės elektros kainos, mažesnė kainų sklaida bei mažesni elektros akumuliavimo poreikiai. Modeliavimo rezultatai parodė, kad išmaniojo dvikrypčio įkrovimo teigiamas poveikis elektros energetikos sistemai yra kiek didesnis nei vienkrypčio. Tačiau skirtumai tarp šių dviejų įkrovimo būdų yra nežymūs.

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2021 – 2022	Impacts of ambitious energy policy pathways (Amber)
2018 – 2022	An integrated modelling and analysis of the deep decarbonization of the economy (DeCARB)
2019 – 2021	Fast, flexible and secure decarbonization of the Baltic states – possible progress in the next Ten years (FasTen)
2017 – 2021	Flexible combined production of power, heat and transport fuels from renewable energy sources (FLEXCHX)
2018 – 2020	Cost and benefit socioeconomic analysis of Kruonis HPP capacity expansion
2015 – 2019	Modelling potential Least-Cost Long-TERM greenhouse Gas Emission Reduction Strategies for Lithuania
2015 – 2019	Role of technologies in an energy efficient economy – model based analysis of policy measures and transformation pathways to a sustainable energy system (REEEM)
2015 – 2016	Methodical guidelines for preparation of national GHG emissions projections
2015 – 2016	Analysis and assessment of the energy sector legal framework and recommendations for improvement of legal regulation
2015 – 2016	District heating development strategy for Kaunas energy
2014 – 2018	Baltic Region Initiative for Long Lasting InnovAtive Nuclear Technologies (BRILLIANT)
2014 – 2016	Research on development of the Lithuanian energy sector and formulation of Lithuanian National Energy Strategy

2014 – 2015 Social and macroeconomic impact assessment of energy development scenarios proposed by the National Energy Strategy of the Republic of Lithuania

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ANNEXES

Annex A. Techno-economic parameters

Table A.1. Techno-economic parameters of electricity-only thermal power plants in the model

	Technical parameters					Economic parameters		
Power plant	Efficiency [%]	Operation time [Share]	Lifetime [years]	Construction time[16] [years]	Installed capacity	Investment costs [Eur/kW]	Fixed costs [Eur/kW/yr]	Variable costs [Eur/kWyr]
Lithuania power plant CCGT (unit 9)	58%	0.95	25	-	455 MW in 2012	-	16.23	16.17
Lithuania power plant GT (units 7-8)	37.70%	0.95	56	-	300 MW in 1968	-	16.23	24.08
Mažeikiai power plant	22%	0.95	40	-	160 MW in 1987	-	15.21	36.62
New CCGT power plant[17]	56% 58% 60%	0.97	25	2.5	-	880 830 800	29.3 27.8 26.0	38.54 36.79 35.04

Source: created by the author based on Danish Energy Agency (2020) and BENTE project (Lindroos et al., 2018) data

[16] Construction time and investment costs were not set for electricity-only thermal power plants that are already built, only for the future ones.
[17] Efficiency, investment costs, fixed cost and variable costs were set to change throughout the modelling years. Each of these parameters have three values: first applies from 2020, second from 2030 and third from 2050.

Table A.2. Technical parameters of CHP plants

		Technical parameters						
		Condensing mode	CHP mode					
	Power plant	Electrical efficiency [%]	Electrical efficiency [%]	Heat efficiency [%]	Operation time [Share]	Lifetime [years]	Construction time [years]	Installed capacity
Steam extraction plants	Vilnius gas 3rd CHP plant	39%	32.3%	59%	0.95	45	-	360 in 1983
	Kaunas gas CHP plant	31%	27.0%	44.00%	0.95	50	-	170 in 1976
	CCGT CHP plants	56% 58% 60%	51.7% 54.0% 56.2%	28.7% 25.5% 27.0%	0.97	25	3	35 in 2008
Backpressure plants	Vilnius waste CHP plant		29.0%	72.1%	0.95	25	3	92 in 2021
	Kaunas waste CHP plant		22.0%	79.0%	0.94	25	3	24 in 2020
	Klaipėda waste CHP plant		22.0%	79.0%	0.94	25	3	21 in 2013
	Biomass CHP plant		13.5% 13.3% 13.6%	98.1% 98.3% 98.0%	0.94	25	1	(1)
	Kaunas biomass CHP plant 2		17.3%	94.3%	0.94	25	-	10 in 2016
	Alytus gas CHP plant		17.0%	68.0%	0.94	25	-	9.2 in 2008
	Other gas CHP plant		34.0%	48.0%	0.94	25	-	(2)
	Vilnius gas-biomass 2nd CHP plant		20.8%	68.2%	0.92	79	-	28.7 in 1951
	Waste heat CHP plant		43.4%	58.6%	0.95	25	-	34.9 in 2008

(1) Installed capacities by modelled regions. Kaunas: 10 MW in 2016. Klaipėda: 1.5 MW in 2007. Šiauliai: 1.5 MW in 2007. Panevėžys: 2.5 MW in 2001. Alytus: 5.4 MW in 2012. Other: 1.75 MW in 2007; 5.64 MW in 2010; 1.65 MW in 2011; 2.1 MW in 2012; 1.34 MW in 2014

(2) Installed capacities in region Other: 0.134 MW in 2002; 1.8 MW in 2007; 10.15 MW in 2008; 0.34 MW in 2009; 1 MW in 2010; 2.4 MW in 2011; 0.2 MW in 2012; 0.6 MW in 2014; 0.1 MW in 2015; 1.7 MW in 2018

Source: created by the author based on Danish Energy Agency (2020) and BENTE project (Lindroos et al., 2018) data

Table A.3. Economic parameters of CHP plants

	Power plant	Economic parameters Investment costs [Eur/kW]	Fixed costs [Eur/kW/yr]	Variable costs [Eur/kWyr]
Steam extraction plants	Vilnius gas 3rd CHP plant	-	20.28	3.76
	Kaunas gas CHP plant	-	20.28	6.21
	CCGT CHP plants	880 830 800	29.3 27.8 26.0	38.54 36.79 35.04
Backpressure plants	Vilnius waste CHP plant	3804	264.8	218.92
	Kaunas waste CHP plant	6667	264.8	218.92
	Klaipėda waste CHP plant	6190	264.8	218.92
	Biomass CHP plant	6500 6200 6000	288.9 280.5 277.9	68.33 67.45 69.20
	Kaunas biomass CHP plant 2	-	293	68.33
	Alytus gas CHP plant	-	20.28	10.54
	Other gas CHP plant	-	20	48.18
	Vilnius gas-biomass 2nd CHP plant	-	81.13	16.98
	Waste heat CHP plant	-	81.1	6.21

Source: created by the author based on Danish Energy Agency (2020) and BENTE project (Lindroos et al., 2018) data

Table A.4. Techno-economic parameters of heating plants

			Gas heating plant	Biomass heating plant	Heat pumps
Technical parameter	Efficiency	[%]	105%	115%	302%
	Operation time	[Share]	0.99	0.97	0.98
	Lifetime	[years]	25	25	25
	Construction time	[years]	1	2	1
Economic parameters	Investment costs	[Eur/kW]	60	493.5	1427.1 1331.9 1331.9
	Fixed costs	[Eur/kW/yr]	1.95	42	2
	Variable costs	[Eur/kWyr]	9.64	23.69	23.56

Source: created by the author based on Danish Energy Agency (2020) data

Table A.5. Installed biomass heating plant capacity in MW by year and region

Year	Regions						
	Vilnius	Kaunas	Klaipėda	Šiauliai	Panevėžys	Alytus	Other
2019	47.6				19.6		64.2
2018			9.9				61.0
2017							57.8
2016	23.8	48.5			15		54.6
2015	44.2	102.7	20				51.4
2014	58.5	20	1	25			48.2
2013		10				15	45.0
2012		26.5			20		41.8
2011	15						38.5
2010							35.3
2009							32.1
2008			2.4				28.9
2007							25.7
2006	61.4		3.6				22.5
2005							19.3
2004							16.1
2003			2.2				12.8
2002							9.6
2001							6.4

Source: created by the author based on the Lithuanian District Heating Association (Lietuvos šilumos tiekėjų asociacija, 2018) data and a mix of other various sources. Other sources used by district heating system: Vilnius (‘Forest biokuro katilinės istorija’, 2018; ‘Vilniuje pradedama statyti biokuro katilinė’, 2014; Večerskytė-Šimeliūnė, Treinys, & Naujokaitienė, 2020; Vilniaus Energija, n.d.); Kaunas (Bakas, 2017a; ‘Kaune „Šilko“ katilinėje paleistas naujas biokuro katilas’, 2015; Lietuvos šilumos tiekėjų asociacija, 2015; UAB Urbanistika, 2015); Klaipėda (Karalius, 2015; Katinas, 2018; Klaipėdos energija, 2017; State Energy Inspectorate under the Ministry of Energy of the Republic of Lithuania, 2018); Šiauliai (Šiaulių energija, 2020); Panevėžys (Panevėžio energija, 2020; Žvirblytė, Aliukonis, Pečkytė, Davidavičius, & Vaičaitis, 2015); Alytus (Statkevič, 2019)

Table A.6. Installed natural gas heating plant capacity in MW by year and region

Year	Regions						
	Vilnius	Kaunas	Klaipėda	Šiauliai	Panevėžys	Alytus	Other
2019							24.6
2018		59.6					29.5
2017							34.4
2016		33					39.3
2015							44.2
2014							49.1
2013		22					54.0
2012							58.9
2011		57.8					63.8
2010		197					68.7
2009					5.6		73.7
2008							78.6
2007		18.25	7.6				83.5
2006		1.6				6.05	88.4
2005					16	46	93.3
2004					0.61	46	98.2
2003	348			22.365		40.7	103.1
2002	116					58.15	108.0
2001	464				58.15	58.15	112.9
2000	116	2.46	66.3	104.67	58	25.1	117.9
1999			367.8	47.25	58		122.8
1998	58.15				58		127.7
1997			246	47.25	18.9		132.6
1996	58.15				18.9		157.1

Source: created by the author based on the Lithuanian District Heating Association (Lietuvos šilumos tiekėjų asociacija, 2018) data and a mix of other various sources. Other sources used by district heating system: Vilnius - (Večerskytė-Šimeliūnė et al., 2020; Vilniaus Energija, 2014); Kaunas (Bakas, 2017a, 2017b; Sesartė & Aukštuolytė, 2014, 2014; UAB EMEKO, 2020; UAB „Energetikos inžinerija", n.d.; UAB Urbanistika, 2015); Klaipėda (Klaipėdos energija, 2017; State Energy Inspectorate under the Ministry of Energy of the Republic of Lithuania, 2018) Šiauliai (Šiaulių energija, 2020); Panevėžys (Panevėžio energija, 2020; Žvirblytė et al., 2015); Alytus (Statkevič, 2019)

Table A.7. Techno-economic parameters of wind power plants

Power plant	Technical parameters			Economic parameters		
	Operation time [Share]	Lifetime [years]	Construction time [years]	Investment costs [Eur/kW]	Fixed costs [Eur/kW/yr]	Variable costs [Eur/kWyr]
Offshore wind PP	0.972 0.982 0.977	27	3	2128.4 1934.6 1777.3	40.1 36.1 32.4	26.0 23.4 21.1
Large onshore wind PP	0.97 0.97 0.98	27	2	1118.8 1035.6 963.1	14.0 12.6 11.3	13.1 11.8 10.6
Medium onshore wind PP	0.972 0.982 0.977	25	1	1342.5 1242.7 1155.7	16.8 15.1 13.6	15.8 14.2 12.8
Prosumer wind PP	0.97	20	1	3800.0 3610.0 3429.5	95.0 90.0 85.0	0

Source: created by the author based on Danish Energy Agency (2020) data

Table A.8. Installed wind power plant capacity in MW by technology and build year

Year	Offshore wind PP	Large onshore wind PP	Medium onshore wind PP	Prosumer wind PP
2019			13.1	
2018			5.5	
2017		7.5	13.4	
2016		202.5	11.3	
2015			4.1	
2014			3.2	
2013		21.4	4.4	
2012		39.1	7.4	
2011		72.7	25.2	
2010		29.1	7.0	
2009		14.0	3.0	
2008		0.0	1.9	
2007		16.0	2.8	
2006		30.0	0.8	
2004			0.7	
2002			0.2	

Source: created by the author based on (Lietuvos ornitologų draugija, Pajūrio tyrimų ir planavimo institutas, & Lietuvos energetikos institutas, 2017; State Energy Inspectorate under the Ministry of Energy of the Republic of Lithuania, 2019) data

Table A.9. Techno-economic parameters of solar PV power plants

			Large solar PV farms	Medium solar PV farms	Prosumer PVs
Technical parameters	Operation time	[Share]	1	1	1
	Lifetime	[years]	35	35	35
	Construction time	[years]	1	1	1
Economic parameters	Investment costs	[Eur/kW]	529.2 376.3 301.6	803.7 631.7 494.1	1128.4 869.5 587.5
	Fixed costs	[Eur/kW/yr]	14 12.6 11.3	11.4 9.2 7.8	17.8 10.0 7.6
	Variable costs	[Eur/kWyr]	0	0	0

Source: created by the author based on Danish Energy Agency (2020) data.

Table A.10. Installed solar PV plant capacity in MW by build year

Year	Large solar PV farms	Medium solar PV farms	Prosumer PVs
2019		8.61	3.65
2018		9.75	4.59
2017		5.74	1.55
2016		2.06	1.29
2015		2.57	0.61
2014		3.27	
2013		46.52	
2012		7.85	
2011		0.71	

Source: created by the author based on (State Energy Inspectorate under the Ministry of Energy of the Republic of Lithuania, 2019) data.

Table A.11. Techno-economic parameters of hydropower plants

			Reservoir hydropower plant	Run-of-river hydropower plants
Technical parameters	Operation time	[Share]	1	1
	Lifetime	[years]	100	100
	Construction time	[years]	-	-
	Storage size	[MWyr]	0.297	-
Economic parameters	Investment costs	[Eur/kW]	-	-
	Fixed costs	[Eur/kW/yr]	15.04	61.72
	Variable costs	[Eur/kWyr]	3.63	3.54

Source: created by the author based on Danish Energy Agency (2020) data.

Table A.12. Techno-economic parameters of pumped hydro storage power plant

			PSHPP
Technical parameters	Operation time	[Share]	1
	Lifetime	[years]	60
	Contruction time	[years]	-
	Storage size	[MWyr]	1.233
Economic parameters	Investment costs	[Eur/kW]	-
	Fixed costs	[Eur/kW/yr]	0.236
	Variable costs	[Eur/kWyr]	15.6

Source: created by the author based on BENTE (Lindroos et al., 2018) data.

Table A.13. Techno-economic parameters of grid batteries

			Grid batteries	Battery size
Technical parameters	Operation time	[Share]	1	1
	Lifetime	[years]	20 25 30	20 25 30
	Storage size	[MWyr]	1.233	
Economic parameters	Investment costs	[Eur/kW]	270 160 60	
		[Eur/kWyr]		92378 56542 29684
	Fixed costs	[Eur/kW/yr]	0.54	
	Variable costs	[Eur/kWyr]	2 1.8 1.6	

Source: created by the author based on Danish Energy Agency (2020) data.

Table A.14. Techno-economic parameters of hydrogen production technologies

		2020	2025	2030	2035	2040	2050
Efficiency, [kt h2/MWyr]	AE	18.4%	18.8%	19.2%	19.7%	20.1%	21.0%
	PEM	15.8%	16.3%	16.9%	17.5%	18.1%	19.4%
	SOE	21.3%	21.7%	22.0%	22.4%	22.8%	23.7%
CAPEX, [eur/t H2/yr]	AE	4779	4225	3735	3302	2919	2281
	PEM	6618	6391	6171	5959	5754	5366
	SOE	5555	5458	5363	5270	5178	4999
OPEX fixed, [eur/t H2/yr]	AE	230.2	225.1	220.2	215.3	210.6	201.4
	PEM	268.6	259.4	250.4	241.8	233.5	217.8
	SOE	198.9	195.5	192.1	188.7	185.5	179.1
OPEX variable, [eur/t H2]	AE	67.76	67.76	67.76	67.76	67.76	67.76
	PEM	67.76	67.76	67.76	67.76	67.76	67.76
	SOE	67.76	67.76	67.76	67.76	67.76	67.76
Lifetime, [years]	AE	8.56	9.32	10.15	11.05	12.03	14.27
	PEM	6.85	7.74	8.75	9.89	11.17	14.27
	SOE	2.28	2.92	3.73	4.77	6.11	9.99
Construction time, [years]	AE	2	2	2	2	2	2
	PEM	2	2	2	2	2	2
	SOE	2	2	2	2	2	2

Source: created by the author based on International Council on Clean Transportation data (Christensen, 2020)

Table A.15. Technical parameters of power plants with CCS

			CCGT CCS PP	**CCGT CHP CCS PP**	**Biomass CHP CCS PP**
Condensing mode	Electrical efficiency	[%]	54.9% 57.1% 59.3%	54.9% 57.1% 59.3%	
CHP mode	Electrical efficiency	[%]		50.5% 53.0% 55.5%	4.5% 6.2% 7.2%
	Heat efficiency	[%]		28.7% 27.0% 25.5%	98.1% 98.0% 98.3%
	Operation time	[Share]	0.95	0.95	0.97
	Lifetime	[years]	25	25	25
	Construction time	[years]	3	3	3

Source: created by the author based on Danish Energy Agency (2020) data.

Table A.16. Economic parameters of power plants with CCS

		CCGT CCS PP	CCGT CHP CCS PP	Biomass CHP CCS PP
Investment costs	[Eur/kW]	1890 1656 1354	2111 1797 1490	48634 31217 22170
Fixed costs	[Eur/kW/yr]	59.6 52.6 42.6	66.3 56.9 46.7	1738 1144 845
Variable costs	[Eur/kWyr]	38.5 36.8 35.0	46.6 44.5 42.5	262.8 210.1 191.2

Source: created by the author based on Danish Energy Agency (2020) data.

Table A.17. Car fuel consumption rate in short distance mode in kg/100 km by class, fuel type and age group

Car age group	A-B			C-D			E-F			J-M		
	Diesel	Petrol	Hybrid	Diesel	Petrol	Hybrid	Diesel	Petrol	Hybrid	Diesel	Petrol	Hybrid
-92	5.3	7.8	4.4	7.7	9.2	5.2	9.2	10.8	6.2	9.2	10.8	6.2
93-96	5.2	7.6	4.3	7.5	9.0	5.1	9.2	10.8	6.2	9.2	10.8	6.2
97-00	5.2	7.7	4.4	7.6	9.1	5.2	8.9	10.5	6.0	8.9	10.5	6.0
01-05	5.2	7.7	4.4	7.6	9.1	5.2	8.7	10.3	5.9	8.7	10.3	5.9
06-10	4.9	7.3	4.1	7.1	8.6	4.9	8.1	9.5	5.4	8.1	9.5	5.4
11-14	4.4	6.5	3.7	6.4	7.7	4.4	7.3	8.6	4.9	7.3	8.6	4.9
15-20	4.2	6.2	3.5	6.1	7.3	4.1	6.7	7.9	4.5	6.7	7.9	4.5
21-25	4.0	5.9	3.4	5.8	7.0	4.0	6.3	7.5	4.3	6.3	7.5	4.3
26-30	3.8	5.6	3.2	5.5	6.5	3.7	5.9	7.0	4.0	5.9	7.0	4.0
31-35	3.5	5.2	3.0	5.1	6.1	3.5	5.6	6.5	3.7	5.6	6.5	3.7
36-40	3.3	4.8	2.8	4.7	5.7	3.2	5.2	6.1	3.5	5.2	6.1	3.5
41-45	3.0	4.5	2.5	4.4	5.3	3.0	4.8	5.6	3.2	4.8	5.6	3.2
46-50	2.8	4.1	2.3	4.0	4.8	2.8	4.4	5.2	2.9	4.4	5.2	2.9
51-60	2.4	3.6	2.0	3.5	4.2	2.4	3.8	4.5	2.6	3.8	4.5	2.6

Source: created by the author based on spritmonitor.de (Fisch und Fischl GmbH, 2021) and U.S. Environmental Protection Agency's Automotive Trends Report (US EPA, 2018) data.

Table A.18. Car fuel consumption rate in a long-distance mode in kg/100 km by class, fuel type and age group

Car age group	A-B Diesel	A-B Petrol	A-B Hybrid	C-D Diesel	C-D Petrol	C-D Hybrid	E-F Diesel	E-F Petrol	E-F Hybrid	J-M Diesel	J-M Petrol	J-M Hybrid
-92	3.8	5.7	5.0	5.6	6.7	5.9	7.3	8.6	7.6	7.3	8.6	7.6
93-96	3.8	5.5	4.9	5.4	6.5	5.7	7.2	8.5	7.5	7.2	8.5	7.5
97-00	3.7	5.5	4.9	5.4	6.5	5.7	7.0	8.3	7.3	7.0	8.3	7.3
01-05	3.7	5.5	4.8	5.4	6.5	5.7	6.7	7.9	6.9	6.7	7.9	6.9
06-10	3.5	5.2	4.6	5.1	6.1	5.4	6.1	7.2	6.3	6.1	7.2	6.3
11-14	3.2	4.7	4.2	4.6	5.6	4.9	5.6	6.6	5.8	5.6	6.6	5.8
15-20	3.0	4.5	3.9	4.4	5.3	4.6	5.1	6.0	5.3	5.1	6.0	5.3
21-25	2.9	4.3	3.8	4.2	5.0	4.4	4.8	5.6	5.0	4.8	5.6	5.0
26-30	2.7	4.0	3.5	3.9	4.7	4.2	4.5	5.3	4.7	4.5	5.3	4.7
31-35	2.5	3.7	3.3	3.7	4.4	3.9	4.2	5.0	4.4	4.2	5.0	4.4
36-40	2.4	3.5	3.1	3.4	4.1	3.6	3.9	4.6	4.1	3.9	4.6	4.1
41-45	2.2	3.2	2.8	3.2	3.8	3.4	3.6	4.3	3.8	3.6	4.3	3.8
46-50	2.0	3.0	2.6	2.9	3.5	3.1	3.3	3.9	3.5	3.3	3.9	3.5
51-60	1.8	2.6	2.3	2.5	3.0	2.7	2.9	3.4	3.0	2.9	3.4	3.0

Source: created by the author based on spritmonitor.de (Fisch und Fischl GmbH, 2021) and U.S. Environmental Protection Agency's Automotive Trends Report (US EPA, 2018) data.

Table A.19. Electric vehicle and fuel cell electric vehicle fuel consumption rate in short and long-distance travel mode by car class

Car class	Electric vehicle [kWh/100 km]	FCEV [kg/100 km]
	Short-distance travel mode	
A-B	10.61	0.97
C-D	10.79	0.98
E-F	13.20	1.20
J-M	13.19	1.20
	Long-distance travel mode	
A-B	18.19	1.08
C-D	17.56	1.04
E-F	20.35	1.21
J-M	21.54	1.28

Source: created by the author based on ev-database.org ('Electric Vehicle Database', 2020) and fueleconomy.gov (U.S. Department of Energy, 2020) data.

Table A.20. Purchase price of a new car by car class, fuel and age group in euros

Car class	Fuel	Car age group -92	93-96	97-00	01-05	06-10	11-14	15-20	21-25	26-30	31-35	36-40	41-45	46-50	51-60
A-B	Diesel	17105	17105	17105	17105	17105	17105	17105	17060	16984	16908	16832	16756	16681	16651
	Petrol	15185	15185	15185	15185	15185	15185	15185	15104	14969	14855	14753	14653	14553	14513
	Hybrid				19441	19441	19441	19441	19035	18376	17935	17633	17336	17044	16928
	Electric				32453	32453	32453	32453	31441	29818	28643	27755	26894	26060	25732
	Hydrogen								33114	29618	28182	27968	27755	27544	27460
C-D	Diesel	27995	27995	27995	27995	27995	27995	27995	27880	27688	27534	27406	27278	27151	27100
	Petrol	24239	24239	24239	24239	24239	24239	24239	24136	23966	23796	23625	23455	23286	23219
	Hybrid				29130	29130	29130	29130	28530	27555	26923	26509	26103	25702	25543
	Electric				32990	32990	32990	32990	32073	30596	29520	28701	27905	27130	26826
	Hydrogen								51753	47198	44926	44025	43142	42277	41936
E-F	Diesel	52700	52700	52700	52700	52700	52700	52700	52485	52128	51878	51698	51520	51342	51271
	Petrol	50150	50150	50150	50150	50150	50150	50150	50044	49868	49692	49515	49339	49164	49094
	Hybrid				60180	60180	60180	60180	59035	57171	55914	55048	54195	53356	53023
	Electric				79200	79200	79200	79200	76991	73435	70839	68859	66933	65062	64326
	Hydrogen								95794	87829	83885	82369	80881	79419	78841
J-M	Diesel	42287	42287	42287	42287	42287	42287	42287	42114	41827	41627	41483	41340	41197	41140
	Petrol	39154	39154	39154	39154	39154	39154	39154	39072	38934	38797	38659	38521	38385	38330
	Hybrid				46985	46985	46985	46985	46091	44636	43654	42978	42313	41657	41398
	Electric				49965	49965	49965	49965	48571	46328	44690	43441	42226	41045	40581
	Hydrogen								51316	47050	44936	44125	43327	42545	42235

Source: created by the author. Current and past purchase prices of new cars were derived based on data on car manufacturers and official retailers' websites, while future prices were calculated based on car price changes in *A portfolio of power-trains for Europe: A fact-based analysis* (FCH JU, 2010) report.

Table A.21. Fuel consumption in road public transport

Age group	City bus Diesel, kg/100 km	City bus CNG, kg/100 km	City bus BEV, kWh/100 km	City bus FCEV, kg/100 km	Trolleybus kWh/100 km	Intercity bus Diesel, kg/100 km	Intercity bus CNG, kg/100 km	Intercity bus BEV, kWh/100 km	Intercity bus FCEV, kg/100 km
-92	38.6	42.1				29.0	31.6		
93-96	38.6	42.1			230.0	29.0	31.6		
97-00	40.7	42.1		8.6		30.5	31.6		9.2
01-05	38.4	43.7			238.0	28.8	32.8		
06-08	38.2	42.3				28.7	31.7		
09-12	38.2	40.8				28.7	30.6		
13-20	35.7	39.4	250.0	8.4		26.8	29.6	271.6	8.9
21-25	35.5	38.8		7.9		26.4	29.1		8.4
26-30	34.3	37.9		7.5	250.0	25.7	28.4		7.9
31-35	33.4	36.9				25.1	27.7		
36-40	32.6	36.0				24.5	27.0		
41-45	31.8	35.1		7.3		23.9	26.3		7.8
46-50	31.0	34.2				23.3	25.7		
51-60	29.9	33.0				22.4	24.7		

Source: created by the author based on (Söderena, Nylund, & Mäkinen, 2019), (Vilniaus viešasis transportas, 2018) data

Table A.22. Purchase price of public transport vehicles in euros

	Fuel	Age group -14	15-20	21-25	26-30	31+
City bus	Diesel	230000	230000	243625	253000	253000
	CNG	270000	270000	285994	297000	297000
	Electric	502500	502500	337932	251250	251250
	Hydrogen	882600	782122	637148	596284	590750
Trolleybus	Electric	345882	345882	345882	345882	345882
Intercity bus	Diesel	288519	288519	288519	288519	288519
	CNG	338696	338696	338696	338696	338696
	Electric	630351	630351	402597	286523	286523
	Hydrogen	1107223	981118	755852	679997	673686

Source: created by the author based on (Ammermann, Ruf, Lange, Fundulea, & Martin, 2015; Hooftman, Messagie, & Coosemans, 2019) data

Table A.23. Fuel consumption of trucks

Age group	Trucks Diesel, kg/100 km	CNG, kg/100 km	BEV, kWh/100 km	FCEV, kg/100 km
-92	31.2	34.0	144.0	8.2
93-96	31.2	34.0		
97-00	30.8	31.8		
01-05	30.2	34.4		
06-10	29.7	32.4		
11-14	29.1	31.7		
15-20	28.5	31.4		
21-25	27.7	30.6		
26-30	27.0	29.8		
31-35	26.3	29.1		
36-40	25.7	28.4		
41-45	25.1	27.7		
46-50	24.4	27.0		
51-60	23.5	26.0		

Source: created by the author based on (Transport & Environment, 2015) data

Table A.24. Truck purchase price in euros

Age group	Trucks Diesel	CNG	BEV	FCEV
-10	102837	152351	1209891	521745
11-14	104728	150052	784941	521745
15-20	109069	146061	320532	440648
21-25	114610	144353	208939	298396
26-30	120378	145175	180335	209788
31-35	125419	146774	169304	177335
36-40	129640	147476	163878	171651
41-45	131875	147019	159508	167075
46-50	132469	146714	155321	162689
51-60	132622	146714	153653	160941

Source: created by the author

Table A.25. Truck O&M costs in €/100 km

		Trucks		
Age group	Diesel	CNG	BEV	FCEV
-10	15.5	18	26	50.5
11-14				
15-20		17.6	22.4	40.0
21-25		16.6	16.7	23.2
26-30		15.8	12.8	14.1
31-35		15.5	11.5	11.5
36-40				
41-45				
46-50				
51-60				

Source: created by the author based on (Navas, 2017) data

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