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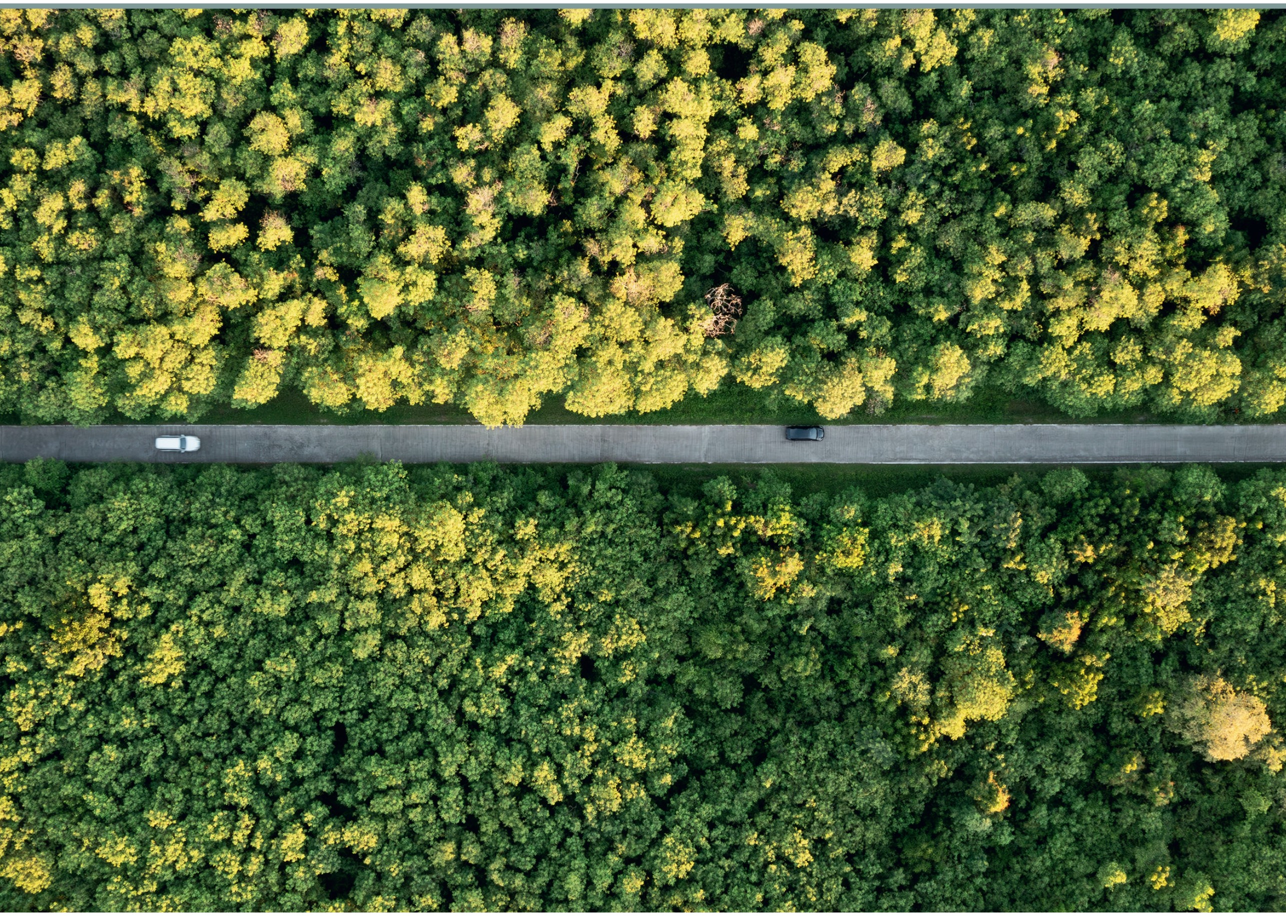
OPTIMAL PATHWAY TO A CLIMATE-NEUTRAL ENERGY SECTOR IN LATVIA

Doctoral Thesis



RTU Press
Riga 2025

RIGA TECHNICAL UNIVERSITY
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OPTIMAL PATHWAY TO A CLIMATE-NEUTRAL ENERGY SECTOR IN LATVIA

Doctoral Thesis

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RTU
Riga 2025

ANNOTATION

The world is experiencing alarming consequences of climate change. In Latvia, although seemingly slower, changes are occurring – the average air temperature is increasing, precipitation levels are rising in autumn and winter, summers experience more frequent droughts and intense rainfall, and strong storms and heatwaves are becoming more common. To mitigate the rapid pace of climate change, the European Union has set ambitious goals, and Latvia, like other EU member states, must achieve climate neutrality by 2050. Economic development, increasing public demands, and rising quality of life make it clear that leaving the economy on a "business as usual" track will not achieve the necessary emission reductions.

Achieving climate neutrality requires significant transformations and substantial investments, necessitating a clear long-term action plan for each sector and sub-sector individually and for the energy system as a whole. To move towards net-zero emissions while simultaneously fostering economic growth, measures must be implemented that not only effectively reduce greenhouse gas (GHG) emissions but also ensure the lowest possible overall costs.

The aim of this work is to evaluate the impact of policy instruments on achieving climate neutrality by modelling and analysing the national energy sector as a whole, as well as its sub-sectors individually. This goal includes adapting a modelling tool for Latvia's energy sector, which provides detailed results and serves as a basis for decision-making at the national, municipal, and business levels; identifying and integrating the most modern technological database and other parameters into the model structure; testing the impact of various policy instruments on achieving climate neutrality; and optimising measures to determine those that enable Latvia to meet its climate neutrality goals with the lowest possible total costs.

The TIMES modelling tool was used as the primary method for this research, combined with a system dynamics model, a forest expert model, and expert surveys.

This Doctoral Thesis is structured as a collection of publications developed during the doctoral studies. The Doctoral Thesis is based on six thematically unified scientific publications, which have been published in various scientific journals, indexed in academic databases, including SCOPUS, and included in international repositories. The aim of these publications is to evaluate policy instruments for achieving climate neutrality in Latvia.

The Doctoral Thesis consists of an introduction and three chapters. The introduction outlines the hypotheses, objectives, and tasks of the research, describes the structure of the Doctoral Thesis, and provides a brief overview of its validation process. The second chapter describes the process of developing the model for the Latvian case study, starting from the design of the energy sector structure, model validation, sensitivity analysis, scenario development, and linking with other models. The third chapter focuses on the modelling results, structured according to the level of detail, ranging from the technology level to results describing the entire energy system. The conclusion summarizes the main findings from the results obtained.

ANOTĀCIJA

Gandrīz ikviens uz pasaules ir ievērojis satraucošās klimata pārmaiņu sekas. Arī Latvijā, šķietami lēnāk, tomēr pārmaiņas notiek – palielinās vidējā gaisa temperatūra, rudens un ziemas mēnešos palielinās nokrišņu daudzums, vasarās – sausuma periodi, biežāk novērojamas spēcīgas lietusgāzes, stipras vētras, karstuma viļņi. Straujo klimata pārmaiņu bremzēšanai, Eiropas Savienība ir uzstādījusi ambiciozus mērķus – Latvijai tāpat kā citām Eiropas dalībvalstīm, līdz 2050.gadam ir jākļūst klimatneitrālai. Ekonomika attīstās, iedzīvotāju prasības un dzīves kvalitāte palielinās. Ir skaidrs, ka tautsaimniecību atstājot pašplūsmā, nepieciešamais emisiju samazinājums netiktu sasniegts.

Klimatneitralitātes sasniegšana pieprasa būtiskas pārmaiņas un apjomīgas investīcijas, tāpēc nepieciešams skaidrs ilgtermiņa rīcības plāns katram sektoram un apakšsektoram atsevišķi, kā arī energosistēmai kopumā. Lai tuvotos nulles emisijas līmenim un vienlaicīgi sekmētu ekonomikas attīstību, ir jāievieš pasākumi, kas ne tikai efektīvi samazina izdalīto SEG emisiju apjomu, bet arī nodrošina pēc iespējas zemākas kopējās izmaksas.

Darba mērķis ir izvērtēt politikas instrumentu ietekmi klimatneitralitātes sasniegšanai, modelējot un analizējot valsts enerģētikas sektoru kopumā, kā arī energosektorus atsevišķi. Galvenie uzdevumi mērķa sasniegšanai ir pielāgot modelēšanas rīku Latvijas energosektoram, kas sniedz detalizētus rezultātus un kalpo par pamatu lēmumu pieņemšanai valsts, pašvaldību un uzņēmumu līmenī; identificēt un iekļaut modeļa struktūrā mūsdienīgāko tehnoloģiju datu bāzi un citus parametrus; testēt dažādu politikas instrumentu ietekmi klimatneitralitātes sasniegšanā; veikt optimizāciju, lai noteiktu pasākumus, kas nodrošina Latvijas klimatneitralitātes mērķus sasniegšanu ar iespējami zemākām kopējām izmaksām.

Kā galvenais rīks pētījuma izstrādei ir izmantots TIMES modelēšanas rīks, apvienojot to ar sistēmdinamikas modeli, meža eksperta modeli un ekspertu aptauju.

Promocijas darbs ir veidots kā publikāciju kopa, kas apvienotas no doktorantūras laikā izstrādātajām publikācijām. Promocijas darba pamatā ir 6 tematiski vienotas zinātniskās publikācijas, kas publicētas dažādos zinātniskajos žurnālos, pieejamas zinātniskās informācijas krātuvēs un ietvertas starptautiskajās datubāzēs. Šo publikāciju mērķis ir novērtēt politikas instrumentus Latvijas klimatneitralitātes sasniegšanai.

Šis darbs sastāv no ievada un trim nodaļām. Darba ievadā aprakstītas darba hipotēzes, iekļauti darba mērķi un uzdevumi, aprakstīta darba struktūra un sniegts īss pārskats par promocijas darba aprobāciju. Darba otrajā nodaļā aprakstīts modeļa izstrādes process Latvijas gadījuma izpētei, sākot ar energosektoru struktūras izstādi, modeļa validāciju, jūtības analīzi, scenāriju izstrādi, visbeidzot sasaisti ar citiem modeļiem. Trešā nodaļa veltīta modelēšanas rezultātiem, kas strukturēti balstoties uz detalizācijas pakāpi, sākot no tehnoloģiju līmeņa, beidzot ar rezultātiem, kas apraksta visu energosistēmu kopumā. Darba noslēgumā aprakstīti galvenie secinājumi par iegūtajiem rezultātiem.

PATEICĪBAS

Vēlos izteikt pateicību profesorei Dagnijai Blumbergai, kura manī saskatīja vairāk kā es pati un bez kuras es neuzdrošinātos kāpt augstāk un visdrīzāk arī neatklātu savu patiku pret stāvēšanu auditorijas priekšā.

Milzīga pateicība profesoram Gatim Bažbaueram, kurš ir ne tikai mans drošais zinātniskā darba vadītājs, bet arī cilvēks, kurš apvieno inteliģenci un vienkāršību, ko ļoti novērtēju. Paldies par skatu no augšas, par atbalstu, iedrošinājumu un cilvēcisku sapratni, kad tas bijis nepieciešams.

Sirsnīga pateicība asociētai profesorei, zinātniskā darba vadītājai, kolēģei Ievai Pakerei, kura bijusi man visvairāk līdzās un atbalstījusi mani izaicinošākajos doktorantūras posmos. Paldies par atbalsta, iedrošinājuma vārdiem, vērtīgajiem ieteikumiem un sarunām par darbu un dzīvi.

Vēlos pateikties saviem zinātnisko rakstu līdzautoriem, kuri bijuši nozīmīgi manā doktorantūras ceļā – Ritvaram par izvešanu cauri TIMES labirintiem, Dzintaram par atbalstu un darba procesa virzīšanu un Andrai par neērtiem jautājumiem, kas paplašina skatu. Paldies Antrai un Līgai par pacietīgu atbalstu studiju un disertācijas iesniegšanas laikā. Paldies VASSI darbiniekiem, profesionālu, radošu, gudru prātu komandai, kuri uzstāda augstus darba kvalitātes standartus un iestājas par patiesi svarīgo.

Bet vismīļākā pateicība manai ģimenei – vīram, kurš ir mans lielākais atbalstītājs, bērniem, kuri ir mani svarīgākie vērotāji un balansa turētāji, mammai, kura satraucas un lepojas visvairāk, un tētim, kurš manu studiju noslēgumu vēro no debesu malas.

Mans doktorantūras ceļš ir bijis garš un piesātināts. Pārmaiņas un pārbaudījumi gan pasaulē, gan personīgajā dzīvē ir mani stiprinājuši un apliecinājuši, ka mēs katrs esam atbildīgi par savu dzīvi, savu rīcību un izvēlēm. Un katra no tām atstāj ietekmi uz pašu, planētu un tās iemītniekiem. Vislabāk, lai mūsu rīcību ietekme ir pozitīva, bet, ja ne pozitīva, tad vismaz klimatneitrāla.

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NOMENCLATURE

CGE – Computable general equilibrium models
CHP – combined heat and power (cogeneration) plants
COM – commercial sector
DH – district heating
ELC – electrical
ETS – European Union emission trading system
GDP – gross domestic product
GHG – greenhouse gas
HP – heating plants
IND – industry sector
LTH – total generated heat from plants in Latvia
LTHL – generated heat from plants in Latvia excluding Riga
LTHR – generated heat from plants in Riga
Mpkm – million passenger kilometers
NECP – National energy and climate plan
non-ETS – part outside European Union emission trading system
O&M – operation and maintenance
PaM – policies and measures
PV – photovoltaic panels
REPowerEU – a plan of EU to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition
RES – renewable energy source
RNW – renewable
RSD – residential sector
SD – system dynamics
SPC – the specific power consumption for lighting

INTRODUCTION

The consequences of global warming have become more realistic and more prominent in all regions. Therefore, policy makers implement various laws, regulations, policy measures, and other regulatory frameworks to limit the increase of the global average temperature. Energy production is one of the main drivers of global warming, which is related to all other sectors.

Research Topicality and Hypothesis

The hypothesis of the research is that the existing policies and measures (PaM) are insufficient to meet Latvia's 2030 climate targets. Achieving the required greenhouse gas (GHG) emission reductions for climate neutrality by 2050 will necessitate the implementation of additional, science-based PaM that are evaluated for long-term effectiveness.

Energy is the foundation of any country and economic sector. The production, export, import, use, and management of energy are among every nation's most critical strategic concerns. Equally significant are the environmental pollution caused by the energy industry and the growing importance of energy security, especially in recent years. This is particularly relevant in Europe, including Latvia.

Despite being grounded in large constructions, transport networks, and logistics, the energy sector remains fragile and sensitive to political developments and economic changes. Effective management requires precise and nuanced research. Recent decades of research in the energy field indicate the necessity of developing renewable environmental technologies, yet investments continue to be made in fossil fuel plants.

Globally, in 2019 compared to 2010, net GHG emissions have increased in all major sectors, and about 34 % of net GHG emissions came from the energy sector. Although the rate of GHG emissions growth between 2010 and 2019 was 1.3 % per year compared to 2.1 % in the previous decade, the amount of average annual GHG emissions was higher than in any previous decade (IPCC, 2023).

It is necessary to be able to make long-term decisions, which must be based on scientific research, at the level of any country, municipality, company, and even household.

Latvia is rich in green resources that must be optimally utilised through cooperation between business sectors, municipalities, ministries, and scientific institutes. Implementing technologies and solutions that are both economically viable and capable of achieving energy efficiency and environmental goals is essential. Energy demand must be met wisely to preserve and improve the surrounding environment.

While each of us is responsible for our choices, the state and municipalities must lead by example by making strategic, scientifically based decisions and supporting innovative technologies and solutions.

Aim and Objectives

The aim of this work is to evaluate various PaM (e.g., increase in fossil fuel tax, subsidies for building insulation, and transition to electric transport) for achieving climate neutrality by modelling and analysing the national energy sector as a whole as well as individual economic sectors separately.

The main objectives for achieving the goal are:

- adapt the TIMES modelling tool to Latvia's energy sector to provide detailed results for justified decision-making at both national and company levels;
- identify and incorporate the latest technology database and other parameters into the model structure;
- analyse the impact of various policy instruments on achieving climate neutrality;
- conduct optimisation to find the most cost-effective solutions for reaching climate goals;
- determine the resource allocation of the energy sector that ensures Latvia's climate neutrality goals with the lowest possible total costs.

Scientific Novelty

A novel TIMES modelling approach has been developed, including innovative solutions (introduction of a comfort level factor in the transport sector, demand for heated m^2 in the residential and commercial sectors, industrial heat recovery in the industrial sector, etc.), which provides expanded opportunities to analyse a wide range of PaM and perform optimisation tasks to determine how to achieve climate goals with minimal total costs and determine the amount of investment necessary to achieve climate neutrality in 2050.

The scientific work is based on three pillars: PaM, climate neutrality, and the optimisation between them, which is carried out using the TIMES modelling tool (see Fig. 1).

The TIMES modelling tool allows, on one hand, the evaluation of the ability of pre-developed PaM to achieve climate neutrality. On the other hand, modelling the attainment of climate neutrality helps identify areas where PaM with lower total costs can be developed.

The optimisation includes an analysis of each economic sector – energy transformation, residential, commercial, transport, agricultural and industrial which are presented in scientific articles listed in Table 1.

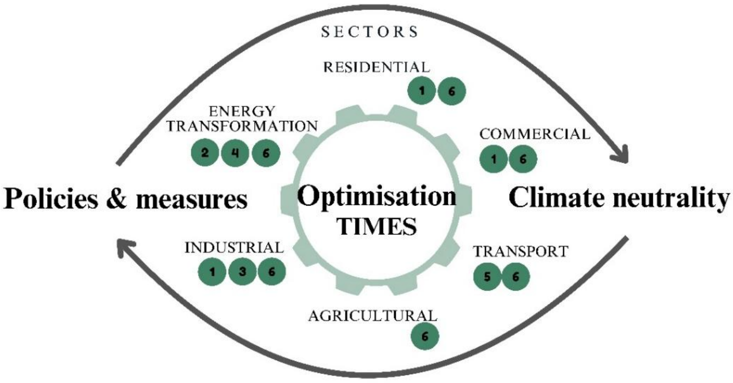


Fig.1. Three pillars of the research algorithm.
Numbers represent scientific articles of the analysed sectors.

Table 1

Scientific Articles Used in the Doctoral Thesis

No	Publication title	Analysed sectors
1.	Adaptation of TIMES model structure to industrial, commercial and residential sectors	Industrial Commercial Residential
2.	Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling	Energy transformation
3.	Decarbonisation Pathways of Industry in TIMES Model	Industrial
4.	Can energy sector reach carbon neutrality with biomass limitations?	Energy transformation
5.	Passenger transport shift to green mobility - assessment using TIMES model	Transport
6.	Cost-Optimal Policy Strategies for Reaching Energy Efficiency Targets and Carbon Neutrality	All

To identify cost-effective PaM for achieving climate neutrality, leading to specific energy efficiency and climate goals, novel modifications to the model have been made, including:

- sector linkages for energy system optimisation have been established;
- a detailed, sector-specific technology database has been included;
- heat recovery from industrial equipment has been incorporated;
- the modal shift of transport modes for different distances has been established, including the social factor;
- the demand for heated and cooled m^2 in the residential and commercial sectors has been incorporated to include energy efficiency measures.

Practical Significance

Enables the adoption and development of science-based, well-reasoned decisions and PaM to achieve climate neutrality goals for:

- ministries (economy, environment) – provides a foundation for national decision-making and the development of PaM;
- municipalities – serves as a basis for making local policy decisions, particularly in the development of heat supply systems;
- representatives of various sectors – aids in investment evaluation.

Approbation of the Research Results

1. Dzintars Jaunzems, Ieva Pakere, Signe Allena-Ozolina, Ritvars Freimanis, Andra Blumberga, Gatis Bazbauers, **Adaptation of TIMES model structure to industrial, commercial and residential sectors,** Environmental and Climate Technologies, 2020, Vol. 24, No. 1, 392–405. ISSN 1691-5208. e-ISSN 2255-8837. doi:10.2478/rtuect-2020-0023

2. Signe Allena-Ozolina, Ieva Pakere, Dzintars Jaunzems, Andra Blumberga, Gatis Bazbauers, **Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling,** 2020, IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2020): Conference Proceedings, Latvia, Riga, 5–7 November

2020. Piscataway: Institute of Electrical and Electronics Engineers Inc., 2020, 456–462. ISBN 978-1-7281-9511-7. e-ISBN 978-1-7281-9510-0. doi:10.1109/RTUCON51174.2020.9316623

3. Signe Allena-Ozolina, Dzintars Jaunzems, Ieva Pakere, Andra Blumberga, Gatis Bazbauers, **Decarbonisation Pathways of Industry in TIMES Model,** Environmental and Climate Technologies, 2021, Vol. 25, No. 1, 318–330. ISSN 1691-5208. e-ISSN 2255-8837. Available from: doi:10.2478/rtuect-2021-0023

4. Signe Allena-Ozolina, Ieva Pakere, Dzintars Jaunzems, Andra Blumberga, Armands Gravelsins, Dagnis Dubrovskis, Salvis Dagis, **Can energy sector reach carbon neutrality with biomass limitations?** Energy, 2022, Vol. 249, Article number 123797. ISSN 0360-5442. Available from: doi:10.1016/j.energy.2022.123797

5. Signe Allena-Ozolina, Ieva Pakere, Dzintars Jaunzems, Ritvars Freimanis, Andra Blumberga, Gatis Bazbauers, **Passenger transport shift to green mobility – assessment using TIMES model** Environmental and Climate Technologies, 2022, Vol. 26, No. 1, 341–356. ISSN 1691-5208. e-ISSN 2255-8837. Available from: doi:10.2478/rtuect-2022-0026

6. Ieva Pakere, Ritvars Freimanis, Signe Allena-Ozolina, Pauls Asaris, Andrea Demurtas, Marine Gorner, Jessica Yearwood, **Cost-Optimal Policy Strategies for Reaching Energy Efficiency Targets and Carbon Neutrality,** Environmental and Climate Technologies, 2023, Vol. 27, No. 1, 999–1014. ISSN 1691-5208. e-ISSN 2255-8837. Available from: doi:10.2478/rtuect-2023-0073

Thesis Structure

The Doctoral Thesis is based on six thematically related scientific articles that have been presented and applauded in various scientific conferences. All articles are accessible in international citation databases. Scientific articles describe the modelling approach to the identification and evaluation of PaM for achieving climate neutrality in the energy sector.

The Thesis consists of an introduction and four chapters:

- Literature review,
- Research methodology,
- Results,
- Conclusions.

The introduction presents the aim of the Doctoral Thesis, the scientific and practical importance of the work, and a brief outline of the approbation of published research results at various scientific conferences.

Chapter 1 section of the Thesis includes a literature review on the topicality of energy system transformation towards climate neutrality. Chapter 2 describes the research methodology for implementing and evaluating PaM for different sectors. Chapter 3 presents the energy resource transition at different levels – technological, process, sub-sector, sector, and finally, overall energy sector. In the last chapter, the main conclusions are drawn.

1. LITERATURE REVIEW

The main goals of the European Union (EU) Green Deal are to reduce greenhouse gas (GHG) emissions by 55 % by 2030, compared to 1990, and to reach climate neutrality by 2050 (EC, 2019). Previous Research on EU Green Deal targets spans various aspects, including the efficiency of effort-sharing regulation and overall binding policy (Veum & Bauknecht, 2019), fairness and ambition levels (Hof et al., 2016), and how these targets mark a shift towards a more technology-neutral EU climate policy (Fitch-Roy et al., 2019). Research shows a need for a governance framework to ensure that Member States contribute to the EU-level target (Resch et al., 2019). Implementation of climate actions and reaching the set EU targets have important impacts on the overall energy system operation (Rafiee et al., 2021; Simoes et al., 2017), environment (Meessen, 2020), and economics (Temursho et al., 2020) as well as on the specific subsectors (Li et al., 2020; Runge-Metzger & Wehrheim, 2019; Siddi, 2021) which need to be considered.

To comply with EU climate ambitions, researchers have been testing different policies and scenarios to develop guidelines for policymakers and search for cost-effective renewable energy solutions (Papadogeorgos et al., 2017). The OECD report (OECD, 2019) reports that even though Latvia has achieved a high renewable energy share, a long way towards more sustainable use of available resources is ahead. Also, other research (Dolge & Blumberga, 2021) confirmed that the existing climate policies are not enough to reach the Green Deal targets in Latvia.

Although TIMES is a powerful modelling tool, some articles discuss the need to consider not only technology development but also feedback loops, social behavioural changes, and other factors (Bolwig et al., 2018). Some TIMES models have been improved by adding consumer behaviour in the optimisation model using social surveys (Li et al., 2018; Reveiu et al., 2015; Cayla & Maïzi, 2014).

1.1. Multi-sectoral energy systems analysis

Different energy models can play a crucial role when developing energy planning strategies.

In France, researchers have developed the integrated MARKAL-EFOM System (TIMES) model to evaluate the possibility of achieving negative emissions in the energy sector by using bio-plants with carbon capture and storage. The study shows that these technologies will be important in achieving European emission targets (Selosse & Ricci, 2014). Soft linking between two models, Dispa-SET and JRC-EU-TIMES, has been done to analyse the potential of sector coupling in Europe (Pavičević et al., 2020). It is concluded that linkage between sectors can play a crucial role in carbon emission reduction and integration of RES. The results also show that different models can be linked to get more detailed and precise results.

Researchers from China have created a multi-sectoral energy model merging electricity, transportation, heat, and industrial sectors to model the decarbonisation of an energy system (Burandt et al., 2019). Often, researchers combine different types of models, for example, technically detailed bottom-up and top-down models that simulate demand and prices on energy

(Andersen et al., 2019; Wu et al., 2018). The system dynamics approach has been used to model the transition from fossil fuels to renewable energy resources by taking into account different techno-economic parameters, political and social aspects, as well as human behaviour (Gravelsins et al., 2018).

In many countries, researchers have used the Integrated MARKAL-EFOM System (TIMES) model generator to analyse local, national, and global energy systems and their potential to reach climate targets. In most cases, the basic sectoral structure of TIMES needs to be adjusted and modified to represent the country-specific energy system. German researchers have developed the TIMES model to improve decision-making related to investments. In the adapted energy model, the country is divided into four regions, but investors are divided into three groups depending on the costs of capital and budget restrictions (Tash et al., 2019).

The energy system model has also been created for Denmark. The model divides the country into two energy regions – Denmark East and Denmark West and covers five sectors – supply, power and heat, industrial, residential, and transport. The authors divide the residential sector according to the building type and construction period, district heating (DH) area, and regions, resulting in 36 building groups. In contrast, the industry sector is divided into 12 sectors, covering primary, secondary, and tertiary sectors. The transport sector has two large groups – passenger and freight, divided into aviation, maritime, and inland. Inland passenger transport has been divided into eight modes, including cars, buses, railways, motorcycles, and non-motorised modes like walking and biking (Balyk et al., 2017).

In a study carried out in 2016, a scenario achieving 100 % renewable energy share in the EU by 2050 was introduced (Connolly et al., 2016) by showing that smart energy systems can be leveraged to achieve 100 % renewable energy share. The introduced scenario includes the decommissioning of nuclear power plants, energy efficiency measures in buildings, electrification of private transportation, use of heat pumps in rural areas and district heating in urban areas, and switching from natural gas to bio-methane. Through this research, it has been proved that the use of biomass for energy production, which is not the most sustainable solution, is not a key pillar of renewable transition by the EU, as shown in previous research (JRC, 2015). Also, for Latvia, decarbonisation is possible with limited use of biomass (Allena-Ozolina et al., 2022). Previous studies concluded that in Latvia, there is a high potential for RES integration and that targeted policies can reduce CO_2 emissions by 70 % in 2050 (Blumberga et al., 2016). Moreover, implementing effective policies toward bio-economy makes it possible to utilise locally available low-quality bioresources for the production of higher-added-value products (Allena-Ozolina et al., 2017).

Detailed modelling tools are necessary to evaluate the long-term impact of complex energy system transformation scenarios. One such is The Integrated MARKAL-EFOM System (TIMES) linear optimisation tool, which has been widely used to simulate the long-term effects of future transformation pathways of energy systems (Zhu & Ming, 2022; Allena-Ozolina et al., 2022; Salvucci et al., 2018). There are many aspects that influence the optimal solution for the integration of renewable energy into the energy system, although these may involve trade-offs, competition for the same resource, and complex interdependencies, such as electrification of all sectors of the region and cross-border transmission of electricity (Pina et al., 2011). It has been found that the electrification of different sectors and the uptake of technologies within a system-integration framework, such as electric vehicles, power-to-gas, and energy storage, can successfully smooth out the variability of renewable energy (Daly et al., 2015).

When using modelling tools, such as TIMES, user input data, such as prices and technical potential for renewable energies, has a major impact on the modelling results; therefore, it is crucial to make modelling tools transparent and make all the input data available to the public, as most of the input data is an assumption and should be further improved by scientific debate (Connolly et al., 2016; Lima, 2019).

1.2. Energy system development in specific sectors and sub-sectors

Residential sector

In many countries, sector‑specific energy models have been developed, such as the household sector model, which analyses and evaluates the implementation of renewable energy systems for regional demand (Han & Kim, 2017). Many simulations are performed to identify heat demand and to simulate future demand by clustering the residential sector in the UK (McCallum et al., 2019). Also, in Quebec (Canada), the electricity supply of households that are already low-carbon has been modeled by combined building model simulations to investigate mitigation opportunities of greenhouse gases (GHG) (Astudillo et al., 2017).

British researchers have developed a model framework in the UK for the residential sector in TIMES to analyse homeowner preferences for heating technologies. Households were divided into three groups depending on a number of bedrooms and into four groups depending on the existing heating technologies – gas heaters, electric heaters, heat pumps, and solid fuel boilers. In this model, 16 time slices have been used, representing four seasons and four-day splits (Li et al., 2018).

Energy transformation sector

There are many studies that analye different parts of the energy sector, e.g., the power sector. Several European countries have set a target to reach carbon neutrality by 2050. One of the first conceptual studies analysing the 100 % renewable energy system was presented for Denmark by Lund et al. in 2010 (Lund et al., 2009). The paper defined a scenario to reach carbon neutrality in the heating sector in 2060 by combining reductions in space heating demands by 75 % and various heating options, including district heating, individual heat pumps, and micro combined heat and power production.

Other Nordic countries have developed a plan to achieve carbon neutrality by speeding up the decarbonisation process in energy-intensive sectors, industrial-scale technologies, incentives for alternative technologies, and increased emission reduction requirements (CE, 2020). In addition, the Finnish government has set a very ambitious target to move toward carbon neutrality by 2035. The strategy includes coal phase-out by 2029 and combining biomass, waste heat sources, heat pumps, and RES power for heat supply decarbonisation (Khosravi et al., 2020).

The role of power storage in covering a higher share of renewable energy in Europe has been analysed by F. Cebulla et al. (2017). Another study has been done on the required backup energy in the case of 100 % renewable energy usage in Europe, considering different grid connection and storage possibilities (Steinke et al., 2013). Research of 100 % renewable power systems in Europe with a focus on the Netherlands (Zappa et al., 2019) shows that to meet this target, there is a need to increase the renewable energy resource (RES) and cross-border transmission capacities, as well as to use technologies with higher efficiency. Other studies cover the whole energy sector, including heat and power generation. Cogeneration and thermal storage potential in energy system has been analysed by J. P. Jiménez Navarro et al. (Jiménez Navarro et al., 2018). Another research focuses on using intermittent RES sources such as wind and solar in smart energy system, which includes smart electricity, thermal and gas grids, and thus decreasing emissions (Mathiesen et al., 2015).

The German energy transition targets (Energiewende) a competitive low-carbon economy until 2050 by excluding nuclear power from the energy balance by 2022 (Schmid et al., 2016). However, decarbonisation of the heating sector in Germany has been associated with the increase of heat pump installed capacities as the power sector is a step ahead of the implementation of RES, such as wind and solar technologies. Wiese et al. (2022) have compared the results from previous research on decarbonisation strategies for Germany and concluded that critical strategies are the reduction in energy demand, an expansion of domestic wind and solar energy, increased use of biomass as well as the importation of synthetic energy carriers. Authors have attributed a limited role for storage but a high potential for demand-side solutions.

The research results for the United Kingdom's heat supply decarbonisation shows that it requires that heat-related emissions of CO_2 from buildings reach a near-zero level by 2050, and there should be a 70 % reduction in emissions from industry (Chaudry et al., 2015). In addition, the modelling results show the small remaining role of natural gas for peak load coverage.

The model of deep decarbonisation for Italy shows that emissions can be cut by 79–97 % compared to 1990 levels due to an increased share of RES, radical electrification of the energy, and increased production energy of technologies (Borasio & Moret, 2022).

Industrial sector

There are also several studies analysing industry sector development, e.g., the bottom-up simulation model FORECAST model was created in order to analyse several scenarios of industry sector decarbonisation (Fleiter et al., 2018). Another model was used for the investigation of the energy efficiency performance of 18 main industrial sub-sectors of Latvia, where composite index methodology was used to develop an energy efficiency index (Dolge et al., 2020). A nonlinear autoregressive distributed lag model was used to investigate the relationship between energy efficiency and economic growth of 11 European Union countries (Marques et al., 2019).

A comparison of possible transition of industry sector performance under a 2-degree target between China, India, and Western Europe was made using the Global TIMES model (Wang & Chen, 2019). In this study, two groups of scenarios were completed – the reference scenario group with no constraints on CO_2 emissions and the 2-degree scenario group with constraints on the global CO_2 budget. Results show that, in the group of the reference scenarios, the global industrial energy demand and CO_2 emissions would increase. The scenarios with constraints on the CO_2 budget are also not sufficient to meet the CO_2 target in 2050. The gap between regions could be narrowed, and China is expected to have a faster CO_2 reduction speed than the average worldwide. It is recommended that stricter energy efficiency standards be implemented, such as low-interest loans and subsidies, to decarbonise the industrial sector and meet the 2-degree target.

Many studies focus on energy-intensive industry subsectors. A techno-economic model based on TIMES has been built for the cement sector in Switzerland (Obrist et al., 2020). In this study, long-term energy consumption and CO_2 emission reduction by 2050 are taken into account. TIMES standard model was expanded by adding additional material and product flows. Results show that it is economically beneficial to replace and use new, more efficient equipment even without policy measures. Results show that in order to comply with the goals of the Paris Agreement, the cement sector relies on CO_2 capture technologies. CO_2 tax needs to be 70 EUR/t to make these technologies economically competitive.

In another study, a detailed and rich technological database was created for the five most energy-intensive industrial subsectors – iron and steel, non-ferrous metals, non-metallic minerals, chemicals, and pulp and paper (Lerede et al., 2021). This database is based on a review of the technological outlook in the bottom-up models belonging to the TIMES family. The study includes 65 technologies, from traditional technologies to technologies that are still in the research phase. A powerful tool for a critical evaluation of other energy model results regarding energy use and CO_2 emissions is provided.

Some other studies covering energy-intensive industries were conducted in other countries. The effect of the European Industrial Emissions Directive on air emission values was evaluated in Spain (Calvo et al., 2021). Researchers conclude that the Directive ensures a more uniform approach in emission level value, which is in line with emission levels associated with the best available techniques. This Directive may lead to the European Green Deal target. Another study on the cement industry was made in France, where an energy model was built to assess future power generation in the cement industry on an international and regional scale (Hache et al., 2020). Energy system models and a material flow models were made to assess the impact on the cement industry's performance in limiting global warming (Dhar et al., 2020). Energy conservation and CO_2 abatement potential were analysed in the cement industry of Germany (Brunke & Blesl, 2014), and specific characteristics of the cement industry were added to the globally integrated assessment model to analyse energy consumption and GHG emissions (Kermeli et al., 2019).

The chemical industry has also been analysed a lot. A life cycle approach was used to create a modelling framework to evaluate the energy and GHG impacts of new technologies (Yao &. Masanet, 2018), while another energy optimisation and prediction model was created to analyse energy efficiency improvements in the petrochemical industry (Geng et al., 2020). The clustering algorithm in the modelling process is used for the assessment of performance and optimisation of energy division in the petrochemical industry (Han et al., 2019). A structural model based on fuzzy theory was made to analyse the energy structure and energy-saving potential of chemical industries (Geng et al., 2018). The iron and steel subsector was also analysed in the United Kingdom of Great Britain and Northern Ireland by modelling technological change and investigating future resource demands and amount of GHG emissions (Griffin & Hammond, 2018; Griffin & Hammond, 2019). Investigation of the possibility of replacing fossil fuels with bio-methane was done for the Swedish iron and steel industry using an optimisation model that minimized the total system's cost (Ahlström et al., 2019). A technology-based floor price model was made to analyse the competitiveness and energy efficiency of the steel industry (Vögele et al., 2020).

Fewer studies focus on non-energy intensive industries like the food industry. A system dynamics model was made to assess energy savings in the United States food industry (Xu & Szmerekovsky, 2017), while a detailed, bottom-up energy model was built for the French food and beverage industry to analyse energy efficiency and amount of CO_2 emissions (Seck et al., 2013). Resource efficiency is assessed in the food industry by using an optimisation model in another study (Jonkma et al., 2020).

Transport sector

A system dynamics modelling approach is also widely used for transport sector modelling. For the case of Latvia, systems dynamics models are developed to analyse CO_2 emission reduction potential in road transport (Barisa & Rosa, 2018; Barisa & Rosa, 2018) and to explore a possible promotion of biomethane (Barisa et al., 2020). The system dynamics model is built to support policymakers in testing different policy scenarios to improve road safety in the USA (Alirezaei et al., 2017). The transition towards alternative fuels (Shafiei et al., 2015) and the potential of biofuels (Shafiei et al., 2015) were modelled in an integrated system dynamics model for Iceland.

An integrated assessment model, ASTRA, based on the system dynamics approach, was developed more than 20 years ago with additional economic and environmental impact assessment for a transport system at the European level (Fiorello et al., 2010). The ASTRA model is used in several studies – to analyse the impact of electric bikes on modal split in Europe (Astegiano et al., 2018) and to test the effect of transport policies on shifting passenger travel to public transport in Portugal (Nunes et al., 2019). In addition, the European Commission's policy of a Europe-wide multimodal transport network, TEN-T, is based on the interaction of two models – ASTRA and TRUST (Schade et al., 2018). Possible employment implications of connected and automated driving (CAD) were tested using ASTRA and NEMESIS models as well (Smit, 2020). Analysis of the development towards a low-carbon energy system in Europe until 2050 was done by coupling different bottom-up models, including ASTRA and TE3, which is also developed for transport sector analysis by applying the system dynamics approach (Möst et al., 2021).

Computable general equilibrium (CGE) models are also used for transport sector analysis. The socioeconomic impact of a public-private partnership's transportation infrastructure is investigated through capital expenditure and tax burden economic effects using CGE (Chen et al., 2017). An investigation of the long-term environmental and economic impact of new rail infrastructure on the cargo transport sector was conducted using the CGE approach with dynamic components (Cardenete & López-Cabaco, 2020). CGE model and a specialist highway model, HERS of the U.S., were combined to analyse infrastructure policies (Dixon et al., 2017).

The linear optimisation TIMES model has been previously used to evaluate the sensitivity of the European road transport sector considering different variations of investment cost and vehicle efficiency (Lerede et al., 2021). Additionally, stochastic multicriteria acceptability analysis is used to evaluate modelling results under an economic and environmental criterion complementing the cost minimisation approach. Electric vehicles are seen as the most favourable in all three dimensions of the study. This methodology supports decision-makers in the analysis of policy frameworks not only from the perspective of cost-effectiveness but also from an economic and environmental viewpoint. Another study presents an introduction of the consumer behaviour aspect into the TIMES optimisation model (Ramea et al., 2018). The classic consumer choice model is incorporated into a typical long-term energy modelling framework as a case study of purchasing light-duty vehicles. Thirty-six consumer segments were created to represent different factors, such as driving distances and acceptance of new technologies.

Modal shift is assessed for Scandinavia's transport sector using the TIMES model (Salvucci et al., 2019). Passenger and freight modal shift is based on a real case study. This approach allows additional measures to be included toward the decarbonisation of the energy sector. Results showed that rail and non-motorised transport modes, e.g., walking and cycling, increase passenger mobility while rail replaces trucks and ships for freight. Also, other papers represent the importance of the modal shift to reach carbon neutrality in the transport sector (Tattin et al., 2018; Salvucci et al., 2018).

When it comes to the transport sector, changes in technology and fuel switching are not enough to mitigate climate change, policies must focus on behavioural change in the use of transportation (Green et al., 2012). Typically, the TIMES model as an optimisation tool does not include competition between different travel modes, but with the introduction of elements such as – travel time budget, travel speed, comfort, etc., it can be applied for broader policy modelling (Brown et al., 2018; Ollier et al., 2022; Dalla Longa et al., 2018).

Previous studies show that issues related to the development of the energy sector are important in terms of individual countries, regions, and sectors. Similarly, developing powerful modeling tools is important for various levels of analysis and decision-making. In Latvia, too, it is necessary to develop a methodology that would be able to find the direction of development of the energy sector to ensure the fulfillment of the obligations set by the Paris Agreement and the European Climate Law - to achieve climate neutrality by 2050. For a small economy like Latvia, it is especially important to find solutions to achieve this goal with the lowest possible total costs, which this Doctoral Thesis offers.

2. METHODOLOGY

2.1. TIMES – optimisation tool for energy systems modelling

The vertically integrated model generator TIMES is used worldwide to model different local, national, or global energy systems. It aims to find the minimum global costs for energy services by considering different input data: energy service demands, estimates of the existing energy stocks, properties of the existing equipment, and future technologies. Furthermore, TIMES allows the analysis of different energy and environmental scenarios and policy measures (Loulou et al., 2016).

Mathematically, a TIMES model can be formulated as a Linear Programming (LP) problem consisting of three main components: (1) the objective function, which is either minimized or maximized; (2) the decision variables, which represent the endogenous quantities determined by optimisation, and (3) the constraints, which are equations that must be satisfied by the optimal solution. Simplified, the model of this study can be written as the following linear programming problem:

$$\text{Minimize} \quad \sum_{t=2017}^{2050} \sum_{i=1}^{I} \sum_{k=1}^{K} c_{it}^{k} X_{it}^{k} \qquad \text{i}=\overline{1,\text{I}};\ \text{k}=\overline{1,\text{K}};\ \text{t}=\overline{1,\text{T}} \tag{2.1}$$

$$\text{Subject to:} \quad \sum_{i=1}^{I} \sum_{k=1}^{K} G_{it}^{k} X_{it}^{k} \geq D_{it} \qquad \text{i}=\overline{1,\text{I}};\ \text{k}=\overline{1,\text{K}};\ \text{t}=\overline{1,\text{T}} \tag{2.2}$$

$$b_{it}^{k} \cdot X_{it}^{k} \leq B_{t} \qquad \text{i}=\overline{1,\text{I}};\ \text{k}=\overline{1,\text{K}};\ \text{t}=\overline{1,\text{T}} \tag{2.3}$$

where

Economic Interpretation of the Endogenous Parameter:

X_{it}^{k} – the **intensity of use** of technology type k for producing energy service type i in period t (e.g., intensity of use of pellet boilers used for heat production, in h/year).

Interpretation of the Indices:

K (k=1,2,…,K) – Categories of **final consumption technologies** (e.g., pellet boilers).
I (i=1,2,…,I) – Categories of **energy services** (e.g., heat energy).
T (t=2017,2018,…,2050) – **period** (year).

Economic Interpretation of the Exogenous Parameters:

<u>Description of the Objective Function Element:</u>

c_{it}^{k} – the production **cost** of energy service type i using technology type k in period t (e.g., equipment operating costs, resource costs, etc., for using pellet boilers in heat production, expressed in €/h).;

<u>Description of Total Demand:</u>

G_{it}^{k}– the total **capacity** of technology type k for producing energy service type i in period t (e.g., the total capacity of pellet boilers for heat production, in MW).

D_{it} – the **total demand** for energy service type i in period t (e.g., the total demand for heat energy, in MWh).

Description of a Specific Constraint Example:
b_{it}^{k} – the **specific resource consumption** when producing energy service type i using technology type k in period t (e.g., pellet consumption in pellet boilers for heat production, in t/h).
B_t – the **set of constraints** in period t (e.g., the total available pellet quantity, in t/year).

In this study, the objective function aims to minimize the total discounted costs (2.1.) of the entire energy system while ensuring the necessary energy supply to various sectors (2.2.) under the constraints outlined in equation 2.3. (e.g., the projected amount of biomass available to the energy sector).

TIMES is also known as a bottom-up, linear programming tool applied for long-term energy systems planning to allow for the analysis of the effect of different scenarios. It optimises the whole energy system, including supply and demand services, by minimizing the total cost in the considered modelling period (Loulou et al., 2016). To achieve the goal of the Thesis, TIMES has been selected as the modelling tool due to its powerful technical and economic capabilities, which allow it to analyse the whole energy system and find the most economical allocation of technologies and resources, allowing to assess the impact of planned PaM.

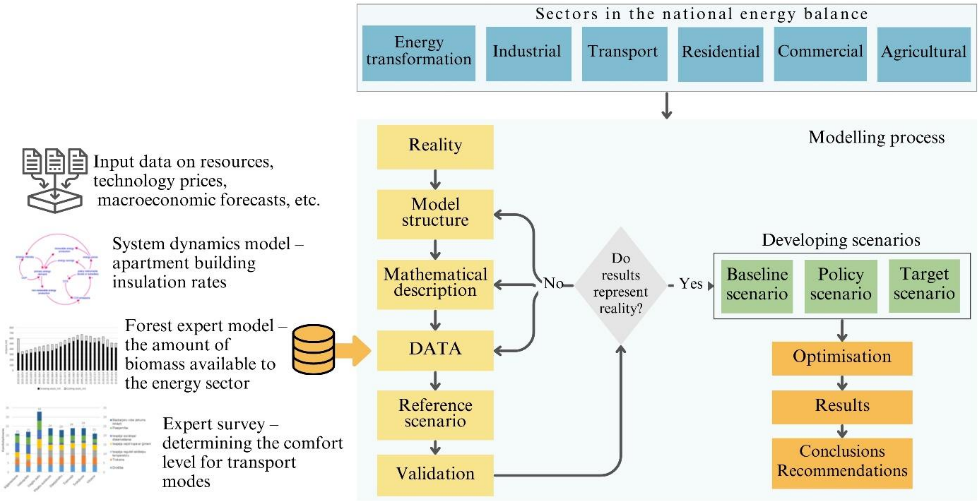


Fig. 2.1. Research algorithm and modelling steps.

The methodology applied in the Doctoral study consists of several steps (see. Fig. 2.1). Description of reality, development of model structure, mathematical description of conditions, and collection of model input data are the first steps. In the next step, the reference scenario is being processed and validated. If the validation results do not describe reality sufficiently well, then the model structure, mathematical description, and data are reviewed and improved. When the validation results match the real situation sufficiently well, optimisation of the scenarios can be done. In the final phase, the results are compiled, and conclusions are put forward.

2.2. Development of the TIMES model for the national level energy system

The built TIMES Latvia model is a linear optimisation tool developed and improved to characterize the energy sector and relevant sub-sectors (Zhu & Ming, 2022; Allena-Ozolina et al., 2022). In the TIMES Latvia energy system model, the full energy system is represented from resource supply to end-use energy services demands, such as space heating, production processes, and personal/freight transport (in passenger or tonne-kilometre) (Ollier et al., 2022). The model represents a broad suite of energy and emission commodities, technologies, and infrastructure (Jaunzems et al., 2020). However, the model does not include detailed analyses and forecasts for non-energy sectors, e.g., agriculture and waste management.

The modelling process analyses each sector separately, making improvements in each of them, bringing the model closer to the real-life situation to obtain more complete results and incorporate different PaM, such as sector-specific funding, taxation, GHG target, etc. The reference energy system describes the structure and energy flows of the energy system of Latvia, covering primary energy resources, conversion technologies (e.g., electricity and heat production technologies), transmission and distribution infrastructure (e.g., electricity grid, heating networks, or gas pipeline), end-use technologies (e. g., boilers, heat pumps, cars) and energy service demands. Certain limitations on available energy sources have been derived as input parameters from the forestry management model and the agriculture model used in previous studies (Allena-Ozolina et al., 2022).

Fig. 2.2 presents the structure of the created TIMES Latvia model. The supply block on the left side, which includes the energy transformation sector with electricity and heat production plants. This supply block also encompasses energy resources, both local and imported, as well as fossil and renewable resources. On the right side is the demand block, which includes five sectors and sub-sectors along with their characteristic technologies and final energy services.

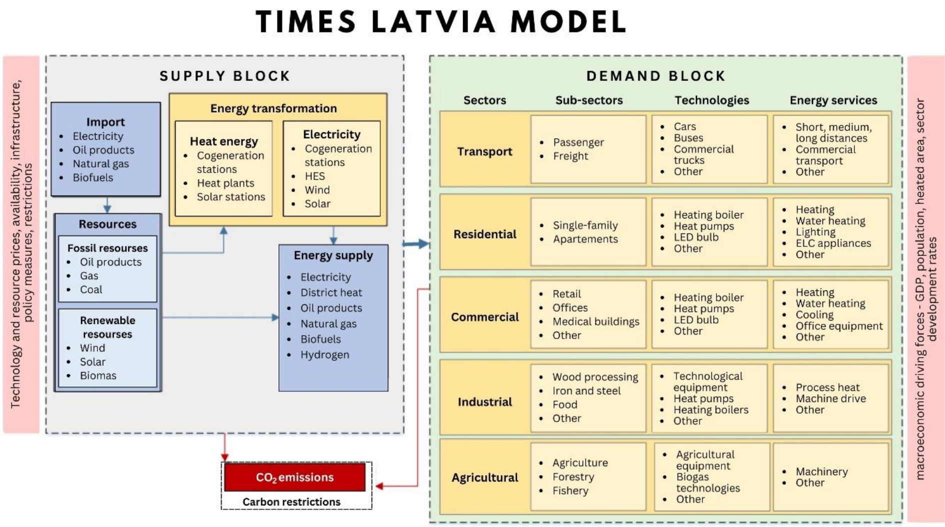


Fig. 2.2. Structure of the created TIMES Latvia model.

The TIMES Latvia model was developed gradually by analysing each sector, incorporating the latest available technology and other parameter databases, and creating sector-specific improvements. This approach ensures the ability to analyse the impact of various PaM. Scientific articles were written sequentially by sector, as shown in Fig. 2.3.

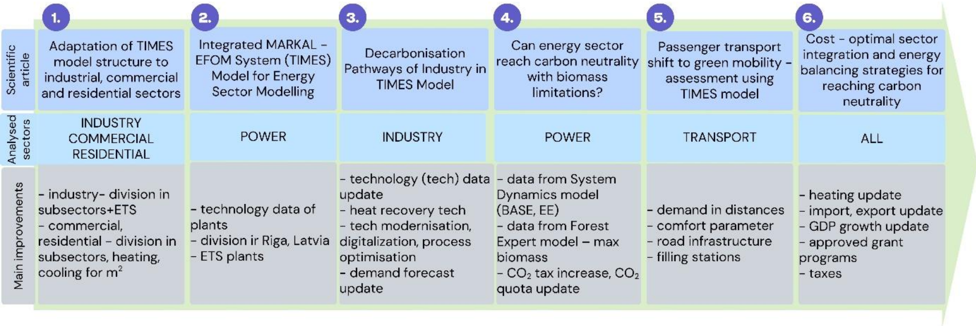


Fig 2.3. Model development in scientific articles.

The industrial, commercial, and residential sectors are described in the first article, which analyses and outlines the main model improvements, such as industry division into sub-sectors and separating of the European Union emission trading system (ETS) part of industry, as well as the commercial and residential sectors adding cooling and heating parameter depending on square meters. The second article examines the energy transformation sector, detailing key technological data and dividing ETS and non-ETS stations, as well as differentiating between Riga and the rest of Latvia. The third article focuses on the industrial sector, highlighting the most significant improvements in technological data updates. The fourth article also addresses the energy transformation sector, but it includes integration with other modeling tools and incorporates CO_2 tax and quota increases. Structural changes in the transport sector are described in the fifth article, while the sixth article covers all sectors. The modeling approach for each sector is detailed in the following subsections.

2.2.1. Modelling of specific sectors and sub-sectors

The following subsections describe the modelling approach and structural improvements for the industrial, commercial, residential, energy transformation, and transportation sectors, specifically passenger transport on land.

Industrial sector modelling

Latvia is a part of the ETS. Therefore, the energy demand of almost every industrial (IND) sector in Latvia has been divided into ETS sector and non-ETS sector consumption (see Table 2.1). The ETS system of Latvia mostly covers power plants and other incineration plants with a nominal thermal input of more than 20 MW. Specific equipment, like coke ovens, iron and steel, cement clinker and other technologies, are included in the ETS system (EP, 2015). In 2017, the ETS sector covered around 15.5 % of the total resource demand in Latvia equal to 5 561 TJ. Non-ETS covered the rest of the demand, i.e. 84.5 % or 30 335 TJ (CSBL, 2017).

Table. 2.1

Industry sub-sectors in Latvia

	1	2	3	4	5		1	2	3	4	5
Iron and steel		V	V	V	V	Mining ETS			V	V	
Iron and steel ETS			V	V		Paper, pulp and print (Paper)		V	V	V	V
Chemical and chemical products (Chemical)	V	V	V	V	V	Wood and wood products (Wood processing)	V	V	V	V	V
Chemical ETS			V	V		Wood processing ETS			V	V	
Non-ferrous metals		V	V	V	V	Food and tobacco	V	V	V	V	V
Non-metallic minerals		V	V	V	V	Food and tobacco ETS			V	V	
Non-metallic minerals ETS			V	V		Construction	V	V	V	V	V
Transport equipment	V	V	V	V	V	Construction ETS			V	V	
Transport equipment ETS			V			Textile and leather (Textile)		V	V	V	V
Machinery		V	V	V	V	Textile ETS			V	V	
Mining and quarrying (Mining)		V	V	V	V	Other – rubber, plastic furniture and others (Other)	V	V	V	V	V

1 – feedstock, 2 – machine drive, 3 – process heat, 4 – building heat, hot water, 5 – cooling, lighting, ventilation, other

Five end-user processes have been analysed in the IND sector: feedstock, machine drive, process heat, building heat and hot water, and other processes, including cooling, lighting, and ventilation (see Table 2.1). For some sectors (Chemical production; transport equipment), all processes have been analysed. However, for sectors included in ETS, only two processes (process heat and building heat and hot water) have been included due to specific plants.

Data from the IND energy audits carried out from 2016 to 2018 were used to determine a share of the total energy sources used for each process. The energy balances from 122 different enterprises were analysed to identify the distribution of various energy sources.

The IND sector is Latvia's third largest energy consumer, accounting for 21 % of the total final energy used in 2017, of which 38 % was wood biomass, 18 % electricity, 14 % oil products, and 13 % natural gas. The IND sector in Latvia consists of 13 subsectors, of which the majority of energy is used in the manufacturing of wood and wood products.

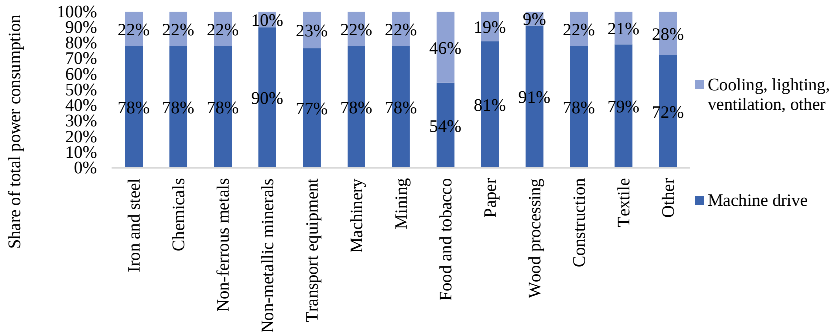


Fig. 2.4. Power consumption structure in IND sub-sectors.

In the TIMES model, power consumption in the IND sector has been divided into two large parts – electricity used for machine drive to ensure manufacturing processes, and auxiliary processes – cooling, lighting, ventilation, and other power-consuming processes. In most IND sub-sectors, around 77 % to 81 % of power is used for machine drive (see Fig. 2.4). A higher share of electricity consumption for machine drive is in the sub-sectors of non-metallic minerals and wood processing industries. In contrast, the lower share of electricity for machine drive is in food and tobacco production, – only 54 %.

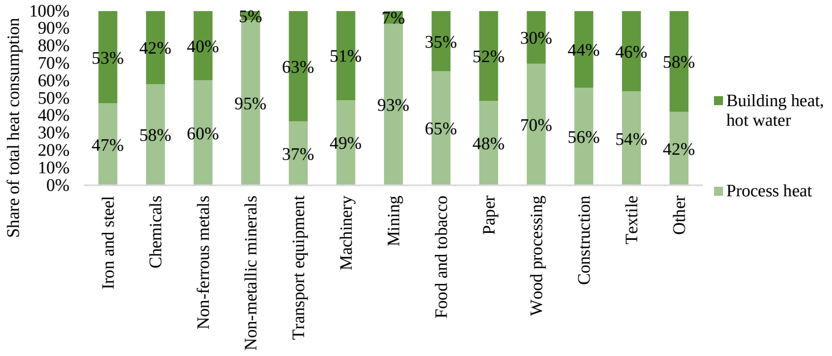


Fig. 2.5. Heat consumption structure in IND sub-sectors.

Heat consumption in the TIMES model has been divided into thermal energy used for space heating and hot water preparation, and process heat used for manufacturing processes. Differences in heat consumption division in subsectors are more significant compared to power consumption (see Fig. 2.5). In some subsectors, less than half of the heat is used for process heat (transport equipment production). Nevertheless, there are subsectors where even more than 90 % of heat has been used for production processes – non-metallic minerals production and mining.

The quality of the model results is highly related to assumptions that are made in the area outside the model structure. One of the key assumptions for the industrial sector is the energy demand trajectory of the sub-sectors up to 2050. Energy demand in sectors of the national economy depends on several drivers, e.g., GDP, economic growth of sectors, population, floor area, etc. The energy demand of the industrial sector is based on the sectoral value added forecast for Latvia (Capros et al., 2016). There is more specific demand in industries defined by energy services, e.g., energy for process heat, machine drive, building heat and hot water, feedstock, and others. According to research done and projections of industry development pathways, the overall demand for energy services in the industry sector is expected to increase by about 31 % in 2050 compared to 2017. The increase in demand for energy services in the wood sub-sector is around 30 %, in the food sub-sector, circa 21 %, but in the minerals sub-sector, around 56 % (see Fig. 2.6).

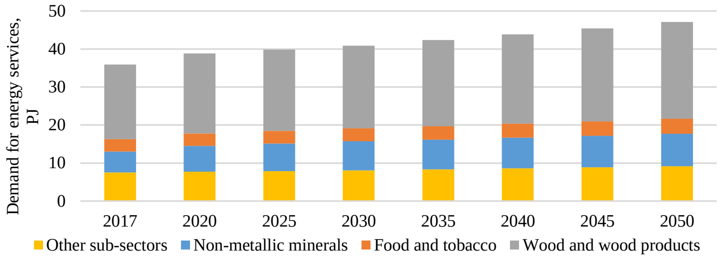


Fig. 2.6. Demand for energy services in the industry sector.

Commercial sector modelling

The commercial (COM) sector has different buildings and resulting energy resource consumption levels. Therefore, it has been divided into seven subsectors (see Table 2.2) based on the building classification (CM, 2018).

Table 2.2

COM sub-sectors in Latvia

Sector	**Total energy consumption in 2017**		**Total area in 2017**	
	TJ	%	m^2	%
Wholesale and retail buildings (Retail)	4085	16.04	4920	15.90
Office buildings (Offices)	4893	19.21	6510	21.03
Hotel buildings (Hotels)	2511	9.86	2310	7.46
Schools, universities and research buildings (Educational)	5144	20.20	6940	22.42
Buildings for medical or health care facilities (Medical)	2281	8.96	2020	6.53
Entertainment event, sports buildings, museums, cultural buildings, cultural and historical sites (Entertainment)	2506	9.84	3320	10.73
Other – garages, communication centres, stations, terminals etc. (Other)	3344	13.13	4930	15.93
COM ETS	704	2.76	-	-
Total	25468	100.00	30950	100.00

Resource consumption for almost all COM sub-sectors has been divided into ten processes: heating, cooling, cooking, lighting, public lighting, refrigeration, ventilation, water heating, office equipment, and others. A new process of heating and cooling demand was created – heating and cooling area (m^2), to add more precise PaM directly to the energy efficiency of specific buildings. To ensure correct process development in the TIMES model, heating and cooling processes have been separated as pre-processes for heating and cooling areas, which are now defined as end demand (see Fig. 2.7).

Like other demand processes, demand for heating and cooling area (m^2) has been affected by demand drivers like GDP growth and elasticity for evolution with GDP. Specific plants appear in the COM sector as ETS participants. Those mainly ensure different manufacturing processes. In the TIMES model, they have been divided separately with similar processes to the IND sector – process heat, building heat, and hot water.

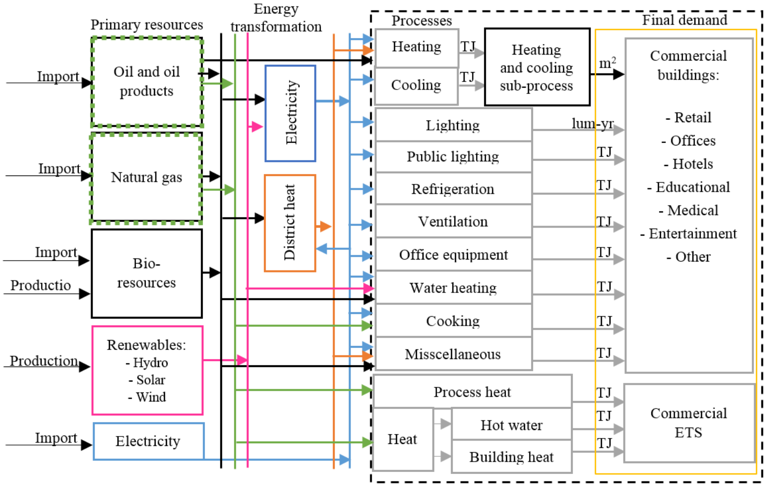


Fig. 2.7. Process scheme of the COM sector.

The available statistical data only present the total consumption of primary energy sources and heat and power in the overall COM sector. Therefore, the specific consumption for different end-use purposes has been determined through several assumptions and calculations.

Table 2.3

Assumptions for energy distribution in COM sector

Parameter	**Retail**	**Offices**	**Hotels**	**Education**	**Medical**	**Entertainment**	**Other**
Share of heated area	85%	80%	75%	80%	80%	70%	30%
Specific heat consumption for space heating, kWh/m^2							
existing buildings	130	140	135	160	160	150	120
renovated buildings				110			
newly built buildings				100			
Specific heat consumption for hot water heating, kWh/m^2	10	10	35	21	24	10	5
Share of mechanically ventilated area							
existing buildings	60%	50%	50%	30%	50%	30%	30%
renovated buildings	70%	70%	70%	50%	70%	60%	40%
newly built buildings	80%	80%	80%	60%	80%	70%	50%
Power consumption for ventilation, kWh/m^2	20	20	20	20	30	30	20
Share of building area with space cooling							
existing buildings	40%	50%	60%	40%	40%	20%	5%
renovated buildings	60%	70%	70%	50%	70%	60%	5%
newly built buildings	80%	80%	80%	60%	80%	70%	20%
Specific cooling consumption, kWh/m^2	53	53	40	40	53	40	20
Average minimum level of illumination, lux	369	383	314	352	457	325	291
Specific power consumption for lighting, kWh/m^2	29	14	12	10	34	13	20

The main input data for calculations is the total floor area of different types of buildings: offices, hotels and restaurants, schools, universities and research buildings (education), hospitals and health care facilities (medical), buildings for entertainment events and sports, museums, cultural and historical sites (entertainment), and other not previously classified buildings. Table 2.3 summarizes the main assumptions related to energy consumption distribution.

Heat consumption for space heating has been calculated by assuming different levels of building efficiencies (specific heat consumption for space heating) according to available data sources (SCCBL, 2018; MoE, 2017; MoE, 2019). The renovated and newly built buildings have been separated as those are subject to the specified standards (CM, 2013). As it is not necessary to maintain a certain indoor temperature throughout all the buildings, it is assumed that only part of the total area is heated. The specific consumption of domestic hot water has been estimated to be greater in hotels and hospitals (Fuentes et al., 2017), as there are high washing and cleaning standards applicable.

Some of the buildings are mechanically ventilated to provide the necessary air exchange. Mechanical ventilation is assumed to be more widespread in the new and renovated buildings than in the existing buildings. Power consumption for the ventilation has been calculated similarly as space heating consumption by assuming the share of mechanically ventilated area and the average power consumption for ventilation (Roth et al., 2002). Higher values have been assumed for medical and entertainment buildings as these buildings have higher requirements for air exchange rates.

Power consumption for space cooling has been determined according to the methodology presented by Werner (Werner, 2016). Similar to previous estimations, the share of the total area cooled during warmer periods and the specific cooling consumption of the particular type of building are assumed. Higher cooling demands have been assumed in retail, office, and medical buildings (Pérez-Lombard et al., 2008).

The minimum level of illumination requirements for different types of buildings have been used to determine the specific power consumption for lighting (CM, 2009).

$$SPC_{lighting} = \sum \frac{Il_i \cdot \beta_{i,j}}{\eta_j} \tag{2.4.}$$

where Il_i – illumination requirements in building type *i*, lm/m^2; $\beta_{i,j}$ –share of specific luminaries *j* used in buildings *i*; η_j- efficiency of luminaries *j*, lm/W.

It is assumed that in the base year three different types of luminaries are used in COM buildings – LED lighting (average share 44 %; average efficiency 100 lm/W), efficient luminaries including luminescent and halogen lamps (average share 43 %; average efficiency 56 lm/W), and inefficient luminaries (average share 13 %; average efficiency 15 lm/W) (Aman et al., 2013).

In addition, power consumption for public lighting has been estimated through regression analyses (see Fig. 2.8). Power consumption for public lighting has been identified in several cities and towns, mainly presented in municipalities' sustainable energy action plans.

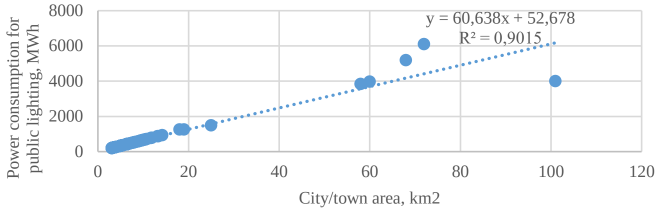


Fig. 2.8. Regression analyses of power consumption for public lighting depending on the populated area.

As can be seen in Fig. 2.8. the size of area of a city or town has a major impact on power consumption for public lighting.

Application of the regression equation allows estimating the total power consumption for public lighting in all populated areas and includes it in the overall energy balance of COM sector.

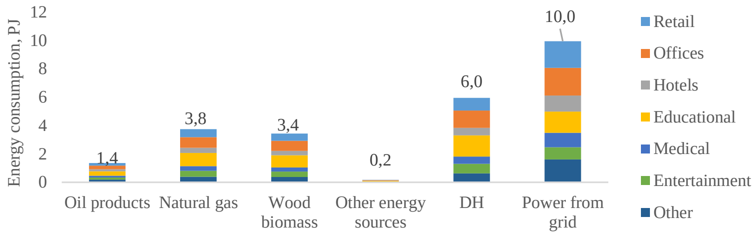


Fig. 2.9. Resource consumption structure in COM sub-sectors in 2017(CSBL, 2021).

The COM sector used 15 % of the total final energy in 2017, equal to 25 PJ. COM sector has been divided into seven sectors based on building classification (CM, 2018). Power is the main resource used in the COM sector, reaching almost 10 PJ and making up 43 % of the total final electricity consumed in 2017. Also, 27 % of the total final natural gas consumption, equal to 3.8 PJ, was used in the COM sector, where most of it was consumed in educational buildings and offices (see Fig. 2.9).

Electricity consumption structure differs in COM sub-sectors (see Fig. 2.10). In retail buildings as well as in buildings for medical facilities and entertainment, most of the electricity is spent on lighting. In office buildings, the office equipment consumes the most power, but in hotel and educational buildings most of it is used for water heating.

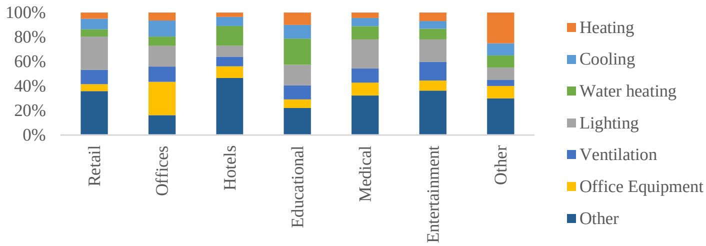


Fig. 2.10. Electricity consumption structure in the COM sector.

DH and primary energy sources have been used for three processes: water heating, space heating, and other processes like cooking. In almost all COM subsectors, heating has mainly been used for space heating and only a small share for water heating.

Residential sector modelling

The residential (RSD) sector was divided into two sections – single-family houses and apartment buildings, as both use different energy resources and differ in their consumption. It is assumed that the single-family houses are not connected to the DH network, but some of the apartment buildings are connected to a centralised heat supply.

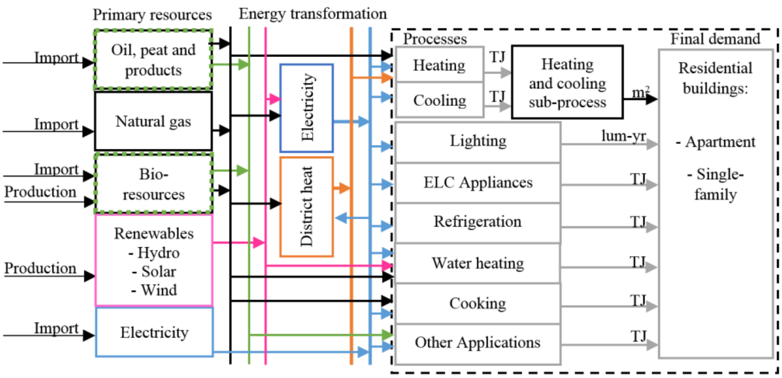


Fig. 2.11. Process scheme of the RSD sector.

Processes analysed in the TIMES model for the RSD sector are heating, cooling, water heating, refrigeration, lighting, cooking, electrical appliances, and other applications. New heating and cooling sub-processes are created similarly to those in the COM sector. This helps to overcome technology linking to a specific type of building and allows the addition of PaM related to the energy efficiency of buildings more precisely. The process scheme for the RSD sector is presented in Fig. 2.11.

In addition, heating and cooling processes have been defined as pre-processes, whereas the rest of the processes, like cooking, lighting, and others, are marked as the final demand and will be analysed in different scenarios. There are also studies where the surface area of the dwelling stock have been set as a demand driver for heating in the RSD sector but it is not applied in the particular research (Kerimray et al., 2018).

The second largest part of the final consumption is dedicated to the RSD sector, reaching 29 %. Most of it was wood biomass consumption, equal to 21 PJ, of which 38 % was used in single-family houses and 62 % in apartment buildings (see Fig. 2.12 a)).

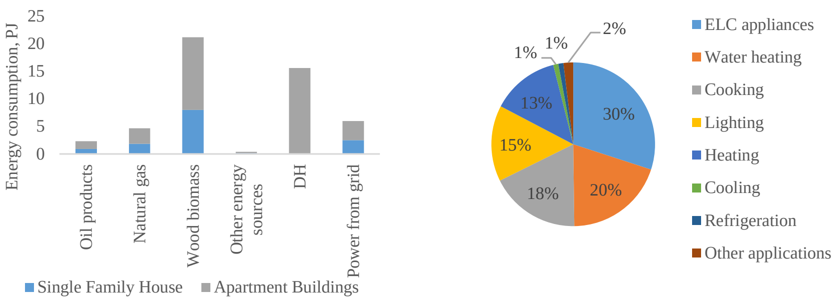


Fig. 2.12. Resource consumption structure (a) and structure of power consumption (b) in the RSD sector in 2017.

The structure of electricity consumption is similar in single-family houses and apartment buildings, as consumer behaviour does not depend on the building type. According to Eurostat (2019), largest share of electricity, i.e. 30 %, is consumed for different electrical appliances (TV, radio, mobile charging etc.), 20 % is used for water heating, 18 % for cooking, 15 % for lighting and 13 % for heating (see Fig. 2.12 b)).

Modelling the energy transformation sector

District heat (DH) in Latvia is mainly produced in heating plants (HP) and combined cogeneration plants (CHP), where power is also generated. In the last ten years, the structure of used energy sources in the DH and power sector has been switched increasingly to renewable energy sources (RES) mainly by consuming wood biomass (see Fig. 2.13). As a result, wood chip share increased from 11 % in 2008 to 41 % in 2020. Therefore, the share of natural gas decreased from 80 % in 2008 to 50 % in 2020.

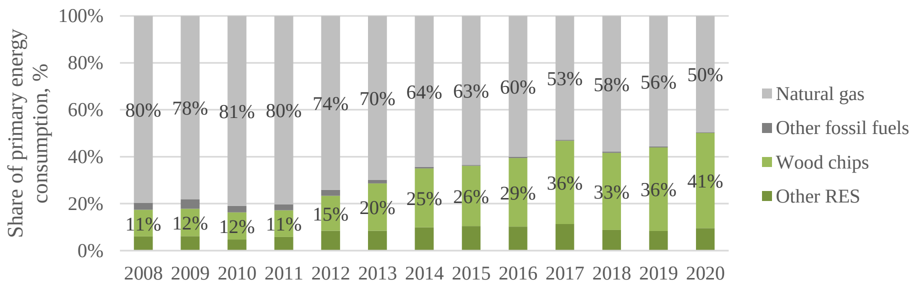


Fig. 2.13. Existing primary energy resource portfolio of DH and power sector.

Most of the thermal energy for DH is produced in CHP, accounting for 63 % - 76 % from 2012 to 2020 (see Fig. 2.14). In 2012, most of the heat in CHP was produced using natural gas (90 %), and only 5 % was produced using RES, while in 2020, around 52 % was produced from natural gas, 42 % from wood chips, and 6 % from other RES, mostly biogas and different types of biomass.

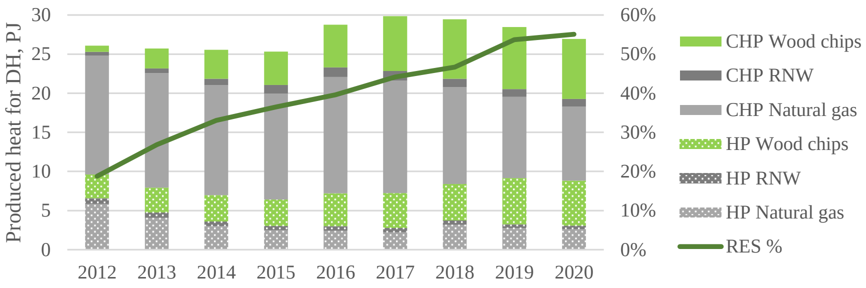


Fig. 2.14. Thermal energy produced in CHP and HP.

The natural gas consumption in HP decreased from 59 % in 2012 to only 29 % in 2020, while RES particular wood chip consumption has increased from 30 % to 65 % in the same period. Also, other RES like firewood and wood pellets are common, but since 2020, solar energy has entered the heat supply balance in Latvia.

The modelled energy sector includes district heating and electricity production (see Fig. 2.15). In order to better model trends in the energy sector, it is divided into two geographic sub-sectors – Riga and the rest of Latvia.

Data on the consumption of primary energy resources and amounts of heat produced are obtained from reports on air pollution (2-Gaiss, 2019) and publicly available annual reports (RS, 2017; Latvenergo, 2017). Data from the Central Statistical Bureau of Latvia and emission permits are used to determine installed capacities of technologies in boiler houses, hydropower plants, wind power plants and cogeneration plants (SES, 2019).

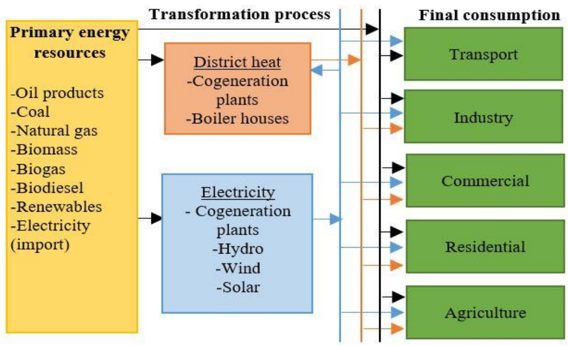


Fig. 2.15. Structure of the modelled energy transformation sector.

Although the amount of electricity produced by solar energy is not reported in the energy balance of Latvia in 2017, which is the reference year of the model, solar power plants are used in households, commercial, and industrial sectors mainly for self-consumption coverage. Therefore, calculations on the proportion of electricity produced by solar panels in the energy transformation sector are made in the model. Due to the lack of data regarding solar electricity not being transferred to the power grid, the information available from permits issued by the Ministry of Economics for the construction of new generation capacity was used (MoE, 2019).

The total amount of solar electricity produced in different sectors was estimated to be around 5.65 TJ in 2017.

In the TIMES Latvia model, the structure of DH is built based on the division in energy balance, including CHP and HP technologies, as well as emission trading system (ETS) and non-ETS plants to model the CO_2 emission costs (see Fig. 2.16) because Latvia is a part of the European Union ETS (EC, 2003). Additionally, the structure has been divided into two regions – Riga and the rest of Latvia because Riga, with the two high-capacity CHPs, is significantly different from the rest of Latvia. The heat from plants in Riga (LTHR) and the rest of Latvia (LTHL) is transferred to the grid and finally to the industrial, residential, commercial, and agricultural demand sectors.

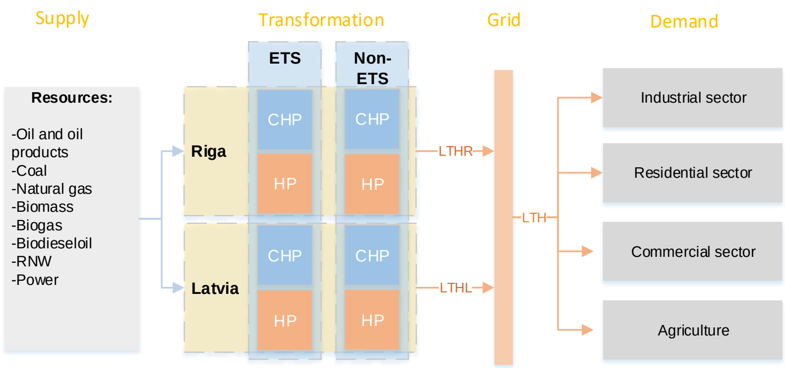


Fig. 2.16. DH structure in the TIMES Latvia model.

The model considers all relevant cost flows – investments, fuel costs, operational costs, and taxes to optimise energy production. One of the essential assumptions is the parameters of available technologies in the energy transformation sector. Therefore, the Danish Technology Catalogue (DEA, 2018) was used to determine the primary technical data of technologies, e. g., operational lifetime, efficiency parameters, capital costs, operational and maintenance costs, and variable costs

Passenger transport shift modelling

The transport sector in the TIMES Latvia model consists of two blocks – passenger travel and freight transport. In this Thesis, passenger land travel has been analysed, excluding traffic by air and water. The road section studied includes road and rail transport as well as individual modes of mobility. Road transport consists of cars, buses, trains, trams, and trolleybuses, while individual transport modes include walking and cycling (see Fig. 2.17).

For more accurate modelling, the demand for three different distances has been included in the model – short distances (up to 5 km), average distances (5–25 km), and long distances (over 25 km). This modelling approach ensures that different transportation modes, which cover a certain distance, can compete with one another, e.g., in short distances walking, cycling, car, bus, tram and trolleybus may substitute for each other if the travel destination matches. In contrast, only cars, intercity buses, and trains can be used for distances of 25km and longer.

The model also includes road infrastructure and car filling stations that require the necessary infrastructure to increase specific types of transport, e.g., electric vehicles.

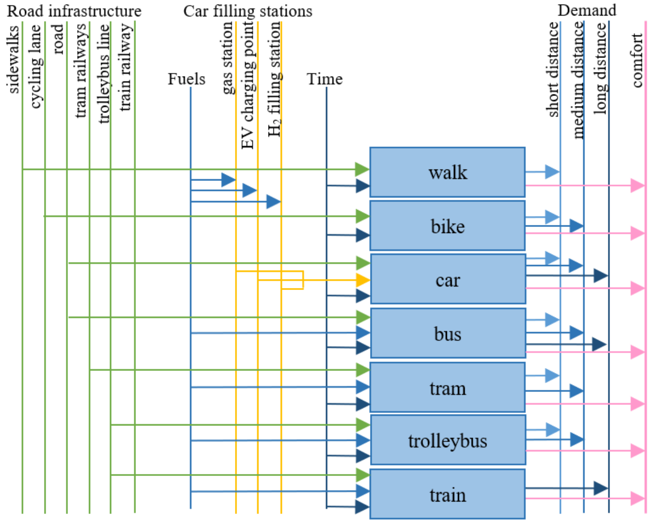


Fig. 2.17. Structure of passenger road transport in the model.

Considering both the forecast of the EU reference scenario (Capros et al., 2021) for the development of the passenger transport activity in Latvia and the estimates of the population, the travel demand is projected to increase slightly in each period from 2020 until 2050 (see Fig. 2.18). The total increase in demand for mobility is growing by 18 % in 2050 compared to 2017.

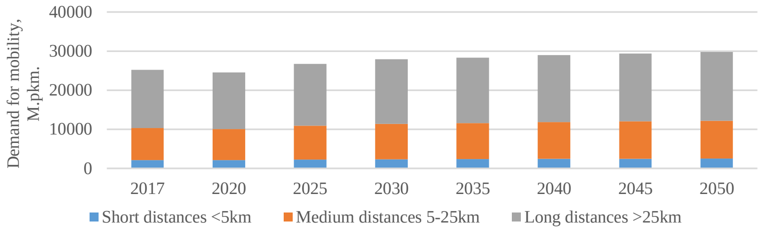


Fig. 2.18. Demand forecast for land passenger transport.

The length of the distances in the TIMES model was split up to account for the existing mobility patterns (CSBL, 2018) for the base year. The limit values for the distances were set to include non-motorised modes of transport – bicycling and walking. Figure 2.19 represents the assumed proportion of transportation modes used in each distance for the base year. These assumptions are based on a study conducted in Denmark (Tattini, 2018) to model the transport sector, which was adapted to the situation in Latvia for the year 2017. Short distances of up to 5 km can be provided by all vehicles, except trains. Average distances from 5 to 25 km are provided by bicycle, tram, trolleybus, city bus, and car, while long distances above 25 km are offered by car, intercity bus, and train. Considering that, on average, 47 km is travelled by train in the base year, and to simplify the model calculations, it is assumed that the train is used only for distances longer than 25 km, which includes the most popular routes in Latvia. The assumptions regarding the distribution of travelled distances are with high uncertainty due to a lack of precise data and can be adjusted in future studies if more detailed national surveys on the traveling habits of the Latvian population are conducted.

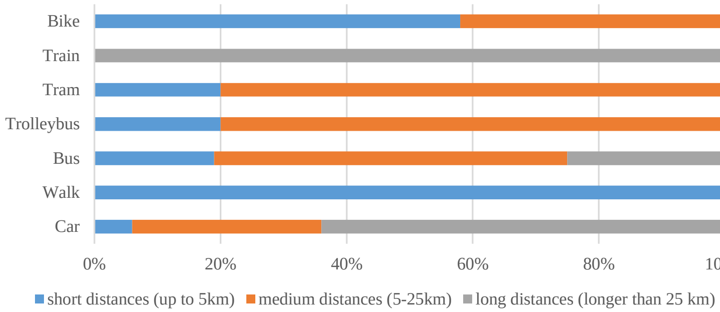


Fig. 2.19. Use of transport modes depending on the distance.

In addition, the level of comfort of different modes has been introduced in the model. As TIMES is an optimisation tool that looks for the most cost-effective system structure, comfort is an essential element that provides more accurate results by including human behaviour. Several experts assessed the comfort level on a scale from 1 to 5 for each vehicle type according to seven factors – safety, noise level, and ability to regulate indoor temperature, ability to travel with family, opportunities to socially distance, accessibility, and barrier-free environment. The availability factor characterises the possibility of immediate use of the vehicle – whether it is available in all conditions (e.g., private car) or whether the vehicle timetable must be followed (for public transport). This parameter does not include the availability of infrastructure, such as cycle lanes, as this parameter is included separately (as road infrastructure) in the model. It was assumed that the highest comfort level is for passenger cars, significantly exceeding the comfort level of other modes of transport (see Fig. 2.20).

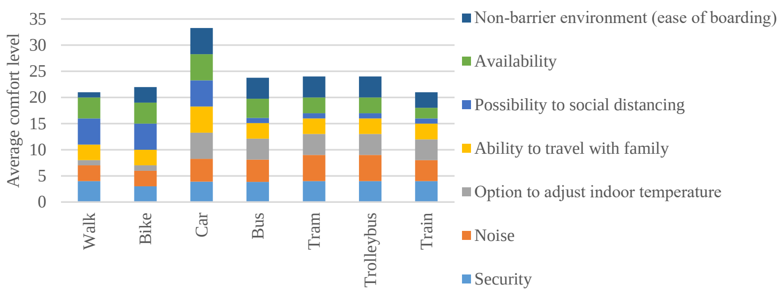


Fig. 2.20. The average comfort level for different types of transportation, based on experts' assessed factors for seven comfort elements on a scale from 1 to 5.

This is not only because the car provides a more comfortable environment but also allows one to travel with family, distance oneself, regulate the indoor temperature, and, most importantly, is always available. The lowest rating is for walking, and the train because it is not so accessible in the whole territory of Latvia due to a lack of railway infrastructure. It is also challenging to get in with a wheelchair or baby carriage in the outdated trains.

2.2.2. Scenario development

Three main scenario types were developed in the Doctoral Thesis – baseline scenarios (BASE, WEM) which include only existing policies and trends, policy scenarios (NECP, WAM) which include different PaM and target scenarios (GHG TARGET, OPT_Solar and OPT_EE) which include GHG reduction target (see table 2.4).

Table 2.4

Scenarios Developed in the Thesis

Name of scenario	Type of scenario	Scientific article	Main additional parameters
BASE	Baseline	2-5	n/a
WEM	Baseline	6	• GDP growth ~3.2 %/year in period 2020-2050; • The approved grant program for the planning period until 2027
NECP	Policy	2-5	• PaM specified in NECP2030
WAM	Policy	6	• GDP growth ~3.2 %/year in period 2020-2050; • The approved grant program for the planning period until 2027; • Additional PaM - EE for buildings, industrial processes, subsidies for electric transport, etc.
GHG_TARGET	Target	4-5	• Total GHG reduction in 2050 by 70 %
OPT_SOLAR	Target	6	• Total GHG reduction in 2050 by 90 %; • Reduction of primary and final energy consumption by ~16 % in 2030 compared to 2020; • Prioritized private solar energy production
OPT_EE	Target	6	• Total GHG reduction in 2050 by 90 %; • Reduction of primary and final energy consumption by ~16 % in 2030 compared to 2020; • Solar energy produced and direct consumption is accounted in final consumption.

2.2.3. Model validation

Validation of the model was done by comparing resource consumption in the energy transformation sector of the model BASE results and official statistical data from the Central Statistical Bureau of Latvia for the years 2018, 2019, and 2020 is shown (see Fig. 2.21).

The total resource consumption in the energy transformation sector in statistical data slightly differs from the model results. The total amount of resources consumed in the energy transformation sector was 949 TJ or 1.7 % less in 2018, 850 TJ or 1.5 % more in 2019, and 588 TJ or 1.2 % less in 2020 than the modelling results.

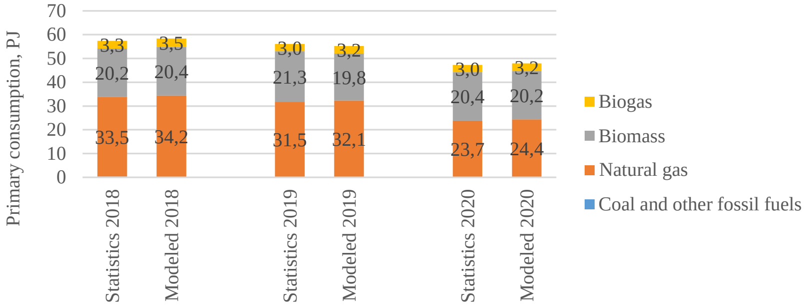


Fig. 2.21. Results of the model and statistical data of primary resource consumption in the energy transformation sector for the years 2018, 2019 and 2020 (CSBL, 2021).

The primary energy sources used in heat supply (natural gas, wood chips, and biogas consumption) obtained from the model gave no more than a 7 % difference from the statistical data. Natural gas consumption of the model is around 2 % higher than in statistics, biomass consumption is 1 % higher in 2018, 7 % less in 2019, and 1 % less in 2020, while biogas consumption was 6 % more in 2018 and 2020 and 4 % more in 2019 compared to statistical data. Therefore, the results of resource consumption in the transformation sector provided by the model match the statistical data sufficiently well.

Also specific validation was done for the transport sector for the years 2018, 2019, and 2020 using data from the Central Statistical Bureau of Latvia (see Fig. 2.22). Total resource consumption in the transport sector differs slightly. For 2018 and 2019, modelling results show slightly lower consumption than identified in the statistics, but in 2020 modelled results are by 1 % higher compared to actual consumption.

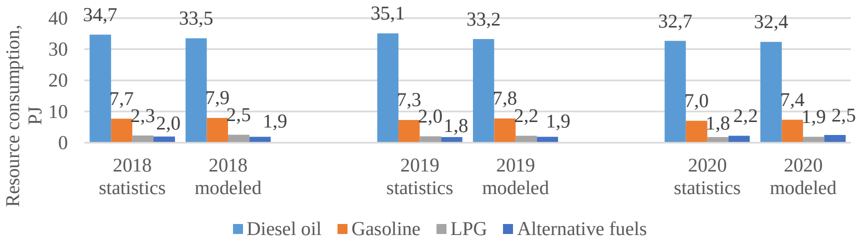


Fig. 2.22. Results of the BASE scenario and statistical data (CSBL, 2021) of resource consumption in the transport sector for the years 2018, 2019 and 2020.

Modelling results show slightly lower (around 1-5 %) diesel oil consumption than actual primary resource consumption in the transport sector in 2018-2020, while gasoline consumption is about 3-6 % higher and LPG around 5-10 % higher than indicated in national statistics in the analysed period. Consumption of alternative fuels like natural gas, bioethanol, biodiesel, and power is 2 % higher in the statistics in 2018 while lower by around 3 to 10 % in 2019 and 2020 than in the modelled results. The difference between the modelling results and statistical data does not exceed 10 %, so the model describes the actual situation well.

2.2.4. Sensitivity analysis

The sensitivity analysis was done for the GHG TARGET scenario by reducing the amount of available biomass for the energy transformation sector by an additional 20 % (GHG TARGET+). It could be evident if the export of biomass resources would continue to grow or stricter biomass cascading principles would come into force. However, due to the high impact of heat pumps in the DH sector, such reduction of available biomass does not cause an elevated difference.

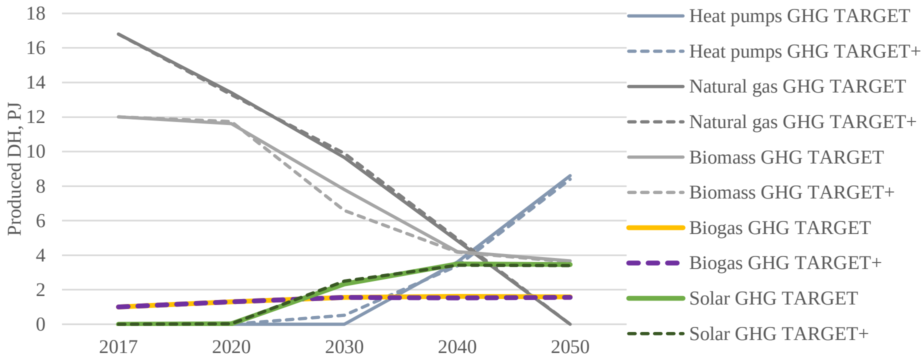


Fig. 2.23. Results of sensitivity analysis – DH produced by the type of resource in GHG TARGET and GHG TARGET+.

Results of heat production rates compared for both scenarios only showed differences in the year 2030 when biomass use decreases by 15 %, substituting it with the help of heat pumps (see Fig. 2.23). If biomass is limited for the energy transformation sector, the use of heat pumps becomes beneficial earlier.

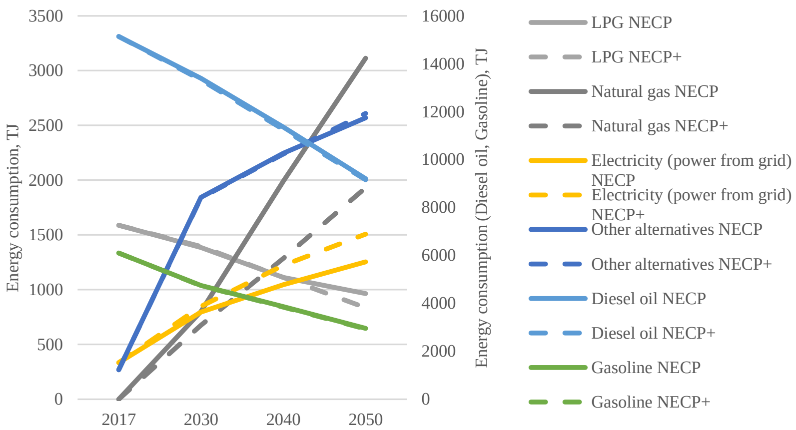


Fig. 2.24. Results of sensitivity analysis – fuel consumption in NECP and NECP+.

Another set of sensitivity analysis was done by increasing the prices of fossil fuels e. g. diesel oil, gasoline, LPG and natural gas for the NECP scenario (see Fig. 2.24). Starting from 2025 it is assumed that the prices for these resources will be two times higher than in the base year, followed by a 5 % increase each year until the end of the modelling period (scenario NECP+).

The results show an insignificant reduction in diesel oil and gasoline consumption while consumption of LPG is 13 % less than in NECP, and consumption of natural gas is even 38 % less in 2050. Consumption of fossil fuels is largely offset by higher electricity consumption, which increases by 20 %. Consumption of other alternative fuels, e.g., biomethane has no change, biodiesel and bioethanol consumption decreases by 0.5 % while consumption of hydrogen increases by 16 % in 2050.

2.2.5. Input data from other modelling tools

The changes in DH consumption in sectors are derived from the SD model. In the BASE scenario, demand for DH is steady in the RSD sector, where the amount of DH is around 16 PJ, while in other sectors, demand for DH is increasing by 10 % in the IND sector, about 33 % in agriculture, and for around 9 % in the COM sector (see Fig. 2.25). On the other hand, in the NECP and GHG TARGET scenario, the heat consumption decreases by around 43 % in the RSD sector due to significant building renovation rates and about 8 % in COM and 7 % in the IND sectors, where also the energy efficiency measures are considered.

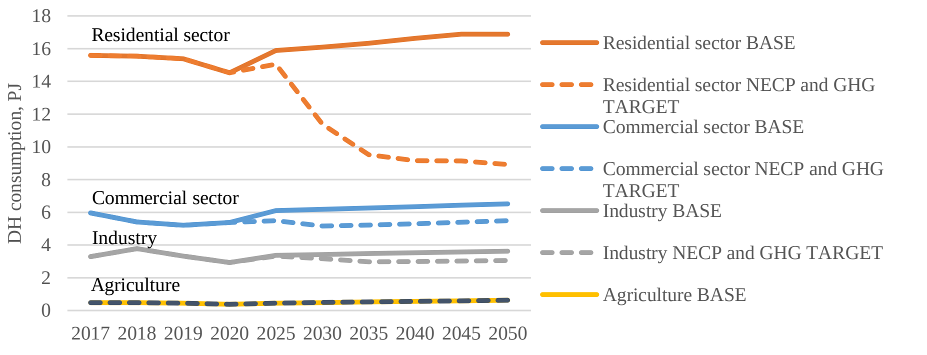


Fig. 2.25. DH demand in sectors.

Results of the forest data processing program "Forest Expert" developed by the Latvia University of Life Sciences and Technologies are used as inputs for the TIMES model. The maximum amount of biomass available for the energy sector is obtained from the "Forest Expert" linear optimisation model, which provides a higher quality of data on the development of forest resources. The model includes tree growth rate models, compliance with binding regulatory enactments and standards for predicting timber outcomes, algorithms of tree trunks, and assortment forecasting. The results of the "Forest Expert" model show that the amount of wood pellets available for the energy sector will increase. Still, the availability of other wood biomass will decrease by around 30 % in 2050 compared to 2017 (see Fig. 2.26).

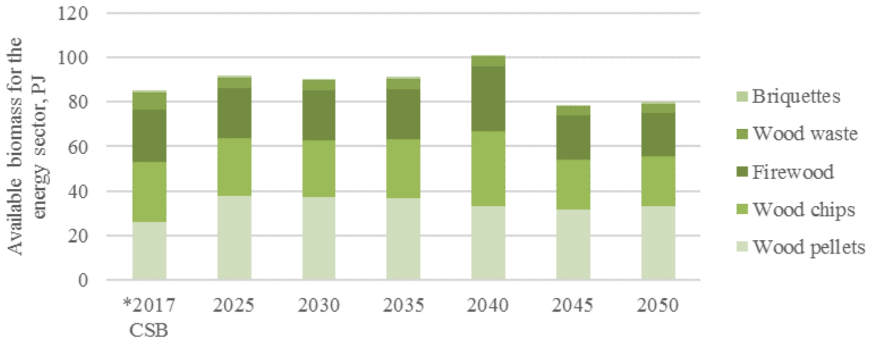


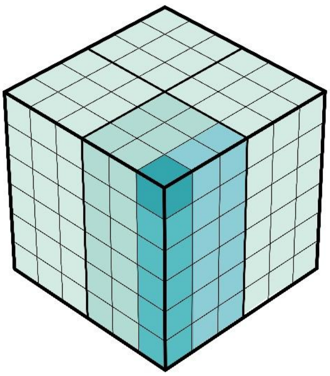
Fig. 2.26. The maximum amount of biomass available for the energy sector (Dubrovskis & Dagis, 2018).

The maximum biomass is achieved in 2040, which is influenced mainly by the availability of white alder, the volume of felling of which is significantly higher (short circulation time ~ 31 years). There are no restrictions to even out-felling volumes in the long run. The assortment of this species mostly goes to firewood. The same biomass limitation derived from the "Forest Expert" model is used in all TIME's scenarios without considering different forest management policies.

3. RESULTS

3.1. Representation of energy service provision at different levels of detail

The results of the Thesis are presented using the bottom-up approach of the TIMES modelling tool. This involves first analysing data at the lowest level of detail – technologies – then progressing to processes, subsectors and sectors, ultimately providing results for the entire energy sector. This approach allows different levels of detail to be represented depending on the intended purpose (see Fig. 3.1).



Level of results	Type of results	Results described
1.	Technological	• in the transport sector – types of passenger transport (private car, bus, train, etc.) • in the energy transformation sector – wind turbines, heat pumps
2.	Process	• in the energy transformation sector – provision of thermal energy
3.	Sub-sector	• in the industry sector – wood and wood products, food and tobacco and non-metallic minerals sub-sectors • in the transport sector – land passenger transport
4.	Sector	• industry
5.	Total energy system	• total energy system

Fig. 3.1. Levels of obtaining and presenting results.

In the next sub-chapters, several examples of the results at different levels are depicted: technological-level modal shifts in the transport sector and renewable technologies in the power sector; process-level resource supply mix in DH; sub-sector and sector-level resource transition; and total energy system total primary and final energy consumption.

3.1.1. Modal shifts in passenger transport and renewable technologies in the power sector (1st level)

The restructuring of the transport sector model enables the inclusion and evaluation of PaM related to modal shifts, such as support for public transport improvements and the creation of bike lanes. Transport sector technologies include vehicles such as private cars, buses, and trains. The Thesis further describes the changes in technology for BASE, NECP, and GHG TARGET scenarios, as well as the share of public transport and electric cars in WEM, OPT_EE, OPT_Solar, and WAM scenarios.

In the base year, 77 % of mobility is covered by private cars while 15 % by buses, 3 % by walking and cycling, 2 % by trolleybuses and trams, and another 2 % by train (see Fig. 3.2). Usage of buses is increasing to 20 % in BASE, 23 % in NECP, and 24 % in GHG TARGET in 2030. In 2050, the usage of buses is growing even more, covering 29 % in BASE and around 39 % in NECP and GHG TARGET scenarios. Walking and cycling, usage of trolleybuses, trams, and trains are about 3 % in each scenario in 2050 except in GHG TARGET, where usage of trolleybuses, trams, and trains is increasing to around 16 % in total.

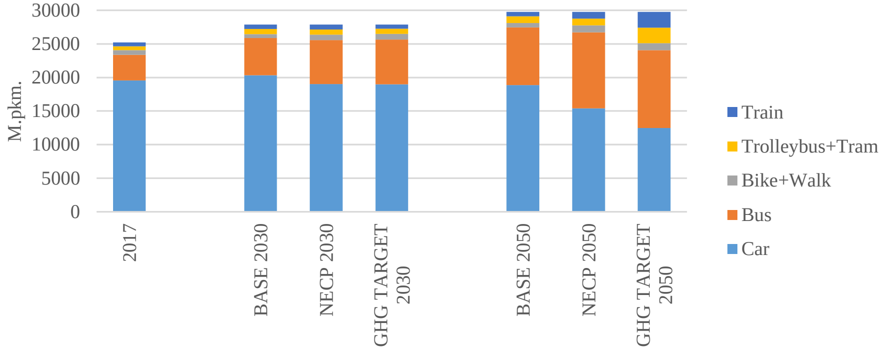


Fig. 3.2. Projection of the use of passenger transport modes for alternative scenarios.

Mainly, private cars are used for mobility in short distances, i.e., up to 5 km, covering around 41 % in the base year (see Fig. 3.3). Also, buses are used a lot, covering 25 % of passenger travel, but walking and cycling provide 28 %. The usage of buses is increasing in all scenarios in 2030, ensuring around 37 % mobility while it is about 50 % in 2050. Cycling and walking are becoming more popular in NECP and GHG TARGET scenarios, covering approximately 27 % in 2030 and 29 % in 2050. In BASE, only 20 % of mobility will be done by individual modes of transport in 2050.

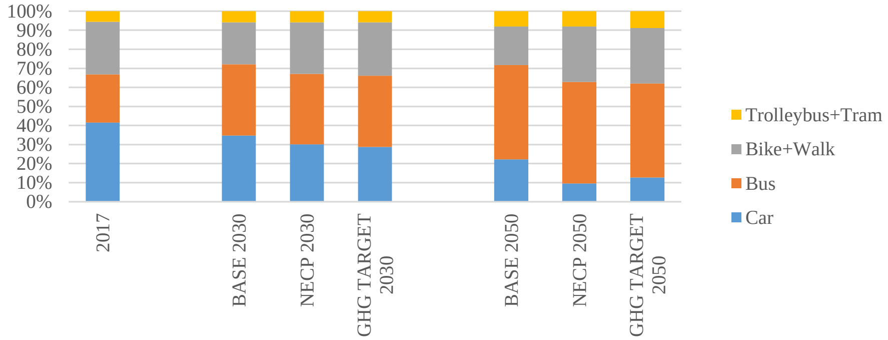


Fig. 3.3. Distribution of passenger transport mode usage for **short distances.**

63 % of mobility in medium distances from 5 to 25 km is done by cars in the base year (see Fig. 3.4). The proportion is decreasing in all scenarios in 2030, covering around 54 %. Still, an even more significant decrease is seen in 2050, where 43 % of mobility in BASE, 38 % in NECP, and only 21 % in GHG TARGET scenarios are traveled by private cars. A significant increase is seen in the usage of buses in all scenarios in 2030, covering around 38 % of mobility and 47 % in BASE, 51 % in NECP, and 55 % in GHG TARGET scenarios in 2050. Also, there is a notable increase in traveling by trolleybuses and trams in the GHG TARGET scenario in 2050, reaching around 20 % of the total mobility. The TIMES optimisation model has chosen

these types of travel as the most economically beneficial by considering the fuel and vehicle costs, implemented restrictions on infrastructure and comfort levels.

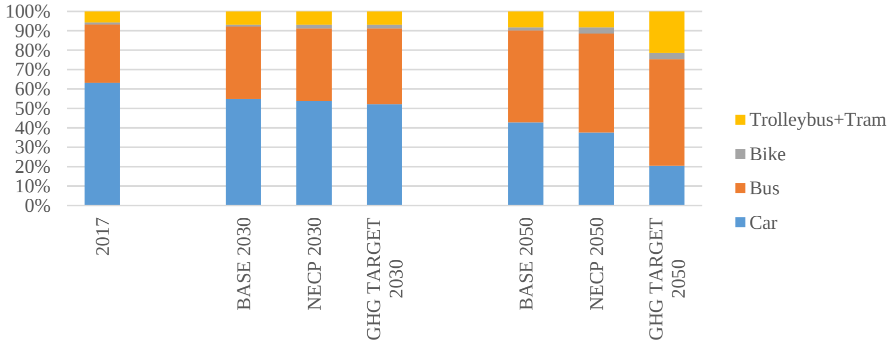


Fig. 3.4. Distribution of passenger transport mode usage for **medium distances.**

Three modes of transportation are being analysed for more than 25 km long distances. Private cars cover around 90 % of mobility in long distances in the base year (see Fig. 3.5), and only 6 % is travelled by bus and 4 % by train. Although the usage of private cars is decreasing, it covers most of the mobility for long distances for all scenarios – 88 % in BASE and 82 % in NECP and GHG TARGET in 2030, and 81 % in BASE, 66 % in NECP and 58 % in GHG TARGET in 2050. Usage of buses is increasing in NECP and GHG scenarios, reaching around 14 % in 2030 and 29 % in 2050 of total mobility. Also, the use of trains is growing in the NECP scenario to 6 % in 2050 and in the GHG TARGET scenario to 13 % due to the development of public transport.

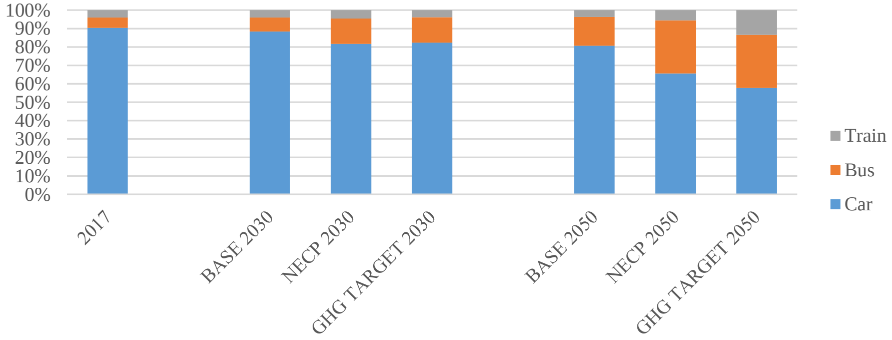
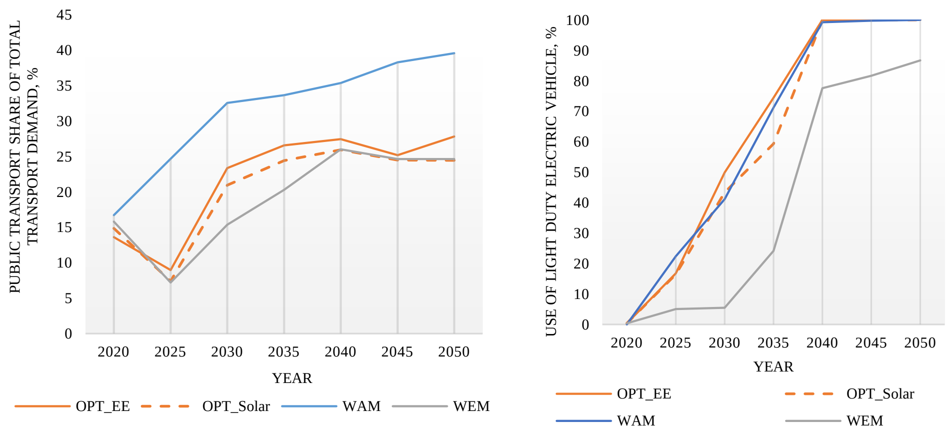


Fig. 3.5. Distribution of passenger transport mode usage for **long distances.**

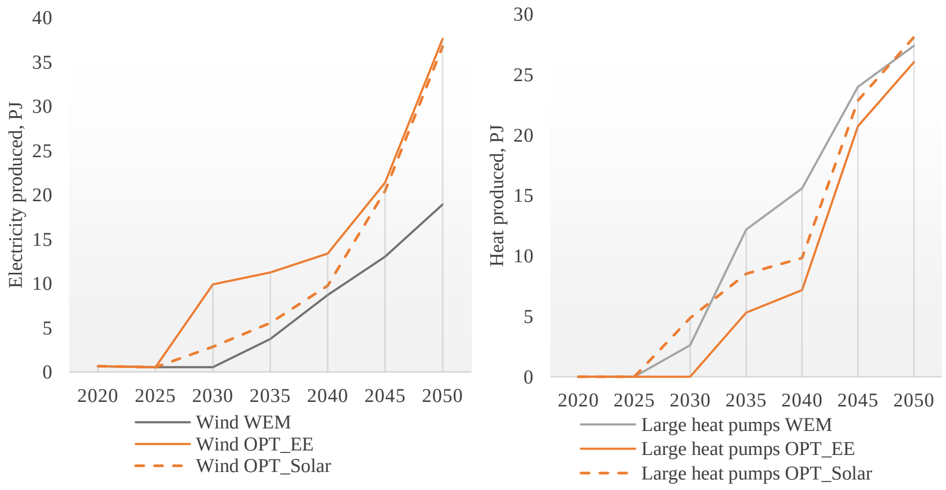
The focus of the integrated policies has been on the transport sector decarbonisation. Therefore, PaM implemented in the WAM scenario increases public transport use from 17 % in the year 2017 to 35 % in the year 2030 and 40 % in the year 2050 (see Fig. 3.6 a). Both optimisation scenarios and the WAM scenario show 100 % conversion to electric vehicles for light-duty vehicles by the year 2040 due to the ban on internal combustion engines (see Fig. 3.7 b).



a b

Fig. 3.6. Results of transport policies: a) Public transport use of total passenger km and b) electric light-duty vehicle shares of total light-duty vehicles.

In OPT_EE and OPT_Solar pathways, the total energy production by the power sector is projected to exhibit a variable trend until 2030, after which a substantial increase in wind capacity is anticipated (see Fig. 3.7. a). Following this, electricity generation is projected to steadily rise until 2050. Due to the availability of low-cost wind power, both optimisation scenarios, as well as the WEM scenario, substantially increase the use of large heat pump (HP) technology in district heating systems (see Fig. 3.7. b).



a b

Fig. 3.7. Comparison of wind production rates (a) and heat production with large, centralised heat pumps (b) in different optimisation pathways.

3.1.2. Resource supply mix in DH (2nd level)

As an example of the results of the 2nd level, the changes in resource supply mix to ensure the demand of DH for the BASE, NECP and GHG TARGET scenarios are shown.

The modelling results show that natural gas and biomass are used the most to ensure DH in the BASE scenario (see Fig. 3.8). Around 56 % of the heat produced in the base year is from natural gas, while about 40 % is from biomass, having approximately 29 PJ of thermal energy. The amount and proportion of natural gas and biomass used to produce DH decrease in 2050, covering around 54 %, both producing around 15.7 PJ for DH. From 2030, heat pumps and solar energy will also become significant in covering the high demand for heating. Heat pumps cover around 24 % of heat demand, but solar energy provides 20 % of necessary heat.

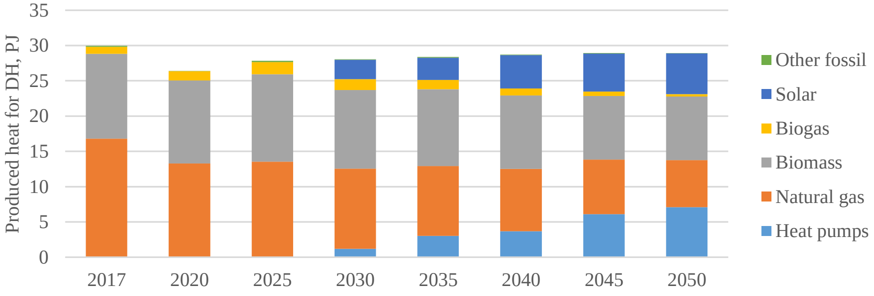


Fig. 3.8. DH produced by the type of resource and technology (heat pumps) in the BASE scenario.

In NECP and GHG TARGET scenarios, demand for DH decreases by around 30 % compared to the BASE scenario. The obtained modelling results in Fig. 10 and Fig. 11 show that the use of natural gas has been eliminated in both scenarios due to low economic benefits compared to alternative solutions. Also, the use of biomass is decreasing in both scenarios. In the NECP scenario, the amount of used biomass is reduced from 40 % to 37 % (biomass), equal to around 6.9 PJ in 2050 (see Fig. 3.9). As a result, in the NECP scenario, heat pumps become cost-effective starting from 2035 and ensure around 7.3 PJ of heat for DH in 2050, equal to 39 % of total produced heat. Solar energy will provide 19 % of delivered heat in 2050.

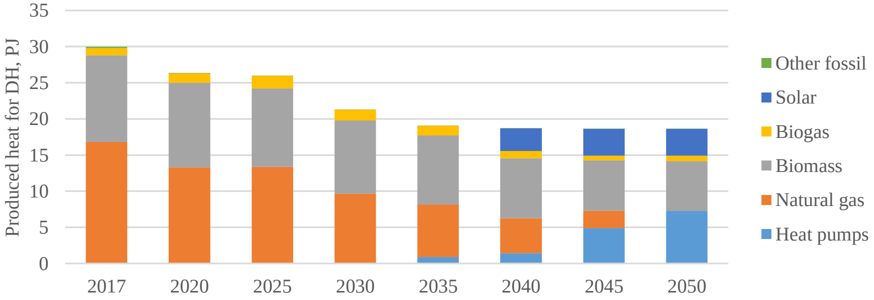


Fig. 3.9. DH produced by the type of resource and technology (heat pumps) in NECP scenario.

In the GHG TARGET scenario, the use of biomass is decreasing from around 12 PJ in 2017 to 3.7 PJ in 2050, providing only around 20 % of necessary heat in the DH sector (see Fig. 3.10). The primary energy source for DH in this scenario in 2050 is large scale heat pumps which provide up to 47 %. Modelling results show that solar energy already become cost-effective in the 2030 scenario and will cover around 19 % of produced DH in 2050. The heat produced by biogas slightly increased from about 3 % in 2017 to about 9 % in 2050.

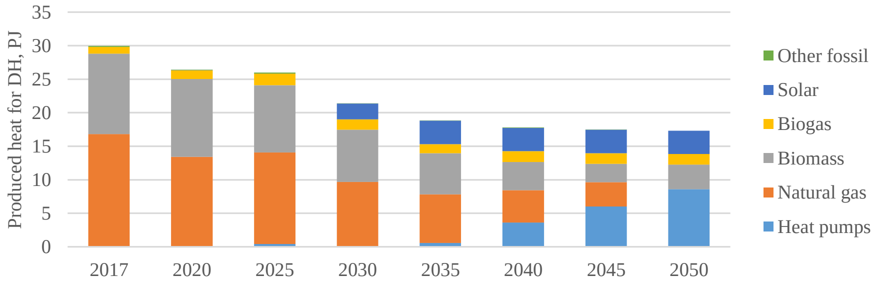


Fig. 3.10. DH produced by the type of resource and technology (heat pumps) in GHG TARGET scenario.

3.1.3. Resource transition in specific sub-sectors and sectors (3rd and 4th level)

Changes in resource consumption at the subsector and sector levels are described for the three main subsectors of the industrial sector: food and tobacco, wood and products, and non-metallic minerals. Additionally, the total energy consumption of the industrial sector as a whole is detailed for BASE, NECP, and NECP+ scenarios. In the transport sector, changes in resource consumption are described for the subsector that includes passenger transport on land for the BASE, NECP, and GHG TARGET scenarios.

Results show that in 2030 final energy consumption in the food sub-sector decreases in BASE (3.2 PJ), NECP (3.1 PJ) and NECP+ (2.8 PJ) scenarios while in the REF scenario consumptions remain steady (3.3 PJ) (see Fig. 3.11).

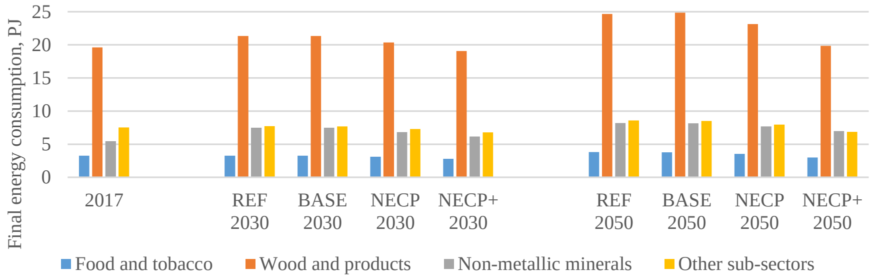


Fig. 3.11. Final energy consumption in the industrial sub-sector in the modelled scenarios.

In 2050, the amount of energy consumption increases in all scenarios – REF and BASE scenarios (3.8 PJ), NECP (3.5 PJ), NECP+ (3 PJ). In 2030, energy consumption in the wood sub-sector is increasing in REF and BASE (21.3 PJ), in NECP (20.3 PJ), while decreasing in NECP+ (from 19.6 PJ in 2017 to 19.1 PJ). In 2050, consumption is increasing in all scenarios – REF (24.7 PJ), BASE (24.9 PJ), NECP (23.1 PJ) and NECP+ (19.9 PJ). Energy consumption in the minerals sub-sector in 2030 and in 2050 is increasing in all four scenarios – REF and BASE (7.5 PJ and 8.2 PJ), NECP (6.8 PJ and 7.7 PJ), NECP+ (6.2 PJ and 7 PJ) accordingly. In other industrial sub-sectors, the total final energy consumption increases in REF and BASE (7.7 PJ) and decreases in NECP (7.3 PJ) and in NECP+ (6.8 PJ), while in 2050 consumption increases in all scenarios – REF (8.6 PJ), BASE (8.5 PJ), NECP (8 PJ) and NECP+ (6.8 PJ).

In the wood sub-sector, the main resource is wood biomass, i.e., wood waste and wood chips dominate in energy consumption compiling 7 PJ and 4 PJ, respectively in 2017 (see Fig. 3.12). Wood chips consumption is increasing to circa 7.5 PJ in all scenarios in 2030 and from 11 PJ to 12 PJ in 2050, while wood waste consumption is from 4.8 PJ to 6.2 PJ in 2030 and from 3 PJ to 7 PJ in 2050.

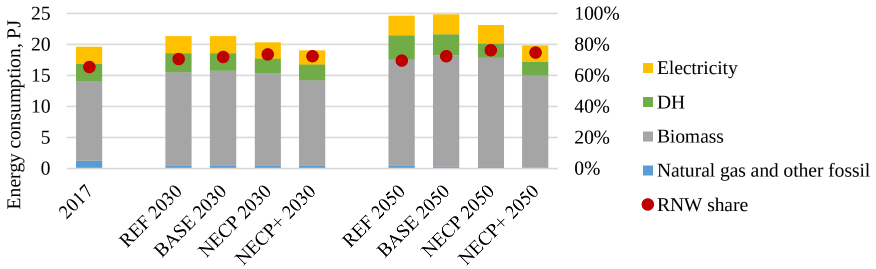


Fig. 3.12. Energy consumption in the wood sub-sector in the modelled scenarios.

Consumption of electricity remains stable for the whole modelling period and is circa 3 PJ. Amount of used DH in 2030 and in 2050 increases in REF (3.1 PJ and 3.9 PJ), in BASE (2.8 PJ and 3.4 PJ), while decreases in NECP (2.4 PJ and 2.3 PJ) and NECP+ scenarios (2.5 PJ and 2.2 PJ).

The main resources consumed in the food sub-sector in 2017 are natural gas and electricity, with values of 1.2 PJ and 1 PJ, respectively (see Fig. 3.13). Consumption of wood chips increases in all scenarios in 2030 from around 0.9 PJ in NECP+ to around 1 PJ in scenarios REF and BASE and in 2050 to around 1.5 PJ in REF, 2 PJ in BASE, 1.8 PJ in NECP and NECP+.

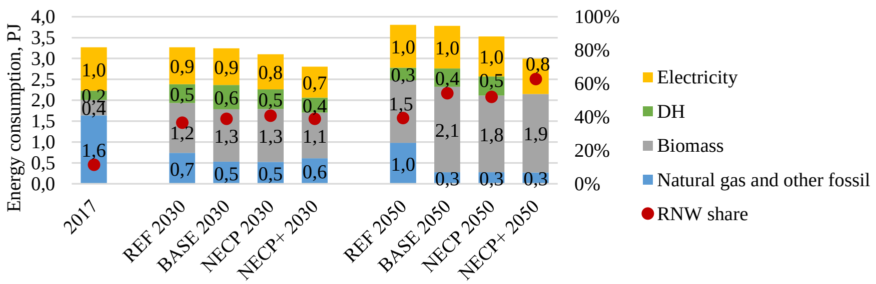


Fig. 3.13. Energy consumption in the food sub-sector in the modelled scenarios.

Electricity consumption in 2030 decreases to around 0.9 PJ in REF, BASE and NECP and around 0.7 PJ in NECP+. In 2050, electricity consumption is increasing to around 1 PJ in REF, BASE, and NECP, to around 0.9 PJ in NECP+. Natural gas consumption is decreasing in all scenarios, reaching around 0.6 PJ in 2030 and around 0.3 PJ in 2050. The share of RES is increasing in all scenarios, with the highest share in the NECP (41%) scenario in 2030 and in the NECP+ (63 %) scenario in 2050.

Energy consumption and tendencies in the minerals sub-sector differ from those other two sub-sectors as the main resources here are fossil fuels (see Fig. 3.14). Natural gas and other fossil fuels, as well as municipal waste, tires, and rubber products, were the dominant resources in 2017, compiling 2.5 PJ and 2 PJ, respectively. In 2030, consumption of natural gas and other fossil fuels increases in REF, BASE (3 PJ), and NECP (2.6 PJ) scenarios but decreases in the NECP+ (2 PJ) scenario. In 2050, consumption decreases in all scenarios – REF (2.5 PJ), BASE (2.4 PJ), NECP (2 PJ), and NECP+ (1.5 PJ). Consumption of municipal waste, tires, and rubber products decreases in all scenarios, reaching circa 1.8 PJ in 2030 and 1.6 PJ in 2050. Consumption of DH and electricity increases in all scenarios, reaching around 0.1 PJ and 1 PJ in 2050. Consumption of biofuels, which mainly consists of wood chips, also increases, reaching circa 1.5 PJ in 2030 and 3 PJ in 2050.

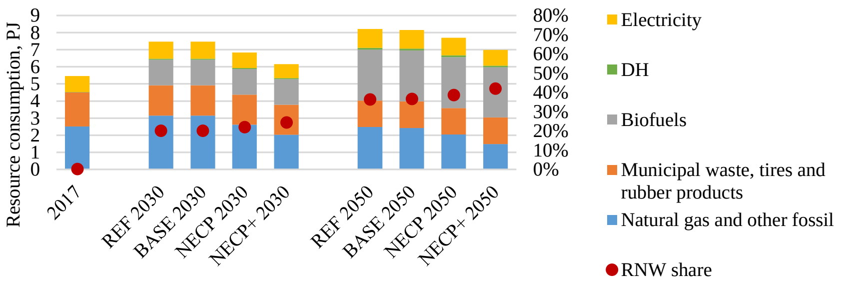


Fig. 3.14. Energy consumption in the minerals sub-sector in the modelled scenarios.

The share of renewable energy in 2017 was almost zero, while in 2030 and 2050, the share increased in all scenarios, reaching the highest share in the NECP+ scenario, which was equal to 24 % and 42 %. Fossil fuel dominance in all scenarios is due to the need for high temperatures in industry processes, which cannot be fully ensured by renewable resources.

Total final energy consumption in the industrial sector in BASE and REF scenarios grow steadily from 33 PJ in 2017 to 43 PJ in 2050, and in the NECP scenario, consumption increases to 40 PJ while in NECP+ to 35 PJ in 2050 (see Fig. 3.15). The increase in final energy consumption is due to the planned economic development of the industrial sector in Latvia and the existing PaM to increase energy efficiency and promote the use of RES. Due to the very narrow PaM in NECP2030, the higher efficiency of new technologies alone is not sufficient to compensate for the increase in demand due to economic growth.

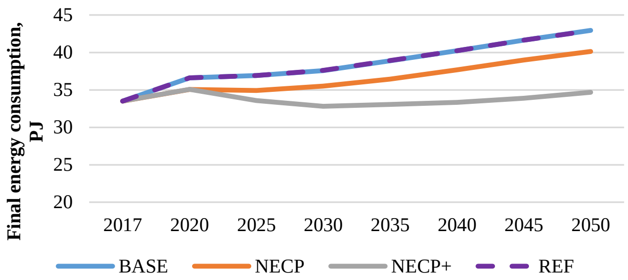


Fig. 3.15. Final energy consumption in the industrial sector in the modelled scenarios.

Further in this section, the resource transition in the passenger land transport sub-sector is analysed. Modelling results show that total energy consumption in the BASE scenario for land passenger transportation will increase by 4 %. In comparison, energy consumption decreases both in NECP (by 2 %) and in GHG TARGET (by 10 %) in 2030 compared to the base year level, which was around 23 PJ (see Fig. 16). In 2050, consumption decreases by 3 % in BASE, 14 % in NECP and 47 % in the GHG TARGET scenario, ensuring the same level of mobility.

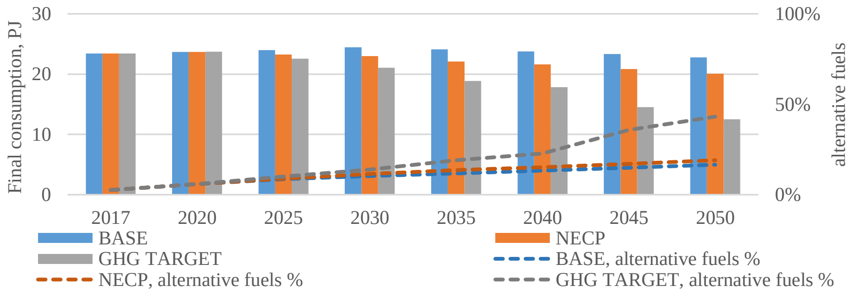


Fig. 3.16. Fuel consumption for the land passenger transportation for alternative scenarios.

Usage of alternative fuels in 2030 increases from 3 % in the base year to 10 % in the BASE scenario, 11 % in NECP and 14 % in the GHG TARGET scenario. More significant growth in usage of alternative fuels is seen in 2050 – in the BASE at 17 %, in NECP at 19 % and GHG TARGET, 43 % of used energy is alternative – biodiesel, bioethanol, electricity, biomethane and hydrogen.

Fossil fuels are mainly used for passenger transport in the BASE scenario (see Fig. 3.17.). Diesel oil is the primary fuel covering around 65 % of resources used in the base year, equal to 15 PJ. The results of the BASE scenario show that the importance of diesel oil will decrease, but it will still cover more than 50 % of fuels used in 2050. Usage of gasoline decreases from 6 PJ in 2017 to 3 PJ in 2050, while usage of LPG remains steady, reaching around 2 PJ. Primary alternative fuels used in the transport sector are electricity (power, bioethanol, and biodiesel). In 2050, biomethane is mostly used as an alternative fuel (covering around 35 % of alternative fuels), and about 25 % of alternative fuels are electricity.

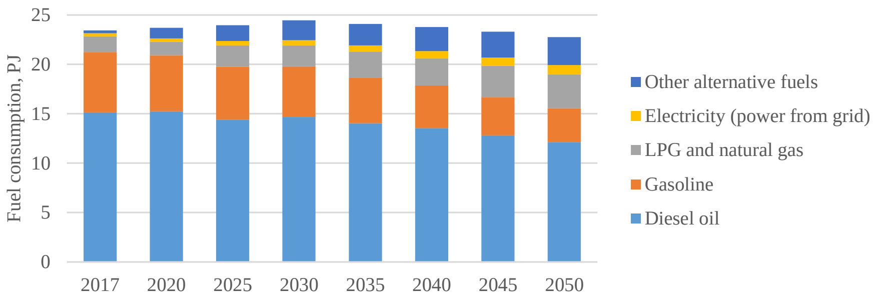


Fig. 3.17. Fuel consumption for the land passenger transportation in the BASE scenario.

Also, in the NECP scenario, usage of diesel oil, albeit decreasing, remains the most critical fuel, covering around 58 % in 2030 and 46 % in 2050 (see Fig. 3.18). Usage of gasoline, LPG, and natural gas decreases from 8 PJ in 2017 to 7 PJ in 2030 and 2050, equal to 35 % of the total fuel consumption. Alternative fuel consumption increases to 11 % in 2030 and 19 % in 2050, most of which are biomethane and electricity.

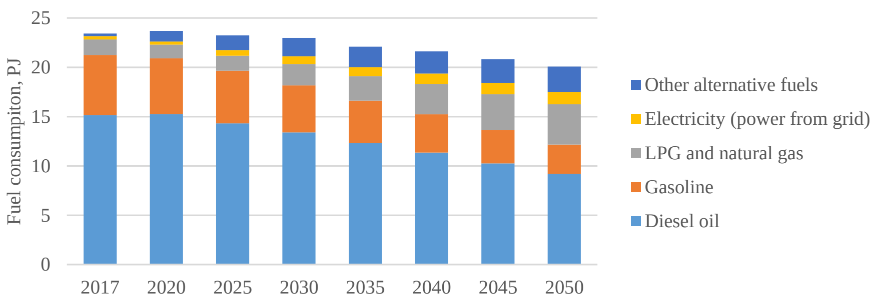


Fig. 3.18. Fuel consumption for the land passenger transportation in NECP scenario.

The GHG TARGET scenario shows the highest reduction in resource consumption as this scenario requires achieving climate neutrality. The total amount of resources decreases from 23 PJ in the base year to 12 PJ in 2050 (see Fig. 3.19).

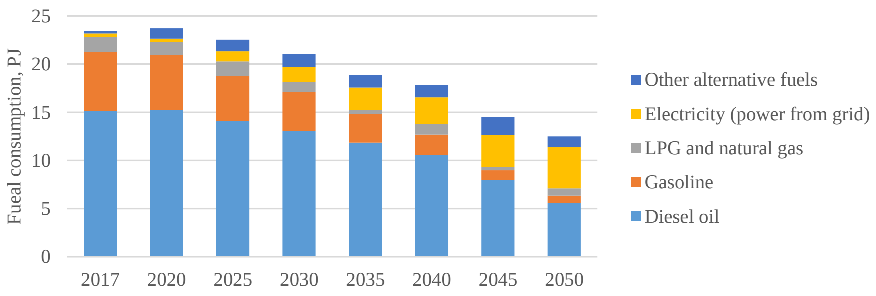


Fig. 3.19. Fuel consumption for the land passenger transportation in GHG TARGET scenario.

Also, in this scenario, diesel oil is the most used fuel, covering around 45 % of the total in 2050. Gasoline, LPG, and natural gas usage decreased from 8 PJ in 2017 to 2 PJ in 2050. 34 % of the total resources used in 2050 is electricity, and 9 % are other alternative fuels, most of which are hydrogen.

3.1.4. Resource transition in total primary and final energy consumption (5th level)

Changes in total and final energy demand, as well as resource consumption, are described for WAM, OPT_EE, OPT_Solar, and WEM scenarios.

The headline results of the self-optimisation run were used to understand which sectors, fuels, and technologies should be targeted by PaM in the bottom-up approach. The WAM scenario run with integrated policies shows a decreasing trend of PEC over time, going from 178 PJ in 2020 to 161 PJ in 2050 (see Fig. 3.20). In the long term, renewables, and in particular bioenergy, will provide most of the PEC, bringing the renewable share to 59 % and 72 % in 2030 and 2050, respectively. Gas consumption is expected to decrease substantially from 37PJ in 2020 to 9PJ from 2045 to 2050. PEC in the WAM scenario is around 8 % lower by 2050 than in the WEM scenario. The main policy measure implemented in the WAM scenario is building renovation, and it reaches a similar level as in the OPT_EE scenario (44 % of total buildings in 2030 and 70 % of total buildings in 2050). However, the WAM scenario does not reach the same level of electricity generation from wind power as in optimisation scenarios, as there are no significant supporting policies included (only the Planning process reform).

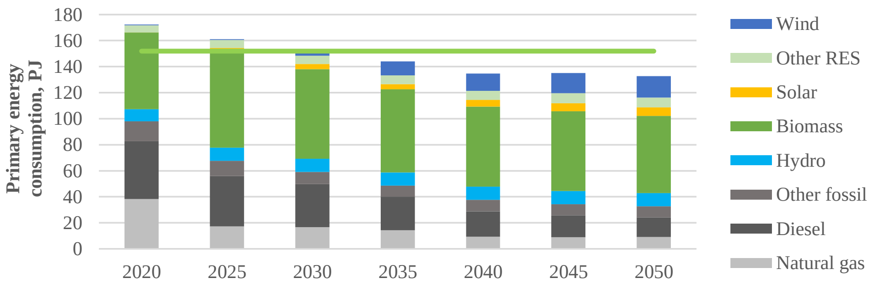


Fig. 3.20. PEC development in WAM scenario.

Figure 3.21 represents the comparison of PEC in optimisation and WEM scenarios. By 2030, wind and hydropower are expected to contribute significantly to the overall electricity supply. Like the baseline scenario, hydroelectric power production is expected to remain constant at 10 PJ / year. Biomass, on the other hand, is projected to make only a marginal contribution after 2040.

Both OPT scenarios demonstrate an increasing utilization of wind power for electricity generation (as shown in Fig. 3.21). However, the OPT_Solar scenario reaches higher overall solar energy production rates because local RES for self-consumption is considered as an EE measure, and therefore, FEC and PEC targets can be achieved with fewer consumption reduction measures. The model tends to install more solar PV panels for self-consumption coverage instead. In the OPT_EE scenario, the most significant reduction in energy consumption within buildings results from an increase in EE due to improved insulation, which leads to a decrease in heat loss.

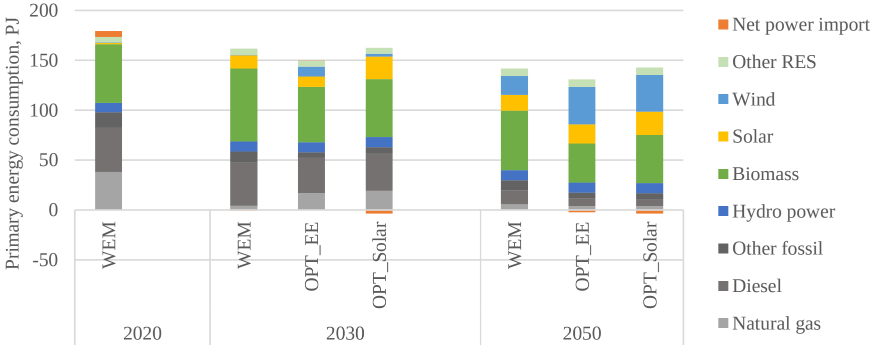


Fig. 3.21. Primary energy mix comparison in different optimisation scenarios.

Optimisation scenarios are designed to reach the REPowerEU FEC and PEC targets in 2030, but as TIMES does not include an annual limit to technology deployment, it switches technology for the target in the last available years. Fig. 3.22. shows the PEC and FEC results of the Reference scenario (WEM) in comparison with two different optimisation pathways. It can be seen that the WEM scenario with existing policies is far from the 2030 targets.

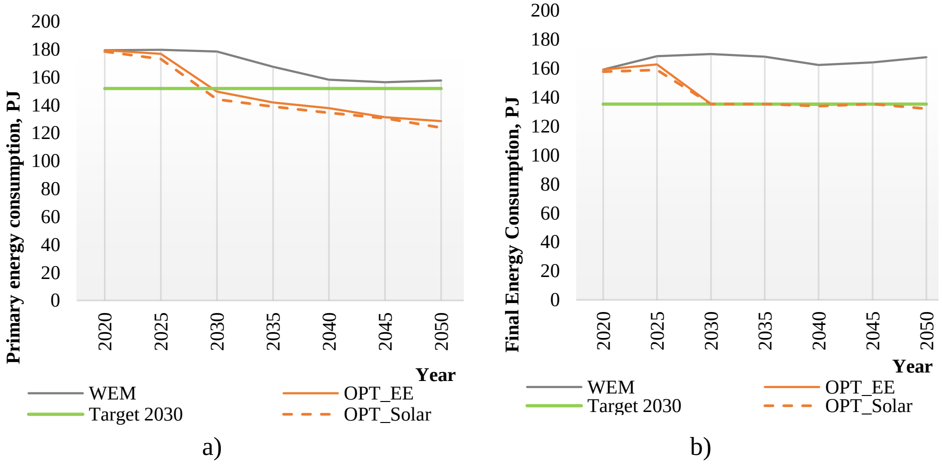


Fig. 3.22. PEC (a) and FEC (b) results in self-optimisation run.

3.2. Contribution of sectors and sub-sectors in achieving climate neutrality

Changes in emission volumes are described for the energy transformation sector and for passenger transport on land based on distances across BASE, NECP, and GHG TARGET scenarios. Additionally, the total emissions of the industrial sector for BASE, NECP, and NECP+ scenarios are detailed. A comparison of emission volume changes for each sector under the WEM, OPT_EE, OPT_Solar, and WEM scenarios is also provided.

Total GHG emissions of the energy transformation sector in the BASE scenario are decreasing by around 53 %, while both the GHG TARGET and NECP scenarios reach climate neutrality in 2050 due to the exclusion of natural gas (see Fig. 3.23).

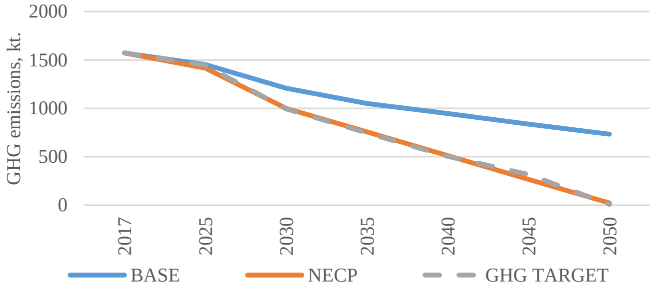


Fig. 3.23. GHG emissions in the energy transformation sector.

In all three scenarios and all distances, the amount of projected GHG emissions is decreasing (see Fig. 3.24). In the BASE scenario, the total GHG emissions will be reduced by 2 % in 2030 and by 14 % in 2050, in NECP by 10 % and 27 %, and in GHG TARGET by 19 % and 69 % for the same period.

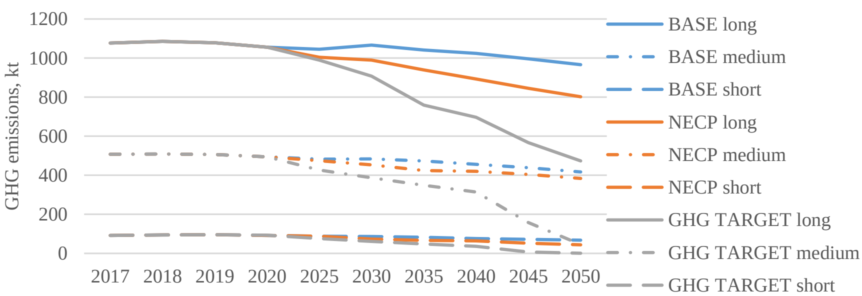


Fig. 3.24. Projection of GHG emissions by distances.

Most of the emissions are released when travelling long distances. Although the amount of GHG emissions is decreasing considerably – from around 1100 kt in the BASE year to 800 kt in NECP and 470 kt in GHG TARGET, the proportion of the decrease is lower than in other distances. Only a 10 % decrease is reached in BASE, 26 % in NECP, and 56 % in GHG TARGET in 2050.

GHG emissions in medium distances are decreasing by 18 % in BASE, 24 % in NECP, and 91 % in GHG TARGET in 2050 compared to the base year. Meanwhile, GHG emissions in short distances are decreasing by 27 % in BASE, 52 % in NECP, and 99 % in GHG TARGET scenarios in 2050.

GHG emissions in industrial sector in 2017 are around 760 kt and in all scenarios emissions are decreasing. The largest reduction is in NECP and NECP+ scenarios where emissions in 2030 decrease to around 510 kt and 470 kt, which is around 33 % and 39 % less than in 2017 (see Fig. 3.25).

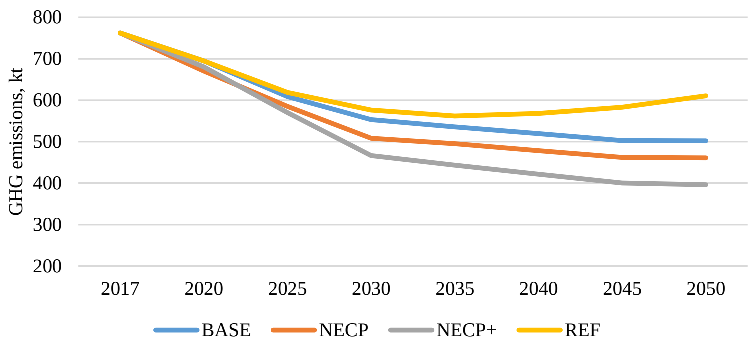


Fig. 3.25. GHG emissions in industrial sector in the modelled scenarios.

In REF and BASE scenarios, emissions in 2030 decrease to 576 kt and 553 kt respectively, which is by 24 % and 27 % less than in 2017. In 2050, the highest amount of emissions is in REF scenario, reaching 610 kt, which is 20 % less than in 2017. In BASE and NECP scenarios, emissions reach circa 480 kt which is 37 % less than in 2017, while NECP+ emissions reach circa 400 kt which is by 48 % less than in 2017.

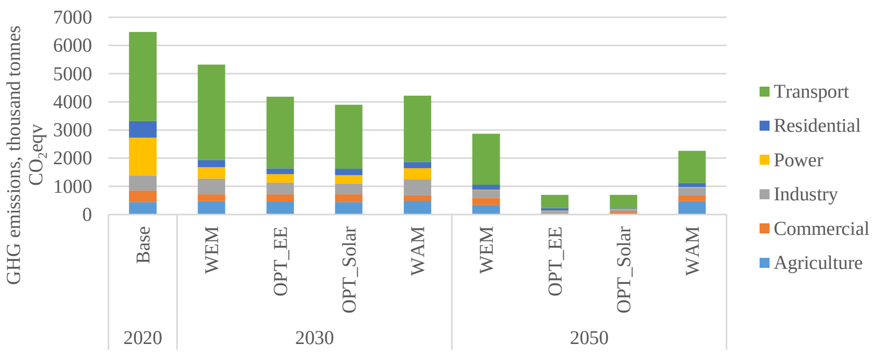


Fig. 3.26. Reached GHG emission of analysed scenarios in different end use sectors.

Figure 3.26 shows the comparisons of reached GHG emissions in analysed scenarios across different sectors. As can be seen, the set of analysed policies in WAM does not fully reach the GHG emission reduction in 2050 due to the lack of additional policies in the transport and agriculture sectors. In the optimisation pathways, the agriculture sector is decarbonised by integrating more biomethane and hydrogen for machinery, but in the transport sector higher electrification rates for freight transport are reached. Therefore, additional PaM should be targeted to integrate carbon-neutral solutions in these sectors.

3.3. Estimates of specific costs and required investment

The total investment volume is described for the energy transformation sector, covering heat and electricity production. As well specific costs for reducing greenhouse gas emissions and the costs of heat energy technologies per unit of heat produced for BASE, NECP, TARGET and TARGET+ scenarios. Costs and investment volumes for the transport sector are outlined for BASE, NECP and GHG TARGET scenarios. Additionally, total investments for various PaM are detailed for WEM, OPT_EE, OPT_Solar and WAM scenarios.

Results demonstrate that the energy transformation sector can produce the required amount of DH and power with almost no emissions. However, to ensure the integration of renewable technologies, new investments in heat and power production technologies took place in the energy transformation sector. The total heat and power production costs, including the power necessary for the operation of heat pump technologies, can be seen in Fig. 3.27. The total energy production costs, including both the investments and all O&M costs, are 22 % higher in NECP and 20 % higher in the TARGET scenario compared with the BASE scenario. The additional biomass limitation increases the total energy production costs by 4 % or 64 MEUR compared to the TARGET scenario. In the NECP scenario, higher prices are dedicated to the power sector as it includes the support for offshore wind power plant installation.

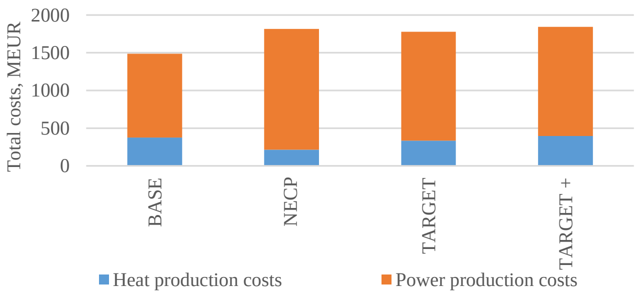


Fig. 3.27. Total investment costs in the energy transformation sector.

The specific costs per reduced GHG emissions in the energy transformation sector during the modelled period from 2017 to 2050 can be seen in Fig. 3.28. (a). Those also include the costs for energy efficiency measures, including insulation of buildings and reconstruction of existing heating grids. These costs have been adopted to be equal in NECP and GHG TARGET scenarios derived from the SD model and account for an additional 1.76 million EUR. As can be seen, only slightly higher GHG emission reduction costs have been obtained in the NECP scenario, accounting for 2307 EUR per ton of reduced GHG emissions compared to the TARGET scenario. The specific GHG emission reduction in the BASE scenario is much lower than in other modelled scenarios. The energy production optimisation in this scenario is only based on reaching the most insufficient investment and operation costs without additional conditions to achieve environmental benefits.

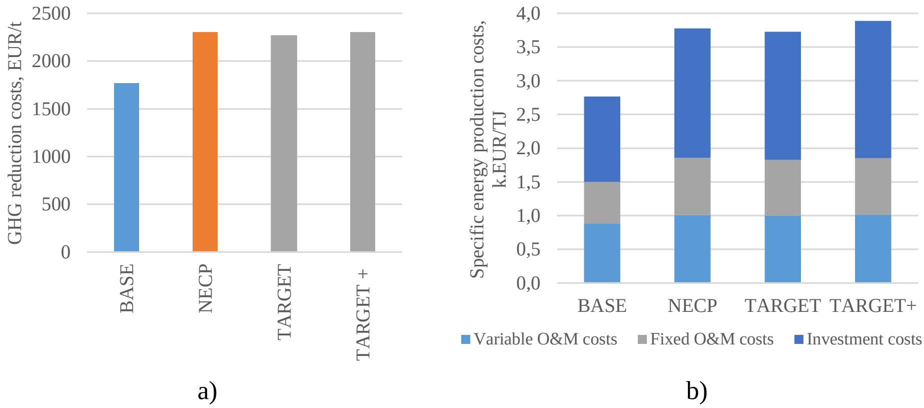


Fig. 3.28. The modelled specific GHG emission reduction costs (a) and typical costs for heating technologies per unit of produced energy in DH (b).

Also, the specific energy production costs increase significantly when comparing the BASE scenario and other modelled scenarios of energy transformation sector development (see Fig. 3.28.(b). Due to the lack of energy efficiency measures, specific energy costs in the BASE scenario are about 37 % lower than the NECP scenario, leading to 2765 euros per one TJ of produced energy (including power and heat production). More efficient and more expensive technologies are used in those scenarios with little or no emissions, e.g., solar collectors and heat pumps. The NECP scenario requires 3778 euros of investment in heat and power-producing technologies per the same amount of thermal energy produced. However, the GHG TARGET scenario requires slightly lower costs – 3726 EUR/TJ investment costs per produced power and heat unit due to energy production optimisation.

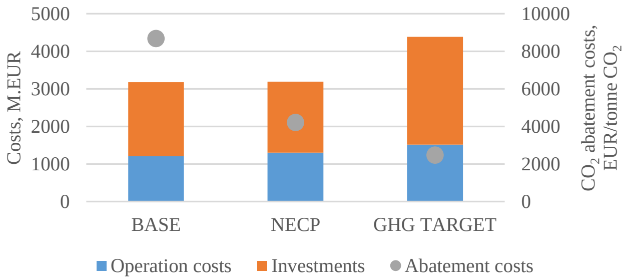


Fig. 3.29. Projection of costs in the transport sector.

Modelling results show that transport decarbonisation in the GHG scenario requires around 2868 MEUR, 38 % more than in the BASE scenario (see Fig. 3.29). However, the CO_2 abatement costs for GHG emission reduction are lower in this scenario as the TIMES model optimises the system to reach the lowest GHG emission reduction costs.

The objective of the modelling task is to meet the required energy service demand at the lowest possible total cost. It is clear that achieving climate neutrality requires significant investments in renewable energy (RES) technologies and energy efficiency measures that promote energy conservation and the transition to renewable energy sources.

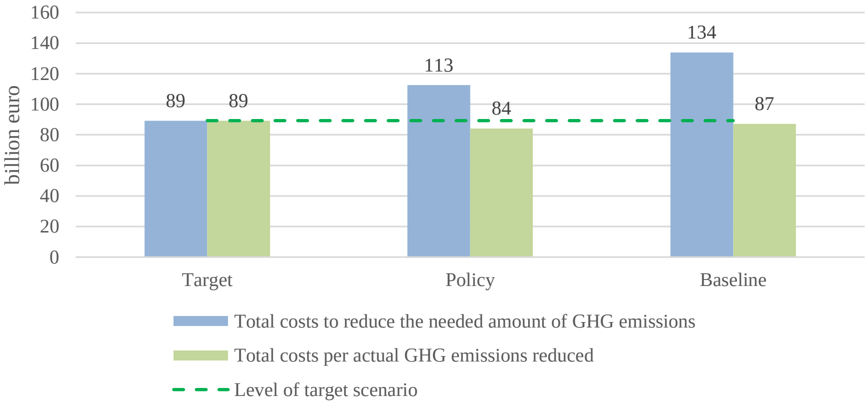


Fig. 3.30. Total system costs for CO_2 reduction for different scenarios.

The results indicate that the target scenario can achieve climate neutrality. However, its total costs are approximately 6 % higher by 2050 than in the policy scenario and approximately 2 % higher than in the baseline scenario when considering the actual reduction in greenhouse gas (GHG) emissions achieved in each case (see Fig. 3.30). Nevertheless, the policy and baseline scenarios fail to achieve climate neutrality, as they do not deliver the necessary GHG emission reductions.

The necessary GHG reductions in the target scenario can be achieved with a total investment of EUR 89 billion by 2050, approximately 8.2 % of the total projected GDP in this period. In contrast, the policy scenario would require EUR 113 billion to achieve the same level of reduction, which is approximately 10.3 % of GDP. In comparison, the baseline scenario would require EUR 134 billion, or approximately 12.3 % of GDP.

This analysis indicates that although the target scenario requires greater investments than the baseline and policy scenarios, it allows for climate neutrality more economically when considering necessary GHG reductions. Specifically, it results in total costs that are 26 % lower than those of the policy scenario and 50 % lower than the baseline scenario.

Total investment and the subsidised part of those investments, for different WAM and WEM scenario measures, are shown in Table 3.1. All the investments and subsidies are shown as a cumulative value from 2020 to 2030. As local RES can be used to achieve energy efficiency targets, OPT_Solar has a higher total investment in PV panels than the OPT_EE scenario and a lower total investment in building renovations.

Table 3.1

Cumulative Investments and Subsidies from 2020 to 2030

	Total investment, billion EUR				**Subsidies, billion EUR**		**Subsidies % of total, %**	
	WEM	OPT_I	OPT_II	WAM	WEM	WAM	WEM	WAM
Building renovation	1.25	8.98	4.13	5.45	0.52	3.59	41.7	65.89
Biomethane production	0.02	0.02	0.02	0.06	0.01	0.03	28.62	41.22
PV panels	1.84	1.16	3.35	1.51	0.02	0.02	1.33	1.63
Consumer heat pumps	0.16	0.16	0.16	0.15	0.00	0.06	0.00	40.29
Industry energy efficiency	0.65	1.42	0.87	0.63	0.06	0.06	8.66	8.91
Power sector	2.70	4.63	4.44	3.09	0.03	0.03	1.23	1.07
Public transport	0.83	1.85	1.53	1.11	0.01	0.05	1.18	4.07
Electric vehicles	1.82	8.98	8.10	3.04	0.01	0.01	0.55	0.33

For both OPT_EE and OPT_Solar scenarios, investments in electric vehicles are equally high. Comparing WEM and WAM scenarios, there is an increase in the subsidized part of the building renovation investments, moreover, there is a significant increase in total investments in building renovations from EUR 1.25 billion in the WEM scenario to EUR 5.45 billion in the WAM scenario, this combination requires a substantial increase in subsidies from EUR 0.52 to EUR 3.59 billion (see Table 3.1).

3.4. Comparison of the target scenario with the scenarios of Energy Strategy Latvia 2050

The leading institution in climate and energy policy in Latvia is the Ministry of Climate and Energy, which, in collaboration with industry stakeholders, has developed a draft Energy Strategy 2050. This strategy outlines five potential development scenarios, incorporating both optimistic and pessimistic local and global trends.

Table 3.2

Comparison of scenarios developed in Energy strategy of Latvia 2050
by the Ministry of Climate and Energy

Scenario name	Assumptions for global and local scale conditions
Baseline (Preferred) Scenario	Current global trends continue. National policy decisions improve productivity, and fossil fuels are gradually replaced with sustainable, local solutions.
Pessimistic 1	Regulations promoting renewable energy (RES) are removed, fossil fuel prices decrease, and the transition to RES slows down.
Pessimistic 2	Geopolitical disruptions and supply chain issues arise, capital costs increase, and the development of RES infrastructure and imported energy replacement slows.
Optimistic 1	Stable global economic growth, transition to sustainable solutions and RES, and reduced dependency on fossil fuels.
Optimistic 2	Development of new RES capacities and innovative technologies.

The Baseline (Preferred) Scenario assumes that current global trends remain unchanged. Pessimistic 1 foresees the removal of RES-supporting regulations, Pessimistic 2 anticipates geopolitical instability, supply chain disruptions, and rising capital costs, Optimistic 1 projects stable global economic growth and a substantial shift toward sustainable solutions, Optimistic 2 envisions the development of new RES capacities and innovative technologies.

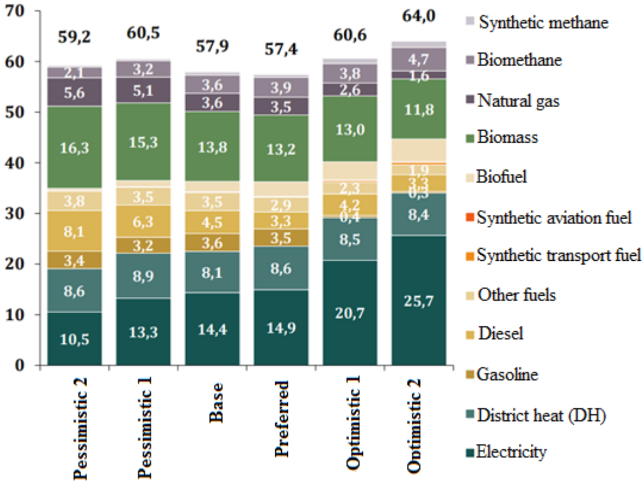


Fig. 3.31. Comparison of energy consumption forecasts for 2050 (TWh, Gross) (MoCE, 2024).

As part of this study, the gross energy consumption structure projected for 2050 in the scenarios developed by the Ministry of Climate and Energy was compared with the results of the target scenario developed in the Doctoral Thesis. The results of the target scenario most closely align with the forecasts of the Optimistic 1 and Preferred (Baseline) scenarios.

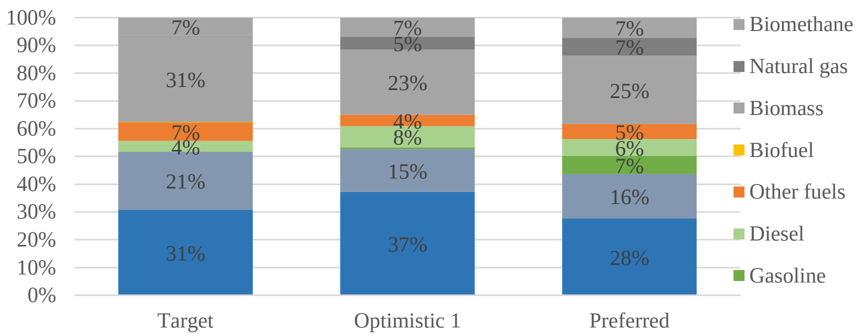


Fig. 3.32. Comparison of the Target scenario of the study and the Energy Strategy Latvia 2050 scenarios (Preferred and Optimistic 1).

All three scenarios show a significant share of electricity in total gross energy consumption: Target scenario – 31%, Optimistic 1 – 37 %, Preferred scenario – 28 %.

Unlike the ministry's scenarios, the target scenario projects a higher share of biomass and DH usage as well a lower share of natural gas, diesel, and gasoline.

Overall, both the ministry's development scenarios and the model-based target scenario show similar trends for the energy sector's future. A significant role in energy consumption is expected to come from electricity-generating technologies and modern biomass technologies.

CONCLUSIONS

The Thesis presents a new methodology for assessing the progress of the Latvian energy sector toward climate neutrality. In the course of the work, a model was developed, and three types of scenarios were formulated.

- Baseline Scenarios (BASE and WEM): These incorporate the current strategy, tax policy, and PaM.
- Policy Scenarios (NECP, WAM): These include various policy instruments, for example, the PaM outlined in the National Energy and Climate Plan until 2030.
- Target Scenarios (GHG TARGET, OPT_EE, OTP_Solar): These aim to achieve climate neutrality by 2050.

The modelling was carried out using the TIMES tool. The main conclusions derived from the Doctoral Thesis are:

1. The model results confirm that, with the current PaM in Latvia, the climate targets set for 2050 will not be achieved. The findings also indicate that the necessary GHG emission reductions for achieving climate neutrality can be attained in the long term with additional targeted PaM.
2. Optimisation results highlight a strong interdependence between the use of heat pumps and wind energy production. This suggests that increasing wind energy utilisation can foster broader adoption of heat pumps and vice versa, thereby ensuring even greater GHG emission reductions.
3. The model shows that final energy consumption in Latvia's industrial sector will increase in all development scenarios, driven by projected economic growth. The existing PaM are insufficient to offset the increase in energy demand in this sector.
4. Biomass is the most important energy resource in the wood sub-sector, gradually replacing natural gas during the modelling period. Similarly, in the food sub-sector, biomass is increasingly replacing natural gas. In the non-metallic minerals sub-sector, natural gas and other fossil fuels, as well as household waste, tires, and rubber products, remain significant energy resources even until the end of the modelling period. At the same time, the share of renewable energy also increases in all analysed scenarios.
5. Centralised district heating consumption remains stable in the baseline scenario. In contrast, in the policy and target scenarios, it decreases by approximately 30 %, thanks to improvements in building energy efficiency, district heating network renovation, and other energy efficiency measures. In the baseline scenario, natural gas and biomass dominate in district heating production, while in the policy and target scenarios, natural gas usage is phased out by 2050. In the target scenario, biomass consumption decreases to about 20 %, with large-scale heat pumps and solar energy producing a substantial share of the heat energy. Sensitivity analysis indicates that stricter biomass availability constraints accelerate the adoption of large-scale heat pumps.
6. Both the policy and target scenarios demonstrate that Latvia's energy transition sector can generate the required volumes of district heat and electricity almost without

emissions, provided that significant investments are made in low-emission technologies. Achieving this requires more than 22 % or more than EUR 326 million in additional investments by 2050 compared to the baseline scenario.

7. An investment of EUR 89 billion is required by 2050 to implement the target scenario. This amount is approximately 8.2 % of the total projected GDP in this period, which is approximately 6 % higher by 2050 than in the policy scenario and approximately 2 % higher than in the baseline scenario regarding the corresponding GHG emission reductions. However, to reach the necessary GHG emission savings for climate neutrality under the policy scenario, an additional investment of roughly 26 % would be needed. In comparison, the baseline scenario would require approximately 50 % more than the target scenario. This is because the target scenario offers the lowest GHG emission reduction cost per ton.
8. The results indicate that targeted policies are crucial for achieving the set REPowerEU and Green Deal goals, as the baseline scenario results, without additional PaM, fall far short of the desired primary energy consumption (PEC) and final energy consumption (FEC) levels for 2030 and 2050. This implies that relying solely on market forces is insufficient; a policy designed to ensure the attainment of climate targets must be implemented. Such a policy could include measures to promote technology replacement, increased carbon taxes, and stricter regulations for market players to facilitate the transition to renewable energy and promote energy efficiency and conservation.
9. A TIMES optimisation simulation, in which only energy efficiency measures are allowed to achieve the 2030 FEC targets, shows that the most cost-effective decarbonisation path largely depends on building renovation and electrification. In an alternative optimisation scenario that allows the installation of solar panels for end-user consumption, the emphasis on building renovation is reduced as solar energy becomes a more cost-effective solution. In cost terms, the optimal decarbonisation strategy thus involves fewer energy efficiency measures but greater investments in renewable energy technologies. Both self-optimisation simulations indicate a shift from fossil fuels to renewables across all sectors after 2030, with the transportation sector exhibiting the slowest transition and retaining the largest share of emissions by 2050.
10. The classic TIMES modelling tool is suitable for general technical-economic analysis. However, introducing innovative solutions into the model is vital for providing a broader analysis of PaM, and for a more accurate determination of the structure of energy consumption, which is an important support for decision-making that contributes to achieving climate goals at lower overall costs. Examples include:
    - Separating the ETS system for the industry and energy transformation sectors in the model allows for the analysis of the impact of emission allowance prices and taxes and the effect of measures directly targeting energy-intensive producers.
    - Including a comfort element in the transport sector accounts for human behaviour, ensuring that results are not based solely on economic profitability.

– Modelling demand for heated square meters in the residential and commercial sectors allows the evaluation of energy efficiency measures. Previously, this was not possible directly, as end demand was based only on heating and cooling volumes.
– The implementation of the industrial waste heat utilisation process in the model allows for analysis of the impact of measures aimed at waste heat utilisation.

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PUBLICATIONS ARISING FROM THIS THESIS

Paper 1: Dzintars Jaunzems, Ieva Pakere, Signe Allena-Ozolina, Ritvars Freimanis, Andra Blumberga, Gatis Bazbauers Adaptation of TIMES model structure to industrial, commercial and residential sectors Environmental and Climate Technologies, 2020, Vol. 24, No. 1, 392.-405.

Paper 2: Signe Allena-Ozolina, Ieva Pakere, Dzintars Jaunzems, Andra Blumberga, Gatis Bazbauers Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling 2020 IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2020): Conference Proceedings, Latvia, Riga, 5.-7. November, 2020. Piscataway: Institute of Electrical and Electronics Engineers Inc., 2020, 456.-462.

Paper 3: Signe Allena-Ozolina, Dzintars Jaunzems, Ieva Pakere, Andra Blumberga, Gatis Bazbauers Decarbonisation Pathways of Industry in TIMES Model Environmental and Climate Technologies, 2021, Vol. 25, No. 1, 318.-330..

Paper 4: Signe Allena-Ozoliņa, Ieva Pakere, Dzintars Jaunzems, Andra Blumberga, Armands Gravelsins, Dagnis Dubrovskis, Salvis Dagis Can energy sector reach carbon neutrality with biomass limitations? Energy, 2022, Vol. 249

Paper 5: Signe Allena-Ozolina, Ieva Pakere, Dzintars Jaunzems, Ritvars Freimanis, Andra Blumberga, Gatis Bazbauers Passenger transport shift to green mobility - assessment using TIMES model *Environmental and Climate Technologies, 2022, Vol. 26, No. 1, pp.341-356.*

Paper 6: Ieva Pakere, Ritvars Freimanis, Signe Allena-Ozoliņa, Pauls Asaris, Andrea Demurtas, Marine Gorner, Jessica Yearwood Cost-Optimal Policy Strategies for Reaching Energy Efficiency Targets and Carbon Neutrality Environmental and Climate Technologies, 2023, Vol. 27, No. 1, .999-1014.

ADAPTATION OF TIMES MODEL STRUCTURE TO INDUSTRIAL, COMMERCIAL AND RESIDENTIAL SECTORS

Environmental and Climate Technologies
2020, vol. 24, no. 1, pp. 392–405
https://doi.org/10.2478/rtuect-2020-0023
https://content.sciendo.com

Adaptation of TIMES Model Structure to Industrial, Commercial and Residential Sectors

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***Abstract* – National energy sector management differs from country to country. Therefore, it is important to develop country-specific energy models to analyse the energy demand, structure and potential policy instruments. The paper presents a pathway for adaption and improvement of the standard TIMES model structure to the specific country requirements. The analysis is based on a three-sector (industrial, commercial and residential) case study of Latvia. Literature review presents experience of other research when developing different energy models as well as adapting the TIMES model structure. The main results show a distribution of the final energy consumption and the validation of the obtained results of the sectors studied. Method and intermediate results presented in the paper are part of an ongoing modelling process of Latvia's energy sector.**

***Keywords* – Energy system modelling; final energy consumption; optimization bottom-up model, TIMES model.**

1. INTRODUCTION

Consequences of global warming have become more realistic and more prominent in all regions. Therefore, policy makers implement various laws, regulations, policy measures and other regulatory frameworks to limit increase of the global average temperature. Energy production is one of the main driver of global warming which is related to all other sectors.

Different energy models can play a crucial role when developing energy planning strategies. Researchers from China have created the multi-sectoral energy model merging electricity, transportation, heat and industrial sectors to model decarbonisation of an energy system [1]. Often researchers combine different types of models, for example, technically detailed bottom-up and top-down models that simulate demand and prices on energy [2], [3]. The system dynamic approach has been used to model the transition from fossil fuels to renewable energy resources by taking into account different techno-economic parameters, political and social aspects, as well as human behavior [4].

In many countries, sector-specific energy models have been developed, for example, the household sector model which analyses and evaluates implementation of renewable energy systems for regional demand [5]. Many simulations are performed to identify heat demand and to simulate future demand by clustering of the residential sector in the UK [6]. Also in Quebec (Canada), electricity supply of households, which are already low-carbon, have been modelled by combined building model simulations to investigate mitigation opportunities of greenhouse gases (GHG) [7].

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Less models have been developed for the industrial sector. Researchers have modeled the potential energy savings and decrease of CO_2 emission in iron and steel industry by using a bottom-up linear optimization model [8]. Another bottom-up model has been developed for industrial sector of Denmark [9]. The highly technologically detailed FORECAST bottom-up model has been created to simulate energy perspectives and develop scenarios for energy sector decarbonisation [10].

In many countries, researchers have used the Integrated MARKAL-EFOM System (TIMES) model generator to analyse local, national and global energy systems and potential to reach the climate targets. In most cases, the basic sectoral structure of TIMES needs to be adjusted and modified to represent the country-specific energy system. German researchers have developed the TIMES model to improve decision-making related to investments. In the adapted energy model, the country is divided into four regions, but investors – into three groups depending on the costs of capital and budget restrictions [11].

The energy system model has also been created for Denmark. The model divides the country into two energy regions – Denmark East and Denmark West and covers five sectors – supply, power and heat, industrial, residential and transport. The year has been divided into 32 time slices representing four seasons, weekly and daily variations. That increases the variability of the model regarding heating demands, availability of intermittent renewable energy sources and technologies like solar PV and wind turbines. In addition, efficiency of large-scale heat pumps is assumed to be dependent on outdoor temperature. Import and export prices are divided into 32 time slices as well. Authors divide the residential sector according to the building type and construction period, district heating (DH) area and regions resulting in 36 building groups. In contrast, the industry sector is divided into 12 sectors, covering primary, secondary and tertiary sectors. Transport sector has two large groups – passenger and freight, divided into aviation, maritime and inland. Inland passenger transport has been divided into eight modes including cars, buses, railway, motorcycle and non-motorised modes like walking and biking [12].

British researchers have developed a model framework in the UK for residential sector in TIMES to analyse homeowner preferences for heating technologies. Households were divided into three groups depending on number of bedrooms and into four groups depending on the existing heating technologies – gas heaters, electric heaters, heat pumps and solid fuel boilers. In this model 16 time slices have been used representing four seasons and four day splits [13].

Although TIMES is a powerful modelling tool, some articles discuss the need to take into account not only technology development but also feedback loops, social behavioral changes and other factors [14]. Some TIMES models have been improved by adding consumer behavior in the optimization model using social surveys [13], [15], [16].

Models are important to increase the quality of research, reduce duplication of work, and there are other benefits [17]. Above all, a representative model is based on the transparency and availability of data. Therefore, this paper presents the TIMES model structure of three different sectors and the methodology, which has been used to determine energy consumption division for different end-use processes.

The main aim of the paper is to present structural adoption of the TIMES model to industrial (IND), commercial (COM) and residential (RSD) sectors of Latvia. The article also presents the necessary data gathering. Along with sectoral specific changes this structure can be adopt to other countries. As far as authors know this is the first TIMES model of Latvia case. Previously there were used MARKAL and MARKAL-TIMES models for Latvia.

2. Methodology

This section presents the methodology for adopting and adjusting the TIMES structure to Latvia's IND, COM and RSD sectors.

TIMES vertically integrated model generator is used to model different energy systems - local, national or global. It aims to find the minimum global costs for energy services considering different input data: energy service demands, estimates of the existing energy stocks, properties of the existing equipment and future technologies. Furthermore, TIMES allows to analyse different energy and environmental scenarios and policy measures [18].

2.1. Industry sector

Latvia is a part of the European Union emission trading system (ETS). Therefore, energy demand of almost each IND sector in Latvia has been divided into ETS sector and non-ETS sector consumption (see Table 1). The ETS system of Latvia mostly covers power plants and other incineration plants with nominal thermal input of more than 20 MW. Also specific equipment, like coke ovens, iron and steel, cement clinker and others technologies, are included in the ETS system [19]. In 2017, the ETS sector covered around 15.5 % of the total resource demand in Latvia equal to 5561 TJ. Non-ETS covered the rest of demand, i.e. 84.5 % or 30335 TJ [20].

TABLE 1. IND SUB-SECTORS IN LATVIA

	1	2	3	4	5		1	2	3	4	5
Iron and steel		∨	∨	∨	∨	Mining ETS			∨	∨	
Iron and steel ETS			∨	∨		Paper, pulp and print (Paper)		∨	∨	∨	∨
Chemical and chemical products (Chemical)	∨	∨	∨	∨	∨	Wood and wood products (Wood processing)	∨	∨	∨	∨	∨
Chemical ETS			∨	∨		Wood processing ETS			∨	∨	
Non-ferrous metals		∨	∨	∨	∨	Food and tobacco	∨	∨	∨	∨	∨
Non-metallic minerals		∨	∨	∨	∨	Food and tobacco ETS			∨	∨	
Non-metallic minerals ETS			∨	∨		Construction	∨	∨	∨	∨	∨
Transport equipment	∨	∨	∨	∨	∨	Construction ETS			∨	∨	
Transport equipment ETS			∨			Textile and leather (Textile)		∨	∨	∨	∨
Machinery		∨	∨	∨	∨	Textile ETS			∨	∨	
Mining and quarrying (Mining)		∨	∨	∨	∨	Other – rubber, plastic furniture and others (Other)	∨	∨	∨	∨	∨

1 – feedstock, 2 – machine drive, 3 – process heat, 4 – building heat, hot water,
5 – cooling, lighting, ventilation, other

Five different end-use processes have been analysed in the IND sector: feedstock, machine drive, process heat, building heat and hot water, and other processes, including cooling, lighting and ventilation (Table 1). For some sectors (Chemical production, Transport equipment) all processes have been analysed but for sectors included in ETS only two processes (process heat, building heat and hot water) have been included due to specific plants.

To determine a share of the total energy sources used for each process, authors used the data from the IND energy audits carried out in the period 2016–2018. The energy balances from 122 different enterprises have been analysed to identify the distribution of various energy sources.

2.2. Commercial sector

There are different buildings and resulting consumption levels of energy resources in the COM sector. Therefore, it has been divided into seven sub-sectors (see Table 2) based on the building classification [21].

Resource consumption for almost all COM sub-sectors has been divided into ten processes: heating, cooling, cooking, lighting, public lighting, refrigeration, ventilation, water heating, office equipment and other. New process of heating and cooling demand was created – heating and cooling area (m^2) to add more precise policy measures directly to energy efficiency of specific buildings. To ensure correct process development in TIMES model, heating and cooling processes have been separated as pre-process for heating and cooling area which now have been defined as end demand (see Fig. 1).

TABLE 2. COM SUB-SECTORS IN LATVIA

Sector	**Total energy consumption in 2017**		**Total area in 2017**	
	TJ	%	m^2	%
Wholesale and retail buildings (Retail)	4085	16.04	4920	15.90
Office buildings (Offices)	4893	19.21	6510	21.03
Hotel buildings (Hotels)	2511	9.86	2310	7.46
Schools, universities and research buildings (Educational)	5144	20.20	6940	22.42
Buildings for medical or health care facilities (Medical)	2281	8.96	2020	6.53
Entertainment event, sports buildings, museums, cultural buildings, cultural and historical sites (Entertainment)	2506	9.84	3320	10.73
Other – garages, communication centres, stations, terminals etc. (Other)	3344	13.13	4930	15.93
COM ETS	704	2.76	–	–
Total	25 468	100.00	30 950	100.00

Similar to other demand processes, demand for heating and cooling area (m^2) has been affected by demand drivers like GDP growth and elasticity for evolution with GDP. Specific plants appear in COM sector as ETS participants. Those mainly ensure different manufacturing processes. In TIMES model, they have been divided separately with similar processes to IND sector – process heat and building heat, and hot water (Fig. 1).

The available statistical data only presents the total consumption of primary energy sources, and heat and power consumption in overall COM sector. Therefore, the specific consumption for different end use purposes has been determined through several assumptions and calculations.

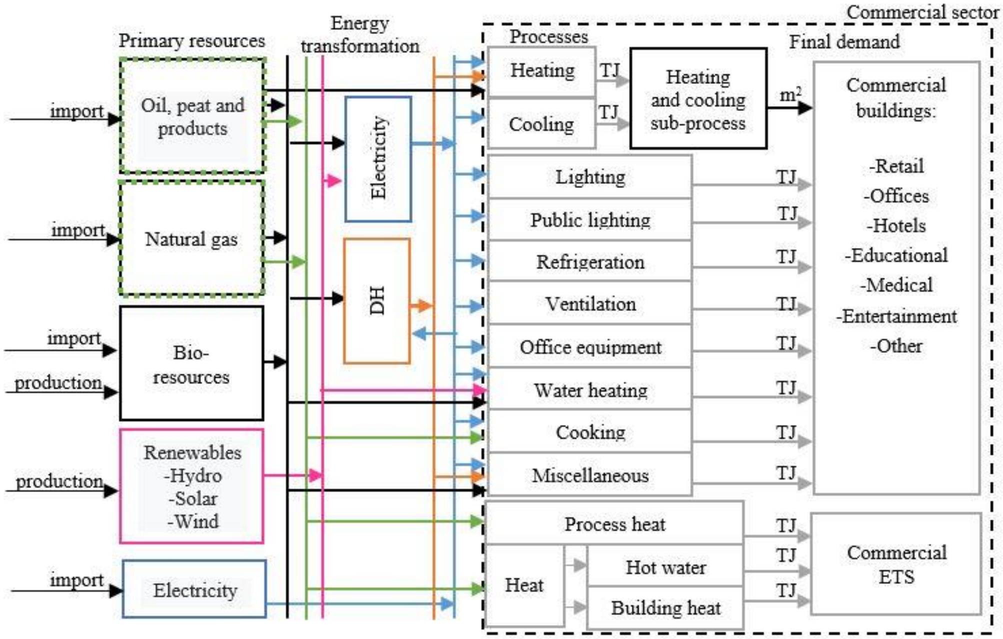

Fig. 1. Process scheme of COM sector.

The main input data for calculations is the total floor area of different types of buildings – offices, hotels and restaurants, schools, universities and research buildings (education), hospitals and buildings for health care facilities (medical), buildings for entertainment events and sports, museums, cultural and historical sites (entertainment) and other not previously classified buildings. Table 3 summarizes the main assumptions related to energy consumption distribution.

TABLE 3. ASSUMPTIONS FOR ENERGY DISTRIBUTION IN COM SECTOR

Parameter	**Retail**	**Offices**	**Hotels**	**Education**	**Medical**	**Entertainment**	**Other**
Share of heated area	85 %	80 %	75 %	80 %	80 %	70 %	30 %
Specific heat consumption for space heating, kWh/m²							
Existing buildings	130	140	135	160	160	150	120
Renovated buildings	110						
Newly built buildings	100						
Specific heat consumption for hot water heating, kWh/m²	10	10	35	21	24	10	5
Share of mechanically ventilated area							
Existing buildings	60 %	50 %	50 %	30 %	50 %	30 %	30 %

Renovated buildings	70 %	70 %	70 %	50 %	70 %	60 %	40 %
Newly-built buildings	80 %	80 %	80 %	60 %	80 %	70 %	50 %
Power consumption for ventilation, kWh/m²	20	20	20	20	30	30	20
Share of building area with space cooling							
Existing buildings	40 %	50 %	60 %	40 %	40 %	20 %	5 %
Renovated buildings	60 %	70 %	70 %	50 %	70 %	60 %	5 %
Newly built buildings	80 %	80 %	80 %	60 %	80 %	70 %	20 %
Specific cooling consumption, kWh/m²	53	53	40	40	53	40	20
Average minimum level of illumination, lux	369	383	314	352	457	325	291
Specific power consumption for lighting, kWh/m²	29	14	12	10	34	13	20

Heat consumption for the space heating has been calculated by assuming different levels of building efficiencies (specific heat consumption for space heating) according to available data sources [22], [23], [24]. The renovated and newly built buildings have been separated as those are subject to the specified standards [25]. As it is not necessary to maintain a certain indoor temperature throughout all the buildings, authors assume that only part of the total area is heated. The specific consumption for domestic hot water has been estimated to be greater in hotels and hospitals [26], as there are high washing and cleaning standards applicable.

Some of the buildings are mechanically ventilated to provide the necessary air exchange. Mechanical ventilation is assumed to be more widespread in the new and renovated buildings than in the existing buildings. Power consumption for the ventilation has been calculated similarly as space heating consumption by assuming the share of mechanically ventilated area and the average power consumption for ventilation [27]. Higher values have been assumed for medical and entertainment buildings as these buildings have higher requirements for air exchange rate.

Power consumption for space cooling has been determined according to the methodology presented by Werner [28]. Similar to previous estimations, authors assume the share of the total area, which is cooled during the warmer periods, and the specific cooling consumption of the particular type of building. Higher cooling demands have been assumed in the retail, office and medical buildings [29].

The specific power consumption for lighting has been determined through the minimum level of illumination requirements for different types of buildings [30].

$$SPC_{lighting} = \sum \frac{Il_i \cdot \beta_{i,j}}{\eta_j},$$

where

Il_i illumination requirements in building type i, lm/m²;

$\beta_{i,j}$ share of specific luminaries j used in buildings i;

η_j efficiency of luminaries j, lm/W.

Authors assume that three different types of luminaries are used in COM buildings – LED lighting (average share 44 %; average efficiency 100 lm/W), efficient luminaries including luminescent and halogen lamps (average share 43 %; average efficiency 56 lm/W) and inefficient luminaries (average share 13 %; average efficiency 15 lm/W) [31].

In addition, power consumption for public lighting has been estimated through the correlation analyses (see Fig. 2). Authors have identified power consumption for the public lighting in several cities and towns, mainly presented in the sustainable energy action plans of municipalities.

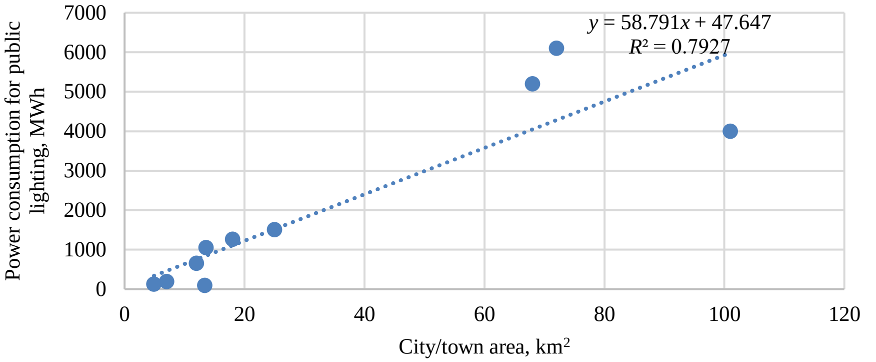

Fig. 2. Regression analyses of power consumption for public lighting depending on the populated area.

As can be seen in Fig. 2, there is a good correlation between power consumption for the public lighting and the city or town area. Application of the regression equation allows estimating the total power consumption for public lighting in all populated areas and includes it in the overall energy balance of COM sector.

2.3. Residential sector

The RSD sector was divided into two sections – single-family houses and apartment buildings, as both use different energy resources and differ in their consumption. It is assumed that the single-family houses are not connected to the DH network, but part of the apartment buildings are connected to centralised heat supply.

Processes analysed in TIMES model for RSD sector are heating, cooling, water heating, refrigeration, lighting, cooking, electrical appliances and other applications. New heating and cooling sub-processes are created similarly to the COM sector. This helps to overcome technology linking to a specific type of building and allows to add policy measures related to energy efficiency of buildings more precisely.

In addition, heating and cooling processes have been defined as pre-processes whereas the rest of the processes like cooking, lighting and others are marked as the final demand and will be analysed in different scenarios. There are also researches where surface area of the dwelling stock have been set as a demand driver for heating in the RSD sector but it is not applied in the particular research [32].

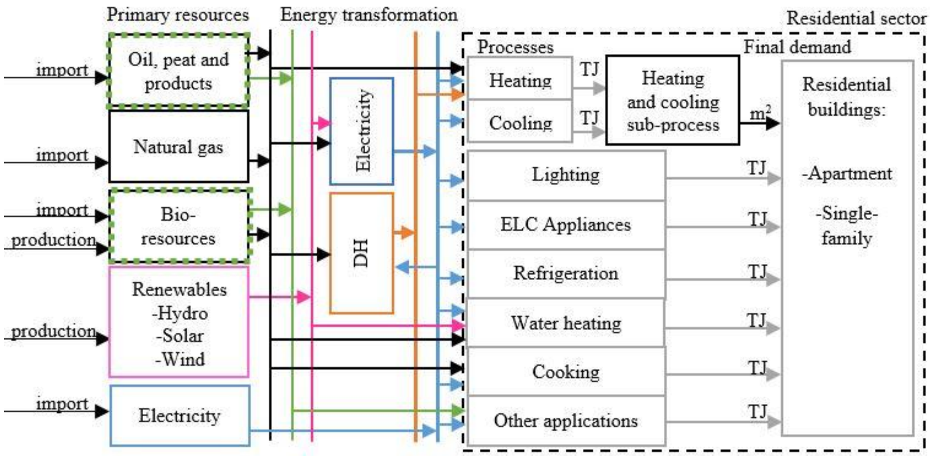

Fig. 3. Process scheme of RSD sector.

3. RESULTS

This section presents intermediate results for the base year of 2017 – the used input data and resource allocation for different processes, as well as validation of the model.

3.1. Data gathering

3.1.1. Industrial sector

The IND sector is the third largest energy consumer in Latvia compiling 21 % of the total final energy used in 2017 of which 38 % were wood biomass, 18 % electricity, 14 % oil products and 13 % natural gas. IND sector in Latvia consists of 13 sub-sectors, of which the most part of energy is used in manufacturing of wood and wood products.

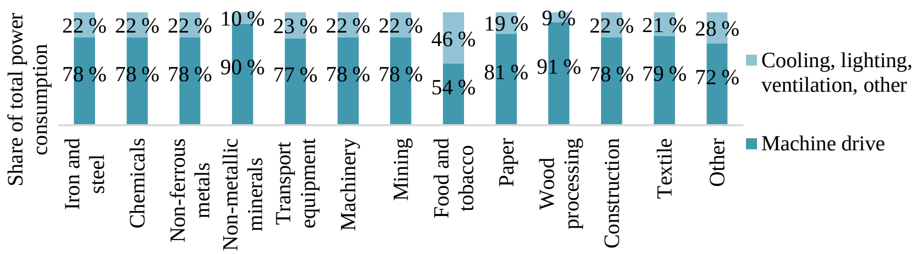

Fig. 4. Power consumption structure in IND sub-sectors.

Power consumption in the IND sector in the TIMES model has been divided into two large parts – electricity used for machine drive, to ensure manufacturing processes, and auxiliary processes – cooling, lighting, ventilation and other power consuming processes. In most of the IND sub-sectors, around 77 % to 81 % of power is used for machine drive (see Fig. 4). Higher share of electricity consumption for machine drive is in the sub-sectors of non-metallic minerals and wood processing industries. In contrast, the lower share of electricity for machine drive is in food and tobacco production – only 54 %.

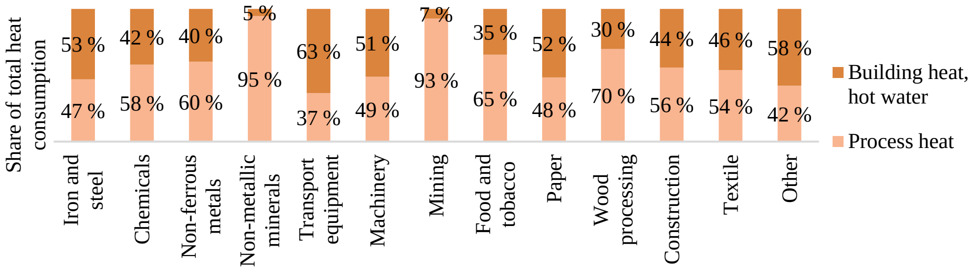

Fig. 5. Heat consumption structure in IND sub-sectors.

Heat consumption in the TIMES model has been divided into thermal energy used for space heating and hot water preparation, and process heat that is used for manufacturing processes. Differences in heat consumption division in sub-sectors are more significant compared to power consumption (see Fig. 5). In some sub-sectors, less than half of the heat is used for process heat (transport equipment production). Nevertheless, there are sub-sectors where even more than 90 % of heat have been used for production processes – non-metallic minerals production and mining.

3.1.2. Commercial sector

The COM sector used 15 % of the total final energy in 2017, equal to 25 PJ. COM sector has been divided in seven sectors based on building classification [21]. Power is the main resource used in the COM sector reaching almost 10 PJ and 43 % of the total final electricity consumed in 2017. Also 27 % of the total final natural gas consumption, equal to 3.8 PJ, was used in the COM sector, where most of it was consumed in educational buildings and offices (see Fig. 6).

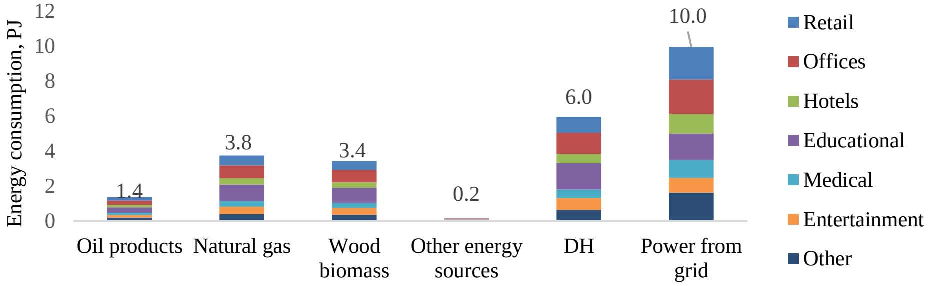

Fig. 6. Resource consumption structure in COM sub-sectors in 2017 [20].

Electricity consumption structure differs in COM sub-sectors (see Fig. 7). In retail buildings as well in buildings for medical facilities and entertainment, most of the electricity is spent for lighting. In office buildings, the office equipment consumes the most power but in hotel and educational buildings most of it is used for water heating.

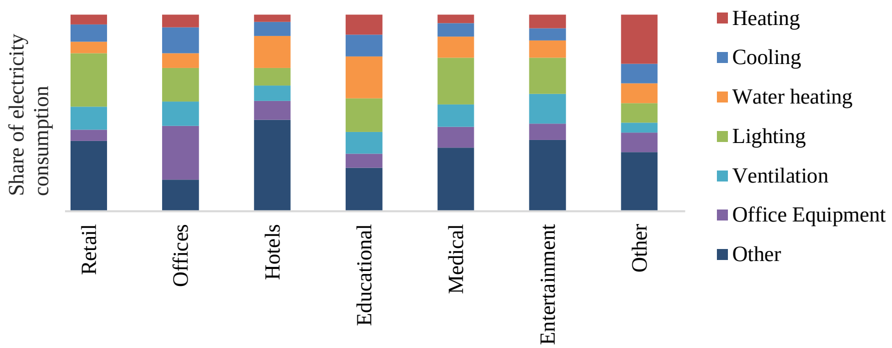

Fig. 7. Electricity consumption structure in the COM sector.

DH and primary energy sources have been used for three processes – water heating, space heating and other processes like cooking. In almost all COM sub-sectors, heating has mainly been used for space heating and only a small share for water heating.

3.1.3. Residential sector

The second largest part of the final consumption is dedicated to RSD sector, reaching 29 %. Most of it was wood biomass consumption, equal to 21 PJ, of which 38 % was used in single-family houses and 62 % in apartment buildings (see Fig. 8a).

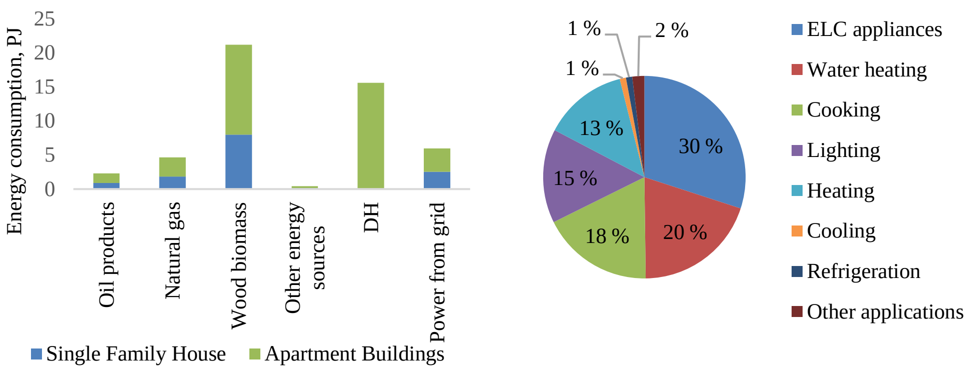

Fig. 8. Resource consumption structure (a) and structure of power consumption (b) in RSD sector in 2017.

The structure of electricity consumption is similar in single-family houses and apartment buildings, as consumer behaviour is not depending on the building type. According to Eurostat [33], largest share of electricity, i.e. 30 %, is consumed for different electrical appliances (TV, radio, mobile charging etc.), 20 % is used for water heating, 18 % for cooking, 15 % for lighting and 13 % for heating (see Fig. 8b).

3.2. Model validation

In order to validate the developed structure of TIMES model, the modeled results of year 2018 have been compared to the national energy balance. The comparison of statistical data and modelled results can be seen in Fig. 9. The total primary energy consumption difference in RSD and COM sectors is around 3 %, but for IND sector the modeled primary energy consumption and actual consumption are equal.

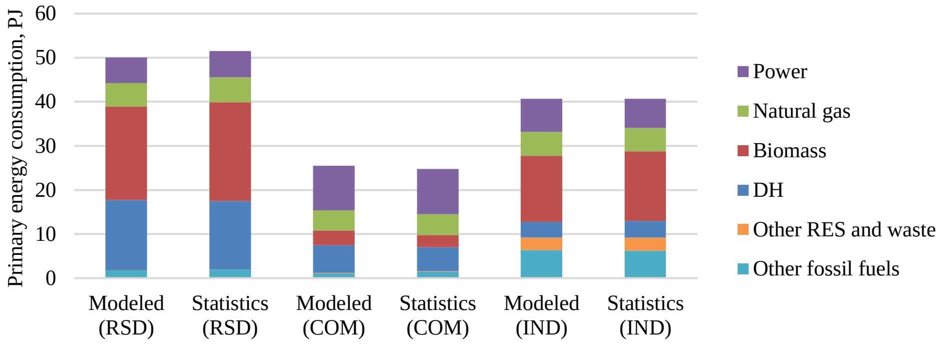

Fig. 9. Validation results analysed in residential, commercial and industry sectors for year 2018.

When evaluating the consumption of particular energy sources the difference of modeled results and statistical data is more prominent. In the RSD sector, the main variance occurs for coal and wood pellet consumption, which is higher in the actual energy balance of 2018 and LPG, which is higher in TIMES model. Similar tendency occurs in COM and IND sectors for coal. TIMES model also forecasts slightly higher increase of power consumption in IND sector than the actual power consumption increase. Such differences arises because the main aim of the model is to optimize the final energy consumption by choosing most efficient technologies and cheapest energy sources which is not always happening in real life. Further validation process could include the comparison of the results for two-year period (2018 and 2019) when the energy balance for 2019 will be available.

4. CONCLUSIONS

It is important to build up an energy model that represents a country-specific situation. The paper presents the methodology for structure adaption of TIMES model for industrial (IND), commercial (COM) and residential (RSD) sectors in Latvia. Authors have identified the necessary structure changes of standard model to build a representative sectors` models. The methodology presents different methods which allows to overcome lack of specific data related to final energy consumption in particular processes. These methods can be used in other countries when developing similar forecasting models.

The intermediate results include energy resource consumption in each of the sectors divided among particular end-processes. The main processes in the IND sector are machine drive and process heat to ensure manufacturing processes, power consuming auxiliary processes (cooling, lighting, ventilation and other) and space heating, and hot water preparation. The COM sector has been divided in 7 sub-sectors depending on the functions of particular buildings (educational, medical, retail, hotel, entertainment, offices and others). Ten different end-processes have been included in the COM sector model. The RSD sector is divided into two groups – single-family houses and apartment buildings with similar end-processes as those in the COM sector.

The obtained results have been validated by comparing modelled and actual data for year 2018. The validation shows that modelled primary energy consumption of analysed sectors are comparable with the historical data. Therefore, the proposed structure can be used for sectors` energy consumption modelling.

Further research will be performed to analyse agriculture, transport and power sectors and to develop an overall energy system model of Latvia. To build up comprehensive energy system model additional research could include the combination of TIMES model with other methods like top-down modelling.

ACKNOWLEDGEMENT

This research is funded by the Ministry of Economics of the Republic of Latvia, project "Energy and climate modelling towards net zero emissions", project No. VPP-EM-2018/NEKP-0001.

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INTEGRATED MARKAL-EFOM SYSTEM (TIMES) MODEL FOR ENERGY SECTOR MODELLING

Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling

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2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON) | 978-1-7281-9510-0/20/$31.00 ©2020 IEEE | DOI: 10.1109/RTUCON51174.2020.9316623

***Abstract*—As climate targets become more critical, an appropriate supportive tools in policy planning are needed. TIMES model is powerful tool for energy scenario analysis allowing assess the impact of potential policy measures.**

The paper presents the methodology and results for energy sector modelling of Latvia by using TIMES model. To analyse further development of electricity and heating sector, three different scenarios have been compared – reference scenario, which excludes the existing tax policy, baseline scenario which considers the existing policy measures and the scenario which includes different policy measures defined in the National Energy and Climate plan until 2030.

Keywords—Climate plan, Energy system modelling, optimization bottom-up model, TIMES model, renewable energy.

I. INTRODUCTION

European Commission has set a goal to become climate neutral by 2050 [1], which means that more attention is focused on energy sector. The energy sector is one of the most important economic sectors and also one with largest emitter of greenhouse gas emissions.

There are many studies analysing different parts of energy sector, e.g. the power sector. The role of power storage in covering higher share of renewable energy in Europe has been analysed by F. Cebulla et al. [2]. Another study has been done on the required backup energy in case of 100% renewable energy usage in Europe considering different grid connection and storage possibilities [3]. Research of 100% renewable power system in Europe with a focus to the Netherlands [4] shows that to meet this target there is a need to increase the renewable energy resource (RES) and cross-border transmission capacities, as well as to use technologies with higher efficiency. Other studies cover a whole energy sector, including heat and power generation. Cogeneration and thermal storage potential in energy system have been analysed by J. P. Jiménez Navarro et al. [5]. Another research focuses on using intermittent RES sources such as wind and solar in smart energy system which includes smart electricity, thermal and gas grids, and thus decreasing emissions [6]. In France, researchers have developed the integrated MARKAL-EFOM System (TIMES) model to evaluate possibility to achieve negative emissions in energy sector by using bio-plants with carbon capture and storage. Study shows that these technologies will be important to achieve European emission targets [7]. Soft linking between two models Dispa-SET and JRC-EU-TIMES have been done to analyse the potential of sector coupling in Europe [8]. It is concluded that linkage between sectors can play a crucial role in carbon emission reduction and integration of RES. The results also show that different models can be linked to get more detailed and precise results.

The main aim of this study is to model and compare energy consumption and distribution of primary energy sources in energy sector by comparing three scenarios. The analysis show the effect of the existing tax policy and the policy measures stated in Latvia's National Energy and Climate plan (NECP). The methodology and results for energy sector modelling of Latvia by using TIMES model is presented. Structure of the model includes different elements of power and heat sectors, and therefore it is possible to analyse several scenarios for further development of these sectors. To our knowledge, this is the first TIMES model applied for Latvia's energy systems, since MARKAL and MARKAL-TIMES models were used in the previous studies.

II. METHODOLOGY

TIMES is bottom-up, linear programming tool applied for long-term energy systems planning allowing to analyse effect of different scenarios. It optimises the whole energy system including supply and demand services by minimizing the total cost in the considered modelling period [9]. TIMES has been selected as the modelling tool in this study due to its powerful technical and economic capabilities which allows to analyse the whole energy system and find the most economical allocation of technologies and resources, and allowing to assess an impact of planned policies.

Methodology applied in this study consists of several steps (see.Fig.1). Description of reality, development of model structure, mathematical description of conditions, collection of model input data are the first steps. In the next step, the base scenario is being processed and validated. If the validation results do not describe reality sufficiently well than the model structure, mathematical description and data is being reviewed and improved. When the validation results match the real situation sufficiently well, optimization of the scenarios can be done. In the final phase the results are being compiled and conclusions put forward.

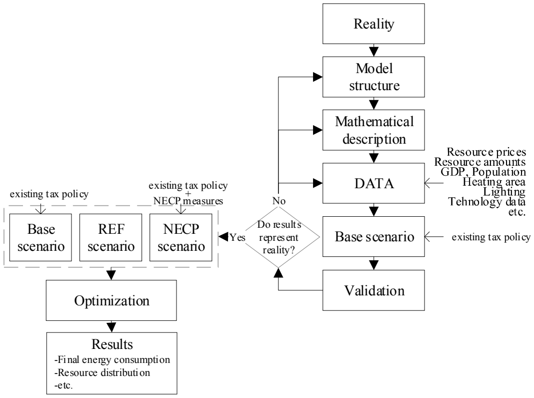

Fig. 1. Structure of methodology steps.

The modelled energy sector includes district heating and electricity production (see Fig. 2). In order to better model trends in the energy sector, it is divided into two geographic sub-sectors – Riga and the rest of Latvia.

Data of consumption of primary energy resources and amounts of heat produced are obtained from reports on air pollution [10] ("2-Gaiss" database) and publicly available annual reports [11],[12]. Data of Central Statistical Bureau of Latvia and emission permits are used to determine installed capacities of technologies in boiler houses, hydropower plants, wind power plants and cogeneration plants [13]. The reference year in the model is 2017.

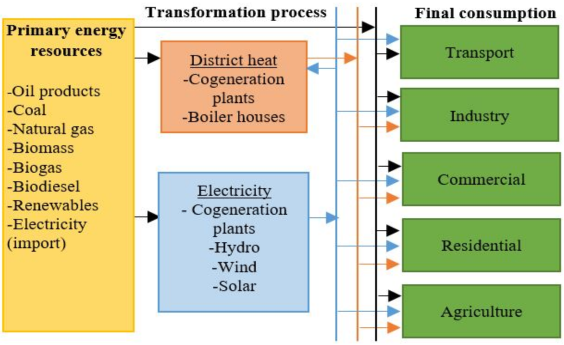

Fig. 2. Structure of the modelled energy sector.

Although the amount of electricity produced by solar energy is not reported in the energy balance of Latvia in 2017, solar power plants are used in households, commercial and industrial sectors mainly for self-consumption coverage. Therefore, calculations on proportion of electricity produced by solar panels in the energy sector are made in the model. Due to the lack of data regarding the solar electricity not transferred to power grid, the information available from permits issued by the Ministry of Economics for construction of new generation capacity were used [14]. The total amount of solar electricity produced in different sectors was estimated to be around 5.65 TJ in 2017.

A. Energy sector in Latvia

Electricity in Latvia is produced mainly by natural gas or biomass-fired cogeneration plants (CHP) and in the hydropower plants. In 2017, 175 CHP's operated in Latvia, using natural gas as the main fuel. Four cogeneration plants with an installed electrical capacity exceeding 20 MW produced the majority (47 %) of thermal energy. The main fuel in these energy sources was natural gas (57 %), while 41 % of the fuel consumed was biomass (wood, chips, pellets, etc.). As can be seen in Fig.3, the produced amount of thermal energy and power have slightly increased during the last decade.

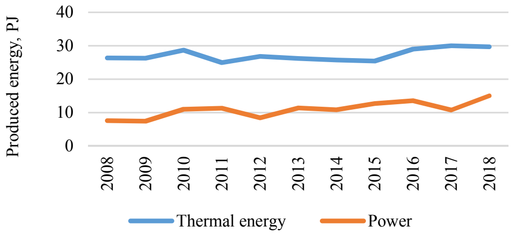

Fig. 3. Produced thermal energy and power in energy sector [15].

B. Input data and assumptions

One of the main assumptions that affects energy sector is the demand of other sectors such as agriculture, commercial, residential and industry. Final energy consumption depends on different demand drivers, i.e. growth of GDP, energy elasticity of GDP, population growth, average number of persons per household and specific sectoral value added.

It is being assumed that GDP will grow steadily and reaches 42887 MEUR in 2050 while population decreases, reaching only 1.46 million people in 2050 (see Fig.4).

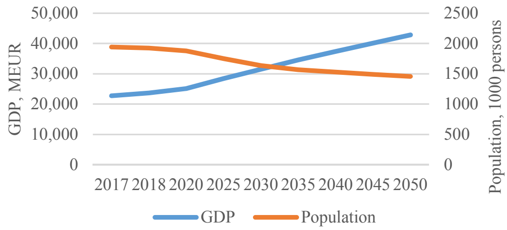

Fig. 4. Assumed dynamics of Latvia's GDP and population.

Important assumptions in energy sector have been done regarding the parameters of available new technologies. TIMES model requires detailed technical data of different power and heating plants to obtain accurate results. Operational lifetime, economic lifetime, efficiency parameters, capital costs, operational and maintenance costs, variable costs and other parameters have been determined from the Danish Technology Catalogue [16], which covers the main technologies used in power production, district heating, as well as in local and individual heating (see Annex 1). The Danish Technology

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Catalogue was used because Latvia has not developed its own catalogue describing the technologies used in the country. A list of new technologies available in energy sector was made, including hydro power plant, four different types of wind turbines (onshore, offshore, nearshore and domestic turbines for residential and commercial use) and three different solar plants (for commercial use, for residential use and large-scale power plant for centralised power generation). In addition, solar thermal systems have been introduced.

New technologies of CHP plants and heating plants have been divided into plants participating in EU Emissions Trading System (ETS plants) and ones which do not participate, i.e. non-ETS plants. The main technologies in non-ETS section are CHP plants and technologies using solid biomass, natural gas, and biogas. In ETS section there are only solid biomass, natural gas and biogas-fired plants. In non-ETS section of heating plants liquid petroleum gas (LPG), diesel oil, residual fuel oils, natural gas, solid biomass technologies and electricity technologies like compression heat, absorption and boiler are on the market. In ETS part LPG, diesel oil, natural gas and solid biomass technologies are available.

Prices of resources and particular technology were considered when choosing the optimal technology model. Fig.5 shows historical data of prices of the main resources used in energy sector from 2006 to 2018 and forecast from 2019 to 2050. All prices shown in the graph exclude taxes.

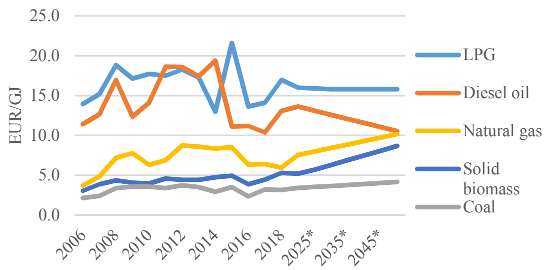

Fig. 5. Historical prices [17] and forecast of main primary resources used in energy sector.

Only the existing taxes are included in the model and it is assumed that the taxes remain constant throughout the modelling period. Energy sector is mostly affected by natural resource tax (NRT) on coal and peat, excise tax on diesel oil, LPG, natural gas and also CO_2 tax on emissions caused by non-ETS plants. The exact values of taxes used in the model are shown in Table 1.

TABLE I.
TAXES USED IN ENERGY SECTOR [18],[19]

Tax	Unit	Resource	2017	2018	2019	2020	2021	2022-2050
Natural resource	EUR/GJ	Coal	10.7	10.7	10.7	21.3	21.3	21.3
Excise	EUR/GJ	Diesel oil	9.6	10.5	10.5	11.7	11.7	11.7
	EUR/GJ	LPG	4.5	5.4	5.4	6.3	6.3	6.3
	EUR/GJ	Natural gas		5.94	5.94	5.94	5.94	5.94
CO_2	EUR/t	CO_2			4.5	9	12	15

C. Development of scenarios

Developed scenarios are based on the horizontal measures and action lines envisaged by the National Energy and Climate plan until 2030 (NECP2030) [20], as well as on specific key objectives to be achieved. Overall measures and action directions of NECP2030 in energy sector are aimed to increase the share of renewable energy in gross energy consumption. It is also supported by combining different potential sources of funding. The total budget allocated to energy sector until 2030 is 1.653 billion EUR.

Scenarios were created by considering the structure of the NECP2030 framework, direction of the measures and actions planned, as well as the allocated funding. Three scenarios - baseline scenario, NECP scenario and the reference scenario have been analysed.

Scenario 0 – reference scenario (REF)

The reference scenario is based on the situation in 2017 regarding energy balance, energy mix, energy demand, population, gross domestic product, etc., i.e. “frozen” 2017. The reference scenario includes funding for insulation of residential buildings, which corresponds to 156 million euros of existing grants provided by EU funds. In practice, this scenario is designed to compare other development scenarios and to provide an opportunity to identify their development rates and trajectory as well as their significant changes. The reference scenario does not include the existing taxes, such as CO_2 tax and NRT. Compared to the baseline scenario the reference scenario allows to assess an impact of the existing tax policy.

Scenario 1 – baseline scenario (BASE)

The baseline scenario is the scenario that describes development trajectory if the existing policy support instruments, taxes and other conditions remain unchanged.

The baseline scenario includes the existing taxes, such as the NRT, CO2 tax, and excise duty on fossil fuels. Also funding for insulation of residential buildings is included. The amount of renovated buildings and energy savings is derived from the system-dynamics model [21] and included as input data in the TIMES model. The results from system dynamic model are used because it takes into account different social factors and dynamic decision making process which cannot be implemented so transparently and easily within the TIMES model.

Scenario 2 – NECP2030 Scenario (NECP)

This scenario analyses the full implementation of the measures (funding and implementing conditions) indicated in Annex 4 of NECP2030. The main measures included in the model directly or indirectly are the following:

- Promoting energy efficiency improvements of public buildings owned by the state and local governments
- Promotion of renewable energy use and energy efficiency in local heating and individual heating
- Promoting the use of solar energy in electricity generation
- Promotion of renewable energy use and energy efficiency improvements in district heating

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- Limitations for the installation of new combustion plants that use only solid or liquid fossil fuels
- Construction of offshore wind park
- Promotion of energy efficiency in residential buildings

D. *Validation of the model*

To validate the model, results from the baseline scenario were compared with statistical data of fuel consumption in cogeneration plants and in boiler houses for years 2018 and 2019 provided by Central Statistical Bureau of Latvia (see Fig.6).

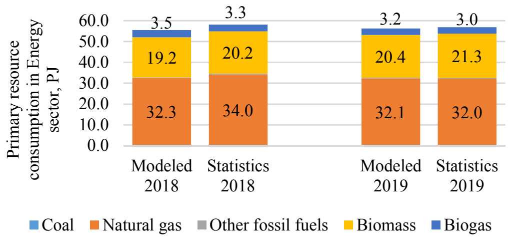

Fig. 6. Modelled results and statistical data [22] for the years 2018 and 2019.

Consumption of natural gas in 2018, provided by the model, is by 1.7 PJ less while in 2019 by 0.1 PJ more than the statistical data show. Also biomass and biogas consumption obtained by the model slightly differs from the statistical data, with difference not exceeding 6%. Validation shows that model results of resource consumption in energy sector match to the real situation sufficiently well.

III. Results

NECP2030 covers time horizon until year 2030; however, scenarios have been developed for the period until the year 2050 since the target of becoming climate neutral by 2050 stated in EU Green Deal [1] is binding for Latvia too.

Operation and consumption of primary resources of energy sector depends on the final energy consumption in other sectors. While demands in all three scenarios remain unchanged, the final energy consumption vary since different technologies and resources are used. Final energy consumption is the highest in the reference scenario, reaching 170 PJ in 2021 and steadily growing till 2050, reaching 179 PJ (see Fig.7).

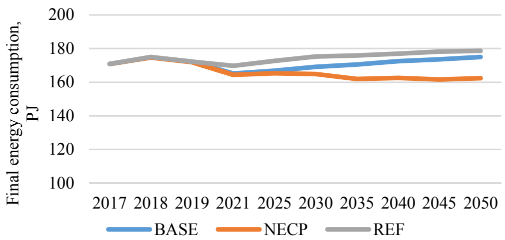

Fig.7. Final energy consumption in the modelled scenarios.

Similar growth is seen in the baseline scenario, in which the final energy consumption reach 175 PJ in 2050, while in NECP scenario the final energy consumption decreases to 162 PJ.

The total primary resource consumed in energy sector in the reference scenario is higher than in other scenarios (see Fig.8). In 2021, primary resource consumption in the reference scenario is circa 3% higher than in baseline and NECP scenarios while in 2030 the difference is around 17% comparing the same scenarios. In the last decade of the modelled time span, the difference in resource consumption has increased even more, reaching around 61 PJ in the reference scenario while in the base and NECP scenarios consumption has decreased to around 54 PJ.

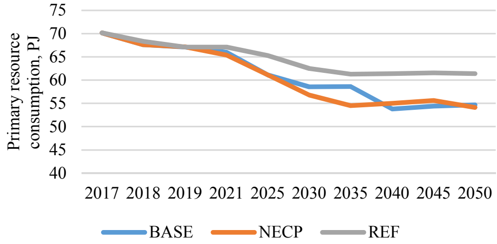

Fig.8. Primary resource consumption in energy sector in the modelled scenarios.

In the base year (2017), natural gas dominates in energy sector consumption reaching more than 21 PJ, which is equal to 35% (see Fig.9) from the total primary energy consumption. Substantial shares are taken also by biomass and hydro power reaching 32% and 26% respectively.

In 2030, in the reference scenario natural gas takes an even higher share compiling 48% of the total primary resources consumed in energy sector. Share of natural gas decreases to 34% in NECP scenario and 42% in the baseline scenario. In the baseline scenario a share of biomass remains at 32% while in NECP it is 26% and in the reference scenario 27%. In NECP scenario, usage of wind energy increases to 13%.

In 2050, share of natural gas decreases in the reference scenario taking half of the total primary energy consumption. Also in NECP scenario natural gas share has decreased to 26% while in the baseline scenario it has decreased to 37% of the total primary energy consumption in energy sector. Share of biomass is similar in all three scenarios – 29% in the baseline, 23% in NECP and 21% in the reference scenario. Share of hydro energy has decreased in the baseline scenario and in NECP scenario reaching 18% and 19% respectively, while in the reference scenario it has increased from 14% in 2030 to 16% in 2050. Solar energy has become a significant source in NECP scenario, reaching a share of 15%. Also the share of wind energy has increased in the baseline and NECP scenarios reaching 6% and 12% respectively (Fig.9).

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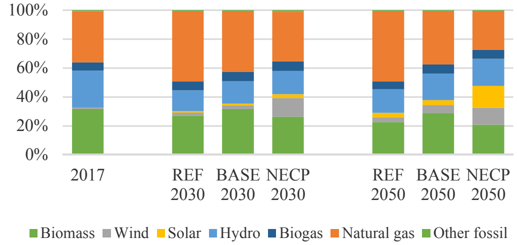

Fig.9. Distribution of consumption of primary energy resources in energy sector in the modelled scenarios.

In the base year, share of renewable energy is 64% (see Fig.10). In the reference scenario, it stays steady from 2018 till the end of the modelling period reaching around 50%.

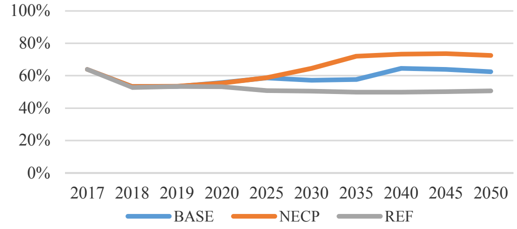

Fig.10. Share of the total renewable energy in energy sector consumption in the modelled scenarios.

Results of the modelling show that the share of renewable energy in the last decades of the modelled time horizon are the highest in NECP scenario, reaching around 73% while in the baseline scenario this share reaches around 58% in the period from 2025 till 2035, and increases to around 63% in the last period.

IV. Conclusions

Article presents the methodology and results for energy sector modelling of Latvia by using TIMES optimisation model. To analyse future development of electricity and heating sector, three different scenarios have been compared – reference scenario which excludes the existing tax policy, baseline scenario which allows to analyse the existing policy measures and NECP scenario which includes different policy measures included in the National Energy and Climate plan for the period up to 2030.

NECP policy covers the period up to 2030 but the greatest impact of NECP policy in primary resource consumption in energy sector is reached in 2035 when all measures are fully implemented. In the following period consumption in energy sector increases which can be explained by higher usage of solar and wind energy in NECP scenario.

The results show that the existing tax policy is working properly and ensures a greater share of renewable energy in the total primary resource consumption in energy sector.

NECP policy ensures decrease in the final energy consumption in other sectors, and the consumption in NECP scenario in 2050 is by circa 8% smaller than in the other two scenarios.

NECP policy promotes the usage of solar and wind energy. It can be concluded that the political measures included in the NECP2030 allow to achieve savings of primary energy sources and higher share of renewable energy. However, it is necessary to set long-term goals for the period up to 2050 already now in order to move towards climate neutrality goals.

Further research should be done to define the exact impact of final energy consumption, policies and technology development on dynamics of primary energy resource consumption. The comparison should be done by separating ETS and non-ETS parts of an energy sector.

Acknowledgment

This work has been supported by the Ministry of Economics of the Republic of Latvia, project “Energy and climate modelling towards net zero emissions”, project No. VPP-EM-2018/NEKP-0001.

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Annex 1. Main technical assumptions of new technologies

Technology	Operational lifetime	Economical lifetime	EFF	Investment cost 2018	Investment cost 2030	Fixed O&M costs 2018	Fixed O&M costs 2030
	years	years		2017thsdEUR /MW	2017thsdEUR /MW	2017thsdEUR/ MW	2017thsdEUR /MW
RENEWABLE POWER PLANTS							
Hydro - Hydro (Run-of-River)	40	13	1.000	2 567	2 310	50.40	36.05
Wind - Onshore	25	8	1.000	1 243	1 040	20.90	12.60
Wind - Offshore	25	8	1.000	2 567	1 930	50.40	36.05
Wind - NearShore	25	8	1.000	2 197	1 660	45.36	34.25
Wind - Domestic turbine (residential/commercial)	20	7	1.000	3 920	3 600	98.00	95.00
Solar - PV Commercial	20	7	1.000	1 128	630	12.60	9.24
Solar - PV Residential	17	6	1.000	1 399	870	14.86	10.82
Solar - PV Central	30	10	1.000	1 088	690	11.10	8.80
Solar - Thermal System	30	10	1.000	474	416	2.78	3.13
COMBINED HEAT & POWER (CHP) PLANTS NON-ETS							
Solid Biomass - Steam turbine	25	8	0.140	6 700	6 200	292.70	280.50
Natural Gas - Combined cycle	25	8	0.350	1 300	1 200	20.00	18.60
Biogas - Combined cycle	20	7	0.220	1 810	1 540	199.19	197.70
Wood Chips - Steam turbine	25	8	0.139	6 410	6 000	283.00	273.00
Wood Pellets - Steam turbine	25	8	0.146	6 160	5 700	273.00	261.00
COMBINED HEAT & POWER (CHP) PLANTS ETS							
Solid Biomass - Steam turbine	25	8	0.280	3 700	3 500	158.40	144.00
Natural Gas - Combined cycle	25	8	0.480	1 300	1 200	30.00	27.80
Biogas - Combined cycle	25	8	0.220	6 700	6 000	96.50	87.40
DISTRICT HEATING PLANTS NON-ETS							
LPG	20	7	1.010	113	104	2.80	2.65
Diesel oil	20	7	0.880	175	163	3.52	3.23
Residual (heavy) fuel oils	20	7	0.880	175	163	3.52	3.23
Natural Gas	25	8	1.010	113	104	2.80	2.65
Solid Biomass	25	8	0.800	700	650	7.22	6.98
Wood Chips - Steam turbine	25	8	1.140	700	660	32.80	31.50
Wood Pellets - Steam turbine	25	8	1.012	725	680	33.24	31.00
Electricity - Compression heat pump	25	8	3.500	683	590	2.00	2.00
Electricity - Absorbtion heat pump	25	8	1.700	586	510	2.00	2.00
Electricity - Boiler	20	7	0.984	150	140	1.10	1.02
DISTRICT HEATING PLANTS ETS							
LPG	25	8	1.030	60	50	2.00	1.90
Diesel oil	25	8	0.880	175	163	3.52	3.23
Residual (heavy) fuel oils	25	8	0.880	175	163	3.52	3.23
Natural Gas	25	8	1.030	60	50	2.00	1.90
Solid Biomass	25	8	1.150	700	650	32.80	31.20

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DECARBONISATION PATHWAYS OF INDUSTRY IN TIMES MODEL

Decarbonisation Pathways of Industry in TIMES Model

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***Abstract* – The industry sector in many countries has a significant role in reaching national long-term emission reductions, energy efficiency and renewable energy targets. New technologies, wide implementation of energy efficiency measures and smart energy management are needed for the industry to ensure local and global competitiveness and reduce emissions. Since the industrial sector is often comprised of sub-sectors that are unique and with local specifics, this paper focuses on three of them, taking Latvia as the case. The sectors are: manufacture of wood and wood products, non-metallic mineral products, as well as food products and tobacco. These sub-sectors together consume around 80 % of the total final energy use in the country's industrial sector. Comprehensive analysis and decomposition of the sub-sectors was made to identify future development pathways. TIMES model was used to elaborate a process-oriented modelling approach to analyze the impact of measures defined in the National Energy and Climate Plan until 2030 as well to gauge the impact of additional measures. Results show that these measures promote the use of renewable energy and improve energy efficiency, however it is necessary to set new measures and activities for the period beyond to reach climate neutrality by 2050.**

***Keywords* – Energy efficiency; final energy consumption; GHG emissions; industry sector modelling; optimization model; renewable energy**

1. INTRODUCTION

As the European Union is set to become the first climate neutral region in the world by 2050 [1], increased attention is also paid to performance of the industrial sector. Energy efficiency and greenhouse gas (GHG) reduction of industry is crucial for sustainable development, and for reaching energy efficiency and GHG emissions targets. Energy system models can help policy makers and decision makers in industry to move towards sustainable development and find the best way to achieve ambitious climate targets.

Industry sector is analysed in several studies, e.g. FORECAST model, which is a bottom-up simulation model that was created in order to analyse several scenarios of industry sector decarbonisation [2]. Another model was used for investigation of the energy efficiency performance of 18 main industrial sub-sectors of Latvia, where composite index methodology was used to develop an energy efficiency index [3]. A nonlinear autoregressive distributed lag model was used to investigate the relationship between energy efficiency and economic growth of 11 European Union countries [4]. TIMES is a bottom-up, linear programming tool applied for long-term energy systems planning to optimise the whole energy system by minimizing the total cost in the modelling period [5]. Comparison of possible transition of

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industry sector performance under 2-degree target between China, India and Western Europe was done using Global TIMES model [6]. In this study, two groups of scenarios were completed – reference scenario group with no constraints on CO_2 emissions and the 2-degree scenario group with constraints on global CO_2 budget. Results show that, in the group of the reference scenarios, the global industrial energy demand and CO_2 emissions would increase. The scenarios with constraints on CO_2 budget are also not sufficient to meet the CO_2 target in 2050. The gap between regions could be narrowed and China is expected to have faster CO_2 reduction speed than the average worldwide. It is recommended to have stricter energy efficiency standards and implement measures like low-interest loans and subsidies to decarbonize the industrial sector and meet the 2-degree target.

Recently, many studies focus on energy-intensive industry subsectors. Techno-economic model based on TIMES has been built for the cement sector in Switzerland [7]. In this study long-term energy consumption and CO_2 emission reduction by 2050 is considered. TIMES standard model was expanded by adding additional material and product flows that allow to account emissions related to the specific cement sector processes. Results show that it is economically beneficial to replace and use new, more efficient equipment even without policy measures. According to current trends, specific energy consumption and CO_2 emission intensity in cement production will decrease by around 20 % in 2050 compared to 2015. Results also show that in order to comply with the goals of the Paris Agreement, the cement sector relies on CO_2 capture technologies. CO_2 tax needs to be 70 EUR/t to make these technologies economically competitive.

Some other studies covering energy intensive industries were made in other countries. The effect of the European Industrial Emissions Directive on the air emission values were evaluated in Spain [8]. Researchers conclude that the Directive ensures a more uniform approach in emission level value which is in line with emission levels associated with the best available techniques. This directive may lead to the European Green Deal target. Another study on the cement industry was made in France where an energy model was built to assesses future power generation in cement industry on an international and regional scale [9]. Energy system models and material flow model were made to assess the impact on the cement industry performance in limiting global warming [10]. Energy conservation and CO_2 abatement potential were analysed in the cement industry of Germany [11], and specific characteristics of the cement industry were added to the globally integrated assessment model to analyse energy consumption and GHG emissions [12].

The chemical industry has also been widely analysed. A life cycle approach was used to create modelling framework to evaluate energy and GHG impacts of new technologies [13], while another energy optimization and prediction model was created to analyse energy efficiency improvements in the petrochemical industry [14]. Clustering algorithm in modelling process is used for assessment of performance and optimization of energy division in the petrochemical industry [15]. A structural model based on fuzzy theory was made to analyse the energy structure and energy saving potential of chemical industries [16]. The iron and steel subsector was also analysed in the United Kingdom of Great Britain and Northern Ireland by modelling technological change and investigating future resource demands and amount of GHG emissions [17], [18]. Investigation of the possibility to replace fossil fuels with bio-methane was done for the Swedish iron and steel industry using an optimization model which minimized the total system's cost [19]. Technology-based floor price model was made to analyse the competitiveness and energy efficiency of the steel industry [20].

In another study, a detailed and rich technological database was created for the five most energy-intensive industrial subsectors – iron and steel, non-ferrous metals, non-metallic minerals, chemicals, and pulp and paper [21]. This database is based on a review of the technological outlook in the bottom-up models belonging to the TIMES family. The study includes 65 technologies, from traditional technologies to technologies which are still in a research phase. A powerful tool for a critical evaluation of other energy model results regarding energy use and CO_2 emissions is provided.

Much fewer studies focus on non-energy intensive industries like the food industry. A system dynamics model was made for assessing energy savings in the United States food industry [22], while a detailed, bottom-up energy model was built for the French food and beverage industry to analyse energy efficiency and amount of CO_2 emissions [23]. Resource efficiency is assessed in the food industry by using an optimization model in another study [24].

2. METHODOLOGY

2.1. Development of industry in Latvia

The industry sector of Latvia is comprised of sub-sectors that are unique and locally specific. There are traditional sub-sectors and branches that have a long history in the country. In general, the industry of Latvia has increased output (turnover, added value, number of employees) after the financial crisis in 2008.

Energy consumption in industry of Latvia has been within 30 PJ in 2009 and 41 PJ in 2018 while the industrial production (volume) index has been within 74 in 2009 and 117 in 2019 (2015=100) (Fig. 1).

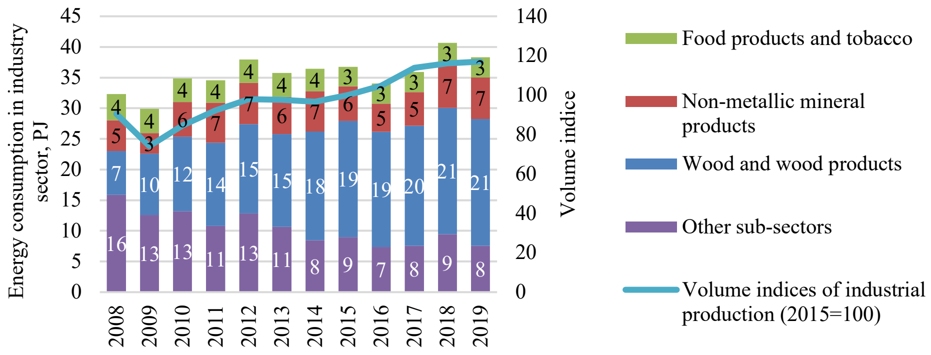

Fig. 1. Industrial production index [25] and final energy consumption [26] in Latvia's industry sector from 2008 to 2019.

Three main sub-sectors covering around 80 % of energy consumption in 2019 are wood and wood products (wood), non-metallic mineral products (minerals) and food products and tobacco (food). Total energy consumption has increased by around 20 % in 2019 compared to 2008 while energy consumption in the wood and wood products sub-sector has increased around three times but in the minerals sub-sector by circa 37 %. In the food sub-sector, energy consumption has decreased by 24 % and in other sub-sectors by 52 % in the respective period.

2.2. Input data and assumptions

The base data of the model applies the national energy balance for the year 2017 [26]. For the industry sub-sectors, ETS [27] and non-ETS energy balances [28] were used as well. Several demand processes e.g. feedstock, machine drive, process heat, building heat and hot water as well as other processes, such as cooling, lighting and ventilation were analysed for each sub-sector. Data from energy audits of 122 companies for the period 2016–2018 were used for the distribution of energy consumption for each of the processes [29].

The quality of the model results is highly related to assumptions that are made in the area outside the model structure. One of the key assumptions for the industrial sector is the energy demand trajectory of the sub-sectors up to 2050. Energy demand in sectors of the national economy depends on several drivers, e.g. GDP, economic growth of sectors, population, floor area, etc. The energy demand of the industrial sector is based on the sectoral value added [30]. There is more specific demand in industries defined by energy services, e.g. energy for process heat, machine drive, building heat and hot water, feedstock and others. According to research done and projections of industry development pathways, the overall demand for energy services in the industry sector increases by about 31 % in 2050 compared to 2017. The increase in demand for energy services in the wood sub-sector is around 30 %, in food sub-sector circa 21 % but in the minerals sub-sector around 56 % (see Fig. 2).

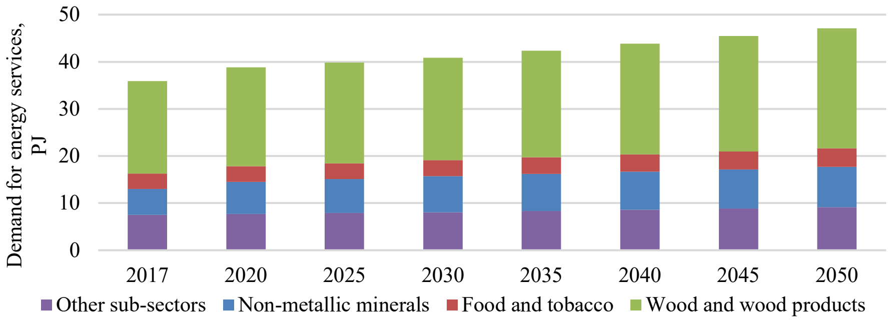

Fig. 2. Demand for energy services in the industry sector.

The trajectory of resource prices significantly affects the results. Currently the main primary resources used in the industrial sector are diesel oil, natural gas and wood biomass like firewood, wood waste and wood chips. Fig. 3 shows historic prices from 2006 to 2018 and forecasts up to 2050 made by authors.

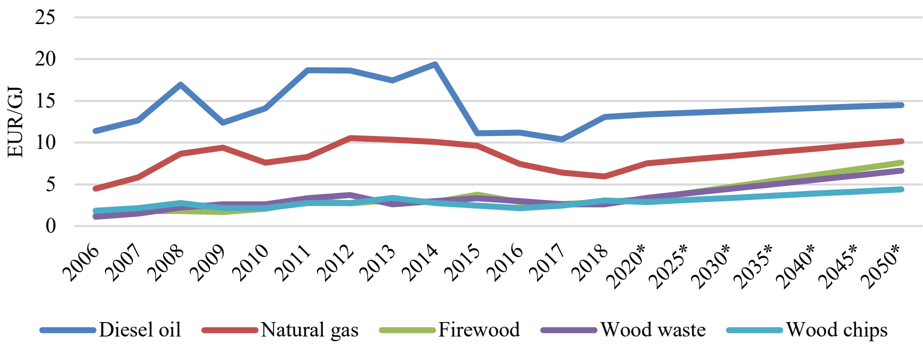

Fig. 3. Historical prices [31] and forecast of the main primary resources used in the industrial sector.

Only the taxes that are currently applied or will be adopted by law in the future (see Table 1) are used in the modelling process. The industry sector is most affected by an excise tax on diesel oil, LPG and natural gas. The excise tax rate for natural gas depends on whether the natural gas is used for industrial production processes or as a fuel for heating and hot water supply. Since fossil fuels are very common in industrial processes, the tax on CO_2 and also the natural resource tax on coal affects the industrial sector as well.

TABLE 1. TAXES USED IN THE INDUSTRIAL SECTOR [32], [33]

Tax	Unit	Resource	2017	2018	2019	2020	2021	2022–2050
Excise	EUR/GJ	Diesel oil	9.6	10.5	10.5	11.7	11.7	11.7
		Natural gas (for industrial production process)	19.8	2	2	2	2	2
		Natural gas (if used as fuel)	115.7	5.94	5.94	5.94	5.94	5.94
CO_2	EUR/t	CO_2	2.85	2.85	4.5	9	12	15
Natural resource	EUR/t	Coal	10.7	10.7	10.7	21.3	21.3	21.3

TIMES is a technology-rich modelling tool that requires detailed data on existing technologies and improved or new technologies that will be available in the future. A wide spectrum of specific parameters, like operational and economic lifetime, efficiencies, capital, variable, operational and maintenance costs were determined for modelling purposes. The Danish Technology Catalogue [34] and PRIMES model data base [35] were used with adjustments made to local conditions and circumstances.

2.3. Scenarios

The horizontal measures covering the industrial sector determined in Latvia's National Energy and Climate plan until 2030 (NECP2030) were used for scenario development. The main purpose of NECP2030 measures is to improve energy efficiency and increase the use of renewable (RNW) resources.

Four scenarios were analysed:

1. Reference scenario (REF) – based on the situation in the base year of the model, i.e. 2017. This scenario does not include existing taxes such as CO_2 tax, excise and natural resource tax. The reference scenario is made to provide the basis for other scenarios to assess the impact of the existing taxation policy.
2. Baseline scenario (BASE) – is also based on the base year of the model but in addition to that, it includes the existing taxation policy – CO_2 tax, excise tax and natural resource tax on fossil fuels. This scenario shows the trajectory of energy consumption and resource allocation in the industry sector if the policy support instruments, laws and taxes remain unchanged.
3. NECP scenario – includes the existing taxation policy and measures determined in Annex 4 of NECP 2030 for the industry sector. The two main measures included in the model are improved energy efficiency and increased use of RNW resources.
4. NECP+ scenario – includes all measures as in the NECP scenario. In addition, it includes support for heat recovery technologies, technological modernization, digitalization, and overall process optimization.

2.4. *Validation*

Validation of the model was done by comparing the baseline scenario results and output with the resource consumption data of industry sector for year 2018 and 2019 from the Central Statistical Bureau of Latvia (see Fig. 4).

The total amount of resource consumption in the industrial sector is the same in the results of the model and in the statistics – 41 PJ in 2018 and 38 PJ in 2019, respectively. However, proportions of resources by type differ within a range of 5 %.

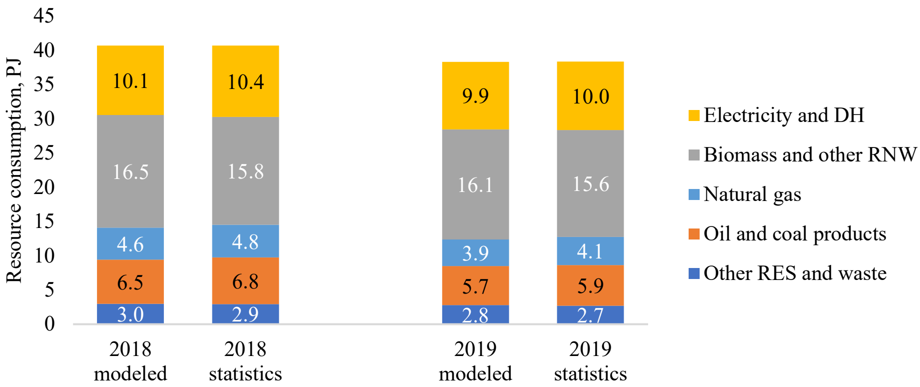

Fig. 4. Results of the model and statistical data [26] of resource consumption in industry sector for the years 2018 and 2019.

Results of electricity from grid, district heat (DH), consumption of fossil fuels, like natural gas, oil and coal products provided by the model have no more than by 5 % lower values than in the statistical data. Results of consumption of biomass and other RNW as well as other resources, such as rubber products and waste, provided by the model have no more than 4 % larger values than in statistical data. The results of industry sector consumption obtained from the model match the real statistical data sufficiently well and do not exceed a range of 5 %.

Sensitivity analysis of baseline scenario was done by increasing and decreasing demand for energy services of industrial sector (see Fig. 2) by 20 %.

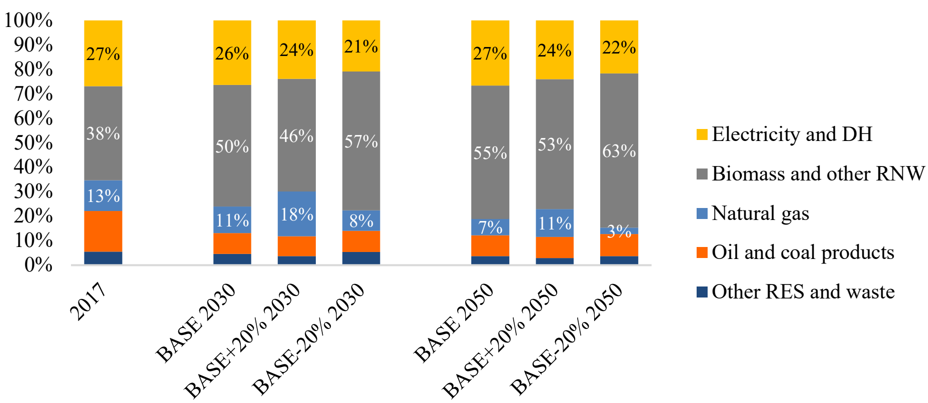

Fig. 5. Results of sensitivity analysis.

Results of sensitivity analysis show that deviation of the relative shares of resource consumption from the baseline scenario in the modelled period do not exceed 8.5 % (see Fig. 5). Also a tendency of resource consumption remains similar and shows an increase in the share of renewable resources. These results indicate that model is relatively robust in relation to assumptions for the demand of energy services.

3. Results and Discussion

As Latvia is also bound to become climate neutral by 2050, the time scale for the modelling process is from 2017 to 2050. However, the timeline and all planned measures in the NECP2030 are only set until 2030.

Final energy consumption in BASE and REF scenarios grow steadily from 33 PJ in 2017 to 43 PJ in 2050 and in the NECP scenario consumption increases to 40 PJ while in NECP+ to 35 PJ in 2050 (see Fig. 6). Increase of final energy consumption is due to planned economic development of industry sector in Latvia, and existing measures to increase energy efficiency and promote the use of RNW resources. Due to very narrow measures in NECP2030, higher efficiency of new technologies alone is not sufficient to compensate the increase of demand due to the economic growth.

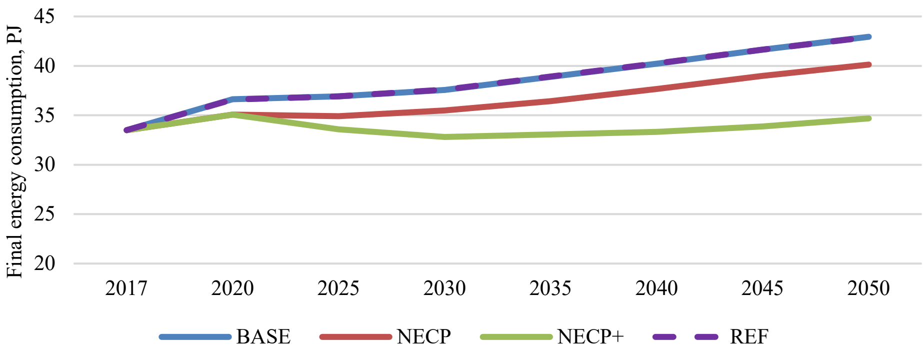

Fig. 6. Final energy consumption in industry sector in the modelled scenarios.

Results show that in 2030 final energy consumption in the food sub-sector decreases in BASE (3.2 PJ), NECP (3.1 PJ) and NECP+ (2.8 PJ) scenarios while in REF scenario consumptions remain steady (3.3 PJ) (see Fig. 7).

In 2050, the amount of energy consumption increases in all scenarios – REF and BASE scenarios (3.8 PJ), NECP (3.5 PJ), NECP+ (3 PJ). In 2030, energy consumption in the wood sub-sector is increasing in REF and BASE (21.3 PJ), in NECP (20.3 PJ) while decreasing in NECP+ (from 19.6 PJ in 2017 to 19.1 PJ). In 2050, consumption is increasing in all scenarios – REF (24.7 PJ), BASE (24.9 PJ), NECP (23.1 PJ) and NECP+ (19.9 PJ). Energy consumption in the minerals sub-sector in 2030 and in 2050 is increasing in all four scenarios – REF and BASE (7.5 PJ and 8.2 PJ), NECP (6.8 PJ and 7.7 PJ), NECP+ (6.2 PJ and 7 PJ) accordingly. In other industry sub-sectors, the total final energy consumption increases in REF and BASE (7.7 PJ) and decreases in NECP (7.3 PJ) and in NECP+ (6.8 PJ) while in 2050 consumption increases in all scenarios – REF (8.6 PJ), BASE (8.5 PJ), NECP (8 PJ) and NECP+ (6.8 PJ).

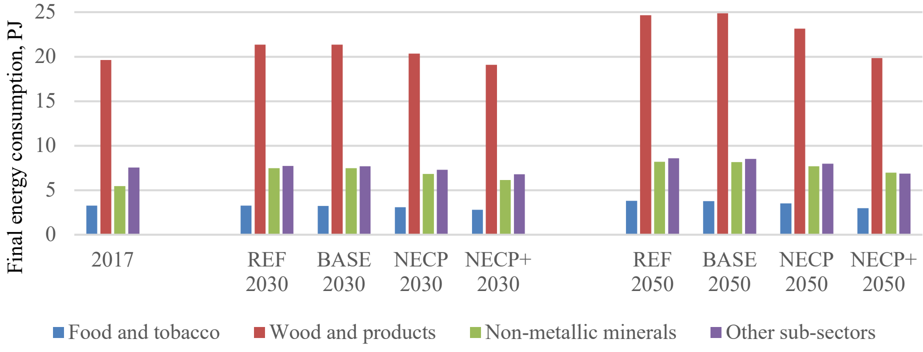

Fig. 7. Final energy consumption in industry sub-sector in the modelled scenarios.

In the wood sub-sector, the main resource is wood biomass, i.e. wood waste and wood chips dominate in energy consumption compiling 7 PJ and 4 PJ respectively in 2017 (see Fig. 8). Wood chips consumption is increasing to circa 7.5 PJ in all scenarios in 2030 and from 11 PJ to 12 PJ in 2050 while wood waste consumption is from 4.8 PJ to 6.2 PJ in 2030 and from 3 PJ to 7 PJ in 2050.

Consumption of electricity remains stable for the whole modelling period and is circa 3 PJ. Amount of used DH in 2030 and in 2050 increases in REF (3.1 PJ and 3.9 PJ), in BASE (2.8 PJ and 3.4 PJ), while decreases in NECP (2.4 PJ and 2.3 PJ and NECP+ scenarios (2.5 PJ and 2.2 PJ).

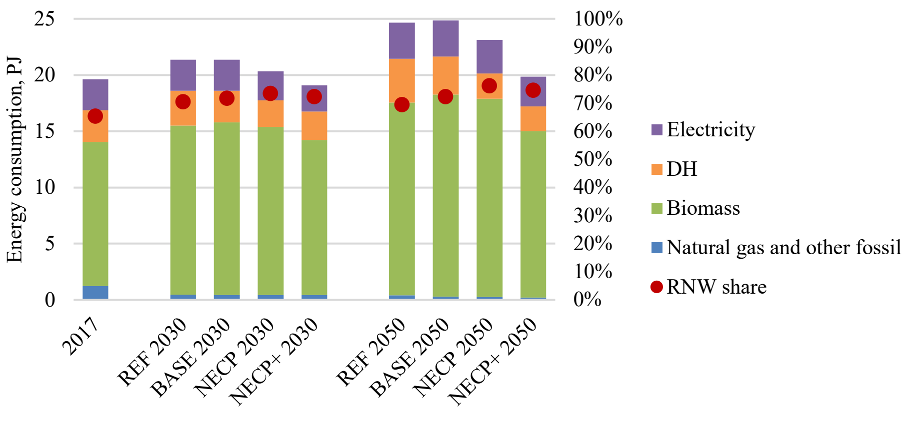

Fig. 8. Energy consumption in wood sub-sector in the modelled scenarios.

The main resources consumed in the food sub-sector in 2017 are natural gas and electricity with values of 1.2 PJ and 1 PJ, respectively (see Fig. 9). Consumption of wood chips increases in all scenarios in 2030 from around 0.9 PJ in NECP+ to around 1 PJ in scenarios REF and BASE and in 2050 to around 1.5 PJ in REF, 2 PJ in BASE, 1.8 PJ in NECP and NECP+. Electricity consumption in 2030 decreases to around 0.9 PJ in REF, BASE and NECP and around 0.7 PJ in NECP+. In 2050 electricity consumption is increasing to around 1 PJ in REF, BASE and NECP, to around 0.9 PJ in NECP+. Natural gas consumption is decreasing in all scenarios reaching around 0.6 PJ in 2030 and around 0.3 PJ in 2050. The share of RNW resources is increasing in all scenarios with the highest share in NECP (41 %) scenario in 2030 and in NECP+ (63 %) scenario in 2050.

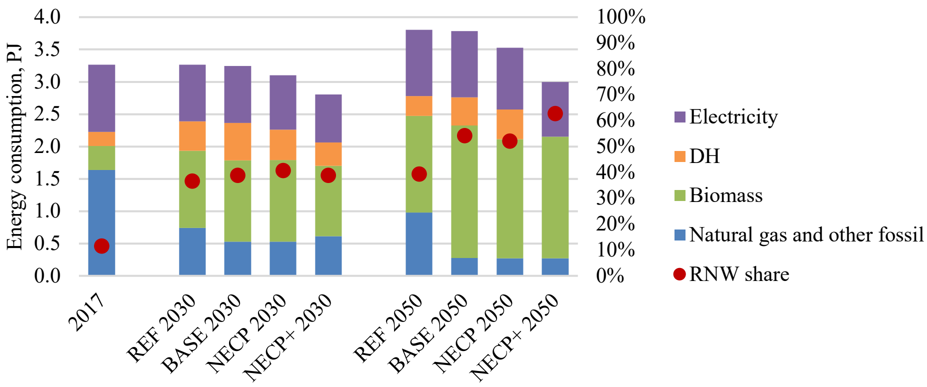

Fig. 9. Energy consumption in food sub-sector in the modelled scenarios.

Energy consumption and tendencies in the minerals sub-sector differs from the other two sub-sectors as here the main resources are fossil fuels (see Fig. 10). Natural gas and other fossil fuels as well as municipal waste, tires and rubber products are the dominant resources in 2017 compiling 2.5 PJ and 2 PJ respectively. In 2030, consumption of natural gas and other fossil fuels increases in REF, BASE (3 PJ) and NECP (2.6 PJ) scenarios but decreases in NECP+ (2 PJ) scenario. In 2050, consumption decreases in all scenarios – REF (2.5 PJ), BASE (2.4 PJ), NECP (2 PJ) and NECP+ (1.5 PJ). Consumption of municipal waste, tires and rubber products decreases in all scenarios reaching circa 1.8 PJ in 2030 and 1.6 PJ in 2050. Consumption of DH and electricity increases in all scenarios reaching around 0.1 PJ and 1 PJ in 2050. Consumption of biofuels, which mainly consists of wood chips, also increases reaching circa 1.5 PJ in 2030 and 3 PJ in 2050.

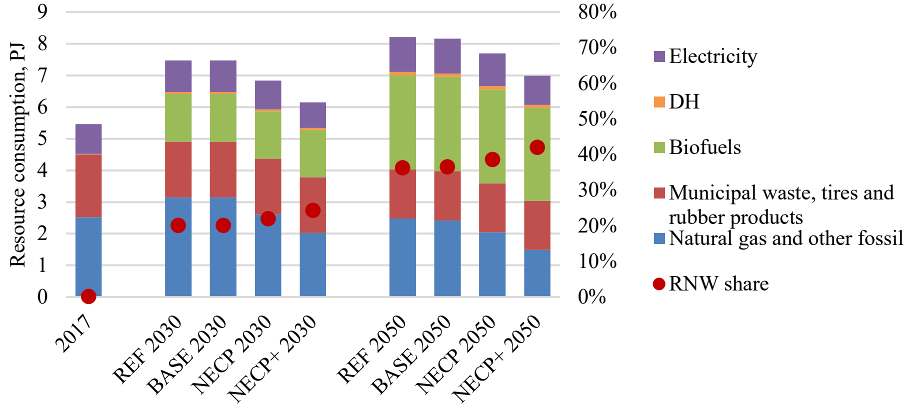

Fig. 10. Energy consumption in minerals sub-sector in the modelled scenarios.

Share of renewable energy in 2017 is almost zero while in 2030 and 2050 the share is increasing in all scenarios reaching the highest share in NECP+ scenario equal to 24 % and 42 %. The fossil fuel dominance in all scenarios is due to the need for high temperatures in industry processes which cannot be fully ensured by renewable resources.

GHG emissions in industry sector in 2017 are around 760 kt and in all scenarios emissions are decreasing. The largest reduction is in NECP and NECP+ scenarios where emissions in 2030 decrease to around 510 kt and 470 kt, which is around 33 % and 39 % less than in 2017 (see Fig. 11).

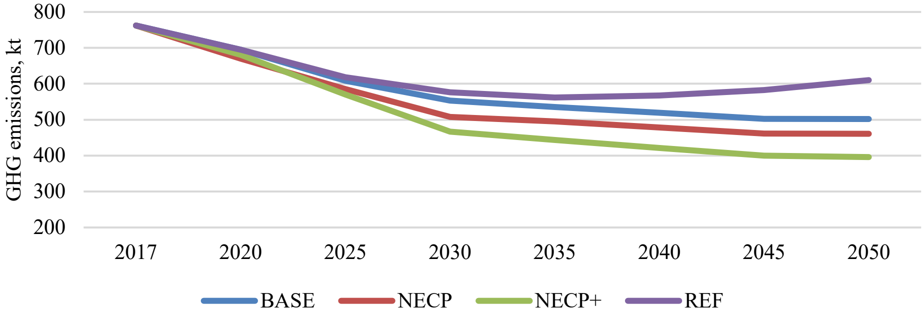

Fig. 11. GHG emissions in industry sector in the modelled scenarios.

In REF and BASE scenarios, emissions in 2030 decrease to 576 kt and 553 kt respectively, which is by 24 % and 27 % less than in 2017. In 2050, the highest amount of emissions is in REF scenario, reaching 610 kt, which is 20 % less than in 2017. In BASE and NECP scenarios, emissions reach circa 480 kt which is 37 % less than in 2017, while NECP+ emissions reach circa 400 kt which is by 48 % less than in 2017.

4. Conclusions

The TIMES tool is used to analyse energy consumption and tendencies of the industrial sector in Latvia. Three sub-sectors – wood and wood products, non-metallic mineral products and food products and tobacco are studied in more detail since these sub-sectors consume circa 80 % of the total energy consumption in the industry.

Four scenarios were compared – REF scenario which excludes the existing tax policy, BASE scenario including existing taxes, NECP scenario including measures regarding industry sector defined in Latvia's National Energy and Climate Plan for the period up to 2030 and NECP+ scenario including additional measures, e.g. support for heat recovery technologies, technological modernization, digitalization, and overall process optimization.

Results show that the final energy consumption is increasing in all scenarios due to the planned economic development of industry in Latvia. Additionally, the existing policy and measures in NECP2030 cannot compensate the increase of energy demand due to economic growth. The lowest consumption of the final energy ensures NECP+ scenario which keeps the amount at the level of the base year by more comprehensive measures (including industrial symbiosis and digitalization).

Results also show that, while the final energy consumption in the industrial sector in REF and BASE scenarios are similar, the existing taxation policy promotes more stable transition to renewable resources. In BASE scenario GHG emissions are by 4 % less than in REF scenario in 2030 while by 18 % less in 2050.

Only NECP+ scenario ensures a decrease of energy consumption in the wood sub-sector in 2030 while in other scenarios the consumption increases. Energy consumption in the food sub-sector remains stable in the REF scenario in 2030 and decreases in other scenarios. In 2050, energy consumption increases in all scenarios. Energy consumption of non-metallic minerals sub-sector increases in all scenarios in 2030 and in 2050.

Wood biomass, especially wood chips and wood waste, dominates in wood sub-sector and while consumption of wood waste decreases, consumption of wood chips increases almost three times. Electricity and natural gas dominate in the base year in the food sub-sector; however, in 2030 and even more in 2050, natural gas is replaced by wood chips. Consumption of natural gas and other fossil fuels as well municipal waste, tires and rubber products dominates and remain important resources in non-metallic minerals sub-sector. The share of renewables is also increasing in all scenarios.

A larger share of renewable resource consumption in the wood sub-sector is ensured in the NECP scenario in 2030 and 2050. The largest share of renewables in 2030 in the food sub-sector is in NECP, but in 2050 in NECP+ scenario. In the sub-sector of non-metallic minerals, the share of renewables is higher in NECP+ scenarios.

Although measures defined in NECP2030 promote the use of renewable energy and improve energy efficiency, it is necessary to set new measures and activities for the period beyond to reach climate neutrality by 2050.

Future research should be done by separating ETS and non-ETS parts of the industrial sector. Other directions in the research to be explored are in total energy system modelling, including and comparing other sectors e.g. agriculture and forestry, energy conversion and commercial.

ACKNOWLEDGEMENT

This work has been supported by the Ministry of Economics of the Republic of Latvia, project "Energy and climate modelling towards net zero emissions", project No. VPP-EM-2018/NEKP-0001.

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CAN ENERGY SECTOR REACH CARBON NEUTRALITY WITH BIOMASS LIMITATIONS?

Energy 249 (2022) 123797

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Can energy sector reach carbon neutrality with biomass limitations?

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ARTICLE INFO

Article history:
Received 30 November 2021
Received in revised form
7 March 2022
Accepted 17 March 2022
Available online 18 March 2022

Keywords:
District heat (DH)
Energy efficiency
Decarbonisation
Renewable energy
TIMES optimisation Model

ABSTRACT

The energy transformation sector, including district heating (DH), is vital in reaching long-term emission reductions and thus climate neutrality set by the European Commission. Biomass for energy production continues to grow in countries with extensive forest resources, e.g. Latvia. However, growing global demand obligates increasing the added value of bioresources, reducing their availability for the energy sector as it is a low value-added application. Therefore, an effective and competitive DH system cannot be developed without high energy efficiency increase of the existing heating infrastructure and building stock. In this study TIMES model supplemented with results of the System Dynamics model and biomass forecasting model was used to elaborate an analysis of the energy transformation sector development. The impact of measures defined in the National Energy and Climate Plan until 2030 and the energy sector pathways towards climate neutrality until 2050 in Latvia was analysed by setting biomass limitations for the energy sector use. Results show that it would be possible to decarbonise the energy sector. Still, it is necessary to increase energy efficiency in the building stock and heating infrastructure and promote renewable sources in the energy transformation sector, including heat pumps and solar energy. It would require an additional investment of more than 326 million EUR compared to the Base scenario.

1. Introduction

Decarbonisation of the energy sector has been a hot topic in recent years due to the introduction of the “Green Deal” framework. Heat production accounts for 40% of global carbon dioxide (CO_2) emissions [1], and 79% of energy in European households is consumed for space heating and domestic hot water preparation [2]. Therefore, reducing heating sector emissions is crucial to reaching ambitious goals.

The use of renewable energy sources (RES) and the improvement of energy efficiency are the main pathways to achieving the goal of climate neutrality in the energy sector. In addition, the necessity of various support policies and long-term planning strategies have been identified as necessary conditions toward zero-emission levels in energy sectors [3].

Furthermore, previous studies highlight different technological solutions and innovations towards eliminating fossil fuels for heat supply. Papadis&Tsatsaronis have summarised various options for decarbonising other energy subsectors – generation of heat and power, end-use, and potential interdependences of the sectors and highlights the role of investments and security of power supply, economic stability, and social aspects [4]. The challenge of decarbonising heat supply is associated with future electrification of end-use sectors and a high share of renewable power [5].

1.1. Technological solutions for heat supply sector decarbonisation

The heating sector can be decarbonised using sector electrification, integration of renewable energy technologies, waste heat and reuse, and the energy efficiency increase of the existing heating infrastructure [6].

The district heating (DH) sector is developing and becoming more effective due to the rapid diffusion of innovative technologies [7,8]. The 4th generation district heating (4GDH) has been introduced as an efficient and intelligent heat supply concept based on RES. The temperature levels in the heat distribution system are adapted to the actual temperature consumed by the user (60–70 °C), resulting in a reduction of network heat losses [9]. In addition, new heat sources such as waste heat from different sources can be integrated within the 4GDH system. Lately, the

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https://doi.org/10.1016/j.energy.2022.123797

ultra-low heat supply concept, also attributed as 5th generation DH has been introduced, referred to as the surrounding ambient loop, which focuses more on local heating [10]. 5GDH concept combines heating and cooling systems to improve the overall efficiency and reduce primary energy consumption [11].

Researches show that only coupling power, heating and transport sectors enable deeper global CO_2 reductions because of insufficient storage capacities [12]. Thomasen et al. have compared the possible impacts of electrification in different countries and concluded that an increase of heat pump capacities in some Baltic and Scandinavian countries (Lithuania, Latvia and Sweden) would not gain climate benefits from such electrification due to relatively clean district heating sectors [13].

Essential RES widely used in Baltic countries is biomass (wood pellets, wood chips, straw etc.). Biomass for energy production continues to grow in countries with extensive forest resources [14]. However, sustainable development and biotechnology principles should be considered when planning to increase biomass plant capacities.

Growing global demand increases the consumption of different bioresources to ensure the food security and production of different products. In addition, the increased use of bioresources is also faced in the energy sector to switch from fossil fuels. Therefore, due to land limitations, the competition between the resources used for food production, biorefinery, added value products, and the energy sector exist [15]. According to Popp et al. in the EU, most biomass is used feed and food products, but 21% is used in the energy sector [16]. Authors conclude that the direct and indirect effects of any land-use change induced by the rising demand for biomass must be considered from a sustainability perspective.

Therefore, policymakers need to reconcile the use of bioresources in the energy sector with the more efficient use of bioresources as material in different industrial sectors. Biomass resources should primarily be used to manufacture high-value products and not energy production [17]. Therefore, the energy sector should implement resource diversification to increase the overall resilience against different unfavourable external conditions [18].

Following the bioeconomy principles, energy efficiency should first be considered when analysing the possible decarbonisation scenarios. Lowes et al. [19] highlight the need to reduce the building heat consumption to decrease the scale of required infrastructural expansion and necessary resources. The studies [20] related to the building sector decarbonisation identify that heat pumps and carbon-neutral district heating systems should provide heating in buildings to achieve climate neutrality. However, the deep renovation of building stock and new energy-efficient buildings are the primary conditions for the decarbonisation of the heating sector.

1.2. Decarbonisation pathways of European countries

Several European countries have set the target to reach carbon neutrality in 2050. One of the first conceptual studies analysing the 100% renewable energy system was presented for Denmark by Lund et al., in 2010 [21]. The paper defined a scenario to reach carbon neutrality in the heating sector in 2060 by combining reductions in space heating demands by 75% and various heating options, including district heating, individual heat pumps and micro combined heat and power production.

Other Nordic countries have developed a plan to achieve carbon neutrality by speeding up the decarbonisation process in energy-intensive sectors, industrial-scale technologies, incentives for alternative technologies, and increased emission reduction requirements [22]. In addition, the Finish government has set a very ambitious target to move toward carbon neutrality until 2035. The strategy includes coal phase-out by 2029 and combining biomass, waste heat sources, heat pumps and RES power for heat supply decarbonisation [23].

The German energy transition targets (Energiewende) a competitive low-carbon economy until 2050 by excluding nuclear power from the energy balance by 2022 [24]. However, decarbonisation of the heating sector in Germany is associated with the increase of heat pump installed capacities as the power sector is a step ahead of the implementation of RES such as wind and solar technologies. Wiese et al. [25] have compared the results from previous research on decarbonisation strategies for Germany and conclude that critical strategies are the reduction in energy demand, an expansion of domestic wind and solar energy, increased use of biomass as well as the importation of synthetic energy carriers. Authors have attributed a limited role for storage but high potential for demand-side solutions.

The research results for United Kingdom's heat supply decarbonisation shows that it requires that heat-related emissions of CO_2 from buildings reach near-zero level by 2050, and there should be a 70% reduction in emissions from industry [26]. In addition, the modelling results show the small remaining role of natural gas for peak load coverage.

The model of deep decarbonisation for Italy shows that emissions can be cut by 79%–97% compared to 1990 levels due to increased share of RES, radical electrification of the energy and increased production energy of technologies [27].

1.3. Modelling methods for energy sector development

Different modelling tools and methods can evaluate and compare different decarbonisation strategies. For example, various energy planning tools have been used to compare several development scenarios for power and heating sectors, such as EnergyPlan [28], energyPro etc. [29]. In addition, different heat production units and heat sources can be modelled using a mixed-integer non-linear programming method to optimise the system operating costs and environmental constraints [30]. There is also wide application of system dynamics modelling method used to analyse the interlinkage of energy sector elements, energy policies, human behaviour and other aspects [31,32].

The essential parameter is the quality of input data and system uncertainty. Pilpola&Lund concludes that for the energy sector forecasts main uncertainty factors are the projected energy consumption, the production of wind power and the potential of biomass [33]. The authors have used the Monte Carlo analysis to analyse the uncertainties' effects on modelled systems. For example, the local heat supply systems can be simulated with higher accuracy by considering the heat flow, substation, and hourly operation conditions, performed by dynamic simulation programs, such as Modelica-based simulations. Another approach involves a spatial resolution to analyse possible decarbonisation scenarios [34]. Vega et al. have used the Cities Optimisation Model for Energy Technologies to consider energy service demands for heating, cooling, electricity, and transport to find cost-effective decarbonisation pathways for Sao Paulo.

The linear optimisation bottom-up energy system model TIMES has been previously applied to analyse the Portuguese power sector [35]. The authors have analysed different levels of decarbonisation and the impact on power cost levels as the ultimate objective of the model is the satisfaction of the energy services demand at the minimum total system costs. The Portuguese TIMES model included more than 60 end-use demands from industry, residential, services, agriculture and transport. Authors conclude that decarbonisation up to nearly 80% does not significantly impact the power sector unit costs.

1.4. Aim and scope of the research

The previous research shows that the decarbonisation of heat supply should focus on energy efficiency improvements and broader electrification. However, the countries with extensive forest areas will also maintain biomass resources, but the existing research does not include in-depth analyses on the available biomass resources for the energy sector. Therefore, the article analyses several pathways to reach the decarbonisation of Latvia's district heating and power sector by combining three main pillars-energy efficiency, biomass availability, and integration of renewable energy sources.

In addition, the article presents the methodology for soft linkage of different modelling tools to improve the accuracy of energy sector modelling. Several models have been used for this study. First, a linear optimisation tool, TIMES, is applied for long-term energy systems planning to find the optimal energy system by minimising the total cost in the modelling period [36]. The System Dynamics model uses a "systems" perspective to address the fundamental structural causes of problems arising in complex dynamic socio-economic systems. In addition, the biomass optimisation model "Forest Expert" results are used, which integrates and combines analysis of available forest resources in full detail from the State Forest Service database.

2. Methodology

2.1. Development of energy transformation sector

District heat (DH) in Latvia is mainly produced in heating plants (HP) and combined cogeneration plants (CHP), in whom also power is generated. In the last ten years structure of used energy sources in the DH and power sector have been switched more and more to renewable energy sources (RES) mainly by consuming wood biomass (see Fig. 1.). As a result, the share of wood chips has increased from 11% in 2008 to 41% in 2020. Thereby the share of natural gas has decreased from 80% in 2008 to 50% in 2020.

Most of the thermal energy for DH is produced in CHP, accounting for 63%–76% from 2012 to 2020 (see Fig. 2.). In 2012 most of the heat in CHP was produced using natural gas (90%), and only 5% was produced using RES, while in 2020, around 52% was produced from natural gas, 42% from wood chips, and 6% from other RES, mostly biogas and different types of biomass.

The natural gas consumption in HP decreased from 59% in 2012 to only 29% in 2020, while RES particular wood chip consumption has increased from 30% to 65% in the same period. Also, other RES like firewood and wood pellets are common, but since 2020, solar energy has entered the heat supply balance in Latvia.

2.2. Input data and assumptions

In the TIMES Latvia model, the structure of DH is built based on the division in energy balance, including CHP and HP technologies, as well emission trading system (ETS) and non-ETS plants to model the CO_2 emission costs (see Fig. 3.) because Latvia is a part of the European Union ETS [37]. Additionally, the structure has been divided into two regions – Riga and the rest of Latvia because Riga, with the two high-capacity CHP, is significantly different from the rest of Latvia. The heat from plants in Riga (LTHR) and the rest of Latvia (LTHL) is transferred to the grid and finally to the industrial, residential, commercial, and agriculture demand sectors.

The model considers all relevant cost flows - investments, fuel costs, operational costs and taxes to optimise energy production. One of the essential assumptions is the parameters of available technologies in the energy transformation sector. Therefore, the Danish Technology Catalogue [38] was used to determine the primary technical data of technologies, e.g. operational lifetime, efficiency parameters, capital costs, operational and maintenance costs, variable costs (see Annex).

CHP provides a large share of heat in the existing energy sector. Therefore, one of the critical parameters within the modelling process of the energy sector is the potential power to heat ratio in these plants. In the TIMES model, the historical data have been used to set the power-to-heat ratio in the BASE scenario presenting the existing situation. However, the average power-to-heat ratio in 2017 was 0.47, which is slightly lower than the average value in the last decade (0.62) due to the significantly higher hydropower production rate in the Base year. However, in the modelling period, the ratio may vary depending on cost-effectiveness not exceeding the technically feasible potential for each cogeneration technology.

The most significant impact on DH production has the following taxes: an excise tax, CO_2 quota price, and natural resource tax. Only known tax rates are included in the model (see Table 1) except CO_2 quota price, which is assumed to change in different scenarios (see section 2.3. Scenarios).

Resource prices significantly impact results as TIMES seeks the lowest total system costs. The primary resources used in DH production are natural gas and biomass, mainly wood chips. It is forecasted that all resource prices will increase until 2050 (see Fig. 4.). In the research, the resource prices are assumed to be equal in all analysed scenarios described in Section 2.3. without the feedback from the increased demand for resources. Similar simplification can also be found in previous energy sector modelling research [41]. To better represent the resource price demand

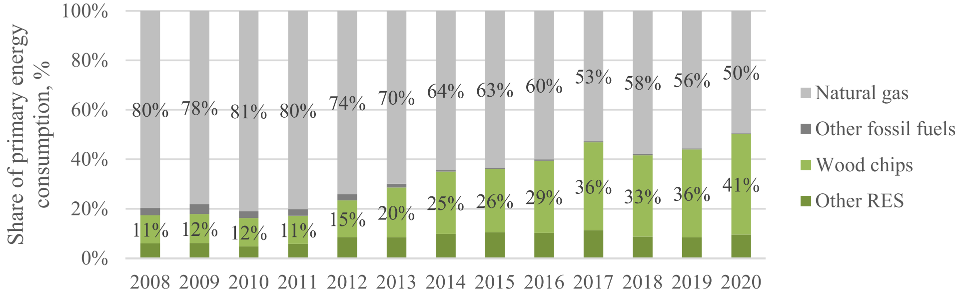

Fig. 1. Existing primary energy resource portfolio of DH and power sector.

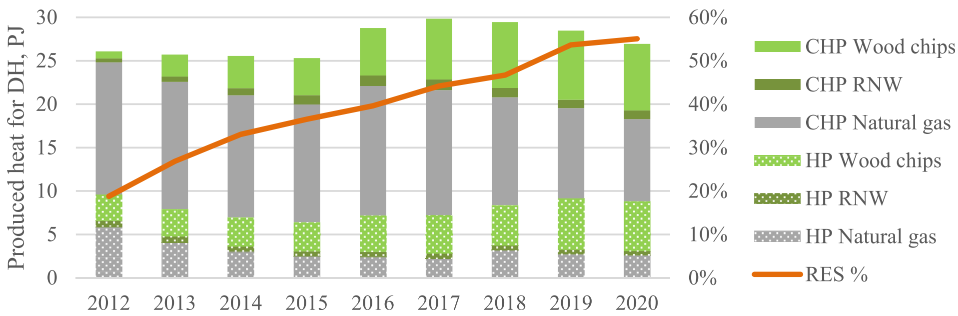

Fig. 2. Thermal energy produced in CHP and HP.

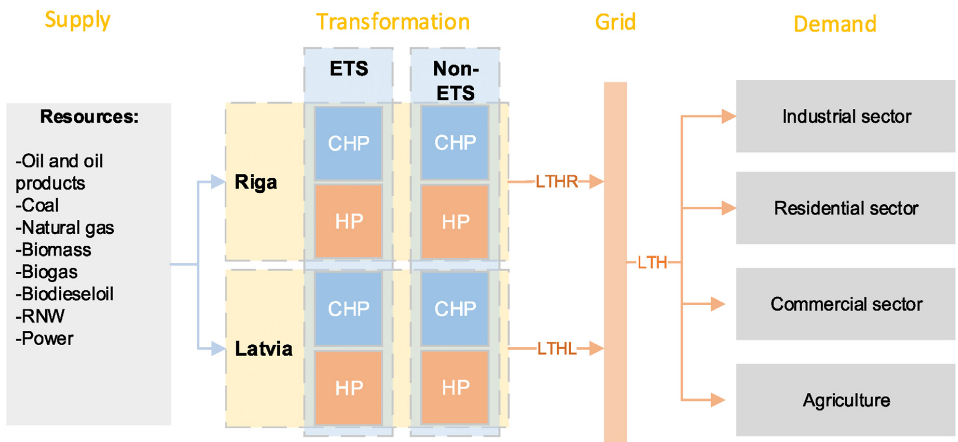

Fig. 3. DH structure in TIMES Latvia model.

Table 1
Taxes used in the model [39,40].

Tax	Unit	Resource	Base year	2019	2020	2021	2022–2050
Excise	EUR/GJ	Diesel oil	10.5	10.5	11.7	11.7	11.7
		Natural gas	5.94	5.94	5.94	5.94	5.94
CO_2	EUR/t	CO_2	2.85	4.5	9	12	15
Natural resource	EUR/t	Coal	10.7	10.7	21.3	21.3	21.3

elasticity, the linkage with the economic models, for example, the Computable General Equilibrium model, could be used allowing to estimate how an economy might react to changes in policy, technology, or other external factors [42]. However, the soft linkage with additional economic models has been considered a next research step. Other authors also conclude that forest wood price is significantly influenced by forest events that cannot be precisely forecasted [43]. Further studies will develop the structural loops between resource demand, resource prices, and other impacting factors such as forest management policies, increased demand for the wood processing industry, and decreased land availability.

The TIMES model is unsuitable for several important socio-technological aspects, especially behaviour and human factors. Therefore, other specific models, i.e., System Dynamics (SD) model and forest optimisation model outputs, were used to supplement the TIMES model to obtain correct results and compensate for shortcomings. The previously built system dynamics model [45] covers energy production and consumption to describe the entire energy supply system. The developed structure of the SD model searches the balance to energy supply and the demand by ensuring the lowest possible energy costs considering the resource costs, necessary investments, maintenance costs and taxes. In addition, the social behaviour factors are considered within the model, such as the decision-making process, inconvenience costs of different technologies and the feedback loops associated with the increased energy efficiency of consumers. The main assumptions within the SD model are in line with those for the developed TIMES model, including the technical parameters and costs of different energy production technologies, resource prices and attributed taxes.

The insulation rate of public buildings and residential sector

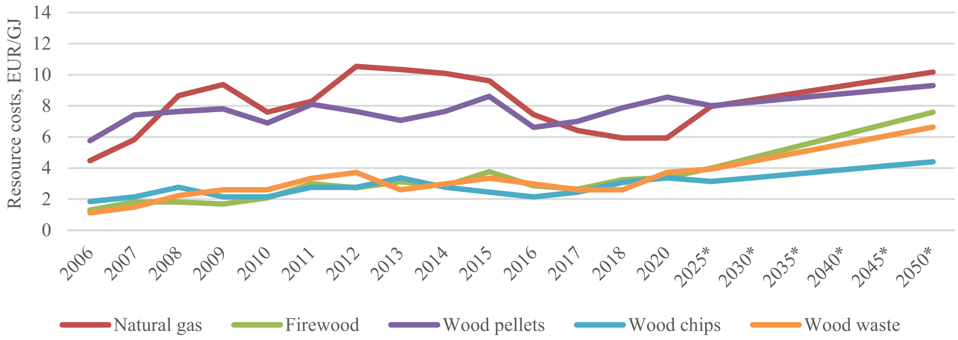

Fig. 4. Historical prices and forecasts [44].

apartment buildings is obtained from the SD model for two scenarios – the SD BASE scenario (SD BASE) and SD Energy efficiency scenario (SD Efficiency) (see Fig. 5.). In SD BASE, the building insulation rate is based on the existing situation without additional funding and measures. Several sectors obtain financial support with different aid intensities in the SD Efficiency. In addition, maximal financial support was also combined with policy instruments such as an information campaign (in industrial, commercial, public, and residential sectors), mandatory implementation of climate and energy plans (in the public sector), mandatory energy management or energy audits (in industrial and commercial sectors), state aid for R&D (in industrial and commercial sectors), a support program for representatives of multifamily houses (in the residential sector). SD BASE scenario shows minimal impact on the insulation rate in contrast to very high insulation rates in SD Efficiency scenario, which reaches 73% of the insulted building in Public sector and 82% insulted buildings of apartment buildings built before 1991.

Results of forest data processing program “Forest Expert” developed by Latvia University of Life Sciences and Technologies are used as inputs for the TIMES model. The maximum amount of biomass available for the energy sector is obtained from the “Forest Expert” linear optimisation model, which provides a higher quality of data on the development of forest resources. The model includes tree growth rate models, compliance with binding regulatory enactments and standards for predicting timber outcomes, algorithms of tree trunks, and assortment forecasting. The results of the “Forest Expert” model show that the available amount of wood pellets for the energy sector will increase. Still, the availability of other wood biomass will decrease by around 30% in 2050 compared to 2017 (see Fig. 6.).

Maximum of biomass is achieved in 2040, which is influenced mainly by the availability of white alder, the volume of felling of which is significantly higher (short circulation time ~ 31 years). There are no restrictions to even out-felling volumes in the long run. The assortment of this species very much goes to firewood. The same biomass limitation derived from the “Forest Expert” model is used in all TIME's scenarios without considering different forest management policies.

2.3. Scenarios

Three scenarios have been developed to analyse the further development of the energy transformation sector and DH consumption and production:

- *Baseline scenario (BASE)* – based on the situation in 2017 (the base year of the model). This scenario includes existing tax policies on fossil fuels and funding allocated for the energy sector under the 2014–2020 programming period of EU funds [47]. This scenario shows the trajectory of energy consumption and resource allocation for DH production if the policy support instruments, laws, and taxes remain unchanged. In addition, the insulation rate of public buildings and residential sector apartment buildings is obtained from the SD BASE derived from the SD model.

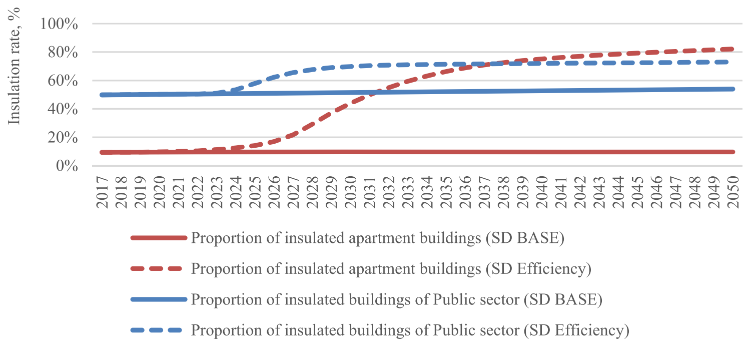

Fig. 5. Insulation rate for an apartment building in the residential sector and the public sector [45].

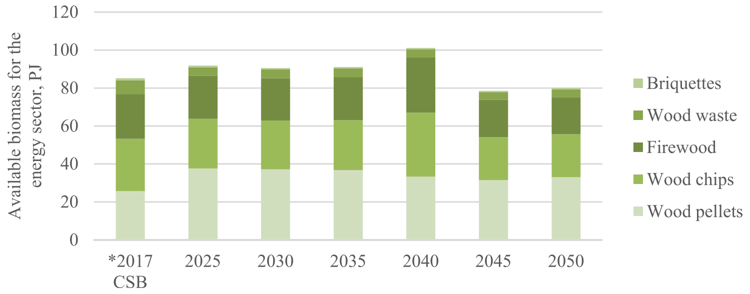

Fig. 6. The maximum amount of biomass available for the energy sector [46].

- *NECP scenario (NECP)* — includes the existing funding policy and measures determined in Annex 4 of NECP 2030 [48]. It is assumed that the CO_2 tax will increase by 50% in 2050 compared to 2022 reaching 22.50 euros per ton, and the price of the CO_2 quota will increase by 50% compared to 2020, reaching 33 euros per ton. The main measures included in the model are improved energy efficiency in DH, increased use of RES, restrictions on the installation of new plants for the combustion of solid or liquid fossil fuels in DH, subsidies for more efficient technologies and offshore wind farm construction of 800 MW capacity. In addition, the insulation rate of public buildings and residential sector apartment buildings is obtained from the SD Efficiency scenario derived from the SD model.
- *GHG Target scenario (GHG TARGET)* — includes the existing funding policy. It is assumed that both CO_2 tax and the price of CO_2 quota will increase to 72,61 euros per ton in 2050 according to recommendations from the European Commission, which forecasts an increase in the quota price to around 50 EUR per 1 quota in 2040. It is a target optimisation scenario that requires the energy sector to become climate neutral in 2050. The insulation rate of public buildings and residential sector apartment buildings is obtained from the SD Efficiency scenario derived from the SD model.

2.4. Validation

Validation of the model was done by comparing resource consumption in the energy transformation sector of model BASE results and official statistical data from the Central Statistical Bureau of Latvia for years 2018, 2019, and 2020 (see Fig. 7).

The total resource consumption in the energy transformation sector in statistical data slightly differs from the model results. The total amount of resources consumed is 1.7% higher in 2018, 1.5% less in 2019, and 1.2% more in 2020 than the modelling results.

The primary energy sources used in heat supply (natural gas, wood chips, and biogas consumption) obtained from the model gave no more than a 7% difference from the statistical data. Natural gas consumption of the model is around 2% higher than in statistics, biomass consumption is 1% higher in 2018, 7% less in 2019, 1% less in 2020, while biogas consumption was 6% more in 2018 and 2020 and 4% more in 2019 compared to statistical data. Therefore, the results of resource consumption in the transformation sector provided by the model match the statistical data sufficiently well.

3. Results

The modelling process has been performed from 2017 until 2050 to assess the progress of the energy sector towards climate neutrality. However, the timeline and all planned measures in the NECP2030 scenario are set until 2030.

The changes in DH consumption in sectors are derived from the SD model. In the BASE scenario, demand for DH is steady in the Residential (RSD) sector where the amount of DH is around 16 PJ, while in other sectors, demand for DH is increasing by 10% in industry (IND), about 33% in agriculture (AGR), and for around 9% in the commercial sector (COM) (see Fig. 8.). On the other hand, in the NECP and GHG TARGET scenario, the heat consumption decreases by around 43% in the RSD sector due to significant building renovation rates and about 8% in COM and 7% in IND sectors where also the energy efficiency measures are considered.

The modelling results forecast that natural gas and biomass are used the most to ensure DH in the BASE scenario (see Fig. 9.). Around 56% of the heat produced in the base year is from natural gas, while about 40% is from biomass, having approximately 29 PJ of thermal energy. The amount and proportion of natural gas and

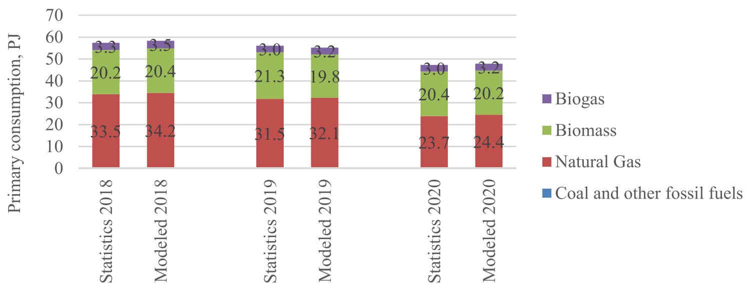

Fig. 7. Results of the model and statistical data of primary resource consumption in the energy transformation sector for the years 2018, 2019 and 2020 [49].

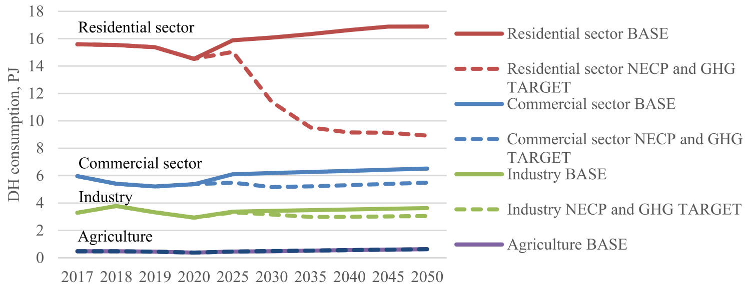

Fig. 8. DH demand in sectors.

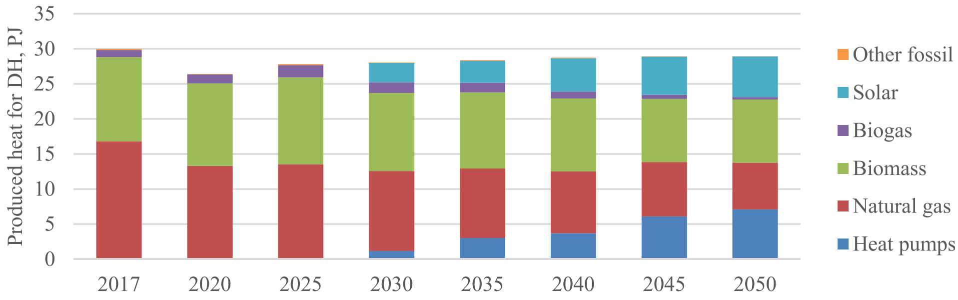

Fig. 9. DH produced by the type of resource in the BASE scenario.

biomass used to produce DH decrease in 2050, covering around 54%, both producing around 15.7 PJ for DH. From 2030, heat pumps and solar energy will also become significant to cover the high demand for heating. Heat pumps cover around 24% of heat demand, but solar energy provides 20% of necessary heat.

In NECP and GHG TARGET scenarios, demand for DH decreases by around 30% compared to the BASE scenario. The obtained modelling results in Fig. 10 and Fig. 11 show that the use of natural gas has been eliminated in both scenarios due to low economic benefits compared to alternative solutions. Also, the use of biomass is decreasing in both scenarios. In the NECP scenario, the amount of used biomass is reduced from 40% to 37% (biomass), equal to around 6.9 PJ in 2050 (see Fig. 10.). As a result, in the NECP scenario, heat pumps become cost-effective starting from 2035 and ensure around 7.3 PJ of heat for DH in 2050, equal to 39% of total produced heat. Solar energy will provide 19% of delivered heat in 2050.

In the GHG TARGET scenario, the use of biomass is decreasing from around 12 PJ in 2017 to 3.7 PJ in 2050, providing only around 20% of necessary heat in the DH sector. The primary energy source for DH in this scenario in 2050 is large scale heat pumps which provide up to 47%. Modelling results show that solar energy has become cost-effective already in the 2030 scenario and will cover around 19% of produced DH in 2050. The heat produced by biogas slightly increased from about 3% in 2017 to about 9% in 2050.

The sensitivity analysis was done for the GHG TARGET scenario by reducing the amount of available biomass for the energy transformation sector by an additional 20% (GHG TARGET+). It could be evident if the export of biomass resources would continue to grow or stricter biomass cascading principles would come into force. However, due to the high impact of heat pumps in the DH

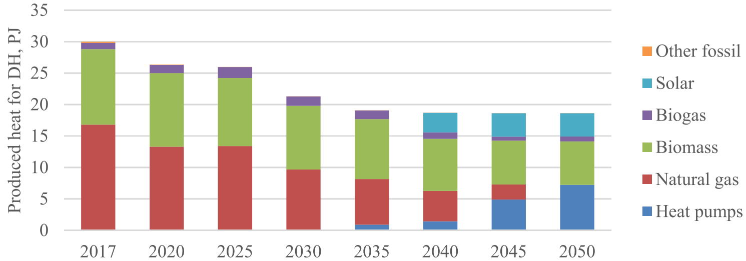

Fig. 10. DH produced by the type of resource in NECP.

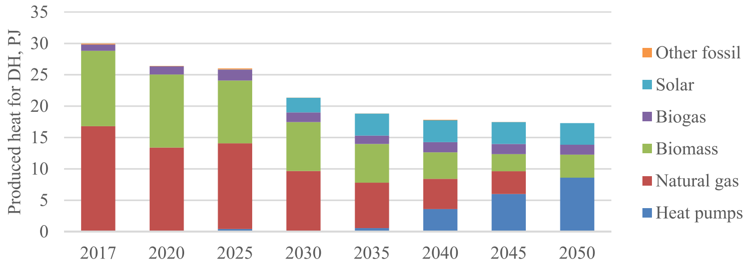

Fig. 11. DH produced by the type of resource in GHG TARGET.

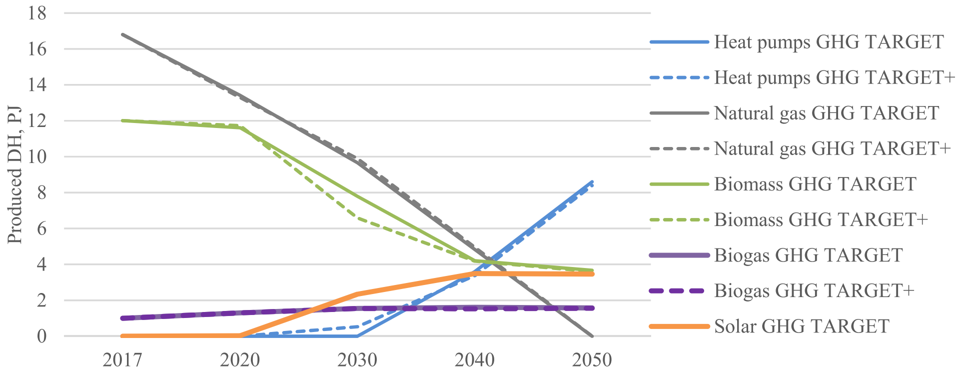

Fig. 12. Results of sensitivity analysis – DH produced by the type of resource in GHG TARGET and GHG TARGET+.

sector, such reduction of available biomass does not cause an elevated difference. Results of heat production rates compared for both scenarios only showed differences in the year 2030 when biomass use decreases by 15%, substituting it with the help of heat pumps (see Fig. 12.). If biomass is limited for the energy transformation sector, the use of heat pumps becomes beneficial earlier.

District heating and power sectors are closely integrated within the future development pathways due to the operation of CHP plants and heat pumps that utilise renewable power. Therefore, the obtained results are further analysed for heating and power sectors. Total GHG emissions of the energy sector in the BASE scenario are decreasing by around 53%, while both the GHG TARGET and NECP scenarios reach climate neutrality in 2050 due to the exclusion of natural gas (see Fig. 13. (a)). It demonstrates that the energy transformation sector can produce the required amount of DH and power with almost no emissions. However, to ensure the integration of renewable technologies, new investments in heat and power production technologies took place in the energy

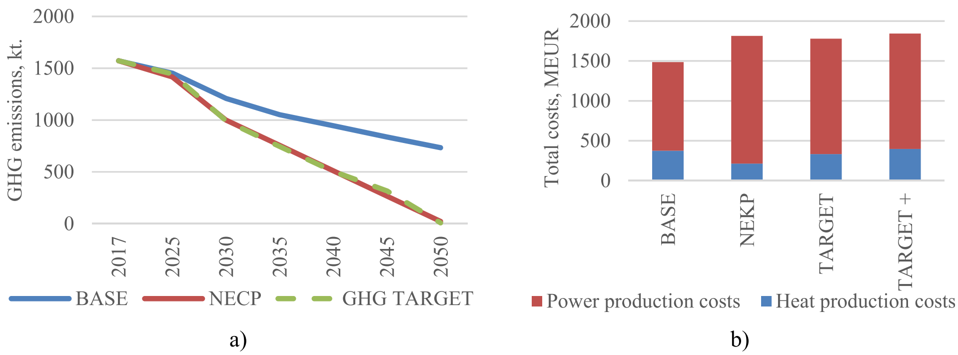

Fig. 13. GHG emissions in the energy transformation sector (a) and the total investment costs in the energy sector (b).

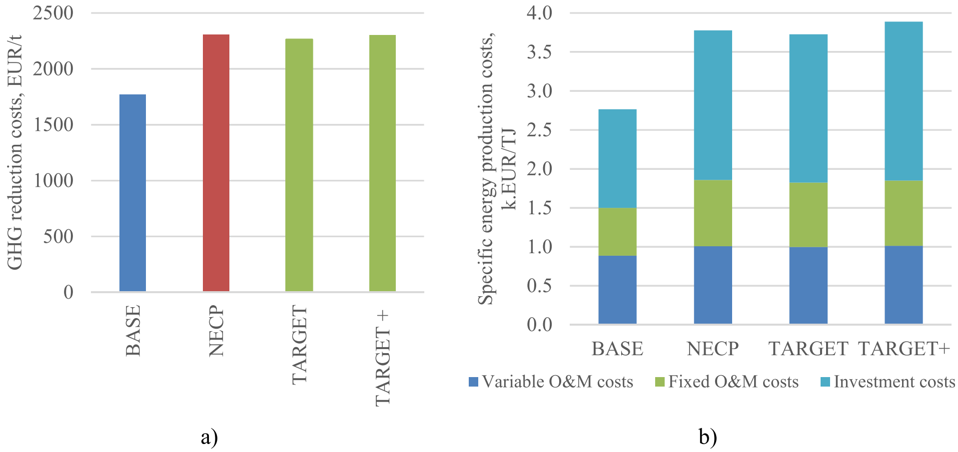

Fig. 14. The modelled specific GHG emission reduction costs (a) and typical costs for heating technologies per unit of produced energy in DH (b).

transformation sector. The total costs for power and heat production can be seen in Fig. 13 (b). The total energy production costs, including both the investments and all O&M costs, are by 22% higher in NECP and by 20% higher in the TARGET scenario compared with the BASE scenario. The additional biomass limitation increases the total energy production costs by 4% or 64 MEUR compared to the TARGET scenario. In the NECP scenario, higher prices are dedicated to the power sector as it includes the support for offshore wind power plant installation.

The specific costs per reduced GHG emissions in the energy sector during the modelled period from 2017 to 2050 can be seen in Fig. 14 (a). Those also include the costs for energy efficiency measures, including insulation of buildings and reconstruction of existing heating grids. These costs have been adopted to be equal in NECP and GHG TARGET scenarios derived from the SD model and account for an additional 1.76 million EUR. As can be seen, the only slightly higher GHG emission reduction costs have been obtained in the NECP scenario accounting for 2307 EUR per ton of reduced GHG emissions compared to the TARGET scenario. The specific GHG emission reduction in the BASE scenario is much lower than other modelled scenarios. The energy production optimisation in this scenario is only based on reaching the most insufficient investment and operation costs without additional conditions to achieve environmental benefits.

Also, the specific energy production costs increase significantly when comparing the BASE scenario and other modelled scenarios of energy sector development. Due to the lack of energy efficiency measures, specific energy costs in the BASE scenario are about 37% lower than the NECP scenario, leading to 2765 euros per one TJ of produced energy (including power and heat production). More efficient and more expensive technologies are used in those scenarios with little or no emissions, e.g. solar collectors and heat pumps. The NECP scenario requires 3778 euros of investment in heat and power-producing technologies per the same amount of thermal energy produced. However, the GHG TARGET scenario requires slightly lower costs – 3726 EUR/TJ investment costs per produced power and heat unit due to energy production optimisation.

4. Conclusions and discussion

The linear optimisation TIMES model linked with two other models, e.g. System Dynamic model and forest optimisation model, is used to analyse DH consumption, energy sector production, and tendencies in Latvia. Three scenarios were compared – BASE scenario including existing energy policies, NECP scenario including measures defined in Latvia's National Energy and Climate Plan for the period up to 2030, and GHG TARGET scenario, which set the effort to become climate neutral by 2050. NECP and GHG TARGET also include existing taxes and the SD model's building energy efficiency scenario results. In addition, the amount of biomass for the energy sector is derived from the forest optimisation model “Forest Expert”. Sensitivity analysis was done by limiting the available amount of biomass by 20% for the energy transformation sector in the GHG TARGET scenario.

Results show that the DH consumption remains steady in the BASE scenario, while in NECP and GHG TARGET scenarios, DH consumption decreases by around 30% due to increased building energy efficiency, reconstruction of heating network and other energy efficiency measures. Natural gas and biomass in the BASE scenario are used the most to ensure demand for DH. In the last decades of the modelling period, heat pumps and solar energy have become meaningful for DH production. While in NECP and GHG TARGET scenario, use of natural gas is eliminated by 2050. The amount of heat from biomass is reduced in the analysed GHG TARGET scenario to around 20%, and the high share of heat demand is covered by large-scale heat pumps and solar energy. Sensitivity analysis showed that large scale heat pumps are used earlier and more if the limitation of biomass increases for the energy transformation sector.

GHG emissions from the production of DH decrease in all three analysed scenarios. The modelled NECP and GHG TARGET scenario demonstrate that the energy transformation sector can produce the required amount of heat and power with almost no emissions. However, it would require an additional amount of investments of more than 326 million EUR compared to the BASE scenario.

TIMES model results show that climate neutrality can be achieved by implementing new technologies that produce energy with little or no emissions. The energy transformation sector is almost entirely able to switch to zero-emission energy production in the analysed case study of Latvia.

Future research should be done by separating ETS and non-ETS parts of the energy transformation sector and including spatial analyses for the most extensive DH system in Riga and the rest of Latvia. More in-depth studies should be dedicated to the potential resource price changes due to higher biomass consumption, which is difficult to forecast due to the high impact of various conditions, both economic, environmental, social, and political conditions.

The soft linkage with the detailed biomass optimisation model allows further research to consider different forest management policies and support decision-making regarding an integrated approach to the strategic planning of forest resources. Further research could include stricter regulation regarding the available biomass for the energy sector. By the principles of the EU Green Deal, countries should consider both the conditions for the extraction of round timber for profit and capital value maximisation as well as the CO_2 accumulation and reduction, the impact of economic activity on employment and the characteristics of biodiversity protection in their forest management strategies. Therefore, the detailed modelling tool allows evaluating the overall effect from forest management strategies on the energy sector decarbonisation potential which will be the next step of the research.

Credit author statement

Allena Ozolina: Investigation, Data curation, Writing, Methodology, Visualization, Validation **Pakere**: Investigation, Data curation, Writing, Methodology, Editing, Visualization **Jaunzems**: Investigation, Project administration **Blumberga**: Project administration, Supervision **Gravelsins**: Methodology, Software. **Dubrovskis**: Data curation **Daģis**: Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work has been supported by the Ministry of Economics of the Republic of Latvia, the project “Energy and climate modelling towards net zero emissions”, project No. VPP-EM-2018/NEKP-0001.

Annex 1. Main technical assumptions of new technologies in the energy transformation sector

Technology	Lifetime	Transformation coefficient	Investment cost 2018	Investment cost 2030	Fixed O&M costs 2018	Fixed O&M costs 2030	Variable and maintenance cost
	years		k.EUR/MW	k.EUR/MW	k.EUR/MW	k.EUR/MW	k.EUR/TJ
Hydro - Hydro (Run-of-River)	40	1.000	2567		50	36.05	1.08
Wind - Onshore	30	1.000	1243	1040	20.90	12.60	0.63
Wind - Offshore	30	1.000	2567	1930	50.40	36.05	1.05
Wind — Near Shore	30	1.000	2197	1660	45.36	34.25	1.08
Wind - Domestic turbine (residential/ commercial)	20	1.000	3920	3600	98.00	95.00	–
Solar - PV Commercial	20	1.000	1128	630	12.60	9.24	–
Solar - PV Residential	17	1.000	1399	870	14.86	10.82	–
Solar - PV Industrial	20	1.000	1128	630	12.6	9.24	–
Solar - PV Central	30	1.000	1088	690	11.10	8.80	–
Solar - Thermal Riga	30	1.000	390	295	0.06	0.06	0.00
Solar - Thermal Latvia	30	1.000	390	295	0.06	0.06	0.00
Solid Biomass - Steam turbine	35	0.140	6700	6200	292.70	280.50	2.17
Natural Gas - Combined cycle	25	0.350	1300	1200	20.00	18.60	1.53
Biogas - Combined cycle	20	0.220	1810	1540	199.19	197.70	–
Wood Chips - Steam turbine	35	0.139	6410	6000	283.00	273.00	2.57
Wood Pellets - Steam turbine	25	0.146	6160	5700	273.00	261.00	1.08
LPG	20	1.010	113	104	2.80	2.65	–
Diesel oil	20	0.880	175	163	3.52	3.23	6.94
Residual (heavy) fuel oils	20	0.880	175	163	3.52	3.23	6.94
Natural Gas	25	1.010	113	104	2.80	2.65	–
Solid Biomass	25	0.800	700	650	7.22	6.98	–
Wood Chips - Steam turbine	25	1.140	700	660	32.80	31.50	0.28
Wood Pellets - Steam turbine	25	1.012	725	680	33.24	31.00	0.28
Electricity - Compression heat pump	25	3.500	683	590	2.00	2.00	0.91
Electricity - Absorption heat pump	25	0.984	586	510	2.00	2.00	0.25
Electricity - Boiler	20	0.984	150	140	1.10	1.02	0.25
Peat	25	0.880	175	163	3.52	3.23	6.94

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PASSENGER TRANSPORT SHIFT TO GREEN MOBILITY - ASSESSMENT USING TIMES MODEL

Passenger Transport Shift to Green Mobility – Assessment Using TIMES Model

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***Abstract* – The transport sector accounts for about one-third of the final energy consumption in Latvia, most of which are fossil fuels in road transport. Fossil fuel consumption increases emissions and demands an immediate change in mobility habits to achieve climate neutrality by 2050. This paper focuses on the in-depth analyses of passenger transport by modelling the potential use of cleaner energy sources and the possible decrease of consumption through the modal shift. As travel modes differ for each distance, the study is done for three distances – short, medium and long. Three scenarios have been analysed – BASE scenario including existing measures and taxation policy, NECP scenario including measures defined in the National Energy and Climate Plan until 2030 and GHG TARGET scenario aiming to achieve climate neutrality by 2050. The proposed modelling approach allows for the development and evaluation of the effectiveness of existing and planned measures in greening mobility. Results proved the need for immediate action and a change in the mobility habits of the population to achieve climate neutrality by 2050.**

***Keywords* – Energy efficiency; decarbonisation; GHG emissions; green mobility; optimisation model; renewable energy; transport sector modelling**

1. INTRODUCTION

Transport and mobility are key factors for the development and welfare of society. However, energy consumption and greenhouse gas (GHG) emissions from the transport sector are still increasing worldwide [1], [2], and in the European Union (EU) [3]. Almost 25 % of all EU GHG emissions are caused by the transport sector. Besides, road transport alone accounts for nearly 72 % of GHG emissions in the transport sector and 20 % of the total GHG emissions [4]. To achieve climate neutrality, it is essential to implement various policies that promote the transition to environmentally friendly modes of travelling, the development of alternative fuels and the reduction of the total energy consumption of the transport sector. Various modelling tools support the decision-making process to create the most effective and optimal set of science-based policy measures.

The linear optimisation TIMES model has been previously used to evaluate the sensitivity of the European road transport sector considering different variations of investment cost and vehicle efficiency [5]. Additionally, Stochastic Multicriteria Acceptability Analysis is used to evaluate modelling results under an economic and environmental criterion complimenting the cost minimisation approach. Electric vehicles are seen as most favourable in all three dimensions in the study. This methodology supports decision-makers in the analysis of policy frameworks not only from the perspective of cost-effectiveness but also from an economic

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and environmental viewpoint. Another study presents an introduction of the consumer behaviour aspect into the TIMES optimisation model [6]. The classic consumer choice model is incorporated into a typical long-term energy modelling framework as a case study of purchasing light-duty vehicles. Thirty-six consumer segments were created to represent different factors, such as driving distances and acceptance of new technologies.

Modal shift is assessed for Scandinavia's transport sector using the TIMES model [7]. Passenger and freight modal shift is based on a real case study. This approach allows to include additional measures toward decarbonisation of the energy sector. Results showed that rail and non-motorised transport modes, e.g., walking and cycling, increase passenger mobility while rail replaces trucks and ships for freight. Also, other papers represent the importance of the modal shift to reach carbon neutrality in the transport sector [8],[9].

A system dynamic modelling approach is also widely used for transport sector modelling. For the case of Latvia, systems dynamics models are developed to analyse CO_2 emission reduction potential in road transport [10], [11] and to explore a possible promotion of biomethane [12]. The system dynamic model is built to support policymakers in testing different policy scenarios to improve road safety in the USA [13]. The transition towards alternative fuels [14] and the potential of biofuels [15] were modelled in an integrated system dynamics model for Iceland.

An integrated assessment model ASTRA, based on the system dynamics approach was developed more than 20 years ago with additional economic and environmental impact assessment for a transport system at the European level [16]. The ASTRA model is used in several studies – to analyse the impact of electric bikes on modal split in Europe [17], and to test the effect of transport policies on shifting passenger travel to public transport in Portugal [18]. In addition, the European Commission policy of a Europe-wide multimodal transport network TEN-T is based on the interaction of two models – ASTRA and TRUST [19]. Possible employment implications of connected and automated driving (CAD) were tested using ASTRA and NEMESIS models as well [20]. Analysis of the development towards a low-carbon energy system in Europe until 2050 was done by coupling different bottom-up models, including ASTRA and TE3, which is also developed for transport sector analysis by applying the system dynamics approach [21].

Computable general equilibrium (CGE) models are also used for transport sector analysis. The socioeconomic impact of a public-private partnership's transportation infrastructure is investigated through capital expenditure and tax burden economic effects using CGE [22]. Investigation of the long-term environmental and economic impact of new rail infrastructure on the cargo transport sector was done using the CGE approach with dynamic components [23]. CGE model and a specialist highway model, HERS of the U.S., were combined to analyse infrastructure policies [24].

Previous research highlights the importance of the transport sector in future efforts to achieve climate neutrality. Therefore, the button-up optimisation model TIMES has been developed to analyse possible GHG emission reduction in the transport sector of Latvia as the case study. The paper presents the methodology for a comprehensive modelling approach linking the transport modal shift and promoting the use of alternative types of fuels. Innovative comfort level criteria have been introduced to model people's desire to change their travel habits (modal shift) more accurately.

2. METHODOLOGY

2.1. Development of the transport sector in Latvia

Around 30 % of the total final energy consumption in Latvia is used for the transport sector. Resource consumption includes demand for international and domestic air transport, road transport, rail transport, inland shipping, and pipelines. The leading resource consumed in the transport sector is fossil fuel which includes fuels like diesel, oil and gasoline. Total resource consumption in the last decade has ranged from around 43 to 53 PJ (see Fig. 1). From 2012 to 2019, there was a slight increase in annual resource consumption. In 2020, the mobility and, consequently, resource consumption dropped significantly due to the global pandemic and decreased travel needs.

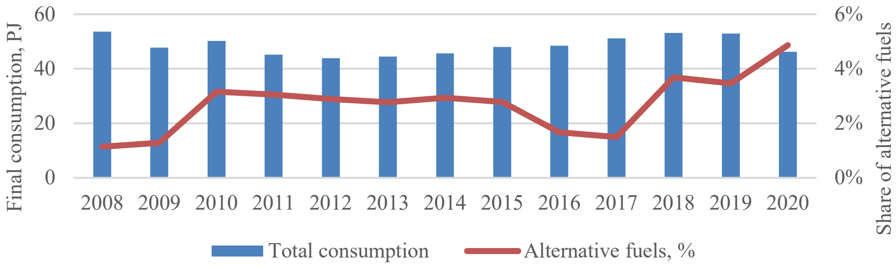

Fig. 1. Final energy consumption in the transport sector and share of alternative fuels from 2008 to 2020 [25].

Road transportation, which includes freight transport and passenger transport, has the highest energy consumption, accounting for more than 80 % [25].

The importance and development of the transport sector in Latvia makes it a necessity to take immediate action in this field, mainly focusing on road transport transformation as fuel consumption plays a dominant role.

2.2. Input data and assumptions

The transport sector in the TIMES Latvia model consists of two blocks – passenger travel and freight transport. In this paper, passenger land travel has been analysed, excluding traffic by air and water. The road section studied includes road and rail transport as well as individual modes of mobility. Road transport consists of cars, buses, trains, trams and trolleybuses, while individual transport modes include walking and cycling (see Fig. 2).

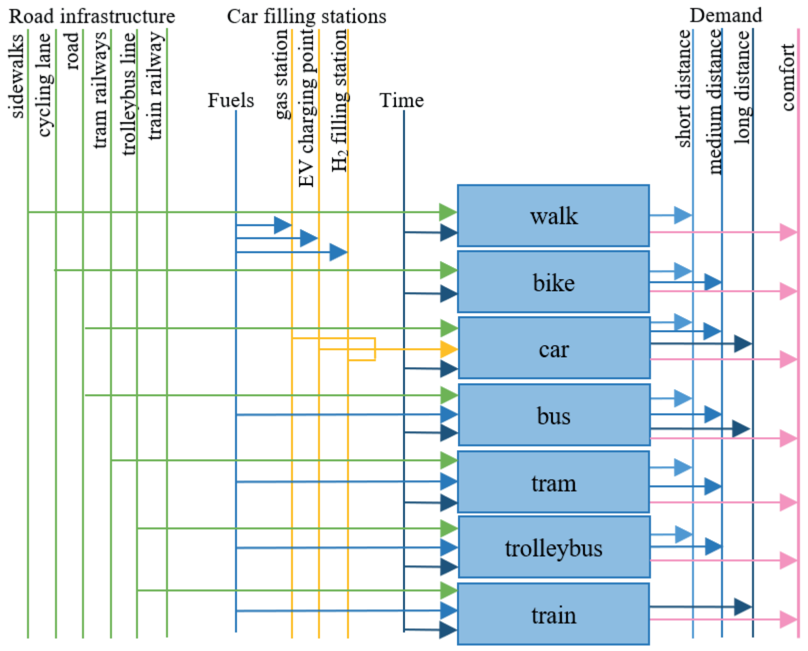

Fig. 2. Structure of passenger road transport in the model.

For more accurate modelling, the demand for three different distances has been included in the model – short distances (up to 5 km), average distances (5–25 km) and long distances (over 25 km). This modelling approach ensures that different transportation modes, which cover a certain distance, can compete with one another, e.g. in short distances walking, cycling, car, bus, tram and trolleybus may substitute for each other if the travel destination matches. In contrast, only cars, intercity buses and trains can be used for long distances. The model also includes road infrastructure and car filling stations that require the necessary infrastructure to increase specific types of transport, e.g. electric vehicles.

Considering both the forecast of the EU reference scenario [26] for the development of the transport sector and the estimates of the population, the travel demand is projected to increase slightly in each period from 2020 until 2050 (see Fig. 3). The total increase in demand for mobility is growing by 18 % in 2050 compared to 2017.

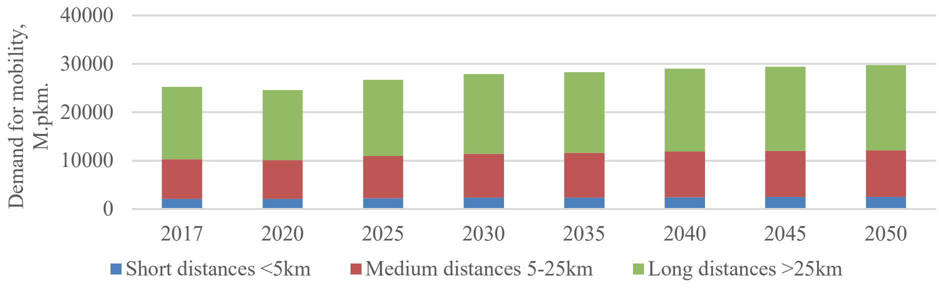

Fig. 3. Demand forecast for land passenger transport.

The length of the distances in the TIMES model was split up to account for the existing mobility patterns [27] for the base year. The limit values for the distances were set to include non-motorized modes of transport – bicycling and walking. Fig. 4 represents the assumed proportion of transportation modes used in each distance for the base year. These assumptions are based on a study conducted by Denmark [8] for modelling the transport sector, adapted to the situation in Latvia for the year 2017. Short distances of up to 5 km can be provided by all vehicles, except trains. Average distances from 5 to 25 km are provided by bicycle, tram, trolleybus, city bus and car, while long distances above 25 km are offered by car, intercity bus, and train. Considering that on average 47 km is travelled by train in the base year, and to simplify the model calculations, it is assumed that the train is used only for distances longer than 25 km, which includes the most popular routes in Latvia. The assumptions regarding the distribution of travelled distances are with high uncertainty due to lack of precise data and can be adjusted in future studies if more detailed national surveys on traveling habits of the Latvian population will be conducted.

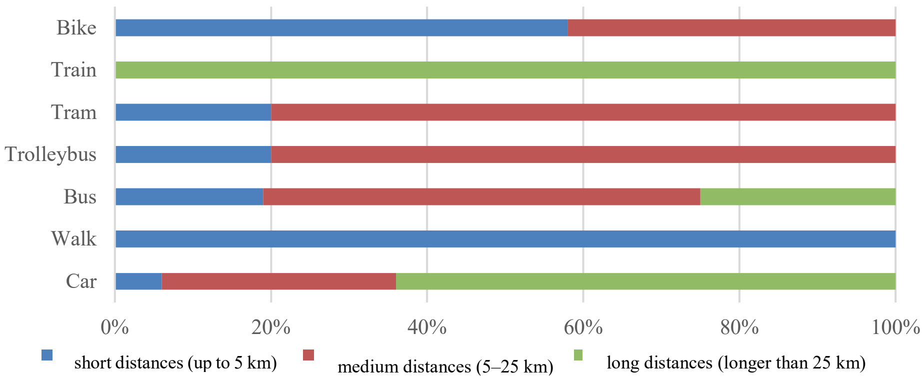

Fig. 4. Use of transport modes depending on the distance.

In addition, the level of comfort of different modes has been introduced in the model. As TIMES is an optimisation tool that looks for the most cost-effective system structure, comfort is an essential element that provides more accurate results by including human behaviour. Several experts assessed the comfort level for each vehicle type according to 7 factors – safety, noise level, ability to regulate indoor temperature, ability to travel with family, opportunities to socially distance, accessibility, and barrier-free environment. The availability factor characterizes the possibility of immediate use of the vehicle – whether it is available in all conditions (e.g. private car) or whether the vehicle timetable must be followed (for public transport). This parameter does not include the availability of infrastructure, such as cycle lanes, as this parameter is included separately (as road infrastructure) in the model. It was assumed that the highest comfort level is for passenger cars, significantly exceeding the comfort level of other modes of transport (see Fig. 5). This is not only because the car provides a more comfortable environment but also allows one to travel with family, distance oneself, regulate the indoor temperature, and, most importantly, is always available. The lowest rating is for walking, and the train because it is not so accessible in whole territory of Latvia due to lack of railway infrastructure, as well as it is challenging to get in with a wheelchair or baby carriage in the outdated trains.

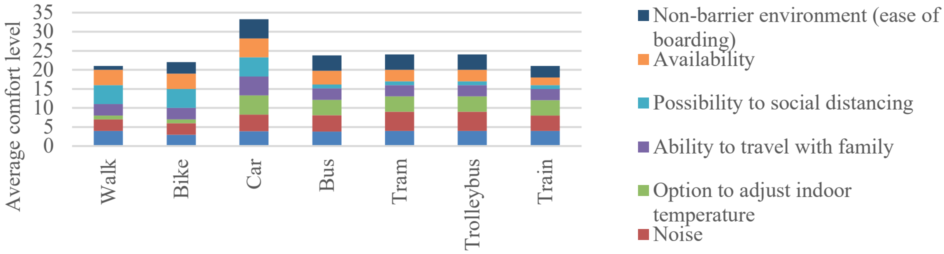

Fig. 5. Assessment of the level of comfort of types of transportation.

The model results are significantly influenced by resource prices, which, along with technology-specific data, determine the direction the sector will transform in future. The transport sector is currently dominated by fossil fuels such as diesel oil and gasoline. It is assumed that the prices of these energy resources will increase in the future based on historical trend (see Fig. 6). The study was conducted before the significant price increase in 2021. The model shows average price increase trend as it is believed that prices will stabilize at some point. A higher increase in the prices is used in the sensitivity analysis seen in Fig. 12.

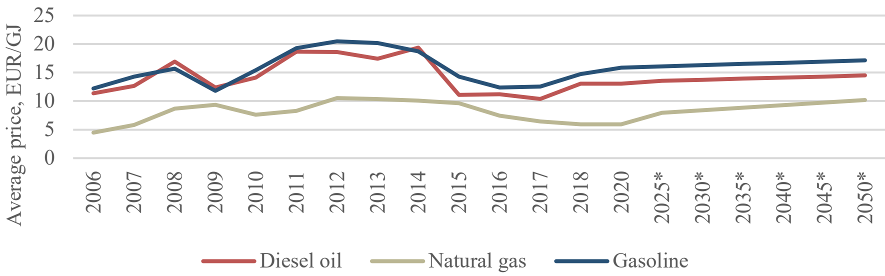

Fig. 6. Average prices of primary energy resources[28] used in the transport sector and forecasts.

The model incorporates current tax rates and rates that have been approved, such as a reduced rate for natural gas in the transport sector between 2021 and 2025 (see Table 1). The current CO_2 tax rate (15 EUR per ton) has been used for base analysis while increased CO_2 rates have been adopted for extended scenario analysis (see Section 1.3.).

TABLE 1. MAIN TAXES USED IN THE MODEL [29], [30].

Tax	Unit	Resource	Base year	2019	2020	2021	2022–2025	2026–2050
Excise	EUR/GJ	Diesel oil	10.5	10.5	11.7	11.7	11.7	11.7
		Gasoline	16.4	16.4	16.9	16.9	16.9	16.9
		LPG	5.4	5.4	6.3	6.3	6.3	6.3
		Natural gas	2.68	2.68	2.68	0.5	0.5	2.8
CO_2	EUR/t	CO_2	2.85	4.5	9	12	15	15

The transport sector also includes defined investment costs for different types of vehicles and a transport operation tax, which is different for new and used cars.

2.3. Scenarios

Three scenarios have been analysed to assess the projection of the transport sector till 2050 under different conditions:

1. Baseline scenario (BASE) is based on the start year of the model (2017) and includes the conditions currently in force, including tax policy (CO_2 tax, excise tax, natural resource tax on fossil fuels, vehicle operation tax) and funding for energy efficiency measures under the 2014-2020 programming period of EU funds [31]. This scenario shows existing resource allocation and transport modes used if the policy instruments, laws, and taxes remain the same.
2. National Energy and Climate Plan (NECP) scenario is based on the BASE scenario conditions and includes measures determined in Annex 4 of the National Energy and Climate Plan 2030 [32]. The main steps covering the transport sector support the construction of sidewalks and cycle lanes, promote the use of public transport, increase the number of electric trains, and subsidise alternative road transport development and the establishment of electric charging points.
3. GHG target scenario (GHG TARGET) includes the existing taxation policy and funding allocated as in the BASE scenario. It is a target optimisation scenario that requires all sectors to become climate neutral without setting specific GHG emission reductions for the transport sector. This scenario requires a GHG reduction level of about 70 % compared to 2017 based on the target set in the Strategy of Latvia for the Achievement of Climate Neutrality by 2050 [34].

Assumptions for a CO_2 tax increase in NECP and GHG target scenarios are set according to the description in [33].

2.4. Validation

Validation of the model is done by comparing modelling results and the actual resource consumption in the transport sector for the years 2018, 2019, and 2020 using data from the Central Statistical Bureau of Latvia (see Fig. 7). Total resource consumption in the transport sector differs slightly. For 2018 and 2019, modelling results show slightly lower consumption than identified in the statistics, but in 2020 modelled results are by 1 % higher compared to actual consumption.

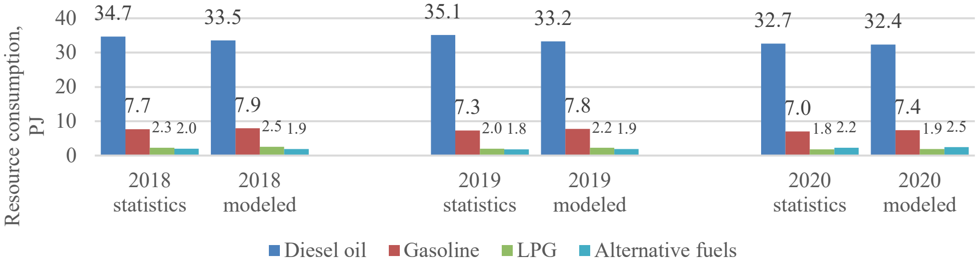

Fig. 7. Results of the BASE scenario and statistical data [25] of resource consumption in the transport sector for the years 2018, 2019 and 2020.

Modelling results show slightly lower (around 1–5 %) diesel oil consumption than actual primary resource consumption in the transport sector in 2018–2020, while gasoline consumption is about 3–6 % higher and LPG around 5-10 % higher than indicated in national statistics in the analysed period. Consumption of alternative fuels like natural gas, bioethanol, biodiesel, and power is 2 % higher in the statistics in 2018 while lower by around 3 to 10 % in 2019 and 2020 than in the modelled results. The difference between the modelling results and statistical data does not exceed 10 %, so the model describes the actual situation well.

3. Results and Discussion

The modelling is being done for the period until 2050. The climate neutrality goal is set in the GHG TARGET scenario while measures for the NECP scenario are implemented until 2030.

Modelling results show that total energy consumption in the BASE scenario for land passenger transportation will increase by 4 % while energy consumption decreases both in NECP (by 2 %) and in GHG TARGET (by 10 %) in 2030 compared to the base year level, which was around 23 PJ (see Fig. 8). In 2050, consumption decreases by 3 % in BASE, 14 % in NECP and 47 % in the GHG TARGET scenario, ensuring the same level of mobility (see Fig. 3).

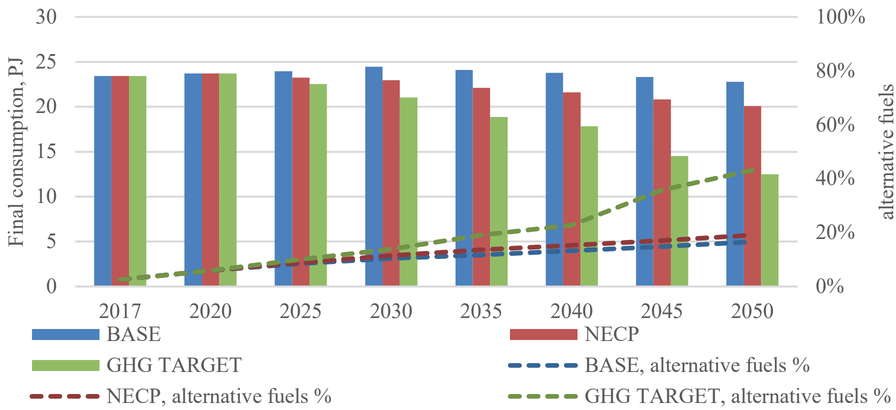

Fig. 8. Fuel consumption for land passenger transportation for alternative scenarios.

Usage of alternative fuels in 2030 increases from 3 % in the base year to 10 % in the BASE scenario, 11 % in NECP and 14 % in the GHG TARGET scenario. More significant growth in usage of alternative fuels is seen in 2050 – in the BASE at 17 %, in NECP at 19 % and GHG TARGET, 43 % of used energy is alternative – biodiesel, bioethanol, electricity, biomethane and hydrogen.

Fossil fuels are mainly used for passenger transport in the BASE scenario (see Fig. 9). Diesel oil is the primary fuel covering around 65 % of resources used in the base year, equal to 15 PJ (see Fig. 9). The results of the BASE scenario show that the importance of diesel oil will decrease but it will still cover more than 50 % of fuels used in 2050. Usage of gasoline decreases from 6 PJ in 2017 to 3 PJ in 2050 while usage of LPG remains steady, reaching around 2 PJ. Primary alternative fuels used for the transport sector are electricity (power, bioethanol and biodiesel). In 2050, biomethane is mostly used as an alternative fuel (covering around 35 % of alternative fuels), and about 25 % of alternative fuels are electricity.

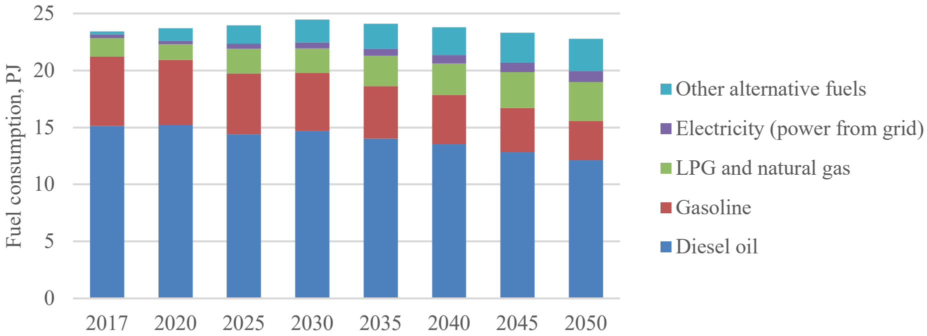

Fig. 9. Fuel consumption for land passenger transportation in the BASE scenario.

Also, in the NECP scenario, usage of diesel oil, albeit decreasing, remains the most critical fuel covering around 58 % in 2030 and 46 % in 2050 (see Fig. 10). Usage of gasoline, LPG, and natural gas decreases from 8PJ in 2017 to 7PJ in 2030 and 2050, equal to 35 % of the total fuel consumption. Alternative fuel consumption increases to 11 % in 2030 and 19 % in 2050, most of which are biomethane and electricity.

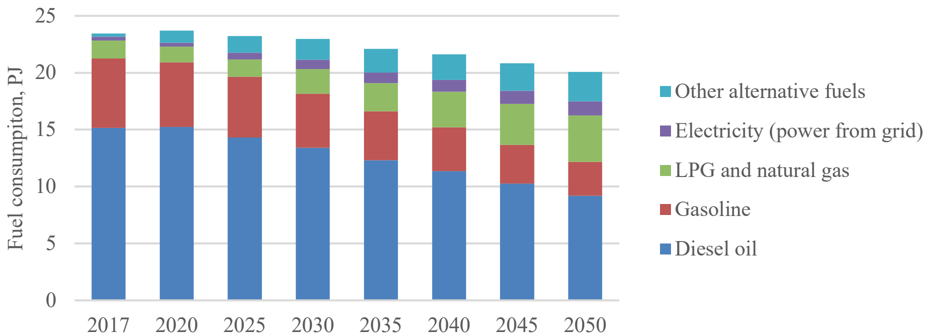

Fig. 10. Fuel consumption for land passenger transportation in NECP scenario.

The GHG TARGET scenario shows the highest reduction in resource consumption as this scenario requires achieving climate neutrality. The total amount of resources decreases from 23 PJ in the base year to 12 PJ in 2050 (see Fig. 11). Also, in this scenario, diesel oil is the most used fuel covering around 45 % in 2050. Gasoline, LPG, and natural gas usage decreased from 8PJ in 2017 to 2 PJ in 2050. 34 % of total resources used in 2050 is electricity and 9 % other alternative fuels, most of which are hydrogen.

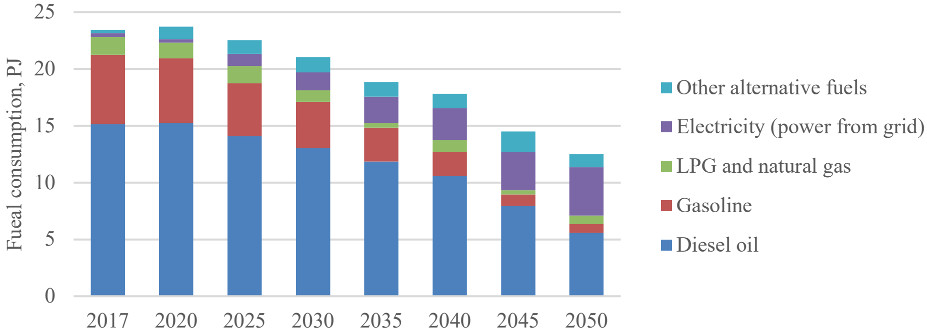

Fig. 11. Fuel consumption for land passenger transportation in GHG TARGET scenario.

The sensitivity analysis was done by increasing the prices of fossil fuels e.g. diesel oil, gasoline, LPG and natural gas for the NECP scenario. Starting from 2025 it is assumed that the prices for these resources will be two times higher than in the base year, followed by a 5 % increase each year until the end of the modelling period (scenario NECP+).

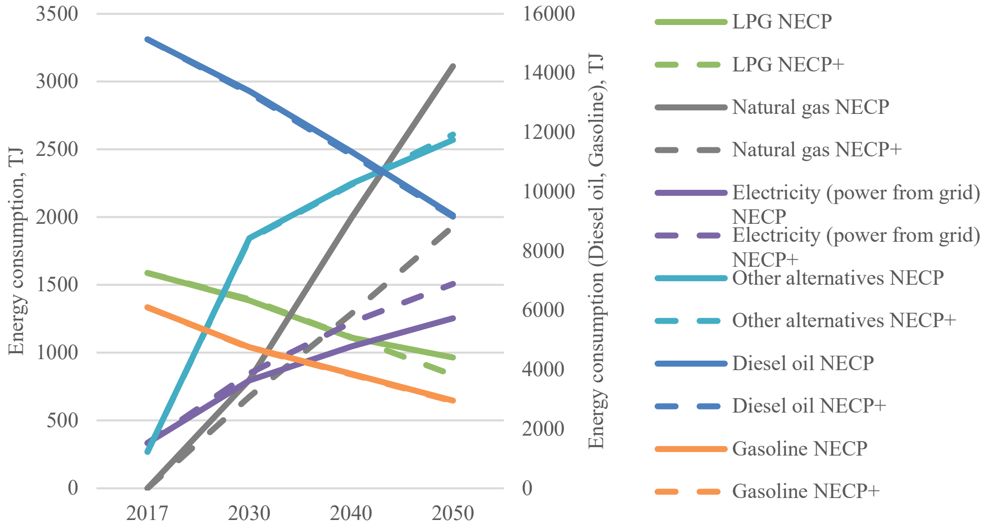

Fig.12. Results of sensitivity analysis – fuel consumption in NECP and NECP+.

The results show an insignificant reduction in diesel oil and gasoline consumption while consumption of LPG is 13 % less than in NECP and consumption of natural gas is even 38 % less in 2050. Consumption of fossil fuels is largely offset by higher electricity consumption, which increases by 20 %. Consumption of other alternative fuels e.g. biomethane has no change, biodiesel and bioethanol consumption decreases by 0.5 % while consumption of hydrogen increases by 16 % in 2050.

Mainly private cars are used for mobility in the base year, covering around 77 % of the total travel modes used (see Fig. 13). Only in the NECP scenario in 2025 the usage of private cars is slightly decreasing to 72 %, while private vehicles are used mainly in the BASE scenario until the end of the modelling period – covering around 63 % of travelling distances in 2050. Usage of public transport or walking and cycling is also increasing in the BASE scenario from 23 % in 2017 to 37 % in 2050. In the NECP scenario, public transport usage and walking and cycling are growing to 48 %, while in the GHG TARGET scenario to 58 %.

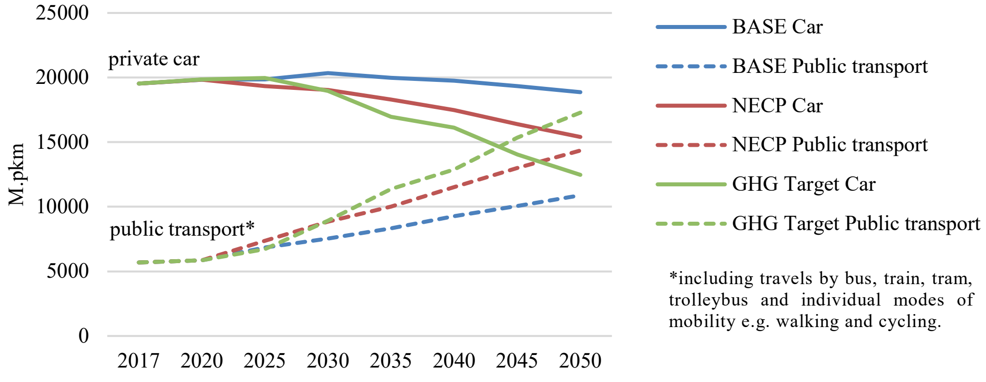

Fig. 13. Use of private cars and greener mobility for alternative scenarios

In the base year, 77 % of mobility is covered by private cars while 15 % by buses, 3 % by walking and cycling, 2 % by trolleybuses and trams and another 2 % by train (see Fig. 14). Usage of buses is increasing to 20 % in BASE, 23 % in NECP and 24 % in GHG TARGET in 2030. In 2050 the usage of buses is growing even more, covering 29 % in BASE and around 39 % in NECP and GHG TARGET scenarios. Walking and cycling, usage of trolleybuses, trams and trains are about 3 % in each scenario in 2050 except in TARGET GHG where usage of trolleybuses, trams and trains is increasing to around 16 % in total.

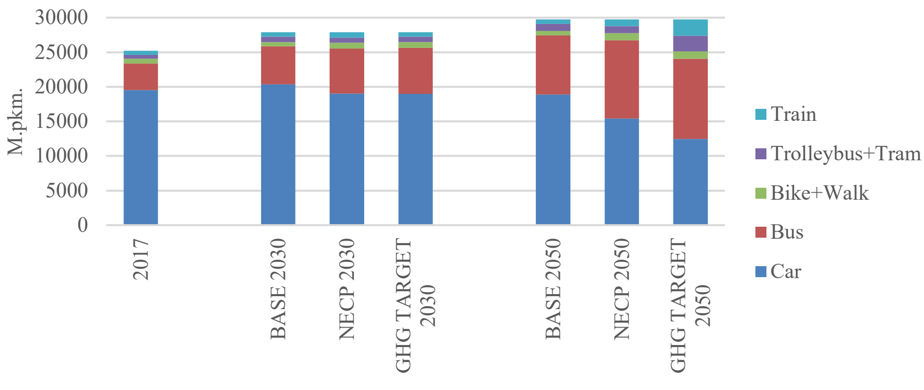

Fig. 14. Projection of the use of passenger transport modes for alternative scenarios.

Mainly private cars are used for mobility in short distances, i.e. up to 5 km covering around 41 % in the base year (see Fig. 15). Also, buses are used a lot covering 25 % of passenger travel, but walking and cycling provides 28 %. The usage of buses is increasing in all scenarios in 2030, ensuring around 37 % of mobility while about 50 % in 2050. Cycling and walking are becoming more popular in NECP and GHG TARGET scenarios covering approximately 27 % in 2030 and 29 % in 2050. In BASE, only 20 % of mobility will be done by individual modes of transport in 2050.

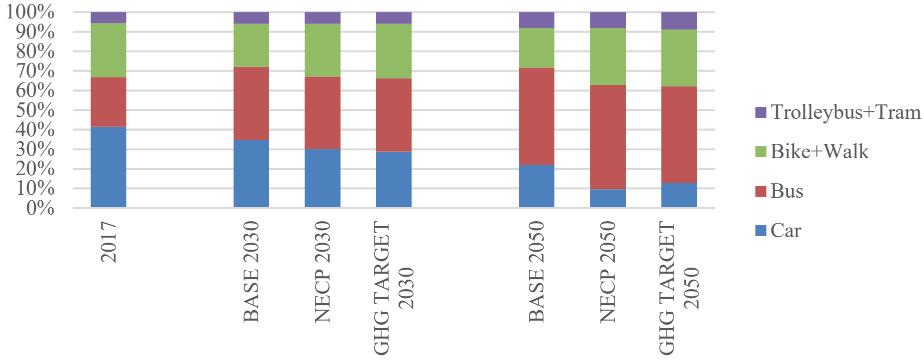

Fig. 15. Structure of modes of passenger transport for short distances.

63 % of mobility in medium distances from 5 to 25 km is done by cars in the base year (see Fig. 16). The proportion is decreasing in all scenarios in 2030, covering around 54 %. Still, an even more significant decrease is seen in 2050, where 43 % of mobility in BASE, 38 % in NECP and only 21 % in GHG TARGET scenarios is travelled by private cars. A significant increase is seen in the usage of buses in all scenarios in 2030, covering around 38 % of mobility and 47 % in BASE, 51 % in NECP and 55 % in GHG TARGET scenarios in 2050. Also, there is notable increase in traveling by trolleybuses and trams in the GHG TARGET scenario in 2050, reaching around 20 % of the total mobility. The TIMES optimisation model has chosen these types of travel as the most economically beneficial by considering the fuel and vehicle costs, implemented restrictions on infrastructure and comfort levels.

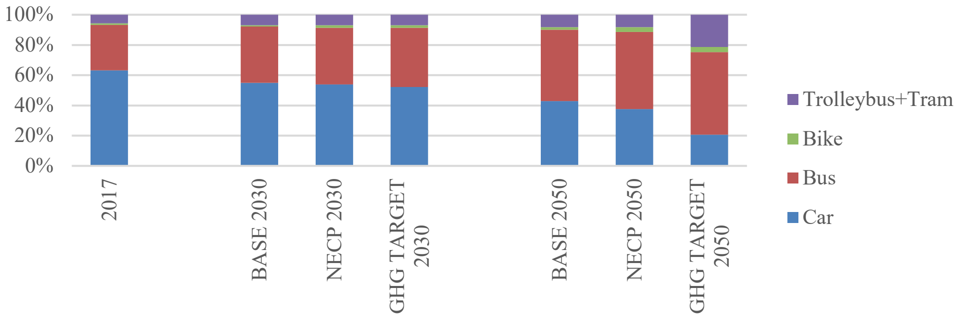

Fig. 16. Structure of modes of passenger transport for medium distances.

Three modes of transportation are being analysed for more than 25 km long distances. Private cars cover around 90 % of mobility in long distances in the base year (see Fig. 17), and only 6 % is travelled by bus and 4 % by train. Although the usage of private cars is decreasing, it covers most of the mobility for long distances for all scenarios – 88 % in BASE and 82 % in NECP and GHG TARGET in 2030, and 81 % in BASE, 66 % in NECP and 58 % in GHG TARGET in 2050. Usage of buses is increasing in NECP and GHG scenarios reaching around 14 % in 2030 and 29 % in 2050 of total mobility. Also, the use of trains is growing in the NECP scenario to 6 % in 2050 and in the GHG TARGET scenario to 13 % due to the development of public transport.

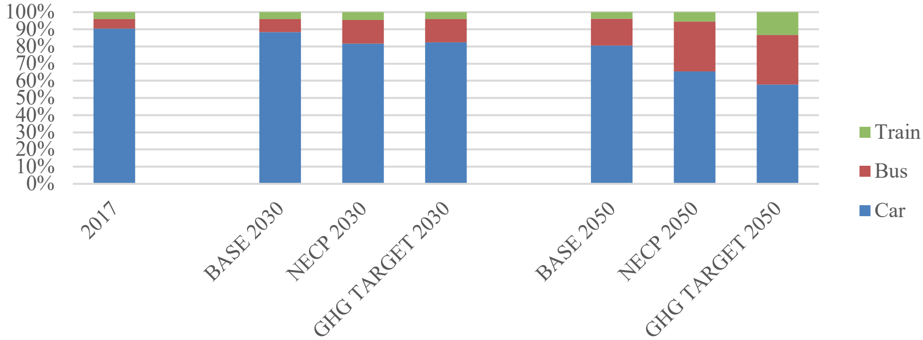

Fig. 17. Structure of modes of passenger transport for long distances.

In all three scenarios and all distances, the amount of projected GHG emissions is decreasing (see Fig. 18). In the BASE scenario, the total GHG emissions will be reduced by 2 % in 2030 and by 14 % in 2050, in NECP by 10 % and 27 %, and in GHG TARGET by 19 % and 69 % for the same period.

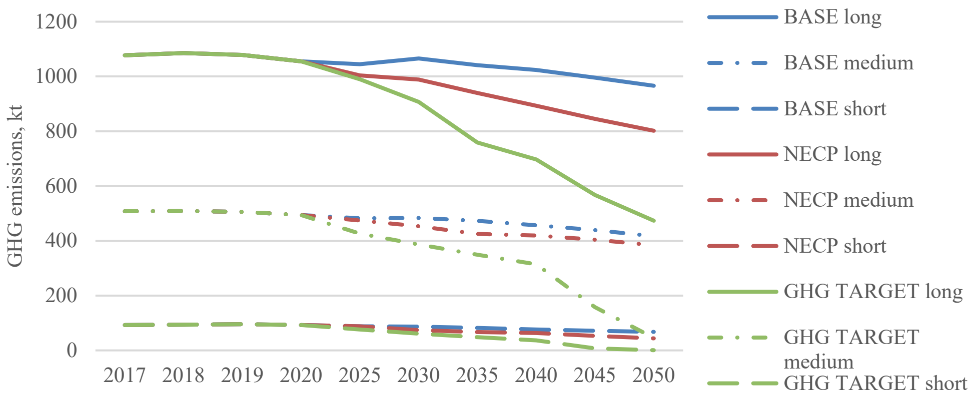

Fig. 18. Projection of GHG emissions by distances.

Most of the emissions are released due to travelling long distances. Although the amount of GHG emissions is decreasing considerably – from around 1100 kt in the BASE year to 800 kt in NECP, and 470 kt in GHG TARGET, the proportion of the decrease is lower than in other distances. Only a 10 % decrease is reached in BASE, 26 % in NECP and 56 % in GHG TARGET in 2050.

GHG emissions in medium distances are decreasing by 18 % in BASE, 24 % in NECP and 91 % in GHG TARGET in 2050 compared to the base year. While GHG emissions in short distances are decreasing by 27 % in BASE, 52 % in NECP and 99 % in GHG TARGET scenarios in 2050.

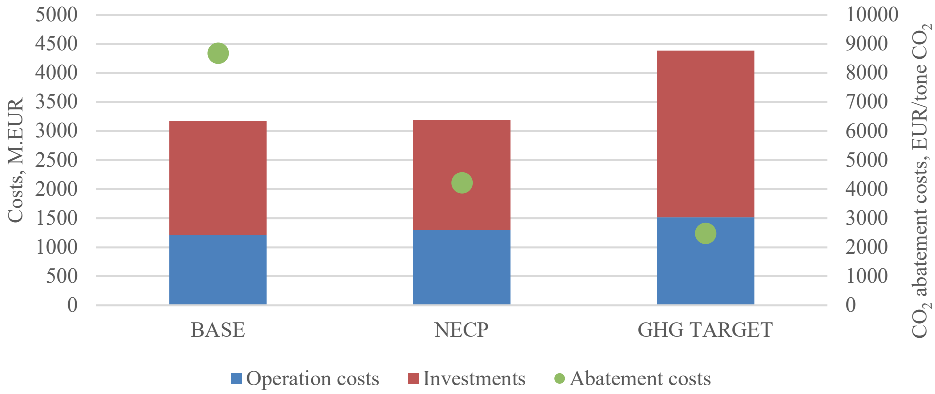

Fig. 19. Projection of costs in each scenario.

Modelling results show that transport decarbonisation in the GHG scenario requires around 2868 MEUR, 38 % more than in the BASE scenario. However, the CO_2 abatement costs for GHG emission reduction are lower in this scenario as the TIMES model optimises the system to reach the lowest GHG emission reduction costs.

4. Conclusions

The TIME's modelling tool is used to assess the passenger transport development until 2050 by analysing three scenarios – BASE scenario, which includes the existing strategies, taxation policy and measures, NECP scenario, which includes measures defined in the National Energy and Climate Plan until 2030, and GHG TARGET scenario, which aims to achieve climate neutrality by 2050.

The base year's final energy consumption for land passenger transportation was 23 PJ. Results show that the level of the final energy consumption is decreasing in all scenarios – by 3 % in BASE, 14 % in NECP and 47 % in GHG TARGET in 2050. Mainly private cars are used for mobility in the base year, covering around 77 % of travel modes. Usage of public transport or walking and cycling is increasing in all scenarios by 2050 – in the BASE scenario from 23 % in 2017 to 37 % in 2050, in NECP to 48 % while in the GHG TARGET scenario to 58 % for the same period.

Mainly private cars are used for mobility in all distances in the base year – covering around 41 % in short lengths, 63 % in medium and 90 % in long distances. Although the usage of private cars is decreasing in all distances and for all scenarios by the year 2050, it still covers most of the mobility, especially for long distances where the highest reduction is seen in GHG TARGET.

Usage of buses is increasing in all scenarios ensuring around 29 %–55 % of mobility by 2050 depending on the distance. Cycling and walking become more popular in the NECP and GHG TARGET scenarios for short distances. In contrast, in medium distances, notable increases are seen for travelling by trolleybus and tram in the case of the GHG TARGET scenario.

Diesel oil is the main fuel used for passenger transport covering around 65 % of resources used in the base year. The importance of the diesel oil will decrease but it will still cover more than 50 % of the fuels used in 2050 in BASE, 46 % in NECP and 45 % in GHG

TARGET. A similar trend can be seen for other fossil resources – gasoline and LPG. The most significant reduction in consumption is achieved in the GHG TARGET scenario.

Primary alternative fuels used for the transport sector are electricity, bioethanol, and biodiesel. Mostly natural gas, biomethane and electricity are used in BASE and NECP scenarios in 2050, while electricity, hydrogen, natural gas and biomethane are used in GHG TARGET. As this paper focuses on the possible achievements of promoting the modal shift in the transport sector, the restrictions, and perspectives on the future development of alternative fuels are not presented and analysed in detail. However, future studies could include analyses on the impact of broader policies for biomethane development if the legislative framework is changed. For example, blending restrictions and delivery through natural gas infrastructure or obligations for biogas production from organic waste could increase the share of biomethane used as a transport fuel. Also, the development of modern biofuels should be promoted in future, but the clear support policies are not yet in place.

In all three scenarios and all distances, the amount of projected GHG emissions is decreasing during the considered period. In the BASE scenario, the total GHG emissions are reduced by 14 %, in the NECP scenario by 27 %, and in the GHG TARGET scenario by 69 % in 2050.

Although measures defined in NECP2030 promote greener mobility until 2030 and promote the use of renewable energy, it is necessary to set new measures and activities for the period beyond 2030. The transport sector is difficult to decarbonise as it depends on human behaviour as well as available alternatives and immediate action is needed to reach climate neutrality by 2050. Even though the model shows that it is reasonable and economically justified to shift from the use of private cars to public transport with the integrated restrictions and defined comfort levels, the achieved decrease of private cars would probably not be so high. Long-term policies and efforts for infrastructure development are necessary to change the travel habits (for example, development of "Rail Baltic" project which is not yet considered in this publication) but still, uncertainty remains if the inhabitants would be ready to decrease the use of private cars.

Acknowledgement

This work has been supported by the Ministry of Economics of the Republic of Latvia, the project "Energy and climate modelling towards net zero emissions", project No. VPP-EM-2018/NEKP-0001.

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COST-OPTIMAL POLICY STRATEGIES FOR REACHING ENERGY EFFICIENCY TARGETS AND CARBON NEUTRALITY

Cost-Optimal Policy Strategies for Reaching Energy Efficiency Targets and Carbon Neutrality

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Received 11.04.2023; accepted 13.11.2023

Abstract – **The TIMES Latvia optimization model was developed to evaluate cost-effective pathways for reaching energy efficiency targets in 2030 and carbon neutrality in the Latvian economy by 2050. The model includes both the end-use sectors such as transport, buildings, industry and agriculture and the energy sector, with a well-developed database of existing and future RES and storage technologies. The modelling framework allows to identify the cost-optimal future energy mix by considering the electrification potential of each sector. Therefore, it allows the analysing of the impact of different policy strategies on sectoral integration levels and the necessity for additional energy storage capacities. The results show that one of the optimal solutions for reaching the energy efficiency targets in 2030 is the wide expansion of heat pump utilization merged with ambitious building renovation policy to increase energy efficiency. The building heat supply transformation also brings higher power consumption and interacts with the wider utilization of wind power. Alternative pathway could rely on increased solar power installation for self-consumption coverage which shows lower costs than building energy efficiency increase.**

Keywords – **Carbon neutral energy generation; energy storage; renewable energy sources, REPowerEU targets; sectoral integration.**

1. INTRODUCTION

The main goals of the European Union (EU) Green Deal are to reduce greenhouse gas (GHG) emissions by 55 % by 2030, compared to 1990 and to reach climate neutrality by 2050 [1]. Previous Research on EU Green Deal targets spans various aspects, including the efficiency of effort-sharing regulation and overall binding policy [2], fairness and ambition levels [3] and how these targets mark a shift towards a more technology-neutral EU climate policy [4], [5]. Research shows that there is a need for a governance framework to ensure that Member States contribute to the EU-level target [6], [7]. Implementation of climate actions and reaching the set EU targets have important impacts on the overall energy system operation [8], [9], environment [10], and economics [11] as well as on the specific subsectors [12]–[14] which need to be considered.

To comply with EU climate ambitions, researchers have been testing different policies and scenarios to develop guidelines for policymakers and search for cost-effective renewable energy solutions [15]. The report of OECD [16] reports that even though there is a high

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renewable energy share achieved in Latvia a long way towards more sustainable use of available resources is ahead. Also, Dolge & Blumberga [17] confirm that the existing climate policies are not enough to reach the Green Deal targets in Latvia.

In a study carried out in 2016 a scenario achieving 100 % renewable energy share in the EU by 2050 was introduced [18] by showing that smart energy systems can be leveraged to achieve 100 % renewable energy share. The introduced scenario includes the decommissioning of nuclear power plants, energy efficiency measures in buildings, electrification of private transportation, use of heat pumps in rural areas and district heating in urban areas and switching from natural gas to bio-methane. Trought this research it has been proved that the use of biomass for energy production, which is not the most sustainable solution, is not a key pillar of renewable transition by the EU as shown in previous research [19]. Also, for Latvia, decarbonization is possible with limited use of biomass [20]. Previous studies concluded that in Latvia there is a high potential for RES integration and that targeted policies can reduce CO_2 emissions by 70 % in 2050 [21]. Moreover, implementing effective policies toward bioeconomy makes it possible to utilize locally available low-quality bioresources for the production of higher-added value products [22].

However, making changes in the energy sector comes with its set of challenges. One significant challenge is the need to balance the supply and demand of energy, which becomes more complicated with the increasing use of intermittent renewable energy sources [23]. To address this issue, experts have proposed several solutions [24], e.g. implementing effective energy storage systems [25] or demand-side management measures [26]. Another solution focuses on strengthening international power transmission networks, allowing for the import and export of electricity across borders. Research conducted in Denmark aimed to understand the relationship between wind energy and the patterns of electricity import and export [27]. The research suggested that the optimal approach is to facilitate the import and export of electricity between regions with high hydropower generation and regions with wind and thermal electricity plants. However, it is essential to recognize that relying solely on electricity import and export can introduce security concerns.

Detailed modelling tools are necessary to evaluate the long-term impact of complex energy system transformation scenarios. One such is The Integrated MARKAL-EFOM System (TIMES) linear optimization tool which has been widely used to simulate the long-term effects of future transformation pathways of energy systems [28]–[30]. There are many aspects that influence the optimal solution for the integration of renewable energy into the energy system, although these may involve trade-offs, competition for the same resource, and complex interdependencies, such as electrification of all sectors of the region and cross-border transmission of electricity [31]. It has been found that the electrification of different sectors and the uptake of technologies within a system-integration framework, such as electric vehicles, power-to-gas, and energy storage, can successfully smooth out the variability of renewable energy [32]. Moreover, when using modelling tools, such as TIMES, user input data, such as prices and technical potential for renewable energies, has a major impact on the modelling results; therefore, it is crucial to make modelling tools transparent and make all the input data available to the public, as most of the input data is an assumption and should be further improved by scientific debate [18], [33]

When it comes to the transport sector, changes in technology and fuel switching are not enough to mitigate climate change, policies must focus on behavioural change in the use of transportation [34]. Typically, the TIMES model as an optimization tool does not include competition between different travel modes, but with the introduction of elements such as travel time budget, travel speed, comfort, etc. it can be applied for broader policy modelling [35], [36].

Recently, the European Commission has presented the new REPowerEU Plan in response to Russia's invasion of Ukraine tightening the energy efficiency and renewable energy targets even more. Therefore, this research presents the analysis of a possible decarbonization policy pathway for Latvia, as a case study to reach the set ambitious REPowerEU efficiency targets for 2030 and climate neutrality in 2050, by combining different support measures and limitations across all sectors. The TIMES optimization model is used to perform self-optimization scenarios and indicate the most cost-effective technologies and processes which should be strengthened. The policy package has been tested under different conditions by showing the role of increased local RES installations for power generation. The research has been conducted in cooperation with policymakers to provide an initial scenario for decarbonisation based on a cost-effective integrated energy system.

2. METHODOLOGY

The previously built TIMES Latvia model is a linear optimization tool developed and improved to characterize the energy sector and relevant sub-sectors [28], [29], [37]. In the TIMES Latvia energy system model, the full energy system is represented, from resource supply to end-use energy service demands, such as space heating, production processes, and personal/freight transport (in passenger or tonne-kilometre) [33]. The model represents a broad suite of energy and emission commodities, technologies, and infrastructure. However, the model does not include detailed analyses and forecasts for non-energy sectors, e.g. agriculture and waste management.

The modelling process analyses each sector separately, making improvements in each of them, bringing the model closer to the real-life situation to obtain more complete results and incorporate different policy measures, such as sector-specific funding, taxation, GHG target, etc. The reference energy system describes the structure and energy flows of the energy system of Latvia covering primary energy resources, conversion technologies (e.g. electricity and heat production technologies) transmission and distribution infrastructure (e.g. electricity grid, heating networks or gas pipeline), end-use technologies (e.g. boilers, heat pumps, cars) and energy service demands. Certain limitations on available energy sources have been derived as input parameters from the soft-linked forestry management model and the agriculture model used in previous studies [20].

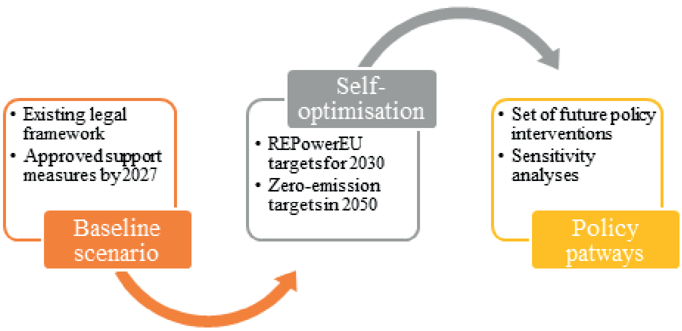


Fig. 1. Main steps for policy pathway definition.

In this study, the TIMES Latvia energy system model was used to investigate various scenarios aimed at achieving Latvia's energy efficiency targets by 2030 and nearing carbon neutrality by 2050 (see Section 2.2). The model's self-optimization run was employed to determine priority sectors and processes for intervention. Subsequently, a range of policies were identified and tested based on the model's self-optimization results to assess their potential effectiveness as interventions and try to achieve the path identified by the optimization run as the most cost-efficient. The modelling approach can be seen in Fig. 1.

2.1. Definition of Baseline Trends

The baseline scenario (also called Without Additional Measures, WEM) in the TIMES Latvia energy system model represents the development of the current energy sector under existing trends without additional support or promotion of future technologies. It is assumed that only existing/in-place energy and climate policies will be included. Throughout the projected period, Latvia undergoes strong GDP growth (around 3.2 % for the 2020–2050 period) based on the projections of the Ministry of Economics of Latvia [38].

The WEM scenario includes the approved support for energy efficiency measures and RES implementation allocated in the upcoming planning period until 2027. The policies have been identified through direct communication with the responsible Ministries and analyses of legal documents. To include these policies in the TIMES model, it is assumed that the specific costs of measures will be like those of already implemented project [39].

The summary of the approved grant programs which will partly cover the necessary investment and building costs is shown in Table 1. From 2022, support is available for apartment and single-family building renovation as a grant to partly cover the building costs. This is planned to increase energy efficiency in 13 450 buildings. Support is also available for enterprises and industries for investment costs of equipment with increased energy efficiency and installation of RES. The expected primary energy savings due to these policies are 19.97 GWh per year, and these will also support 90 MW of new RES capacities. There will also be support available for energy efficiency improvements in public buildings, and it is expected that the grant will promote the renovation of 522 313 m^2 of public buildings. From 2023, support is available to power producers, municipalities, and energy communities for RES power installation, and this is expected to lead to the installation of 13 MW of new RES capacity. In addition, support in the form of subsidies will be available for biogas treatment, and the development of biomethane transportation infrastructure. This is expected to lead to an increase of 16 MW of biomethane production capacity.

The WEM scenario includes fossil tax rates approved by 2022 which are assumed to remain constant in the modelling period until 2050 [20]. Excise tax reductions are applied for diesel fuel used in the agriculture sector, and for biodiesel and natural gas used in industrial processes. In addition, natural resource taxes are applied for the use of coal (21.3 EUR/t). The natural resources tax does not apply to the household sector.

Within the TIMES Latvia model, the energy consumers are divided into those enrolled in the Emission trading system (ETS) and those who are not, due to different fiscal policies. According to existing legislation in Latvia, polluting activities included in the EU-ETS for which a GHG emission permit is necessary are those with a total rated thermal capacity exceeding 20 MW and/or several specific industrial processes. For the emissions accounted into the ETS system, CO_2 quota prices are attributed. For emissions in the ETS sector, costs are increasing from 25 EUR/tCO_2 in 2025 to 260 EUR/t by 2050.

For the transport sector, registration tax and operation taxes associated with CO_2 emissions have been included in the WEM policies. The tax rates have gradually changed in the period from 2017 to 2021, but further changes are not foreseen until 2050 in the WEM scenario. It should be noted that electric and hydrogen-fuelled vehicles are excluded from taxation.

The projections on fossil fuel resource prices have been derived from the European Union Reference Scenario 2020 which uses projections of international fossil fuel prices produced by the global model POLES-JRC and included in the Global Energy and Climate Outlook report [39]. Following historical trends, increased price projections have also been assumed for bioresources.

TABLE 1. SUMMARY OF APPROVED SUBSIDY POLICIES IN THE UPCOMING PLANNING PERIOD UNTIL 2027

Sector	Supported activities	Implementation year	Amount of subsidy, EUR
Residential	Increase the energy efficiency of apartment buildings	2024	229.63
	Increase the energy efficiency of private buildings and RES	2022	5.64
Industrial	Increase energy efficiency and implement RES	2024	166.38
Commercial/ Public	Increase energy efficiency and implement RES in governmental buildings	2024	176.21
	Increase energy efficiency and implement RES in municipal buildings	2024	29.30
Power	Support for solar RES power	2024	23.49
Transport	Support for private electric vehicles	2022	10.0
	Support for electric buses	2025	10.0
	Support for zero-emission vehicles (public transport)	2027	24.39
	Support for EV charging infrastructure for duty vehicles	2025	35.0
	Support for electric railway infrastructure	2026	74.0
Agriculture	Support for biomethane production	2024	21.75

2.2. Model Self -Optimization

In a self-optimization run (OPT scenario), the model chooses the cheapest energy mix that meets the constraints imposed, based on the technology costs and energy prices included as part of the assumptions. The additional constraints included (besides the technical and baseline constraints) are REPowerEU energy efficiency targets for 2030 and 2050 target for CO_2e emissions – set as a 90 % reduction from baseline to reach EU Green Deal ambitions.

The REPowerEU targets set certain values for primary energy consumption (PEC) and final energy consumption (FEC) (see Table 2). PEC measures total domestic energy demand, while FEC refers to what end users consume. The difference relates mainly to what the energy sector needs itself and to transformation and distribution losses. For combustible fuels (fossil and renewable fuels) the PEC is calculated as the heat value generated during fuel combustion. For non-combustible energies (hydro, wind, solar and others) the primary energy is defined as the first flow in the production process with a practical energy use (heat or electricity). FEC is calculated through a bottom-up approach – aggregation of consumption in various sectors of consumption (industry, transport, residential, commercial and others). A hard limit of GHG, PEC and FEC was introduced to the model through the scenario file. Those limits are set to match the necessary targets. In this way the model still needs to meet the set demand in the model, but with imposed limits.

TABLE 2. PRIMARY AND FINAL CONSUMPTION TARGETS

	Actual value	**REPowerEU target**
	2020	2030
Primary energy consumption, PJ	179	152
Final energy consumption, PJ	161	135

This paper examines two optimization pathways to achieve the 2030 energy efficiency targets. In the first scenario (OPT_solar), distributed onsite generation is prioritized and locally produced electricity from solar power is used for self-consumption. Higher installed photovoltaic (PV) capacities could facilitate the attainment of energy efficiency targets due to PEC and FEC calculation methods when the solar power generated and directly consumed in end-use sectors is not accounted for. In contrast, the second optimization scenario (OPT_EE) includes the solar power generated and directly consumed in the calculation of FEC. This approach emphasizes the importance of EE measures on the consumer side. To obtain these two scenarios, changes in the counting of FEC are done by removing/adding the unnecessary dummy outputs within the TIMES Latvia model.

2.3. Policy Modelling

Table 3 provides an overview of the main policies per sector included in the modelling analysis described as a scenario with additional measures (WAM) based on the self-optimisation run. The table also provides some key details on how they have been modelled.

The policy package includes support in the form of investment subsidies for residential (RSD) and commercial (COM) building renovations. Support is dedicated to the heat pump installation in RSD buildings, as this is a promising option to decrease the FEC compared to existing non-efficient biomass heating in this sector. A wide range of policies are aimed at the upgrade of the transport fleet towards electric transport.

Several regulatory measures are included as potential policy pathways. Those include higher energy efficiency standards for building insulation and limits for non-efficient technology use. Non-emission zones in urban areas have also been modelled through an increased public transport load factor and availability, as well as an increased comfort factor for cycling, walking and EV.

Additional policy tools include the revisions of the RES planning process, with reduced implementation times for wind stations and other RES power technologies. The support for research could reduce biofuel prices and fixed costs for hydrogen production. It has been assumed that landfill gas availability could increase due to higher biological waste sorting standards.

TABLE 3. COMPARATIVE TABLE OF POLICIES/MEASURES

Policy area and type	**Modelling approach and assumptions**	
Subsidies		
EE in buildings	Private buildings Government and municipal buildings	65 % of renovation costs are subsidised from 2024.
EE in industrial processes	Industrial processes with high EE or that rely on RES other than biomass	Finances 50 % up to a yearly ceiling of €14.4 million from 2027 to 2030, and €7.2 million from 2031 to 2050.
Renewable heat	Heat pumps in RSD and COM sectors	Finances 50 % of investments from 2025 and 2050.

Electric vehicles and charging	New electric buses	100 % subsidised, with a ceiling for total subsidies offered of €3 million/year from 2025 to 2030, and €5 million/year from 2031 to 2050.
Public transport	Zero-emission public transport	100 % subsidised, with a ceiling for total subsidies offered of €5 million/year from 2025 to 2050.
	Electric trains	100 % subsidised, with a ceiling for total subsidies offered of €5 million/year from 2025 to 2050.
Alternative fuels	Biomethane production	50 % subsidised with a ceiling for total subsidies offered of €10 million/year from 2028 to 2030 and €5 million/year from 2031 to 2050.
Regulation		
Buildings	Increased EE standards for new housing and commercial buildings	Decreased energy use per square meter from 2027
	Ban on low-efficiency appliances for residential and commercial buildings	Ventilation, cooling, lighting, and electric appliances processes with the lowest energy efficiency rating not available from 2027
Transport	Zero and low-emission zones from 2024	Increased public transport load factor; Increased availability and comfort factor for cycling and walking Increased EV comfort factor from 2024
	ICE vehicle sales phase-out	No new installations are allowed from 2035
	Increased blend share for biofuels	Increased blend shares to 15 % for biodiesel and 10 % for bioethanol from 2025
Programmes		
Transport	Rapid electrification of urban services and government fleets	5 % of light commercial trucks in urban areas electrified after 2027
	Promotion of shorter distances and non-motorised transport	ICE buses on short-distance trips are not allowed from 2027
Energy generation	Planning process reform	Decreased RES project development time from 2024
Research	Biogas and biomass: improving organic waste management	Biogas (landfill gas) availability increase by 20 % from 2025
	Extend research, including specific research on alternative fuels	Reduced biofuel prices and reduced fixed costs for hydrogen from 2025

3. Results and Discussion

The section presents the results of several TIMES model runs including the Baseline simulation (WEM), self-optimization (OPT_Solar and OPT_EE) and policy pathway (WAM).

3.1. Optimisation Pathways

Optimisation scenarios are designed to reach the REPowerEU FEC and PEC targets in 2030 but as TIMES does not include an annual limit to technology deployment, it switches technology for the target in the last available years. Fig. 2 shows the PEC and FEC results of the Reference scenario (WEM) in comparison with two different optimization pathways. It can be seen that the WEM scenario with existing policies is far from the 2030 targets.

Fig. 3 shows the comparison of PEC in optimization and WEM scenarios. By 2030, wind and hydropower are expected to contribute significantly to the overall electricity supply. Like the baseline scenario, hydroelectric power production is expected to remain constant at 10 PJ/year. Biomass, on the other hand, is projected to make only a marginal contribution after 2040.

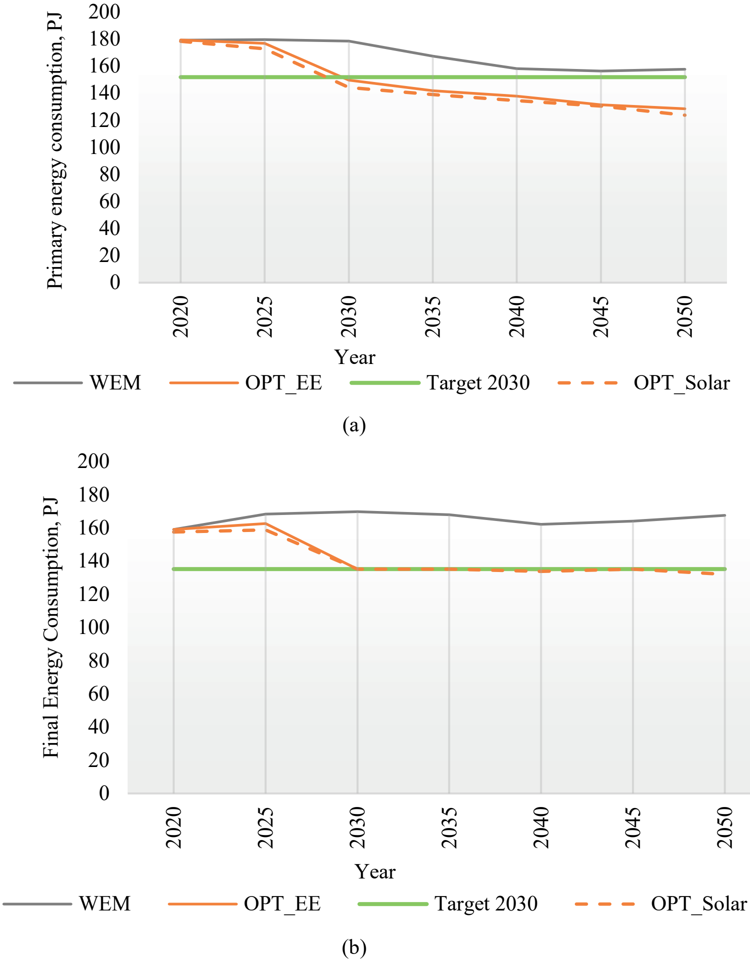


Fig. 2. a) PEC and b) FEC results in self-optimization run.

Both OPT scenarios demonstrate an increasing utilization of wind power for electricity generation (as shown in Fig. 4). However, the OPT_Solar scenario reaches higher overall solar energy production rates, because local RES for self-consumption is considered as an EE measure and therefore, FEC and PEC targets can be achieved with fewer consumption reduction measures. The model tends to install more solar PV panels for self-consumption coverage instead. In the OPT_EE scenario, the most significant reduction in energy consumption within buildings results from an increase in EE due to improved insulation, which leads to a decrease in heat loss.

In both optimisation pathways, the total energy production by the power sector is projected to exhibit a variable trend until 2030, after which a substantial increase in wind capacity is anticipated (see Fig. 4). Following this, electricity generation is projected to steadily rise until 2050. Due to the availability of low-cost wind power, both optimisation scenarios, as well as the WEM scenario, substantially increase the use of large heat pump (HP) technology in district heating systems (see Fig. 4).

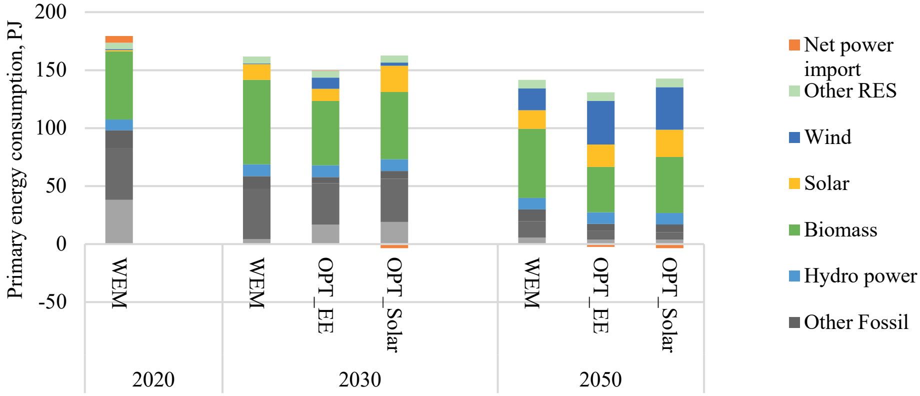
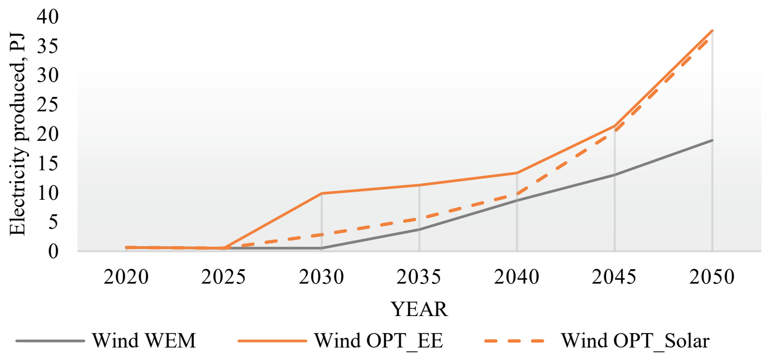
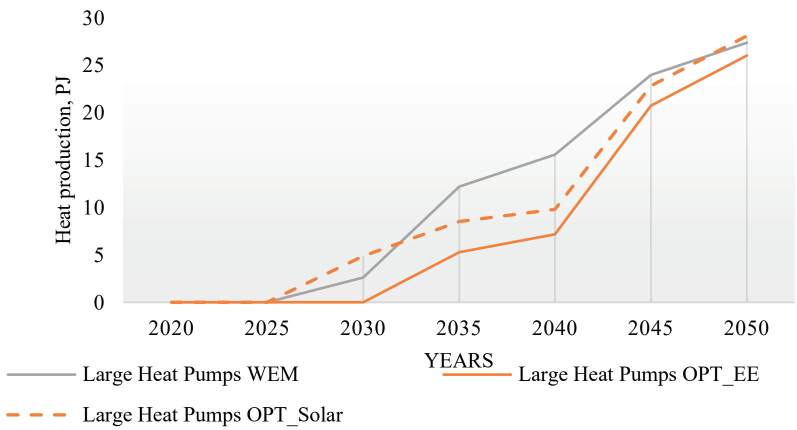


Fig. 3. Primary energy mix comparison in different optimization scenarios.



(a)



(b)

Fig. 4. Comparison of: a) wind production rates and b) heat production with large, centralised heat pumps (b) in different optimisation pathways.

Moreover, in scenario OPT_EE, renovated and new buildings reached 60 % of the building stock by the year 2030 and 80 % of the building stock by the year 2050 (expressed as total habitable area, including commercial spaces like offices and stores, see Fig.5.) to reach the set FEC and PEC targets. However, in scenario OPT_Solar renovated and new building stock reach only 30 % and 40 % by the years 2030 and 2050 respectively.

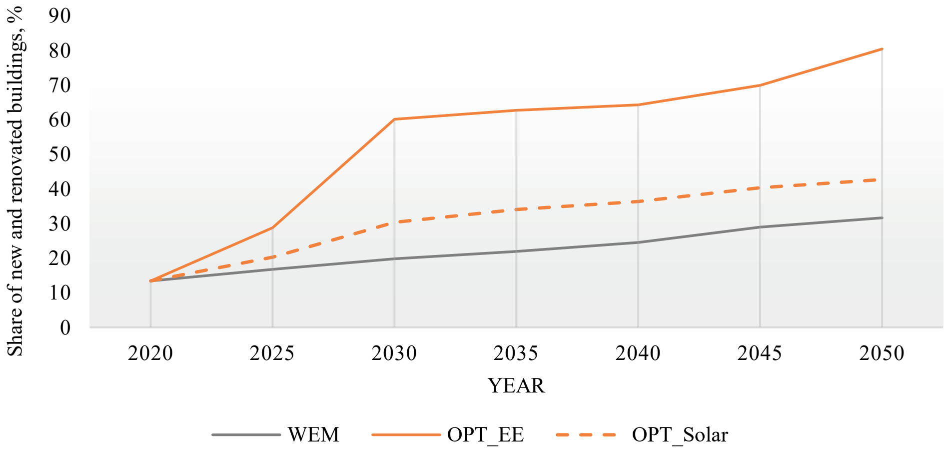


Fig. 5. New and renovated buildings by m^2.

3.2. Policy Analyses Scenario

The headline results of the self-optimisation run were used to understand which sectors, fuels and technologies should by targeted by policies and measures in the bottom-up approach. The WAM scenario run with integrated policies (See Section 2.3) shows a decreasing trend of PEC over time, going from 178 PJ in 2020 to 161 PJ in 2050 (see Fig. 4). In the long term, renewables, and in particular bioenergy, will provide most of the PEC, bringing the renewable share to 59 % and 72 % in 2030 and 2050, respectively. Gas consumption is expected to decrease substantially from 37 PJ in 2020 to 9 PJ from 2045 to 2050. PEC in the WAM scenario is around 8 % lower by 2050 than in the WEM scenario. The main policy measure implemented in the WAM scenario is building renovation and it reaches a similar level as in OPT_EE scenario (44 % of total buildings in 2030 and 70 % of total buildings in 2050). However, the WAM scenario do not reach the same level of electricity generation from wind power as in optimisation scenarios as there are no significant supporting policies included (only the Planning process reform), see Fig. 6.

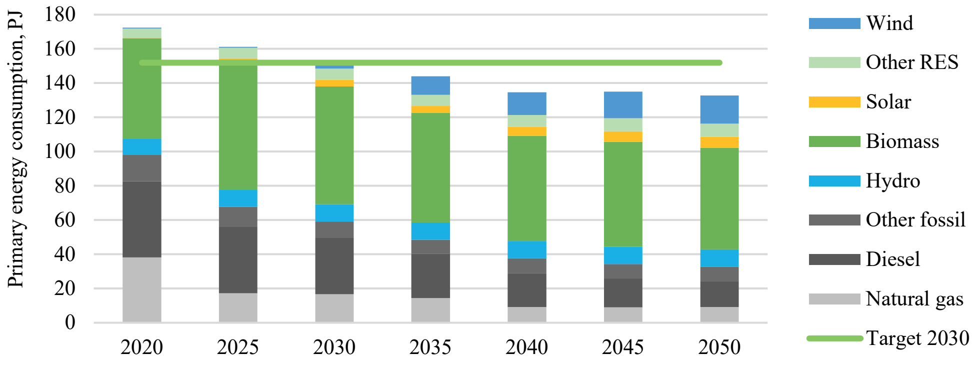
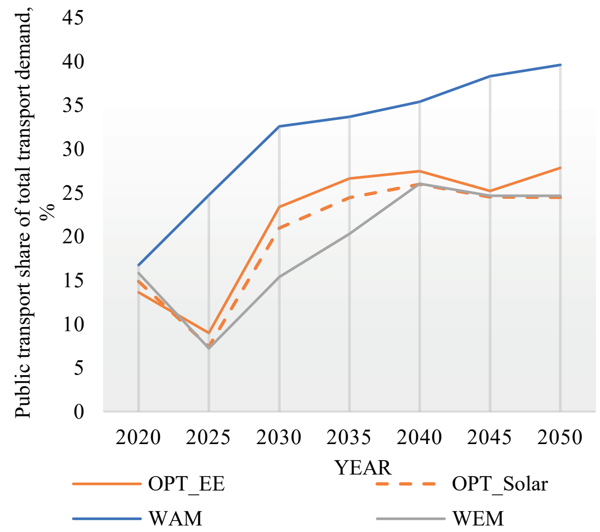


Fig. 6. PEC development in WAM scenario.

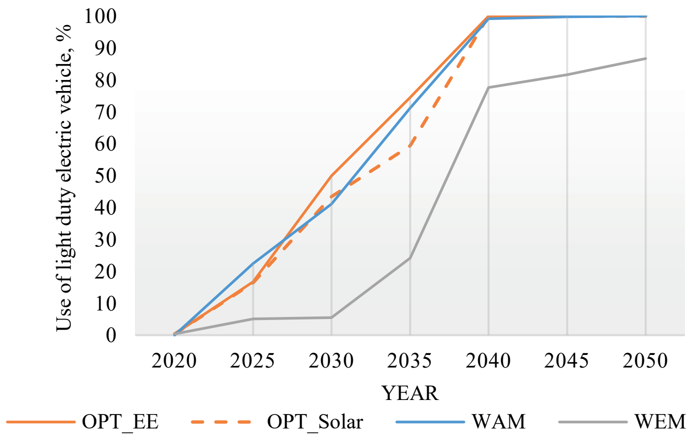
The focus of the integrated polices has been on the transport sector decarbonization. Therefore, measures implemented in the WAM scenario increase the public transport use from 17 % in the year 2017 to 35 % in the year 2030 and 40 % in the year 2050 (see Fig. 7(a)). Both optimization scenarios and WAM scenario show 100 % conversion to electric vehicles for light-duty vehicles by the year 2040 due to ban of internal combustion engines (see Fig. 7(b)).

Fig. 8 shows the comparisons of reached GHG emissions in the analysed scenarios across different sectors. As can be seen, the set of analysed policies in WAM does not fully reach the GHG emission reduction in 2050 due to lack of additional policies in transport and agriculture sectors. In the optimization pathways the agriculture sector is decarbonized by integrating more biomethane and hydrogen for machinery, but in transport sector higher electrification rates for freight transport are reached. Therefore, additional policy measures should be targeted to integrate carbon neutral solutions in these sectors.

Total investment and the subsidized part of those investments, for different WAM and WEM scenario measures, are shown in Table 4. All the investments and subsidies are shown as a cumulative value from the year 2020 till the year 2030. As local RES can be used to achieve energy efficiency targets, OPT_Solar has a higher total investment in PV panels than the OPT_EE scenario and a lower total investment in building renovations. For both OPT_EE and OPT_Solar scenarios, investments in electric vehicles are equally high. Comparing WEM and WAM scenarios, there is an increase in the subsidized part of the building renovation investments, moreover, there is a significant increase in total investments in building renovations from 1.25 trillion EUR in the WEM scenario to 5.45 trillion EUR in the WAM scenario, this combination requires a substantial increase in subsidies from 0.52 to 3.59 trillion EUR (see Table 4).



(a)



(b)

Fig. 7. Results of transport policies: a) Public transport use of total passenger km and b) electric light-duty vehicle shares of total light-duty vehicles.

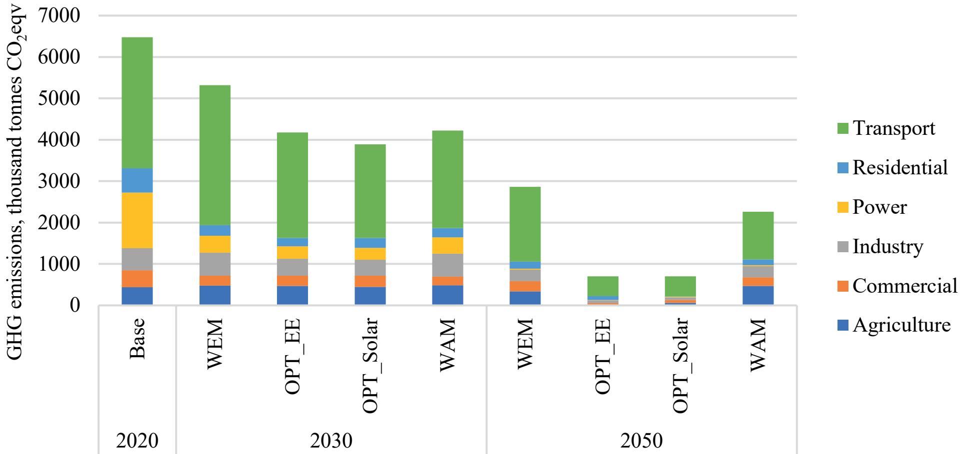


Fig. 8. Reached GHG emission of analysed scenarios in different end use sectors.

TABLE 4. CUMULATIVE INVESTMENTS AND SUBSIDIES FROM THE YEAR 2020 TILL 2030

	Total investment, Trillion EUR				**Subsidies, Trillion EUR**		**Subsidies of total, %**	
	WEM	OPT_I	OPT_II	WAM	WEM	WAM	WEM	WAM
Building Renovation	1.25	8.98	4.13	5.45	0.52	3.59	41.7	65.89
Biomethane production	0.02	0.02	0.02	0.06	0.01	0.03	28.62	41.22
PV panels	1.84	1.16	3.35	1.51	0.02	0.02	1.33	1.63
Consumer Heat pumps	0.16	0.16	0.16	0.15	0.00	0.06	0.00	40.29
Industry Energy Efficiency	0.65	1.42	0.87	0.63	0.06	0.06	8.66	8.91
Power sector	2.70	4.63	4.44	3.09	0.03	0.03	1.23	1.07
Public transport	0.83	1.85	1.53	1.11	0.01	0.05	1.18	4.07
Electric vehicles	1.82	8.98	8.10	3.04	0.01	0.01	0.55	0.33

4. CONCLUSIONS

The research results show that targeted policies are crucial in achieving the set REPowerEU and Green Deal targets because the Baseline scenario results without additional policy measures are far from the desired PEC and FEC levels in 2030 and 2050. This implies that simply relying on market forces may not be sufficient to achieve the desired outcome. It is necessary to implement policies that are specifically designed to address the challenges faced in achieving the targets. Such policies may include incentives for renewable energy use, carbon taxes, and regulations that encourage energy efficiency and conservation.

According to the TIMES self-optimising simulation where only energy efficiency measures are allowed to reach FEC targets in 2030, the most cost-effective decarbonisation pathway for Latvia relies extensively on building renovation and electrification. In the alternative optimization pathway, which allows to install the solar panels for self-consumption coverage at end-users, the building renovation does not play so crucial role due to solar energy being less cost intensive opportunity. If Latvia was left to its own pathway to decarbonize, the cost optimal solutions would be a scenario with less energy-efficiency measures and more RES generation. However, the REPowerEU targets force to overinvest in the energy efficiency measures in buildings in the short term, which overall results in higher costs and higher subsidies. In both self-optimisation runs, the model prioritizes fuel switch across all other sectors after 2030, with the transport sector trailing behind and being the major emitter in 2050.

The TIMES Latvia model optimization results highlight the interdependence between heat pumps and wind energy production. The increase in the use of heat pumps is driven by the increase in electricity production from wind energy and vice versa. This implies that the promotion of wind energy production can lead to an increase in heat pump use, which in turn can contribute to reducing energy consumption and GHG emissions. However, the ambitious building renovations measures also interact with the necessity to install heat pumps and wind power installation.

The electrification of the transportation sector is the most optimal solution for decarbonizing the transport sector. This is because electric vehicles have zero emissions and can be powered by renewable energy sources. Therefore, increasing the adoption of electric vehicles can contribute significantly to reducing GHG emissions from the transportation sector. However, additional policy measures should be found to promote electrification for all types of transport, including freight vehicles.

Further analysis could be dedicated to the actions proposed in the policy scenario (WAM) in isolation. This research looked at the combined effect of several actions across the total emissions from Latvia's energy use. However, each action could be analysed on its own once the actions have been defined more precisely. In addition, further research could incorporate Cradle to Cradle Life Cycle analysis for all available technologies in the TIMES model. By incorporating this analysis, researchers can obtain a more comprehensive understanding of the environmental impact of different technologies and their contribution to decarbonization targets.

ACKNOWLEDGEMENT

The research has been conducted within the project "Energy and Climate Modelling and Energy System Integration in Latvia" funded by the EU via the Structural Reform Support Programme.

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