Energy

Assessment of Latvia’s renewable energy supply-demand economic potential and policy recommendations, VPP-EM-2018/AER_1_0001

VERIFICATION of the SYSTEM DYNAMICS MODEL

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INTRODUCTION

The "Model building" phase of the project includes the development of a system dynamics model to determine the economic and market potential of renewable and local energy sources, considering also territorial, spatial planning, regulatory constraints, and long-term settings of energy, environmental and climate policies. The model forecasts change in energy sources used in electricity production, consumption of energy produced and consumed, wind and solar energy potential, allocation of resources in district heating, availability and use of low-quality wood between 2017 and 2050. It also addresses the final consumption of resources in the industry sector, services and public sector, final consumption of the household sector and aggregate final consumption in different regions of Latvia.

The system dynamics model is based on both models already created by project applicants and newly created sub-models that complement existing models. Mathematical equations of the model are taken from the literature review as well as from model-building group seminars with stakeholders and are based on expert opinions. As part of the activity, data has been collected from statistical sources, scientific literature data sources and publicly available reports.

The system dynamics model of renewable energy system was completed in current phase of the project and has been verified to evaluate the relevance of the baseline scenario to the real conditions. The report summarises the results of the various verification tests of the system dynamics model, which assess both the model structure and behaviour.

The future development of the project will identify a variety of policy instruments that will be integrated into the system dynamics model to assess the potential impact on the increase in the share of renewable energy sources.

1. SYSTEM DYNAMICS MODELS VERIFICATION METHODOLOGY

The purpose of the verification or approval of the system dynamics (SD) model is to determine the validity of the model structure. The accuracy of reproduction of the real behaviour of the model is also assessed, but this is only meaningful if we already have sufficient confidence in the structure of the model. Thus, the overall logical validation order is to first check the validity of the structure and then start testing the accuracy of behaviour only after the model structure is perceived as adequate. This logical sequence is shown in Figure 1.1.

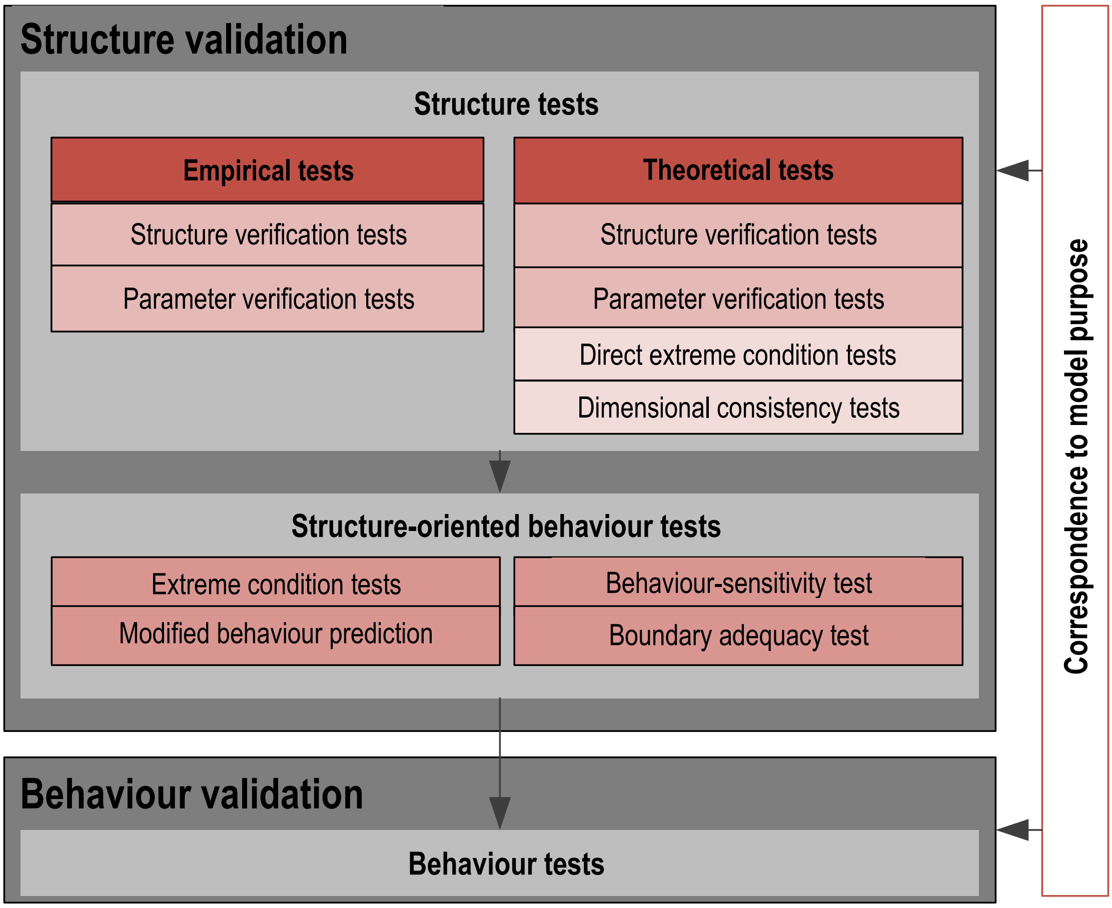


Fig.1.1. SD model validation tests and the performance sequence (Barlas & Erdem, 1994)

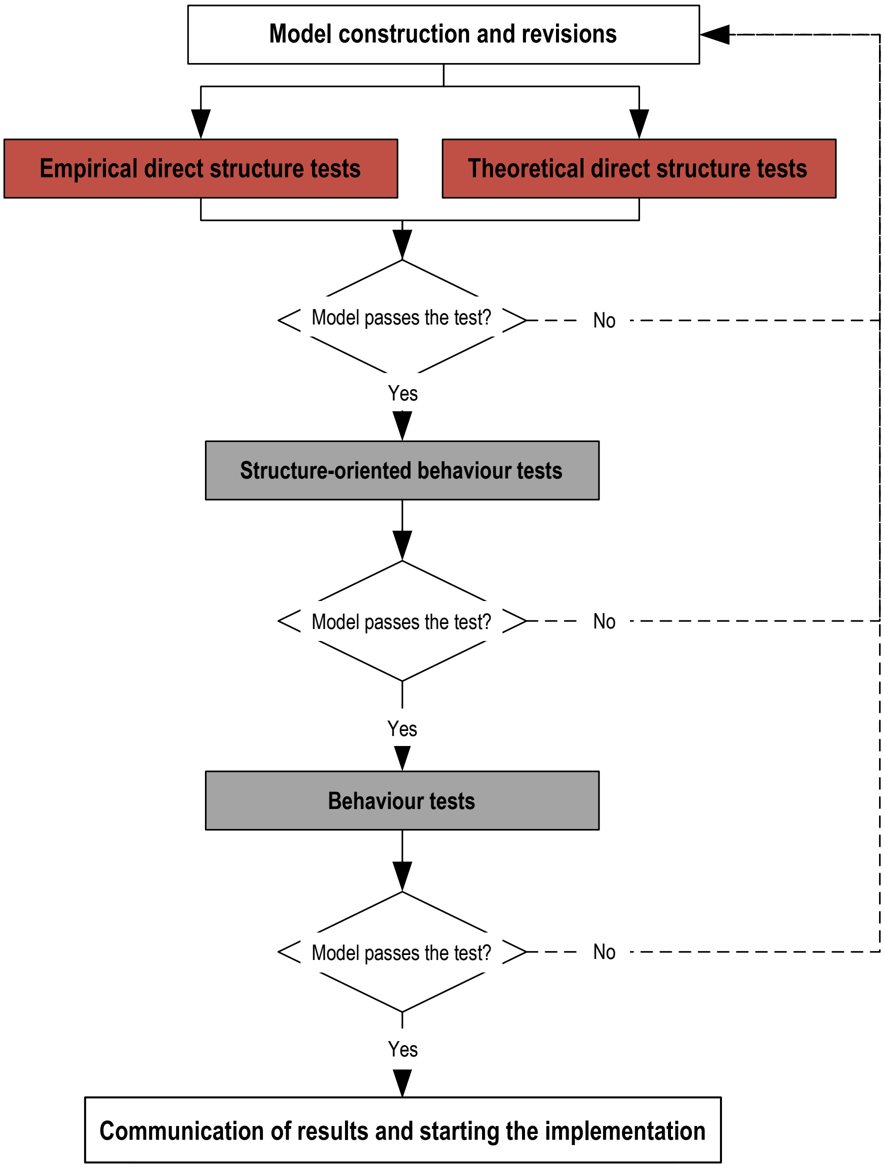


Fig. 1.2. Steps and sequence of the model validation process

Verification is a model analysis stage. The purpose of the verification is to ensure that the model is sound and useful. Verification of SD models has a number of system structures and behaviour assessment methods. Model verification provides answers to the following questions:

- Does the model boundary match the given purpose?
- Isn't the model too complicated or simple?
- Are all the elements explaining the problem included?

No model exactly matches the real object or system being modelled, so there are no absolutely reliable models. Models are considered credible and valid if they can be used with confidence. (Forrester & Senge, 1980) finds that confidence is the proper criterion because there can be no proof of the absolute correctness with which a model represents reality. In order to establish confidence in its validity as a result of the validation of a model, the purpose of the model must be clearly defined first.

There are a variety of validation tests for SD models to increase confidence in their validity and reliability. Verification tests for SD models may be divided into three groups:

1) model structure verification tests that assess the structure and elements of the model without analysing the relationship between the structure of the system and its behaviour;
2) model behaviour verification tests that assess the adequacy of the model structure by analysing the behaviour generated by the system;
3) policy impact assessment tests.

1.1. Model structure verification tests (structure tests)

According to the SD theory, the behaviour of the system is determined by its structure. Therefore, the first stage of the verification of a SD model is the verification of the correspondence of the system structure.

Model structure verification test

The model structure must not contradict knowledge about the structure of the real system. Each element included in the SD model must have an appropriate counterpart in the real system, and each significant factor in the real system must be reflected in the model. The verification of the structure may include a verification of model assumptions by specialists in the sector concerned, as well as a comparison of the assumptions used in the model with the information found in relevant literature. In most cases, the initial structure verification test is carried out on the basis of the model builder's knowledge of the system. It is later extended to include other stakeholders' experience with the real system.

Parameter verification test

The verification test of model structure is closely linked to the model parameter verification test. Parameter verification means comparing model parameters to knowledge of the real system to determine if parameters correspond conceptually and numerically to real life. Conceptual correspondence means that parameters match elements of system structure. Numerical parameter correspondence means that the values of the given parameters match the real values within the confidence limits. If possible, parameter values can be checked directly by comparing them to historical data. However, dynamic modelling of social systems may face situations, when there is a lack of available data, they are unavailable in the required form, or are incorrect. There may also be factors in the real system which are not usually quantified but which are significant in the modelled system. These elements should also be included in the model. Many of the required parameter values may not exist in reality and need to be figured out.

Boundary adequacy test

The boundary adequacy tests of model structure analyse the level of detail of the model and its correspondence to the building purpose. In order to be confident about the validity of the SD model, the model boundaries must be consistent with the building purpose. The boundary adequacy test may involve developing hypotheses relating to correspondence of the proposed model structure for the performance of its goal. The purpose of the model – the problem it is solving – should be defined first. Then it is necessary to identify the feedback relations between the problem and the associated factors and a hypothesis on what could affect the results should be proposed. If it is not possible to develop plausible hypotheses on other aspects that may affect the behaviour resulting from the problem, the model passes this test. If a plausible hypothesis for needing additional structure is developed, new assumptions should be included in the model and their impact on the behaviour of the system should be analysed.

Extreme condition test

An extreme condition test is also important in assessing the correspondence of the SD model structure. The ability of the model to function properly in extreme conditions contributes to the efficiency of the model as a policy assessment tool and increases the confidence of the model user. It is almost always possible to improve the model by analysing system behaviour in extreme conditions.

To make the extreme conditions test, each model flow equation must be assessed with each auxiliary element equation and stock to which it relates and the implications of imaginary maximum and minimum (minus infinity, zero, plus infinity) values for each stock and stock combination should be considered to assess the plausibility of the resulting flow equation.

The extreme conditions test is important to detect, first, defects or flaws in the model structure or parameter values, as many proposed formulations look plausible until considered under extreme conditions. Secondly, the appropriate behaviour of the model in extreme conditions increases the plausibility of the model's ability to function adequately in different conditions and the confidence that the model created is useful for analysing policies that can guide the system beyond the historical limits of its behaviour.

Examples of extreme conditions – if inventories of final goods reach 0, then shipments must be 0; if there are no houses in a city, then migration to the city will be strongly discouraged; and if pollution rises high enough, then death rate must rise.

Dimensional consistency test

Since SD root back to the engineering theory, SD models must ensure dimensional consistency. The dimensional consistency test provides an analysis of the dimensions of the parameters used in the model equations. The SD model should not include elements intended solely for scaling of dimensions, but which have little or no meaning in real life, as these elements may lead to a flawed model structure. The test should preferably be carried out at the same time as the parameter verification test.

1.2. Model behaviour verification test

Model behaviour verification tests assess the adequacy of the model structure by analysing the behaviour generated by the system and comparing it to the behaviour of the modelled system.

Behaviour reproduction test

Behaviour reproduction tests are based on a historical reproduction of the observed system behaviour and a comparison with the behaviour shown by the system. The initial input information of the model is historical data on the functioning of the studied system, and the model-generated behaviour trend is compared with the behaviour observed in the real system from the time of the input parameters and until now. The model-generated behaviour trend should match the observed behaviour of the real system. When performing this test, it should be assessed what the observed coincidence should be, since historical data are not always accurate and it should be verified again that the model structure is consistent with the building objective.

Behaviour prediction test

The purpose of the behaviour prediction test is to analyse whether the model creates a well-established structure of future behaviour by assessing the various predicted values of the model and their changes.

Behaviour anomaly test

The purpose of the SD model is to show the behaviour of the real system. If anomalous features of model behaviour are detected that do not match the behaviour of the real system, the cause should be sought in the model structure, parameter values, model boundaries, or other similar factors. However, the behaviour of the model may not match the behaviour of the real system, also because of an error in the input data on the behaviour of the real system, to which the model is compared. Behaviour anomaly tests are not only important auxiliary tools in model building, but also enhance confidence in the plausibility of the model.

Surprise behaviour test

The surprise behaviour test refers to the recognition of the behaviour of a real system that has existed for a long time but has not been noticed until the model was built.

The more comprehensive the SD model is, the more likely it will show the behaviour that exists in the real system that so far has not been recognised. Often, such unexpected behaviour surprises the model builder. In this case, the model builder must look for the causes of behaviour in the model structure and then compare them with the real system. Once previously unrecognized behaviour is identified in the real system, confidence in the validity of the model increases.

Extreme policy test

Extreme policy tests include testing radical policy changes in the model to see if the model behaviour is similar to what it should be in the real system in such circumstances.

The extreme policy test makes it possible to ascertain the possible response of the real system to radical changes. The better the model passes a variety of extreme policy tests, the greater the confidence in its adequacy for the analysis and formation of normal policies.

Boundary adequacy (behaviour) test

The boundary adequacy (behaviour) test is an extended boundary adequacy (structure) test, which was reviewed above. In this case, a model behaviour analysis is included. The test assesses whether the model boundary is adequate for deviations that may result from different policy alternatives.

Behaviour sensitivity test

The behaviour sensitivity test analyses the effect of changes in the values of the parameters on behaviour shown by the model. The behaviour sensitivity test looks at whether there exist equally plausible set of parameter values that can lead the model to fail to generate observed patterns of behaviour or to behave implausibly under conditions where plausible behaviour was previously exhibited.

Behaviour sensitivity tests are typically conducted by experimenting with different parameter values and analysing their impact on behaviour. Small, reasonable changes in model parameter values should normally not lead to radical changes in observed patterns of behaviour. If the behaviour of the model is not significantly affected by plausible changes in parameter values, confidence in the model increases. Sensitivity test criterion – any response to the change in parameters demonstrated by the model must not only be plausible but also compatible with the behaviour of the real system.

2. SD MODEL VERIFICATION RESULTS

2.1. Model structure verification

The model structure was validated through expert assessment and scientific literature. During the modelling process, a number of modelling sessions were set up, involving different experts in the sector. The model structure was also verified in a narrower circle between project performers. The lessons learned from the working groups helped to raise awareness of the missing elements of or the necessary revisions to the model.

The verification of the structure was also carried out using scientific literature, identifying mutually affecting factors. Certain parts of the model have been tested and published in scientific journals where their adequacy has been assessed by the scientific community through the review process (Asere & Blumberga, 2015; Blumberga et al., 2018; Bolwig et al., 2019; A. Gravelsins et al., 2019, 2018; Armands Gravelsins et al., 2019; Rozentale et al., 2020; Ziemele et al., 2017).

2.1.1. Extreme condition test

In order to check whether the model structure works in non-standard situations, extreme condition tests are carried out in the model's stock and flow structures. This makes it clear that the model will be able to generate reliable results also in extreme situations.

This chapter shows an example from the sub-model of the transport sector. The stock and flow structure of the number of cars is selected (Figure 2.1). The structure of this model is responsible for regulating the number of new and used cars, depending on the overall demand for cars. In the model, the investment share for new and used cars is calculated in a separate sub-model and depends on different cost items, which are compared among different fuel cars, but for the sake of simplicity, the investment share for this test is assumed to be constant. It is assumed that 10% of the total number of cars purchased is new, while 90% are used cars. The overall demand for cars is accepted as 100,000 cars. The lifetime of a new car is 5 years, because the car is out of date after 5 years and goes to a the stock of cars that is older than 5 years. The service life of a used car is assumed to be 15 years.

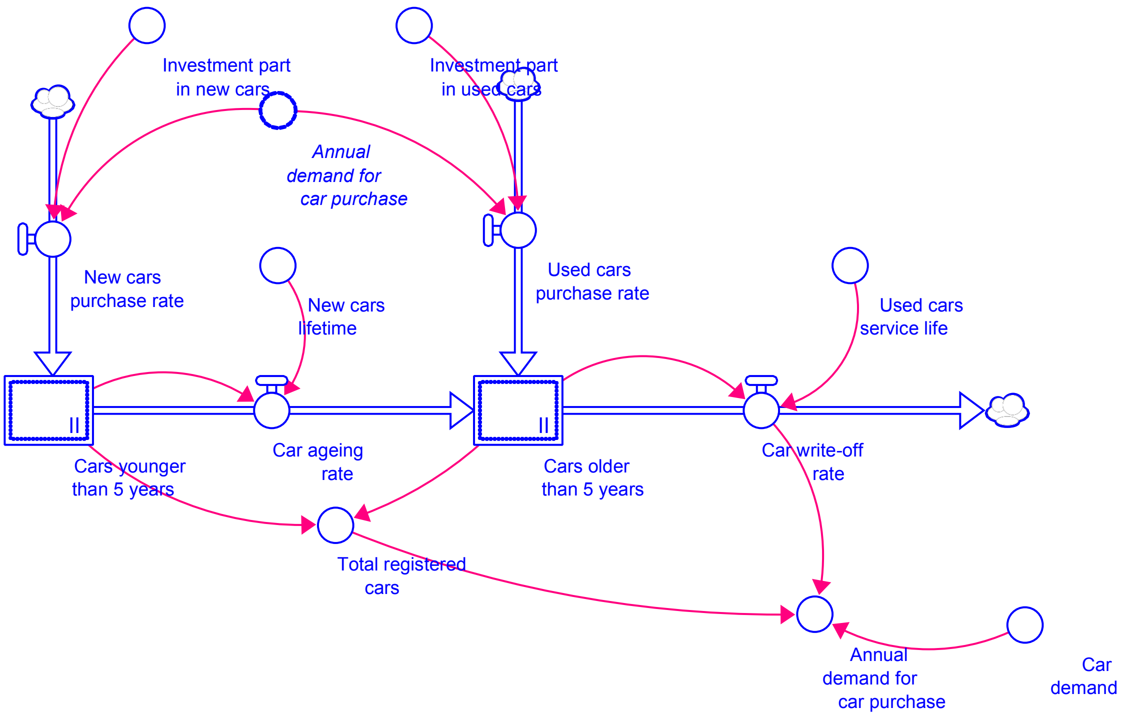
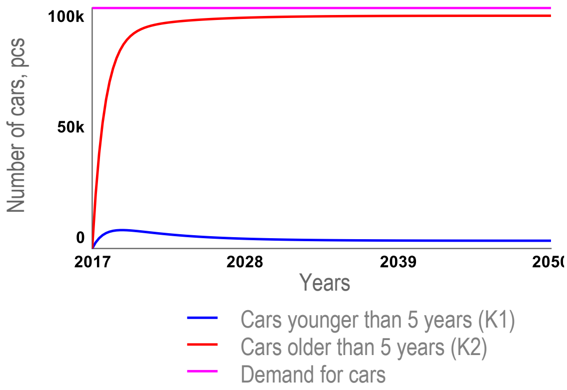


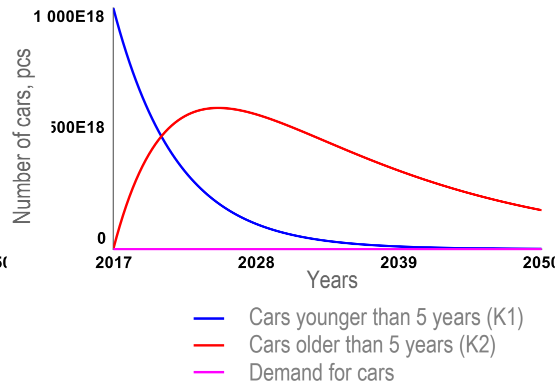
Fig. 2.1. Stock and flow structure of the number of cars

Four test simulations were performed to test if the model structure works properly, selecting extreme values 0 or 10^{20} for each of the stocks. Negative values were not tested because the stock created in the model has a condition that the stock value cannot be negative, which corresponds to the real system where the number of cars cannot be less than 0. The K1 abbreviation has been assigned to the car stock younger than 5 years and the K2 abbreviation has been assigned to the car stock older than 5 years.

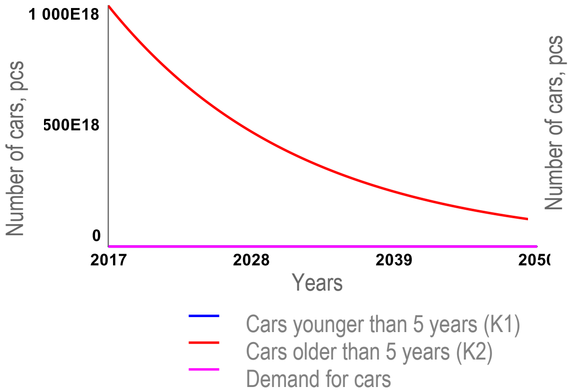
Figure 2.2 shows test results. The graphs show how the stock values change when their original values are set to 0 or the number imitating an infinitely high value 10^{20}. In addition, the overall demand for cars, as previously defined, is 100,000 cars. Graph a), where the two initial stock values are 0, shows that the system attempts to struggle to satisfy the demand, and this is done quickly with the majority of cars getting into the used car stock, which also corresponds to the previously defined distribution between the new and used car purchases. When stock value total reaches the demand, the system balances and the number of cars written off and purchased is nearly the same each year.



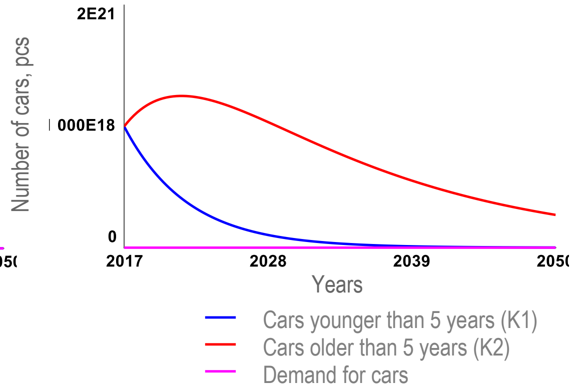
a) K1=0 and K2=0



b) K1= 10^{20} and K2=0



c) K1=0 and K2=10^{20}



d) K1=10^{20} and K2=10^{20}

Fig. 2.2. Extreme condition test results for the new and used car stock structure

Graph b), where the used car stock is originally 0 but the value of the new car stock is infinitely high, shows that the number of new cars is rapidly reducing as a result of car ageing and is moving to the used car stock. New cars are not purchased because the number of existing ones exceeds demand significantly. It shows that the system is moving towards a balance or the car demand value. What slows down the achievement of balance is the defined car service life, which is long enough for the system not to be able to reach a balance quickly enough.

Graph c) shows that the initial number of new car stock is 0, but the value of the used car stock is infinitely high. Since the total number of car stock is significantly above demand, there is no new car purchase in this case, and for example, the value of the new car stock will remain at 0 throughout the simulation period. The used car stock is shrinking rapidly, trying to reach the system balance, but, like in graph b), the system balance is not achieved due to the long car service life. By reducing the service life and/or extending the duration of the simulation, at which point the system would strike a balance corresponding to the balance shown in graph a).

In graph d), where the initial values of both stocks are infinitely high, the trend is similar to the behaviour in graph b) and c). All new cars rapidly move to the used car stock, and therefore initially increases, and then decreases on its way to the system balance.

All four graphs, regardless of the original stock values, tend to move towards one defined system balance, which means that the model structure passes the extreme condition test and works at any parameter values.

Similarly, other stock and flow structures included in the model were also tested using the extreme condition test.

2.1.2. Dimensional consistency test

Since SD root back to the engineering theory, SD models must ensure dimensional consistency. Below is the example how model elements are formulated in the model structure shown in Figure 2.3, and how the dimensional consistency test is performed. The example shows the model structure responsible for installing energy production capacity for different technological solutions. The model structure concerned is used for the modelling of electricity capacity, district heating capacity and individual heating capacity.

Investments in ordering a specific technology are described using the formula below:

$$I = IF\ (JPA > 1, 0, INV_i * \frac{(I_D + IT)}{PL * DL}), \quad (1)$$

where

I – investments in ordering a specific technology, GW/year;

JPA – capacity/consumption ratio;

INV_i – investment decision in any of the energy production technologies;

I_D – amount of energy that should be covered as a result of dismantling the existing equipment, GWh/year;

IT – energy shortage, GWh/year;

PL – time necessary for ordering energy production technologies, years;

DL – number of full-load hours of energy production equipment, h/year.

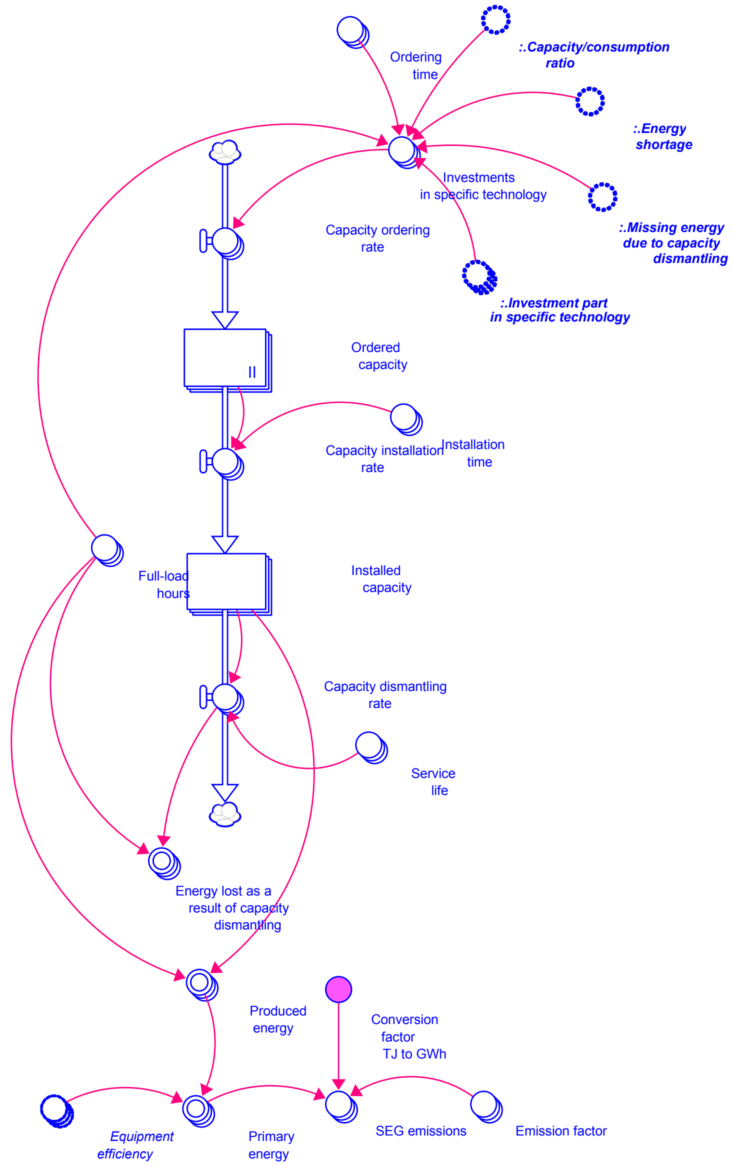


Fig. 2.3. Capacity installation sub-model

As seen from the formula (1), an IF function is used, if the value is 0, but if it is not, a mathematical expression with several elements is used – investment decision, missing energy as a result of capacity dismantling, energy shortage, ordering time and number of full-load hours. The power/consumption ratio and the investment decision in one of the energy production technologies are the relations calculated from the elements where the numerator and denominator have the same dimensions, so these elements can be considered dimensionless. The following shows how the dimensions are compared for the left side of the equation and for the mathematical expression given by the IF function *False*. When adding and cancelling, it appears that the dimensions on the left and right sides of the equation match. So the equation is described correctly.

$$\frac{GW}{year} = dimensionless * \frac{\left(\frac{GWh}{year} + \frac{GWh}{year}\right)}{\cancel{years} * \frac{h}{\cancel{year}}} = \frac{\left(\frac{GWh}{year}\right)}{h} = \frac{GW\cancel{h}}{\cancel{h} * year} = \frac{GW}{year}$$

The rate of commissioning of energy production capacity is expressed using the following equation:

$$ENJ = \frac{PJ}{UL}, \quad (2)$$

where
ENJ – capacity installation rate, GW/year;
PJ – ordered capacity, GW;
UL – installation time, years.

It follows from the equation (2) that on the left side of the equation, the dimension is GW/year, while on the right side GW is divided with years that also constitutes GW/year. So this equation is described correctly.

$$\frac{GW}{year} = \frac{GW}{year}$$

Rate of dismantling of capacities not in service:

$$NJ = \frac{UJ}{KL}, \quad (3)$$

where
NJ – capacity dismantling rate, GW/year;
UJ – installed capacity, GW;
KL – service life of energy production equipment, year.

Similarly to the equation (2), that on the left side of the equation (3), the dimension is GW/year, while on the right side GW is divided with years also forming GW/year.

$$\frac{GW}{year} = \frac{GW}{year}$$

Taking into account the installed capacity and the service life of each technology, the energy output produced is determined:

$$P = UJ * DL, \quad (4)$$

where
P – amount of energy produced, GWh/year.

The equation (4) shows that the product of the elements on the right side of the equation constitutes the same dimension as on the left side of the equation — GWh/year. So the equation is correct too.

$$\frac{GWh}{year} = GW * \frac{h}{year} = \frac{GWh}{year}$$

Primary energy consumption is determined by taking into account the efficiency of each technology:

$$E = \frac{P}{\eta}, \quad (5)$$

where
E – primary energy consumption, GWh/year;
η – technology efficiency.

In equation (5), the efficiency is the energy produced against the resource consumed, or it can be expressed as a dimensionless value, because both the numerator and the denominator have the same dimension. Taking this into account, the dimensions for the equation (5) can be described as indicated below, and it can be seen that the dimensions for this equation are also the same on both sides.

$$\frac{GWh}{year} = \frac{(\frac{GWh}{year})}{dimensionless} = \frac{GWh}{year}$$

The GHG emissions generated are calculated taking into account the emission factors of each energy source:

$$SEG = P * E_f * 3{,}6\,, \qquad (6)$$

where
SEG – GHG emissions generated, t/year;
E_f – emission factor, t/TJ;
3.6 – conversion factor from TJ to GWh.

The equation (6) uses the conversion factor from TJ to GWh when calculating GHG emissions, as the emission factor is given in TJ, while energy is calculated in GWh. By cancelling all excess dimensions, we get t/year corresponding to the dimension on the left side of the equation. So the equation is correct, and the dimensions match.

$$\frac{t}{year} = \frac{\cancel{GWh}}{year} * \frac{t}{\cancel{TJ}} * \frac{\cancel{TJ}}{\cancel{GWh}} = \frac{t}{year}$$

According to the principle described above, the dimensional consistency test has been performed for the entire model.

In the *Stella Architect* modelling tool, where the modelling is performed, the dimensional consistency test is performed automatically, and the programme points to the erroneous places where either the equation is incorrectly written or an incorrect dimension has been entered for one of the input parameters. This allows for timely identification of errors resulting from the input of erroneous formulas and allows the necessary modifications to the model to be made in a timely manner.

2.2. Model behaviour verification

A comparison of the results of the model with historical statistics was carried out to assess the behaviour of the SD model and its correspondence to the real conditions. Indicators for which more accurate historical statistics are available were used as the main reference parameters:

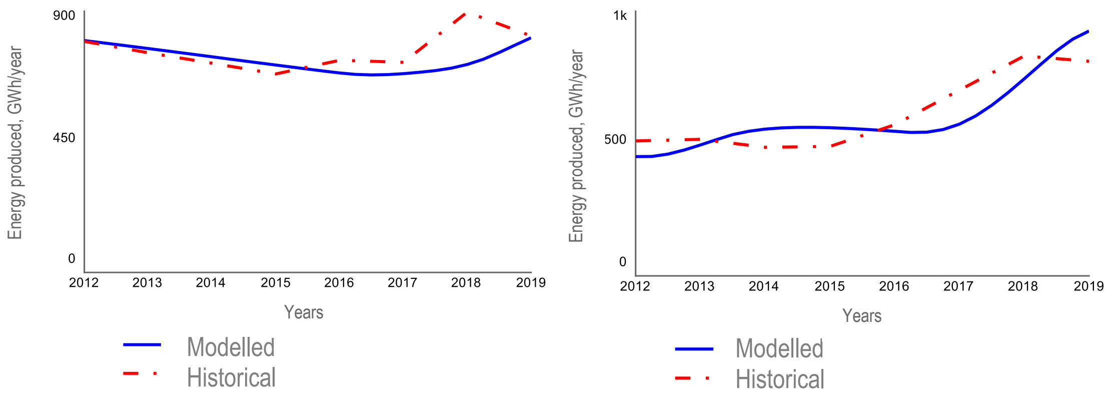
- Amount of heat produced in statistical regions;

- Amount of electricity produced in statistical regions;
- Electricity produced by resource in statistical regions;
- Number of renovated multi-apartment buildings;
- Transport fuel prices;
- Fuel consumption for transport;

Model verification has been carried out for common and regional indicators, but the report examines in depth the examples of validation results for Kurzeme and Vidzeme regions, which allow an assessment of the plausibility of the model behaviour.

2.2.1. Verification of total heat and electricity produced by region

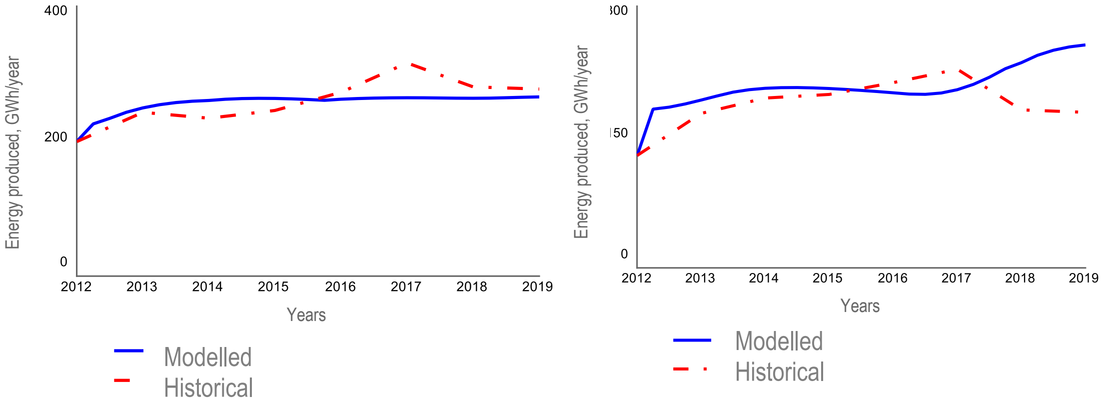
For model behaviour verification historical change in the amount of energy produced has been compared with the modelled changes. Figure 2.4 shows changes in heat energy produced in Kurzeme and Vidzeme regions from 2012 to 2019. In the Kurzeme region, historical heat consumption has increased significantly from 2018, which is due to an increase in industrial or commercial heat consumption, as the amount of heat supplied to households has not increased during that period. Although modelled values vary in individual years, the overall development trends for modelled values and the real amount of heat produced match. Since the task of a SD model is to model trends rather than exact values, it can be considered that the built model is capable of successfully modelling development trends.



e) Heat produced Kurzeme region f) Heat produced Vidzeme region

Fig. 2.4. Validation results of heat produced by regions

Figure 2.5 shows the real and modelled amount of electricity produced in Kurzeme and Vidzeme regions. The main differences are observed in the Vidzeme region in 2018 and 2019, when electricity produced by cogeneration plants decreased. The main reason for these changes was the uncertainty in the mandatory electricity procurement (MPC) policy, which is currently not included in the SD model, as it is not clearly defined how MPC payments will change. The analysis of potential policy instruments to increase the share of RES will also include a detailed analysis of the impact of different MPC policy scenarios on the amount of energy produced.



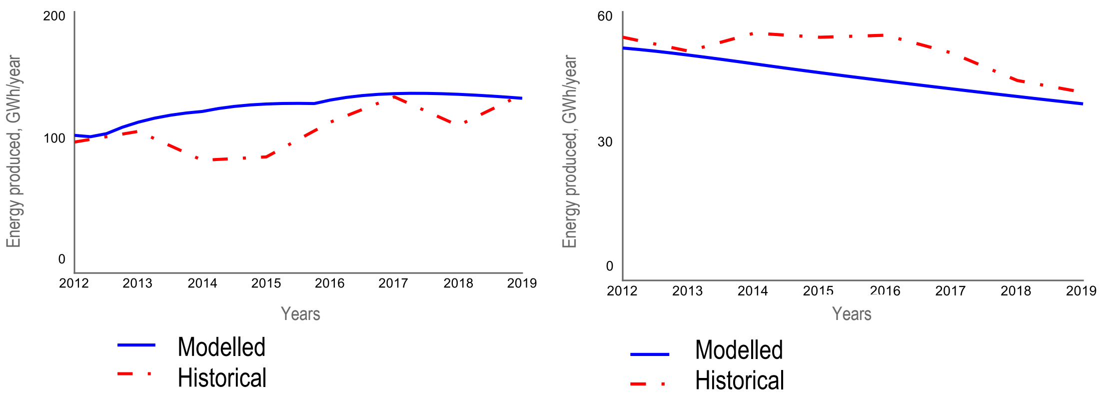
a) Electricity produced Kurzeme region

b) Electricity produced Vidzeme region

Fig. 2.5. Validation results of electricity produced by regions

2.2.2. Electricity production by resources

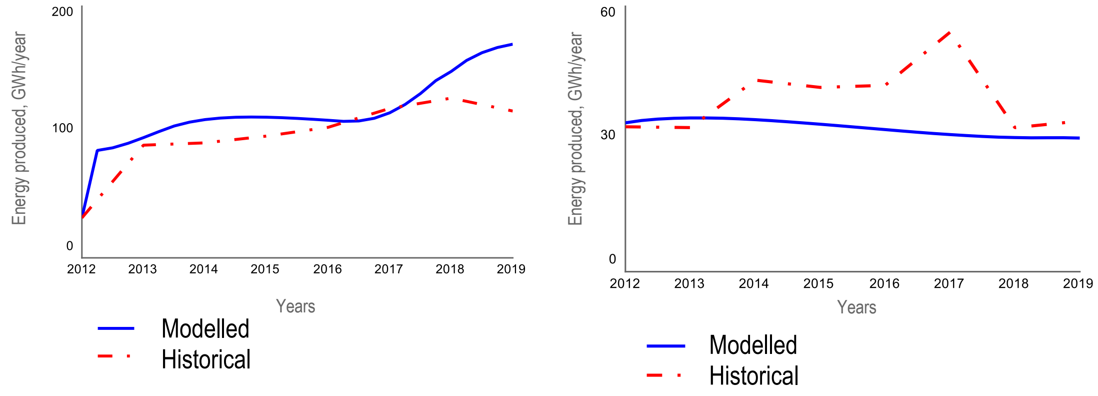
As the SD model aims to predict the trend in the share of renewable energy sources, then it is important to analyse the possibilities of modelling changes in the consumption of individual energy sources. Figure 2.6 shows the modelled amount of electricity produced by individual energy sources in the Kurzeme region that is comparable to historical statistical data. The historical amount of electricity produced from wind energy shows a relatively large change over the years, which is explained by aspects of the operation of wind turbines, but the SD model does not model such changes. It is shown that the overall wind electricity growth trend in the Kurzeme region matches. The analysis of the amount of electricity produced from natural gas shows that the amount modelled in the SD model is slightly lower, which is explained by the fixed ratio of heat to electricity produced in cogeneration plants (alpha factor), but in reality, cogeneration plants often also operate in condensation mode thus producing more electricity. The higher amount of electricity produced at biogas cogeneration plants in the Vidzeme region shown in Figure 2.7 has a similar reason.



a) Electricity produced from wind energy

b) Electricity produced from natural gas

Fig. 2.6. Electricity produced by resource in Kurzeme region



a) Electricity produced from biomass   b) Electricity produced from biogas

Fig. 2.7. Electricity produced by resource in Vidzeme region

Figure 2.7 shows that the modelled and real amount of electricity produced in cogeneration plants is similar between 2012 and 2017, but the differences are visible from 2018 when the MPC payments started.

2.2.3. Verification of household sector indicators

Verification of a number of household sector indicators has been carried out to assess the energy consumption section. Figure 2.8 compares the modelled and historical areas of renovated multi-apartment buildings in the Kurzeme region. The historical area of renovated buildings has a cyclical trend following the available funding while the modelled amount has a constantly growing trend.

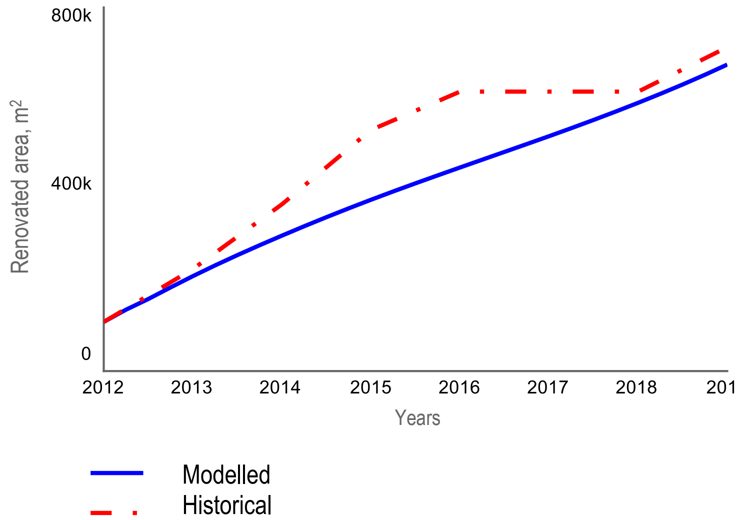
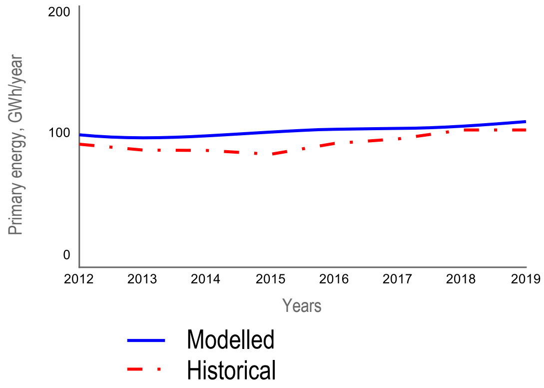
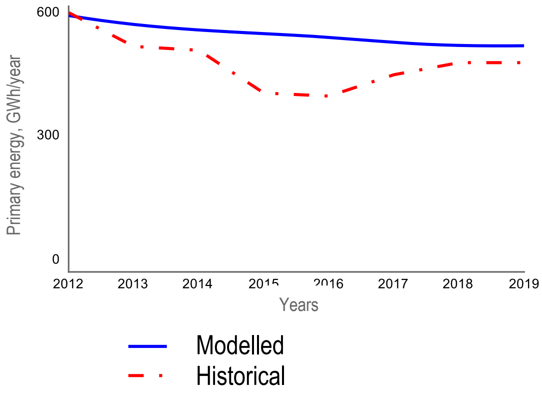


Fig. 2.8. Areas of renovated multi-apartment buildings in Kurzeme region

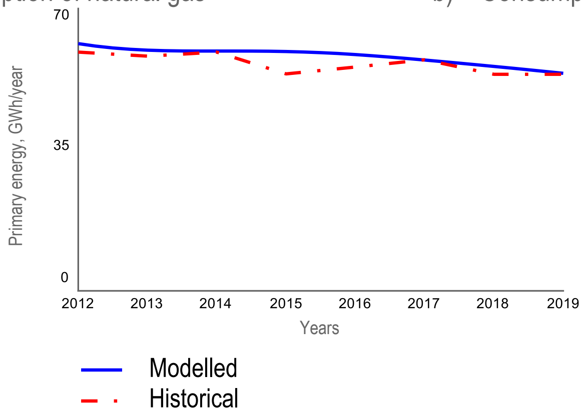
Figure 2.9 summarises modelled and historical data on consumption of energy sources in the household sector in the Kurzeme region. Modelled and historical data are similar for the consumption of natural gas, oil and coal in the household sector, but differences are observed for the consumption of biomass, which is calculated in the model based on the area of the residential stock and the choice of heating solutions. Historical biomass consumption indicators in the Kurzeme region are obtained by making a conversion of the total consumption of biomass in the country and the amount of heat consumed in the region, which is one reason for the mismatch between the modelled indicators. Additional mismatches are due to the complex accounting of biomass consumption in the household sector.



a) Consumption of natural gas



b) Consumption of biomass



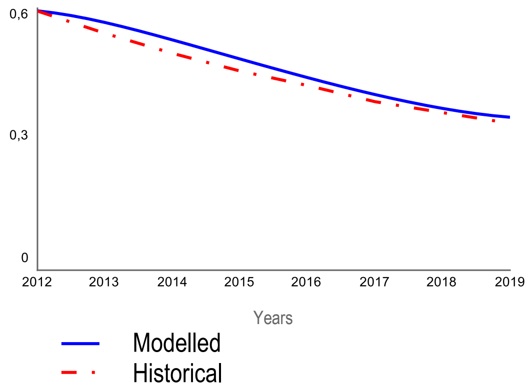
c) Consumption of petroleum products and coal

Fig. 2.9. Consumption of primary sources in the household sector in the Kurzeme region

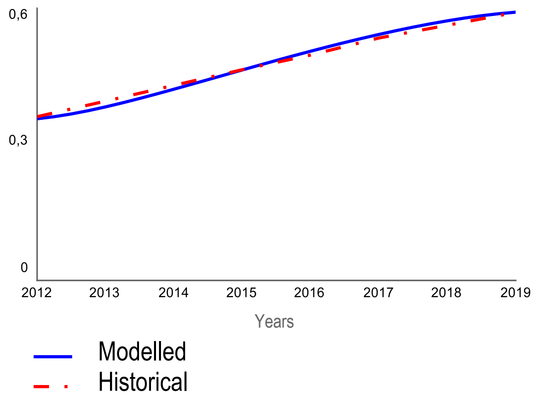
Although the consumption of individual energy sources shows a slight difference from the modelled amount, the overall trends in consumption of sources are the same.

2.2.4. Verification of transport sector indicators

To verify the behaviour of the transport sector sub-model, modelled and historical indicators on the number of cars with different types of fuel engines, fuel prices and fuel consumption in the transport sector were analysed.



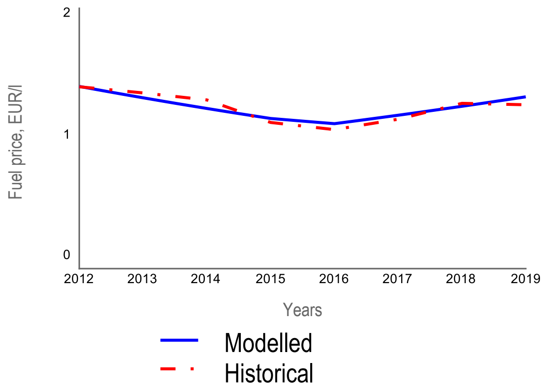
a) Share of petrol engine cars



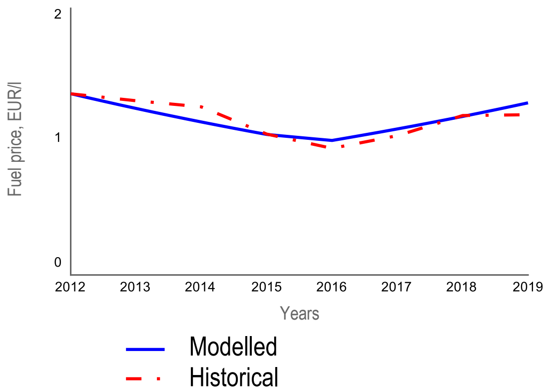
b) Share of diesel engine cars

Fig. 2.10. Share of cars by fuel type consumed

Figure 2.10 shows that the modelled number of cars with a petrol engine and a diesel engine almost entirely matches with historical indicators. The trend shows that the number of vehicles with a petrol engine is decreasing and the number of vehicles with a diesel engine is increasing. Figure 2.11 shows modelled and real prices of petrol and diesel that are almost the same.



a) Price of petrol



b) Price of diesel

Fig. 2.11. Historical changes in fuel prices

Figure 2.12 shows a comparison of the modelled total fuel consumption for road transport with historical indicators. It can be seen that the modelled indicators almost entirely match the real consumption indicators.

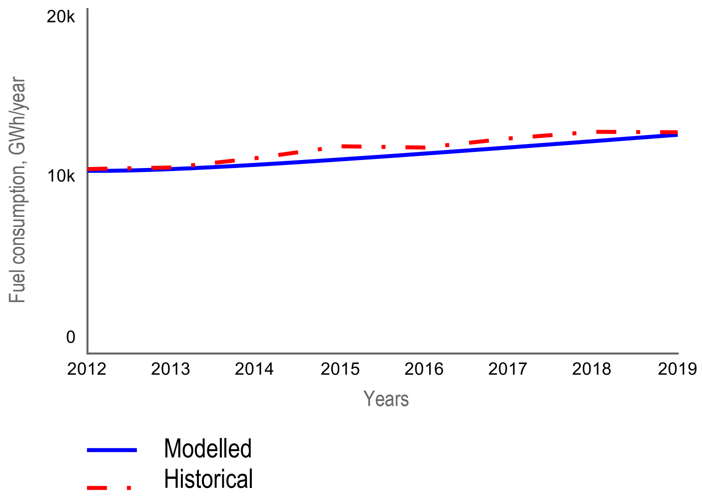
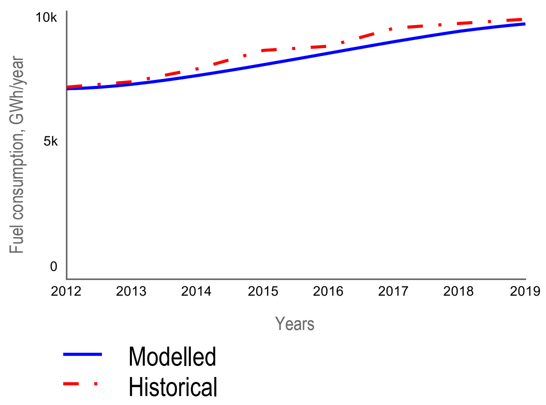
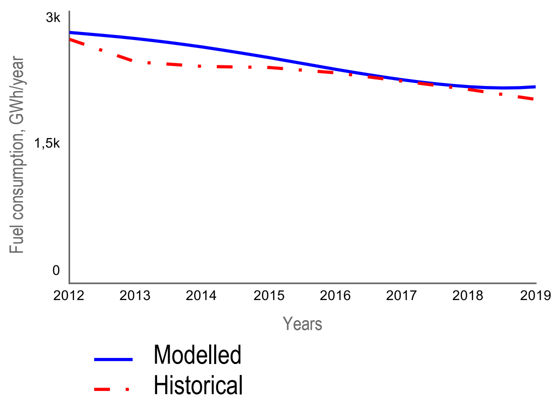


Fig. 2.12. Fuel consumption in road transport

Slightly bigger differences in historical and modelled indicators are seen in the analysis of consumption by consumption of different fuels (see Fig. 2.13). Historical diesel consumption indicators are slightly higher than the modelled indicators, but modelled petrol consumption is slightly lower than historical indicators between 2013 and 2015.



a) Diesel consumption



b) Petrol consumption

Fig. 2.13. Fossil fuels consumption validation results

Figure 2.14 shows renewable fuels consumption validation results. In 2016 and 2017, a significant drop in the consumption of biofuels is observed, while the modelled consumption of biofuels has a gradually growing trend. Also, the historical consumption of biodiesel has a growing trend after 2017, and if there had not been a huge drop in 2016 and 2017, then the trend should have been similar to the modelled result. The decrease in the historical consumption of biofuels is due to the fact that until 1 April 2018 the mandatory biofuel blend in Latvia allowed an exemption for the diesel fuel used in arctic and harsh winter conditions. With such a regulation, fuel traders continued to trade arctic diesel during the summer period starting in 2016. On 1 April 2018, amendments to Regulations of the Cabinet of Ministers No. 332 of 26 September 2000 "Requirements for Conformity Assessment of Petrol and Diesel Fuel" entered into force, which enshrined the mandatory requirements for the biofuel blend in diesel.

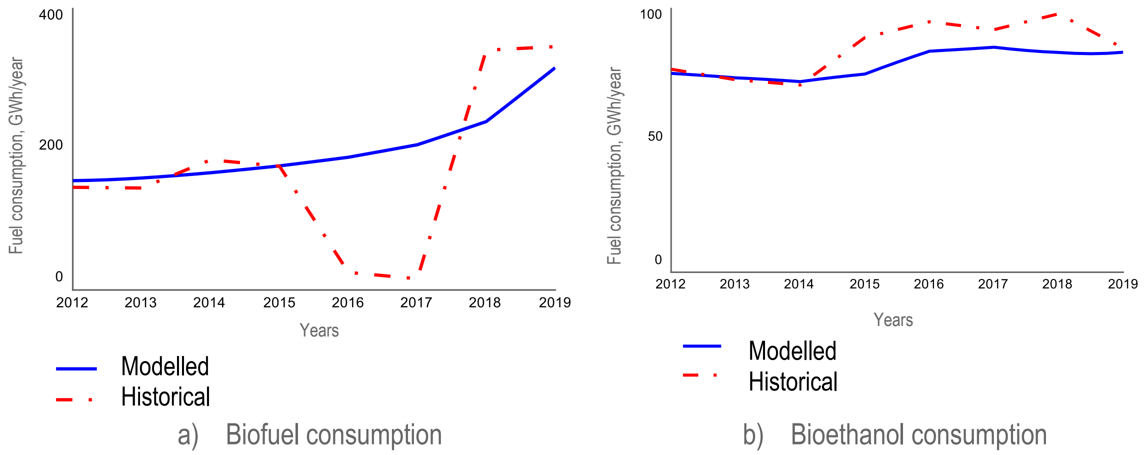


Fig. 2.14. Renewable fuels consumption validation results

Bioethanol consumption also increased more rapidly between 2015 and 2019, which is slightly higher than the modelled indicators. Overall, the modelled and historical result have with a similar trend. A more accurate result could be obtained by incorporating into a model the causes of the decline in biodiesel in 2016 and 2017, but since the model aims to model future development trends rather than analyse the past shocks or accounting inaccuracies, the existing result can be considered to be sufficiently close and adequately describing the existing system.

2.3. Extreme policy and sensitivity test

2.3.1. Electricity and district heating

An extreme policy test was carried out to check whether the behaviour of the modelled system matches what was expected in extreme circumstances. It was tested how atypical values of various elements affect the behaviour of the system and whether it matches the understanding of how the system should respond to changes in parameters.

Figure 2.15 shows the projected situation of the modelled system in electricity production, based on real input data and projected future parameters. Taking into account everything that is known about the current state of the system and future technology costs, resource prices and other forecasts, it appears that a reduction in the use of natural gas and an increase in the use of wind energy is projected, while no significant changes in consumption are observed for other resources.

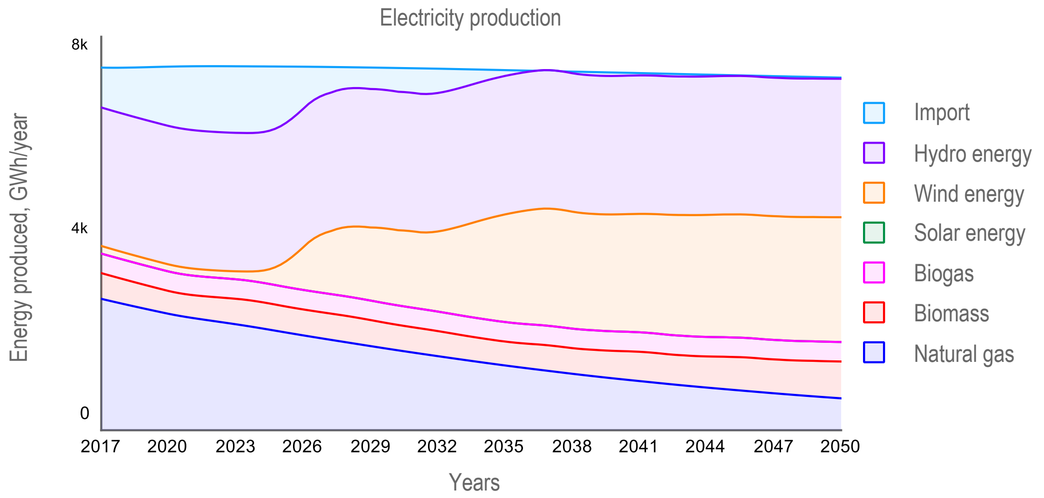


Fig. 2.15. Distribution of resources in electricity production with standard parameters

Figure 2.16 shows the projected situation of the modelled system in district heating based on real input data and projected future parameters. Similarly, to electricity production, a decrease in the use of natural gas as well as an increase in the use of solar and biomass energy are expected also in district heating.

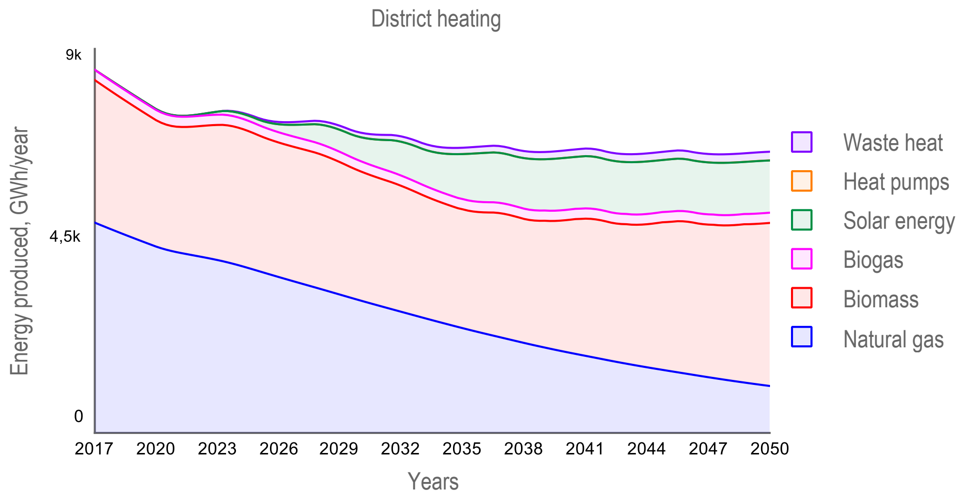
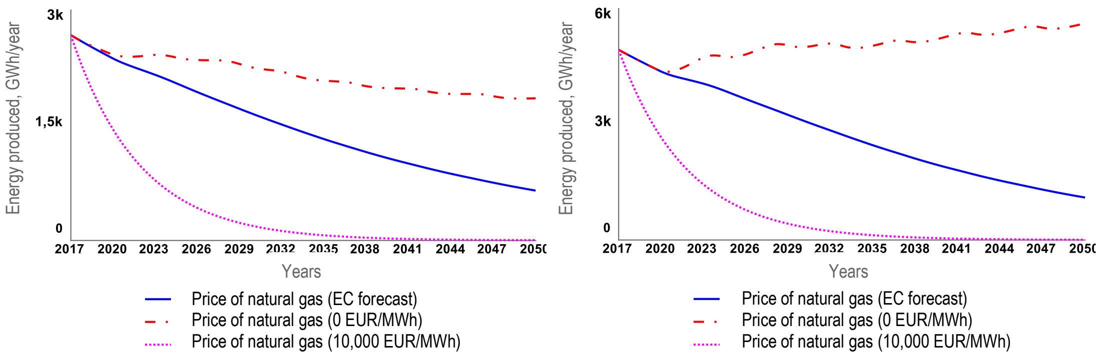


Fig. 2.16. Distribution of resources in district heating with standard parameters

The price of resources was used as one of the parameters tested. Figure 2.17 shows an example with changes in the price of natural gas and their impact on the use of natural gas in electricity production and district heating.

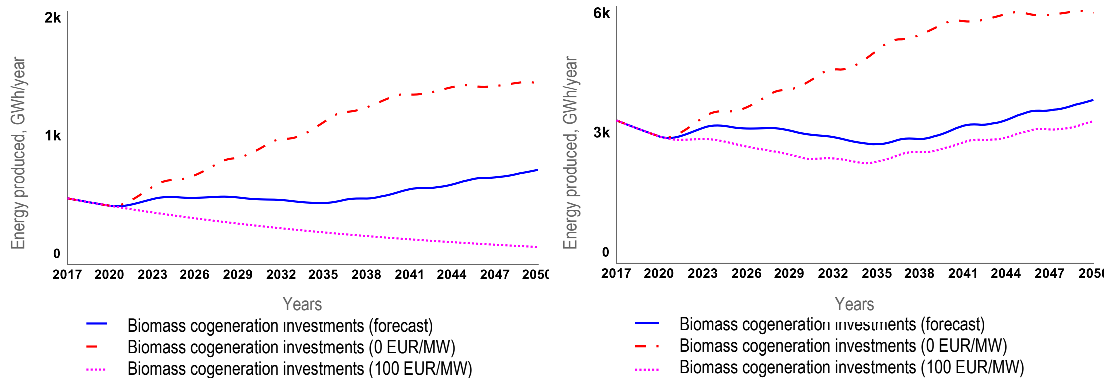


a) electricity production b) district heating

Fig. 2.17. Impact of the price of natural gas on the amount of use

As can be seen from Figure 2.17, when the price of natural gas changes according to the current forecasts, its use in electricity and heat production will decrease significantly over time. The modelling of the situation with free natural gas (while maintaining the excise duty, the natural resources tax, the price of the ETS allowances, etc.) shows that the decline in the use of natural gas in electricity production could be much smaller, while the intensity of the use of natural gas in district heating could even increase. Conversely, the modelling of a situation where the price of natural gas is abnormally high shows that the use of natural gas in the model reduces rapidly until it reaches level 0. Taking into account that electricity and heat production is a business where costs play a key role in the choice of technology, the graphs described above are logical and reflect how the real system could react in a similar situation. Similarly, prices of other resources and their impact on the system were tested.

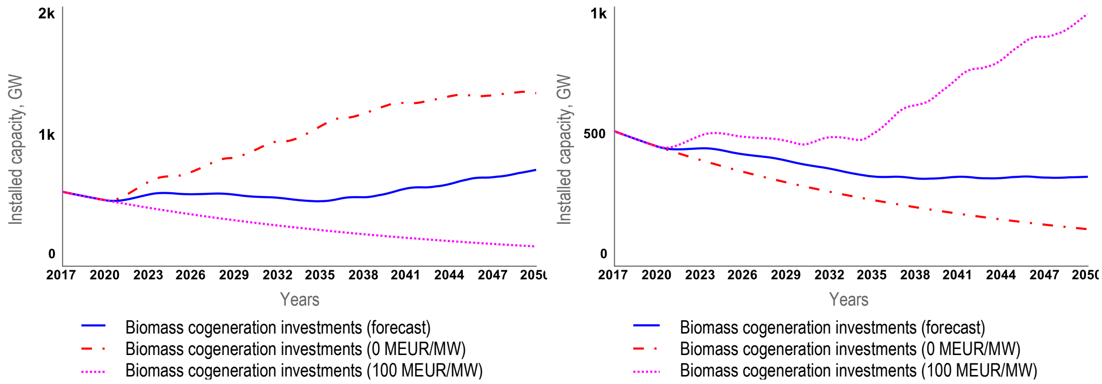
Figures 2.18 and 2.19 illustrate an example of the impact of technology investment costs on the behaviour of the system. Investment costs for biomass cogeneration plants are used as an example. The change in investment costs in the given example applies only to biomass cogeneration equipment, but does not apply to other resource technologies, as well as to biomass boilers that are not operating in cogeneration.



a) electricity production b) district heating

Fig. 2.18. Impact of biomass cogeneration investments on the amount of use of biomass

Figure 2.18 shows that the investment costs of biomass cogeneration plants have a significant impact on the use of biomass for electricity and heat production. Graph a) shows that, at investment costs of 0 euro per megawatt, the use of biomass in electricity production would increase while with a significant increase in investment costs (100 million euro per megawatt), new biomass cogeneration capacities are not installed, and the use of biomass reduces with the wearing off of existing capacities. In terms of the use of resources, a different situation forms in district heating where tested. In the case of 0 investments, the use of biomass in cogeneration plants increases in a similar way to electricity production, but in the case of 100 million euro per megawatt investments, no significant reduction in the use of biomass in the system is observed. This is because biomass boilers are the next most cost-effective solution. This can be seen very vividly in Figure 2.19.



a) biomass cogeneration heat capacity b) biomass boiler heat capacity

Fig. 2.19. Impact of biomass cogeneration investments on the capacity of biomass equipment in district heating

Figure 2.19 shows that if the biomass cogeneration equipment investments are 0 euro per megawatt, the installed capacity of biomass cogeneration plants increases significantly, while the capacity of biomass boilers decreases. An opposite situation is observed, if biomass cogeneration equipment investments are 100 million euro per megawatt. In this case, new biomass cogeneration heat capacities are not installed, but the installed heat capacity of biomass boilers increases. The above corresponds to how the system should respond to changes in parameters. Similarly, the costs of other technology investments were also tested.

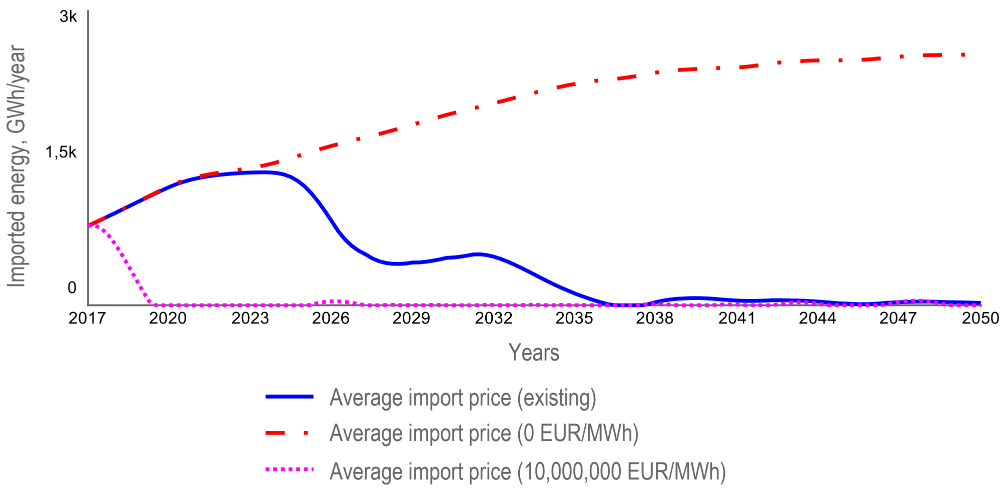


Fig. 2.20. Impact of the price of import electricity on electricity imports

Figure 2.20 shows the impact of the price of imported electricity on the amount of imports. The baseline scenario shows net imports that are decreasing over time as wind energy develops.

If the price of imported electricity reduces to 0 euro per megawatt hour, net imports would increase as it would be more profitable to import electricity than to produce it on site. At the same time, electricity production would not stop and not all electricity would be imported, but existing equipment would continue to operate to ensure the energy independence of the system. When testing the case with an inadequately high price of electricity imports, it can be seen that net imports fall sharply and the system is rapidly switching to more intensive local electricity production.

2.3.2. Final consumers

Since final energy consumption was also modelled, extreme policy tests were also carried out for the part of the model relating to final consumption. The example shows the impact of different parameters on the rate of renovation of multi-apartment buildings, which has an impact on energy consumption in the household sector and, consequently, on demand for district and individual heating. Similarly, other end-use sectors – industry and the services sector – were tested.

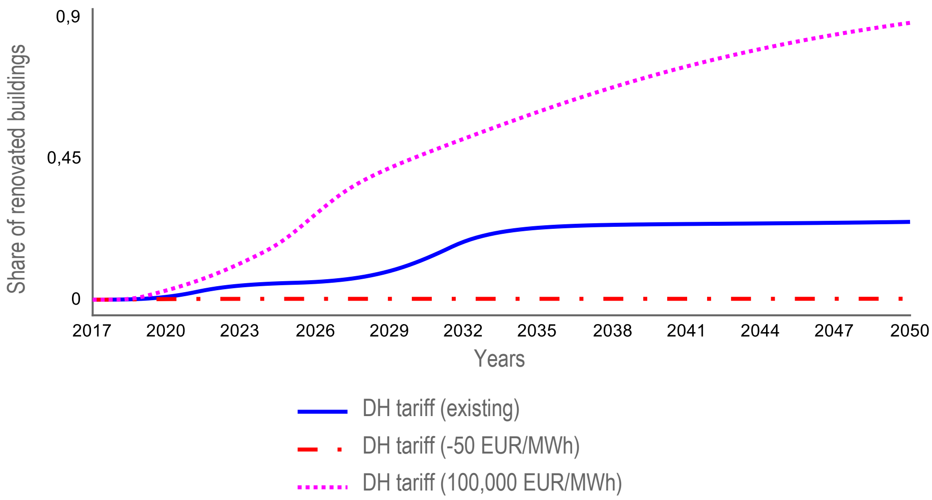


Fig. 2.21. Impact of the district heating (DH) tariff on renovation of multi-apartment buildings

Figure 2.21 shows the results of testing the impact of the district heating tariff on the rate of renovation. The rate of renovation with the existing district heating tariff is relatively slow and it is seen that only part of the multi-apartment buildings is renovated. Looking at the situation with a negative heating tariff value (the merchant pays for energy acceptance), it is seen that there is no interest in the renovation and that the buildings are not renovated, which is consistent with the understanding of reality. If a payment for energy consumption is received, the consumer has no interest in reducing energy consumption, as this would reduce the amount for which payment can be received. Otherwise, when the heating tariff is abnormally high, it is seen that the renovation rate is significantly higher and the share of renovated buildings is approaching 90%. A faster rate of renovation is not possible due to the lack of construction capacity, as existing capacity does not allow more buildings to be renovated at the same time, but it takes time to increase capacity. The share of renovated buildings is not approaching 100%, as not all buildings use district heating and therefore the high tariff does not affect them.

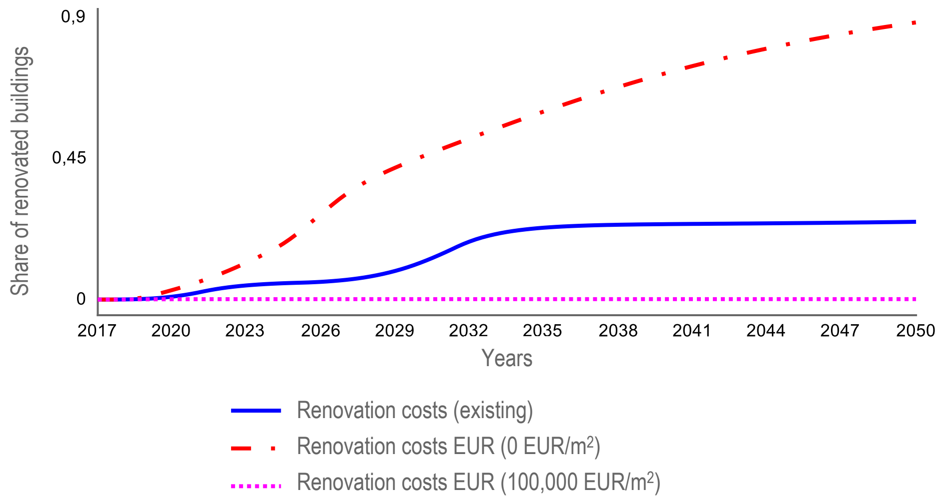


Fig. 2.22. Impact of renovation costs on renovation of multi-apartment buildings

Figure 2.22 shows how the costs of renovation affect the share of renovated buildings. With the existing renovation costs, the share of renovated buildings is similar to the baseline scenario in Figure 2.21. If the renovation could be carried out free of charge, the pace of the renovation would be much more rapid and the share of renovated buildings would rise to 90%. Similarly to the previous test, the more rapid rate of renovation is also prevented by a lack of construction capacity. When testing a case with inadequately high renovation costs, it is seen that there is no interest in renovation and the share of renovated buildings remains at the initial level.

2.3.3. Transport sector

This section presents examples of extreme policy tests carried out in the transport sector. Examples are given from extreme policy tests on the structure of passenger car transport, but similar tests were also carried out on public and freight transport.

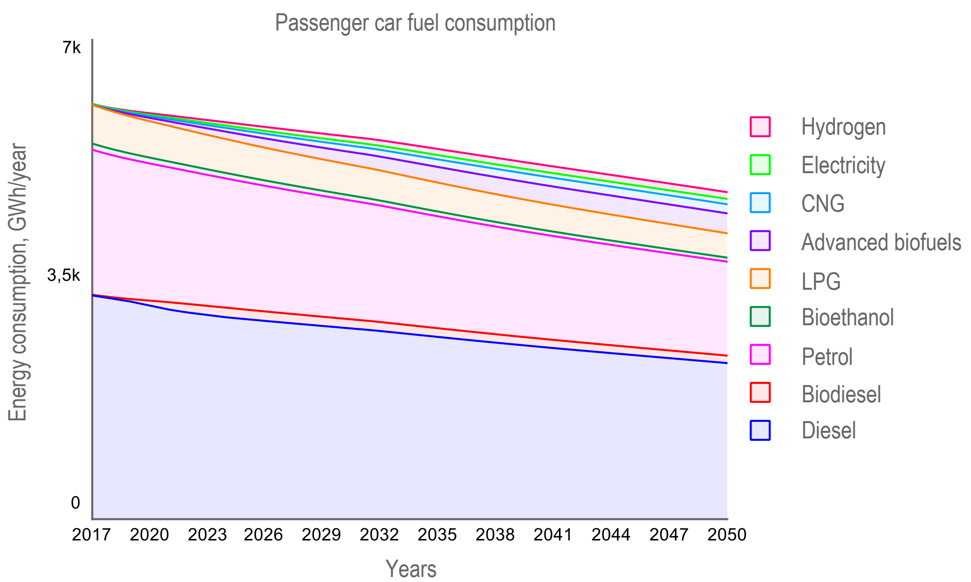


Fig. 2.23. Fuel consumption of passenger car

Figure 2.23 shows resource consumption and development forecasts for passenger cars modelled in the baseline scenario, based on passenger demand, technology costs and fuel price forecasts. It can be seen that overall energy demand is falling as the efficiency of existing transport technologies grows and new and more efficient solutions appear. A decline in petroleum products, as well as an increase in consumption of renewable sources are expected.

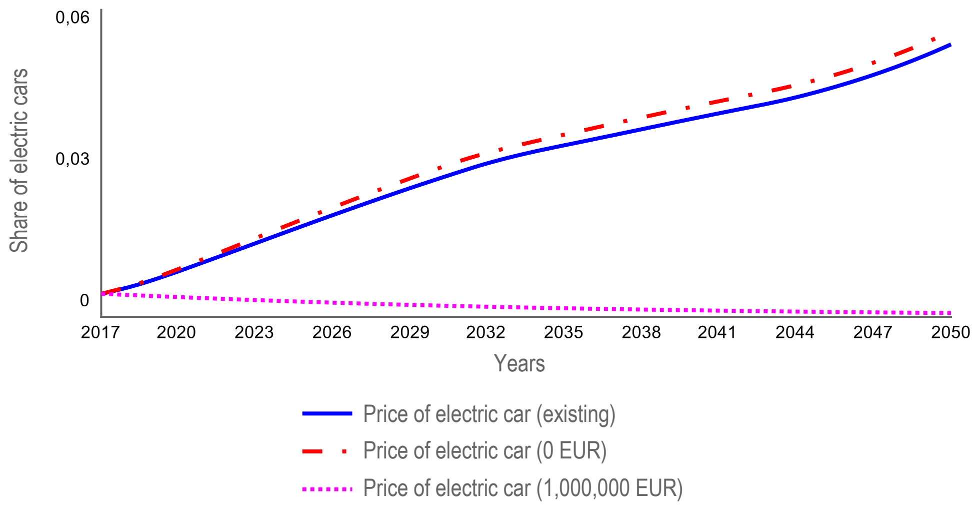


Fig. 2.24. Impact of the price of electric car on the share of electric cars

The impact of different vehicle prices on the distribution of resources used has been tested in the model. Figure 2.24 shows an example from testing of changes in prices of electric cars. It can be seen that with the current price level, the rate of development of electric cars is relatively low and rises to only 5% of the total car fleet. The case when the price of an electric car is 0 euro is tested. As can be seen, the growth rate is only slightly higher than the baseline scenario. This is due to the fact that the original model assumes that the charging infrastructure remains at the level of 2017. The insufficient charging infrastructure leads to a situation that, even in the case of free electric cars, there is little interest in them, because the cost of inconveniences resulting from a lack of charging infrastructure is too high. When testing the case with an inadequately high price of electric cars, it can be seen that there is no demand for electric cars and their share decreases as existing electric cars are wearing down.

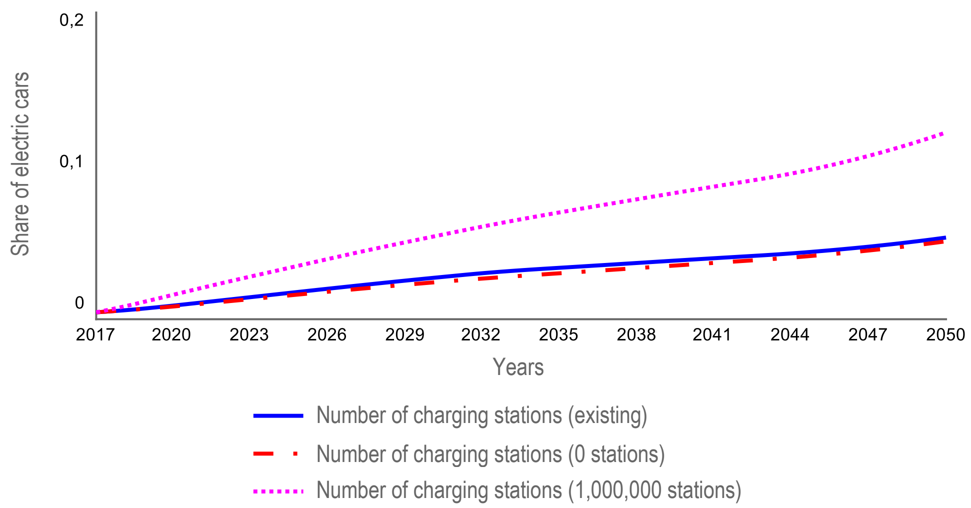


Fig. 2.25. Impact of charging infrastructure on the share of electric cars

The impact of the car charging infrastructure on the distribution of resources was also examined, as the inconvenience costs related to the insufficient charging infrastructure is one of the main obstacles to the rapid entry of new fuels into the system. The example shows the charging infrastructure for electric cars. Figure 2.25 shows that with the charging infrastructure of 2017 and non-existent electric car charging infrastructure (possibility of charging cars at home only), the share of electric cars is almost the same. If the number of rapid charging points significantly increased (1 million charging points) and the whole of Latvia was covered, the increase in the share of electric cars would be much more rapid. This is consistent with the understanding of reality.

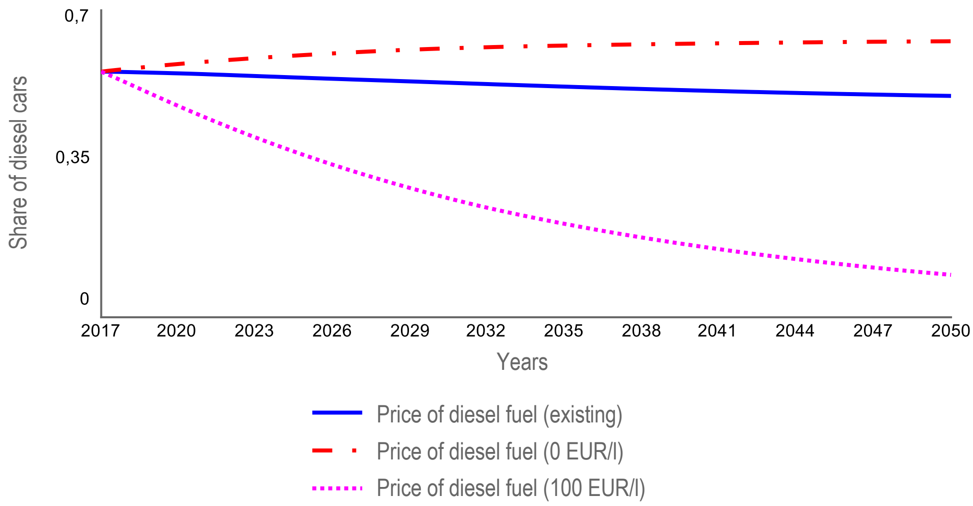


Fig. 2.26. Impact of the price of diesel fuel on the share of diesel fuel cars

Figure 2.26 shows a test that has been performed for the impact of the price of diesel fuel on the share of fuels used. Similarly, prices for other fuels were tested. As can be seen, with the current price level, the share of diesel-powered cars does not change significantly, but if the price is reduced to level 0, the share of diesel cars increases. It does not reach 100% because other cost items remain. By significantly increasing the price of diesel fuel, it can be seen that the share of diesel-powered cars declines rapidly.

Parameters such as upkeep and maintenance costs, operating tax, insurance costs, fuel consumption, car service life and other parameters were also tested in the transport sector.

2.3.4. Sensitivity analysis

A sensitivity analysis was also carried out in the model to see how much changes in different parameters affect the result. This chapter gives an example of three parameters – the price of natural gas, the price of biomass and investments in onshore wind turbines, and their impact on the overall system. In the sensitivity analysis, the price of natural gas was 20 EUR/MWh, the price of biomass was 10 EUR/MWh and the investment in wind turbines was 1.07 MEUR/MW. The parameters were changed between -20% and +20% of the initially defined value.

The sensitivity analysis assessed the impact of changes in parameters on electricity production and district heating and the how the amount of energy produced from biomass, natural gas and wind changes.

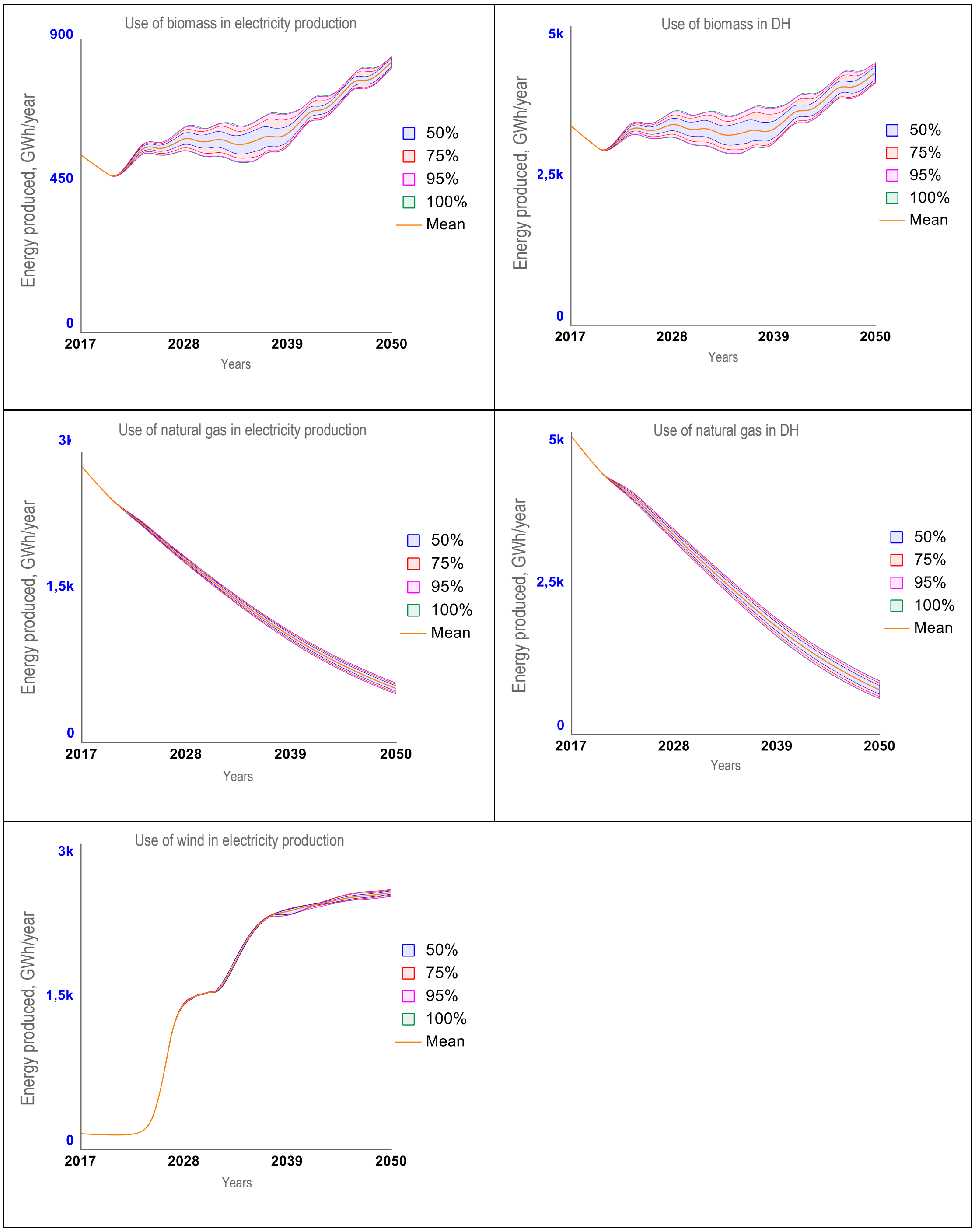


Fig. 2.27. Sensitivity analysis for changes in prices of biomass

Figure 2.27 shows that changes in the price of biomass have a significant impact on the use of biomass in electricity and heat production, but a relatively minor impact on the use of natural gas and the use of wind energy.

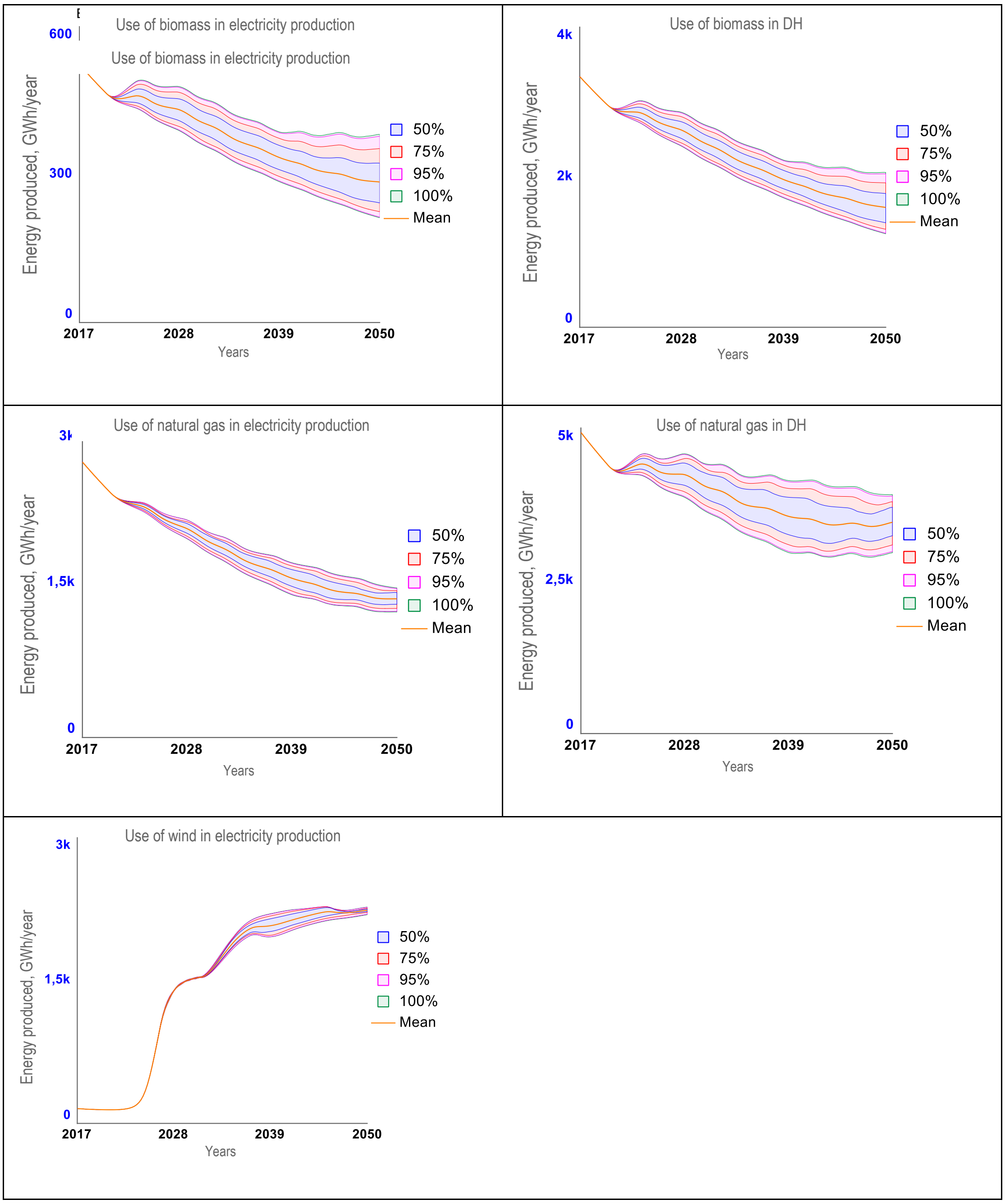


Fig. 2.28. Sensitivity analysis for changes in prices of natural gas

Figure 2.28 shows that changes in the price of natural gas have a much more significant impact on the behaviour of the system than was seen in Figure 2.27 in case of changes in the price of biomass. Changes in the price of natural gas have a significant impact not only on the use of natural gas in electricity production and district heating, but also on the extent of the use of biomass. Changes in the price of natural gas also have little impact on the use of wind energy.

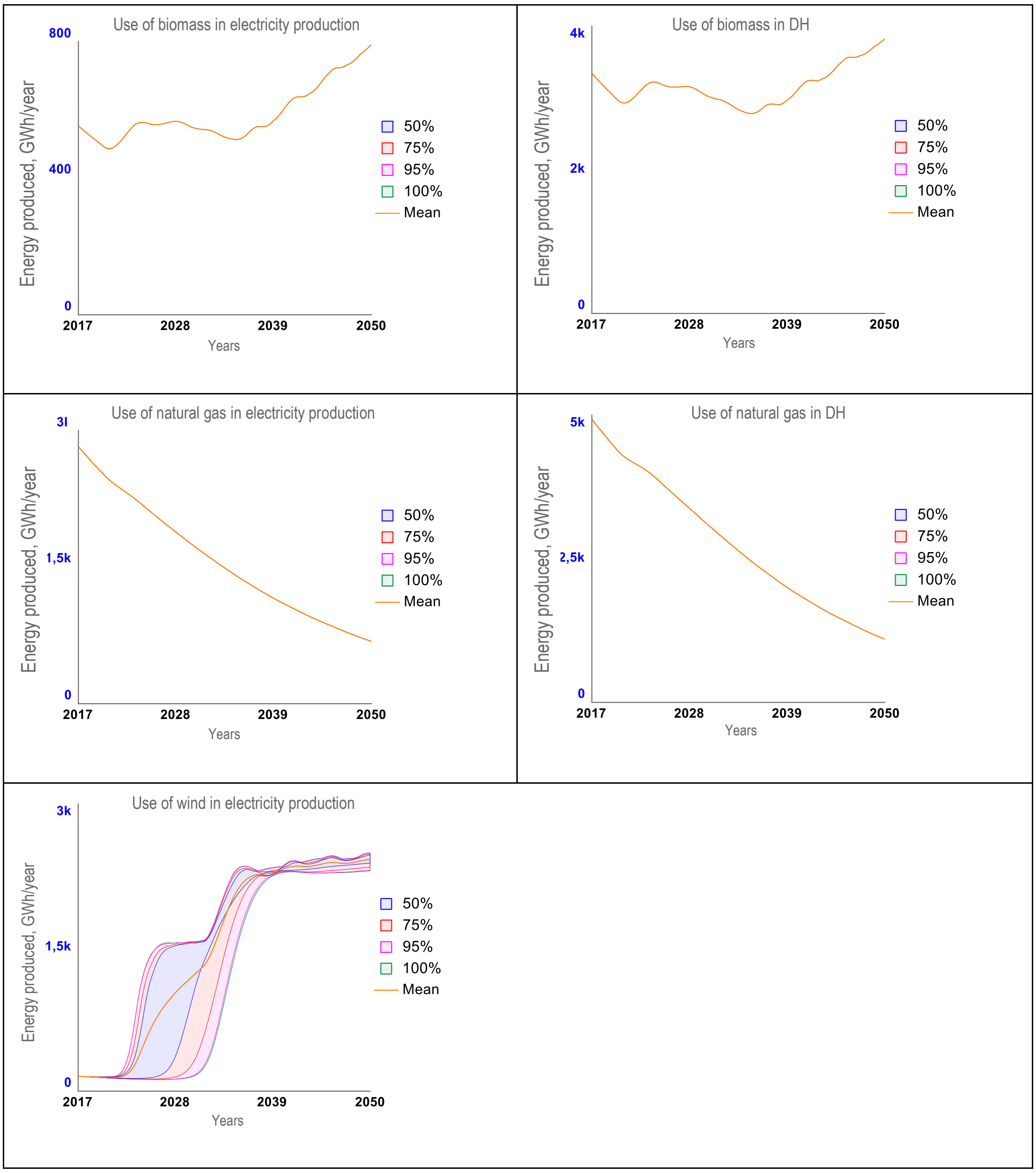


Fig. 2.29. Sensitivity analysis for changes in wind turbine investment costs

Figure 2.29 shows the results of sensitivity analysis for investment costs for onshore wind turbines. As can be seen from the figure, the costs of wind turbines have a significant impact on the use of wind energy in electricity production, but there is virtually no impact on the use of biomass and natural gas. This is due to the fact that natural gas and biomass compete with each other mainly in the heating sector, and cogeneration is only created if there is a heat load to cover while wind turbines are installed independently of the heat load. For wind turbine investments, the biggest impact is directly on the speed of wind energy deployment, not the amount of final energy, as final energy is limited by the availability of areas.

CONCLUSIONS

The created SD model has been verified using different verification methods to check that both the model structure and the behaviour adequately match the real conditions.

The extreme conditions tests carried out show that the model tends to maintain a balance at different extraordinary parameter values, such as significantly higher or lower numbers of new or used passenger cars. For example, if the used car stock is originally 0 but the value of the new car stock is infinitely high, the number of new cars is rapidly reducing as a result of car ageing and is moving to the used car stock. New cars are not purchased because the number of existing ones exceeds demand significantly. What slows down the achievement of balance is the defined car service life, which is long enough for the system not to be able to reach a balance quickly enough.

Dimensional consistency tests were carried out during development of the model. In the *Stella Architect* modelling tool used, the dimensional consistency test is performed automatically, and the programme points to the erroneous places where either the equation is incorrectly written or an incorrect dimension has been entered for one of the input parameters. This allows for timely identification of errors resulting from the input of erroneous formulas and allows the necessary modifications to the model to be made in a timely manner.

A comparison of the results of the model with historical values was carried out to assess the behaviour of the model. Indicators for which historical data are more accurate were used as the main reference parameters (amount of heat produced in statistical regions, amount of electricity produced in statistical regions, electricity produced by resource in statistical regions, number of renovated multi-apartment buildings, transport fuel prices and fuel consumption for transport). Although modelled values vary in individual years, the overall development trends for modelled values and the real indicator values match. Since the task of a SD model is to model trends rather than exact values, it can be considered that the built model is capable of successfully forecasting future development of energy sector

An extreme policy test was carried out to check whether the behaviour of the modelled system matches what was expected in extreme circumstances. It was tested how typical values of various elements affect the behaviour of the system and whether it matches the understanding of how the system should respond to changes in parameters. Extreme policy tests have been carried out by assessing district heating and electricity production in case of different changes in investment and resource prices, the heat insulation rate in case of different changes in factors, as well as the consumption of transport fuels in case of different input data values.

The results of the verification tests show that the model structure developed and behaviour accuracy are sufficient to analyse the impact of various policy instruments on increasing the potential for the integration of renewable energy sources in the future phase of the project.

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