D6.2

Regional Energy Security Case Study of the Baltic region and Finland

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About this report

This report presents a comprehensive analysis of energy security in the Baltic region (Estonia, Latvia, and Lithuania) and Finland in the context of energy transition. This report has been undertaken under WP6 of the REEEM project "Energy System Integration", and constitutes Deliverable D6.2 "Regional Energy Security Case Study report". This report is the outcome of a collective effort of the REEEM consortium.

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About REEEM

REEEM aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. This project is developed to address four main objectives: (1) to develop an integrated assessment framework (2) to define pathways towards a low-carbon society and assess their potential implications (3) to bridge the science-policy gap through a clear communication using decision support tools and (4) to ensure transparency in the process.

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Summary

Energy security is defined as "the ability of the energy system to uninterruptedly supply energy to consumers under acceptable prices and to resist potential disruptions arising due to technical, natural, economic, socio-political and geopolitical threats". Energy security is one of the most important priorities of the EU energy policies and in the Baltic States.

Energy security analysis in this REEEM project study was based on mathematical modelling of prospective energy sector development and functioning. Various possible disruptions were modelled to assess the resistance of the planned energy system to possible threats. Disruptions were generated taking into account their possible scale (amplitude) and probability.

Measures that ensure energy security have to be foreseen already at the energy planning stage and timely put into practice. In this research, energy security measures are selected in accordance with the real conditions of the functioning of the energy system. Energy security in Estonia, Finland, Latvia, and Lithuania is considered in the context of the development of the energy sector operating under market conditions that determine the cost-effectiveness of different individual energy generation sources as well as the attractiveness of energy security measures. Environmental restrictions associated with climate change mitigation as well as country specific and EU energy policy requirements also are taken into account.

Enhanced multiregional mathematical model for analysis of energy sector prospective development and operation is used in the study to assess technological changes in the system and foresee necessary energy security measures. The major enhancement is related to the detailed modelling of reservation services in the system, balancing of intermittent electricity generation from renewable energy sources, as well as to detailed representation of energy system operation regimes. For the proper assessment of reservation services, the need and supply of frequency containment reserves, frequency restoration reserves and replacement reserves are modelled in detail. Balancing of variable electricity generation from renewable energy sources is based on renewable energy generation probability curves. For detailed representation of operation regimes increased seasonal, diurnal and spatial resolution, as well as modelling of multiple fuel use in power plants and boiler houses is used.

Three energy security scenarios are analysed in the study. They are based on Base and HighRES pathways analysed in the REEEM project. Harmonization of the energy security analysis in the Baltic States and Finland with the global analysis of energy system development at the European Union level, is based on exchange of ideas among researches on the modelling principles, exchange of initial information about energy systems, result of the TIMES PanEU model and feedback provided.

Energy security issues in the Baltic States are largely related to the electricity system. Although positive from a diversification point of view, significant share of intermittent electricity generation (in particular wind) creates additional energy security challenges as it requires the power system to maintain sufficient balancing capacities at all time. Balancing power obtained via interconnectors from available sources in neighbouring countries, gas

turbine CHPs, gas turbine power plants and plants with internal combustion engines are the most cost effective measures to reduce the generation intermittence problem.

Substantial amount of electricity imports from third countries to Baltic countries together with possible malfunctions of individual elements of the electricity system is another energy security concern because it requires large reserve capacities. The results of the case study suggest that the number of interconnectors and their throughput capacities, used for electricity trade between countries as well as for providing balancing and reservation services, should be maintained or even extended. Existing fossil fuel power plants, currently not competitive in the electricity market can still be a cost-effective option to provide reserve services and ensure energy security in the transition period.

The choice of energy security measures is a challenging task due to both the broad variety of threats to be addressed and the need to ensure that the benefits for the national economy due to increased energy security exceed the costs of energy security measures. Moreover, the implementation of energy security measures is a challenge itself, since some measures require additional policy measures or market mechanisms to be implemented.

1 Introduction

The REEEM project[1] aims to gain a clear and comprehensive understanding of the system-wide implications of energy strategies in support of transitions to a competitive low-carbon EU energy society. Along with sustainability, affordability and efficiency, energy security is considered as one of the key issues in the provision of energy services. Energy security is also one of the most important priorities of energy policy in the EU and particularly in the Baltic States.

Energy security is defined as "the ability of the energy system to uninterruptedly supply energy to consumers under acceptable prices and to resist potential disruptions arising due to technical, natural, economic, socio-political and geopolitical threats". This report presents a comprehensive analysis of energy security in the Baltic region (Estonia, Latvia, and Lithuania) and Finland in the context of energy transition. Energy security analysis in this study was based on enhanced mathematical modelling of prospective energy sector development and functioning linked with probabilistic model used to assess the resistance of the planned energy system to possible threats.

The report is structured as follows: the remaining part of the introduction presents the concept of energy security, the second part of the report provides an overview of the past research related to the energy development and energy security in the region, the third part is focused on the methodology, fourth part presents modelling assumptions, scenarios, and results, while the main conclusions are listed in the fifth part.

The energy security research is continuing in the REEEM project: the additional analysis on widely accepted energy security indicators in the energy system context (TIMES model will be applied for this analysis) will be a part of deliverable D1.2b Integrated Impact report.

1.1 What is energy security?

Energy security is a complex and multidimensional concept that has evolved over time, starting its early conceptualization, following the 1970s oil crises and concerns on fossil fuel import dependence. Lately, it encompasses increasingly diverse and interdisciplinary issues, such as affordability, social acceptance, and environmental impacts. Consequently, energy security is an increasingly popular research subject.

Various research articles concentrate on defining and measuring energy security, e.g. [1]–[5], but no consensus has been reached in either composing a clear definition or an indicator that would be useful in comparing and assessing energy security in different countries. Regarding the lack of a clear definition, however, there is no lack of attempt: Ang et al. [1] found 83 different definitions for energy security in academic literature. For instance, Cherp and Jewell [6] define energy security as '*low vulnerability of vital energy systems*', and Ren and Sovacool [7] define it as '*equitably providing available, affordable, reliable, efficient, environmentally benign, proactively*

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[1] www.reeem.org

governed and socially acceptable energy services to end-users'. The lack of a useful metric to capture energy security (i.e. a composite indicator), on the other hand, has to do with the complex nature of energy security. Energy security includes dimensions that are very difficult to compare with each other, such as self-sufficiency, system balance, and the long-term impacts of climate change. As Böhringer and Bortolamedi [8] puts it, a money-metric translation of changes in energy security indicators that could make these amenable for a rigorous economic cost-effectiveness assessment is missing.

One way to assess the different dimensions of energy security is the four A's: availability, accessibility, affordability and acceptability [9]. However, the approach has also been criticised for not addressing the following three questions, which are derived from the proposition that energy security is an instance of security in general [6]:

- Security for whom?
- Security for which values?
- From what threats?

A framework developed by the Global Energy Assessment (GEA), on the other hand, examines energy security through three different perspectives: sovereignty, robustness and resilience [10]. Ang et al. [1] found seven major themes that repeated in most energy security related studies: energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. However, few studies comprise all these dimensions. Therefore, due to the difficulties regarding the definition and dimensions of energy security, it is sensible to analyse energy security of the system as such taking into account its unique features.

With regard to the energy security in Finland and in the Baltic countries, the most relevant energy security dimensions are generation adequacy, self-sufficiency and system costs, with the underlying pressure to decarbonise the energy systems. All these dimensions fall to the definition of energy security as "the ability of the energy system to uninterruptedly supply energy to consumers under acceptable prices and to resist potential disruptions arising due to technical, natural, economic, socio-political and geopolitical threats.

Generation adequacy and self-sufficiency are discussed briefly in the following sections.

1.2 Generation adequacy

Generation adequacy refers to the ability of all the generating units as a whole to meet the energy demand at all times. Concerns over generation adequacy in the Nord Pool area (Finland, Sweden, Norway, Denmark, Estonia, Latvia, Lithuania) have increased notably during the past decade. For example, the estimated available capacity during winter peaks in Finland still exceeded the demand peaks in the early 2000s [11], whereas The country imported over 4,200 MWh/h of electricity to meet the demand peak in 2016 due to retirement of existing capacity. Moreover, the European Network of Transmission System Operators for Electricity (ENTSO-E) published a Mid-term Adequacy Forecast in late 2017 [12] with a bleak outlook on generation adequacy in Finland, which revived the concerns after the milder winter in 2017. However, the Finnish Transmission System Operator (TSO)

Fingrid together with the other Nordic TSOs published a report in April 2018 that corrected some of the estimates in the forecast by ENTSO-E, stating that generation adequacy in Finland is in fact much better than that estimated by ENTSO-E [13]. The developments are connected to the ongoing energy transition: concurrently with the gradually decreasing thermal capacity, weather-dependent generation, particularly wind power, has increased significantly in Nord Pool area and in Europe, annual demand peaks have grown, and the electricity price level of 2012–2017 has not encouraged investment in new generation capacity in the Nord Pool area.

With regards to Estonia, more than 80% of its electricity is produced by domestic oil shale and a majority of it in the Narva Power Plants. Most of these plants were constructed between 1959–1973 and some of them will probably face decommissioning by 2024 [14]. Therefore, the availability of thermal capacity and hence the self-sufficiency of electricity supply and generation in Estonia in 2030 remains uncertain.

Many current concerns in the Finnish and Baltic energy markets are in fact connected to generation adequacy. For example, the future role of combined heat and power (CHP) and the impacts of severe droughts in the Nord Pool area are also issues pertaining to generation adequacy. These themes have been studied recently and are presented in the following sections. Generation adequacy is very strongly tied to another dimension of energy security, that of system costs. Technically, there are no obstacles for commissioning abundant reserves and excess capacity. However, the issue has to do with finding the best compromise between economic optimisation of the system and an acceptable level of security of supply.

1.3 Self-sufficiency

Self-sufficiency in power generation is a two-sided issue. One side is the self-sufficiency regarding capacity, generation adequacy, which was discussed in the previous section. This practically means whether electricity imports are needed in order to meet the demand during peak times. The question is ultimately of political nature: how much e.g. Finland should be willing to invest in its power sector in order not to be a net importer of electricity from the main source of import, Sweden, and, more importantly, why? The other side is self-sufficiency regarding primary energy and energy fuels. The EU imports over half of its consumed primary energy [15]. Consequently, the European Commission (EC) has set energy security as one of its key energy policy targets. In response to the European gas supply concerns in 2006 and 2009, the EC released an Energy Security Strategy in May 2014 [16]. In order to improve energy security in Europe, the strategy proposes e.g. increasing energy efficiency and energy production within the Member States, development of an integrated European energy market, and reducing the dependence on one supplier, particularly on Russia [16]. The last item is particularly interesting, as Finland and the Baltic States share borders, history and significant energy trade with Russia. Moreover, the Baltic power systems still operate synchronously with IPS/UPS area of former Soviet Union.

As with generation adequacy, self-sufficiency related concerns are strongly tied to a variety of trade-offs. Finland and the Baltic States could deploy all the domestic resources available, such as wind power and biomass, in order to reduce dependence on imported energy. However, energy security is by nature balancing between different priorities such as system costs, emissions, sovereignty, system balance, and trade balance deficits, to name a few. The following sections include academic research papers that analyse self-sufficiency of Finland and the Baltic States.

2 Energy security related research in the Baltic States and in Finland

2.1 Trouble Ahead? An Interdisciplinary Analysis of Generation Adequacy in the Finnish Electricity Market

Jääskeläinen and Huhta analysed the debate regarding generation adequacy in Finland after the record-high demand peak in 2016 [17]. They analysed the market situation during the peak and modelled the resilience of the system in case one or more major power system components failed at the same peak time. The system modelling was conducted with the EnergyPLAN simulation tool. Moreover, the article analysed the investment prospects in generation capacity and the Finnish legislation with regards to subsidising generation capacity investment.

The article concluded that despite the concerns in 2016, the system still had much available capacity during the peak and a variety of fail-safe mechanisms to cope with unexpected faults. However, the investment profitability analysis conducted by Jääskeläinen and Huhta signalled a bleak outlook on investment with the electricity price level of 2012–2017: the cheapest generation methods were wind power and bio-CHP, which both had a levelised cost of electricity (LCOE) almost two times too high in order to be feasible under the current market conditions. From a legal point of view, justifying intervention in the market-based approach to supply the demand for electricity needs legitimate need to do so. Therefore, with the underlying uncertainty regarding the issue, subsidisation of generation capacity due to a plausible generation inadequacy in the future, is likely not to comply with EU law.

2.2 Future of cogeneration in Finland

Combined heat and power (CHP) generation accounts for a notable share in the Finnish electricity generation and it is expected to sustain this trend, considering the Finnish Energy and Climate Strategy [18]. However, several simultaneous trends set the future of Finnish CHP generation on an ambiguous path. Closer to 3,000 MW of condensing capacity has been decommissioned or mothballed in Finland since year 2000 and with the electricity price level of 2012–2017, CHP capacity would be next in line. This has raised concerns regarding generation adequacy in Finland.

Helin et al. analysed the energy security impacts in case a notable share of Finnish CHP capacity was decommissioned by 2030 [19]. CHP plants are a source of capacity, flexibility and inertia with contribution to both self-sufficiency and generation adequacy. However, the article concludes that there are currently no clear price signals indicating a scarcity of any of the aforementioned, and the planned new nuclear power plants and new crossborder transmission lines should compensate for a significant decrease in the Finnish CHP capacity. Moreover, in line with the new Energy and Climate Strategy, the most probable fuel for new CHP plants in Finland would be biomass. The amount of biomass needed to substitute the retiring CHP production based on coal and natural gas, however, is dubious when considering sustainability and climate change mitigation. One conclusion of the article is that limiting the analysis to the Finnish energy system, leads to local optimisation: if decommissioning a CHP plant in Finland results in a corresponding increase in separate heat and power generation with higher emissions in the neighbouring energy systems, it is questionable to justify whether this is a sustainable pattern.

Jääskeläinen et al., on the other hand, analysed the economics of biomass-based CHP generation in Finland and the legislation regarding plausible subsidisation of CHP capacity on the basis of generation adequacy [20]. The article concluded that, despite the current feed-in tariff mechanism, the electricity price level of 2012–2017 is not enough to justify an investment in CHP plant instead of a heat only boiler (HOB). Moreover, none of the analysed price development scenarios justified an investment in a steam boiler with the turbine investment option later on. Regarding the possibilities of State financing in the interest of generation adequacy, legal analysis in the article indicated that it is unlikely to comply with EU law.

2.3 Impacts of a severe drought in the Nord Pool area

The whole Nord Pool area relies heavily on hydropower generation. Despite hydropower being among the most flexible generation methods, there can be significant fluctuation in annual generation volumes based on the hydrological conditions. Thus, Jääskeläinen et al. analysed the impacts of a severe drought on generation adequacy in Finland [21]. The study modelled and applied the hydrological conditions of the worst drought of the century (1939–1942) in the present and future Finnish energy system. The drought was modelled with the Finnish Environment Institute's Watershed Simulation and Forecasting System. In addition to weekly power generation, maximum generation during peak times was estimated. This data was used as input in the energy system simulations, which were conducted with the EnergyPLAN simulation tool. The following Fig. 2.1 presents the differences in Finnish hydropower generation during the drought and good hydrological conditions.

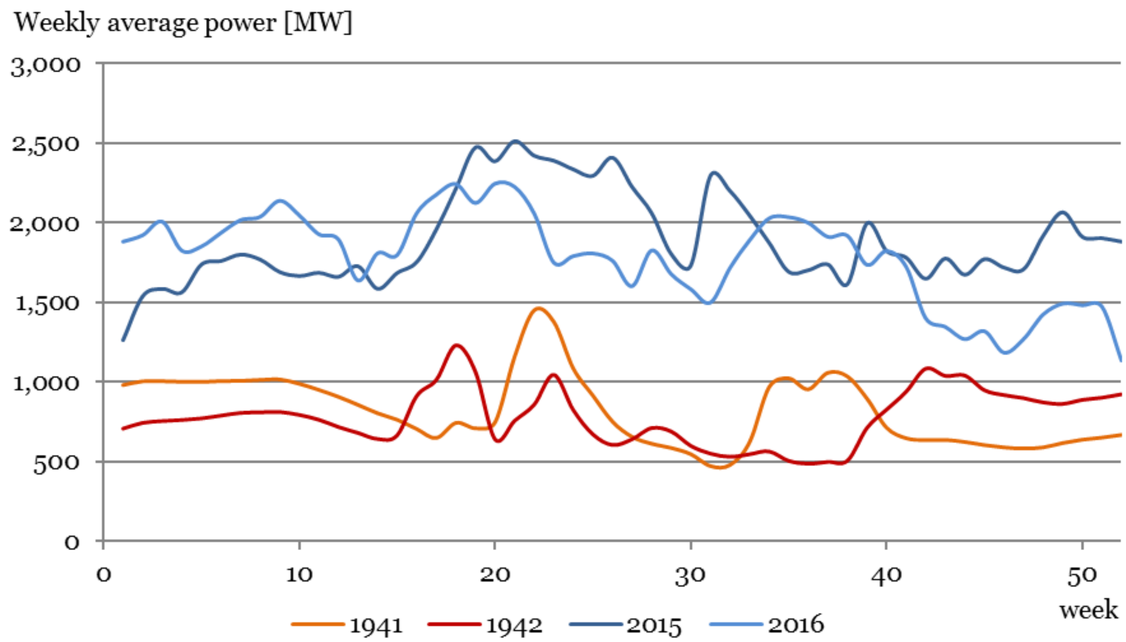


Figure 2.1. Weekly average hydropower production in Finland with the hydropower capacity of 2016 and the hydrological conditions of 1941–1942 and 2015–2016 *[21]*.

The article concluded that the Finnish energy system could withstand a similar drought occurring in Finland without severe implications. However, a similar drought occurring also in Norway and Sweden would cause severe problems in the Nord Pool area. Finland has become a net exporter of electricity to Sweden already during less severe droughts, and therefore the Finnish power system could not count on import from Sweden to meet the annual demand peaks.

Estonia has a modest hydropower capacity and is currently self-sufficient in supplying its demand during peak times. However, Estonia's net electricity import from Finland was 5.0 TWh in 2015 and net export to Latvia was 5.9 TWh, which is a significant flow of electricity comparing to Estonia's own annual consumption of 7.4 TWh [14]. On the other hand, Latvia and Lithuania, have notable hydropower capacities, and a transmission line between Lithuania and Sweden, NordBalt, was commissioned in late 2015. Therefore, a drought in Sweden would affect Finland also indirectly via the availability of electricity import from the Baltics.

2.4 Utilization of a Power Market Simulator in Power Adequacy Assessment

Jarkko Tulensalo conducted a probabilistic analysis method for the assessment of generation adequacy in the Baltic Sea market area based on the use of a power market simulator and Monte Carlo simulation in his master's thesis [22]. The method took wind power, hydro inflows, demand, CHP and outages of both power plants and interconnectors during each hour of the year into account stochastically. Moreover, a stochastic outage generation tool was introduced to model outages according to a lognormal distribution function. The applicability of the proposed method was evaluated by assessing the generation adequacy of Finland with two case studies, which showed that the method produces sensible results. The study used an EMPS (EFIs Multi-area Power scheduling Model) and a BID3 model developed by Pöyry to conduct the analysis. The analysis provides different adequacy indices, which are presented in the following Table 2.1:

Table 2.1. Generation adequacy indices

Abbreviation	***Description***	***Unit***
ENS	*Energy Not Served*	*MWh/year*
LOLP	*Loss of Load Probability*	-
LOLE	*Loss of Load Expectancy*	*h/year*
Remaining Capacity	*Remaining Capacity*	*MW*
ELCC	*Effective Load Carrying Capacity*	*MW*

According to the results, generation adequacy in Finland decreases during the years 2012–2023 as a result of decreasing thermal capacity of Finland and its neighbouring countries. The second study showed that 800 MW reinforcement on the interconnector capacity between North Sweden and Finland would significantly improve generation adequacy in Finland. Tulensalo concludes that the method can be used as a tool for long-term power system adequacy analysis in various applications.

2.5 Finland's Dependence on Russian Energy—Mutually Beneficial Trade Relations or an Energy Security Threat?

Jääskeläinen et al. analysed energy trade between Finland and Russia and whether Finland's notable dependence is an energy security threat [23]. They applied the interdependence framework to analyse the energy systems and energy strategies of Finland and Russia, and the energy security issues related to the import dependence on one supplier. Moreover, they analyse the plausible development of the energy trade between the two countries in three different energy policy scenarios until 2040.

The applied model consists of three dimensions: physical energy flows, the dominance of the energy agenda in mutual relations, and the influence of the European Union. Thus, due to the complex nature of the trade relations, the analysis includes societal and geopolitical aspects in addition to the techno-economic analysis. The article found no acute energy security threats through purely techno-economic analysis, despite the fact that the Finnish-Russian energy relations are constantly being discussed on Finnish and Russian media and in diplomatic meetings. Finland imports all of its natural gas and significant shares of its oil, coal, uranium and electricity from Russia. Disturbances in the supply of electricity and natural gas are the most tangible, as they are connected to the existing infrastructure. However, natural gas consumption in Finland and Russian electricity imports have decreased notably during the 2010s. For coal, oil and uranium, there is a variety of suppliers globally. Moreover, Finland has storages for all of these fuels apart from natural gas, but the critical demand for natural gas can be substituted with oil. Therefore, the article concludes that disturbances in the fuel supply would not cause an immediate energy crisis. Furthermore, the primary energy import dependence should decrease in all scenarios analysed in the paper.

Regarding energy security issues beyond techno-economic analysis, the issue is much more complex. There are connections and projects that are highly political in nature, such as the Fennovoima nuclear power plant that Rosatom is about to build in Finland. Therefore, there are societal, political and economic trends, risks and feedback loops that could affect the Finnish energy security.

2.6 Electricity independence of the Baltic States: Present and future perspectives

The Baltic States were part of the former Soviet Union in the past, which left a strong energy dependence on Russia in terms of energy resources, electricity interconnection infrastructure, and financial flows. Bompard et al. [24] developed a framework with methodologies to assess the electricity independence of the Baltic States. They provided three indices: *adequacy*, *security* and *economic factor*. The proposed framework and methodologies are applied for assessing the electricity independence of the Baltic States in 2014 and future scenarios for 2020 and 2030. The dimensions of the framework and methodology are presented in the following Fig. 2.1.

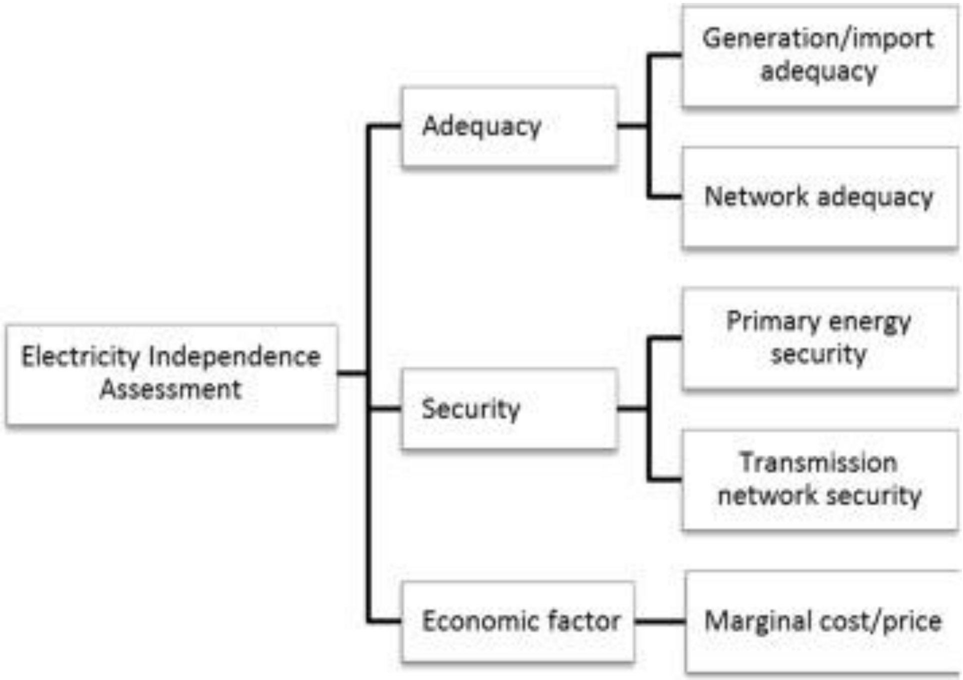


Figure 2.2. Framework and methodology of electricity independence assessment [24].

As common practice in energy security related research, no single indicator or conclusion could be provided by the study [24]. This is due to the complex nature of energy security and the various dimensions embedded in the analysis, and any final decisions are left to political decision-~~markers~~makers. However, the main conclusions of the analysis are the following:

- Generation is anticipated to be adequate in the coming decades, even though generation adequacy in 2030 might be lower than in the current scenarios;
- Network adequacy is expected to remain at satisfactory levels even while the network might experience local security and adequacy issues;
- The planned network developments will improve the transmission network security in 2020;
- Network security level in 2030 will be lower than the current security level;
- The expected cost of electricity will be slightly lower.

2.7 Future of Lithuanian energy system: Electricity import or local generation?

Norvaiša and Galinis model the long-term development of the Lithuanian energy sector with the goal of analysing the arguments for self-sufficiency against those for increasing dependence on neighbouring energy systems [25]. Lithuania is an interesting country with regards to its energy system, as its import capacity exceeds that of its own power production.

The article applied the MESSAGE modelling tool to create a detailed mathematical model of the Lithuanian energy system. The fundamental principle of this modelling software is the optimisation of an objective function, which is the total costs of energy system in this case. The model concentrated on the following components: the electricity supply system, the centralised heat supply systems of largest towns, and all possible fuel supply alternatives, etc. However, conclusions focused on the electricity supply system and the timeframe is until 2050.

Results of this analysis show that a high level of electricity import is economically the most attractive option to supply electricity for Lithuania. However, the high share of electricity import makes the country vulnerable and is an energy security issue as such. Various factors in the neighbouring markets could impact the availability of electricity import. However, practically any measures taken to improve the country's security of supply results in an increase in the system costs. Norvaiša and Galinis conclude that additional costs of energy system development for year 2050 may be defined as costs of supply of security and are following in comparison with business as a usual scenario:

- *~6.4 EUR/MWh, when electricity supply security is ensured by "installed capacities" able to generate 50% of needed electricity, and electricity import conditions are favourable;*
- *~13 EUR/MWh, when "installed capacities" ensure capability to generate 100% of needed electricity, and electricity import conditions are favourable;*
- *~15 EUR/MWh, when electricity supply security is ensured with construction of Visaginas Nuclear Power Plant (NPP);*
- *~28 EUR/MWh, when "non-nuclear generation" alternative is realised.*

Self-sufficiency in power production is technically possible, but it comes with a cost. Lithuania does not have political or economic leverage to avoid the influence of global markets. Therefore, Lithuania should focus on flexibility, effectiveness and rationality in the energy sector and be prepared to adapt to the changing local and global conditions. The political decision-makers need to balance between the trade-offs between system costs and self-sufficiency.

2.8 Sustainable energy development – Lithuania's way to energy supply security and energetics independence

Katinas et al. analyse Lithuania's possibilities to increase security of supply and self-sufficiency via increasing the use of domestic renewable energy sources [26]*. The article reviews the energy system of Lithuania thoroughly, including statistics of primary energy, power sector, and energy policy, and presents the recent developments in the energy sector. The article recognised the high need for investment, the lack of financial resources to implement governmental policies, and long payback periods as the main obstacles of increasing the share of renewable energy sources.*

2.9 Review of and comparative assessment of energy security in Baltic States

Zeng et al. analyse trends in energy security in Estonia, Latvia and Lithuania [27] in the period of 2008–2012. The aggregate measures of energy security are devised by the means of multi-criteria decision-making (MCDM) techniques. The indicators of energy security are based on the priorities set in the EU energy policy. The approach is supplemented by the restricted models, where certain bounds are defined for groups of criteria, describing energy security in economic, energy supply chain, and environmental dimensions. Zeng et al. apply the DEA-linked approach by Kao and a modified Simple Additive Weighting (SAW) approach by Wang and Luo. Both of these techniques rely on min-max (linear) normalisation.

The assessment of energy security by integrating e.g. economic, social and environmental indicators of energy security indicated that the best performing country in the analysed period is Latvia. The previous studies have favoured Estonia as the best performing country due to the lowest energy import dependence, as the country has a high share of domestically extracted oil shale. Lithuania, on the other hand, needs stronger policies to increase energy efficiency, the use of renewables, and diversification of fuel mix.

2.10 Modelling the Baltic power system till 2050

Blumberga et al. developed a dynamic energy-economy model by applying a system dynamics modelling (SDM) approach in order to evaluate changes in the Baltic energy system until 2050 [28]. The model is based on energy flows according to the national electricity mixes of Baltic States, and it calculates energy production costs of each technology taking into account national energy policies, e.g. subsidies. Nature of the modelling, including the key stocks and flows, is presented in the following Fig. 2.3.

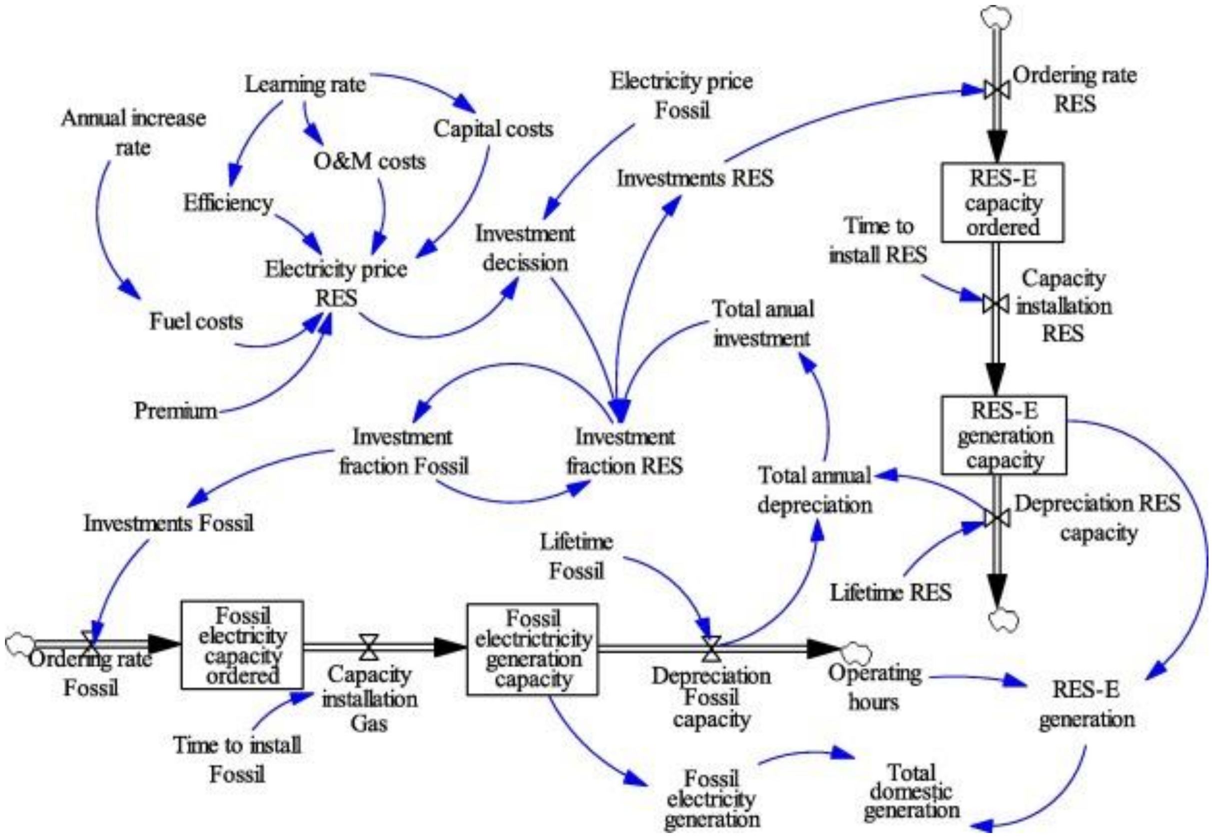


Figure 2.3. Key stocks and flows of the system dynamics modelling [28].

The installed capacity of each production form is determined based on cost estimation. Results of the modelling suggest that wind energy has the potential to acquire a dominant share in the Baltic region. This is explained via the increasing competitiveness of wind power generation costs compared to fossil fuel-based generation. Solar energy has the potential to increase its share from 2025 onwards due to decreasing generation costs. The market share of other renewable power generation methods, such as hydropower and biomass, will continue to increase, reaching their maximum between 2020 and 2030. Biogas plants will not reach a considerable role in electricity generation. Development of the installed power capacity in the Baltic region until 2050 is presented in the following Fig. 2.4. Installed capacities in the countries separately are presented in the article.

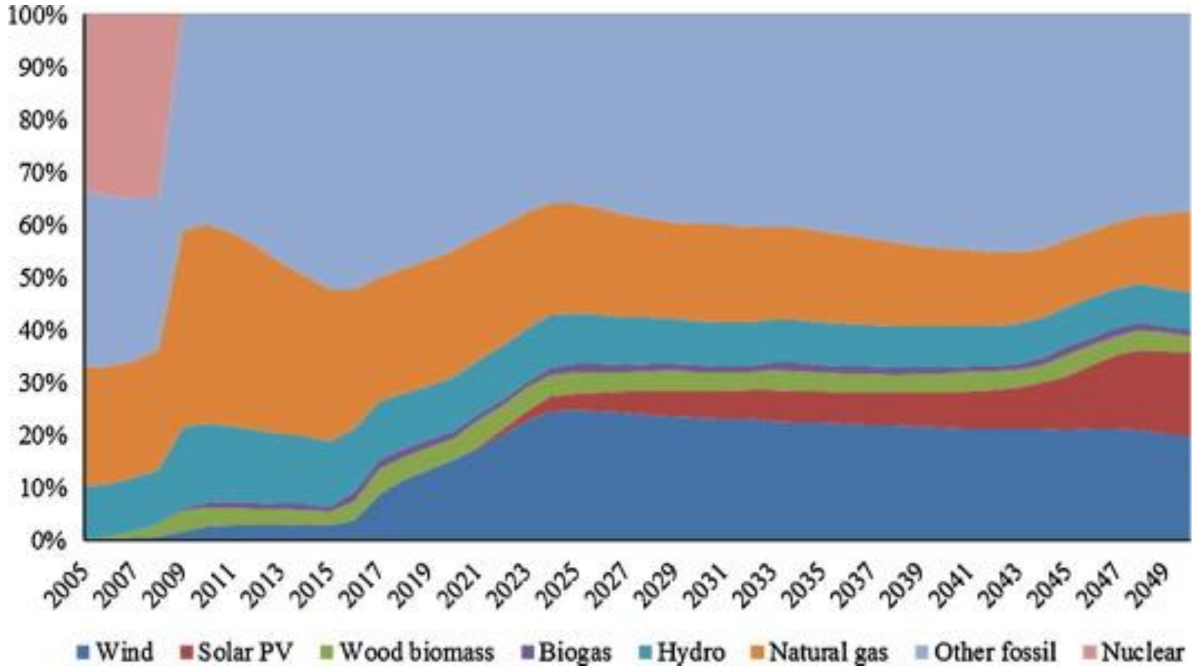


Figure 2.4. Installed electricity production forecast for Baltic States [28].

2.11 Conclusions of the literature review

As seen from the spectrum of the research in the literature review, energy security is indeed a complex and multi-dimensional issue. Moreover, it is of great importance to Finland and the Baltic States due to their cold climate and national energy resources, or the lack thereof. The aforementioned lack of a global composite energy security indicator to compare nations with each other, however, has to do with the vast differences in inter alia political environment and climate-related issues around the world. However, Finland and the Baltic States have a lot in common regarding energy security. Therefore, this study attempts to quantify energy security in the countries in different future scenarios. Methodology for the applied energy security analysis is presented in the following section.

3 Methodology for energy security analysis

The analysis of previous research has shown that energy security in the region is in most cases considered either as an additional argument in the analysis of energy system development or as a phenomenon that is analysed separately from the development of the energy sector. In the present research we focus on energy security in Finland and Baltic countries as an important determinant and analyse it in line with the modelling of energy development scenarios. Research on energy security, analysis is based on mathematical modelling of the development and operation of energy systems in Finland, Estonia, Latvia and Lithuania (Finland and Baltics), and subsequent testing of energy systems to determine their resistance to various disruptions. The technical-economic analysis of the development and operation of energy systems (see Fig. 3.1) is performed by a mathematical model created in the environment of the MESSAGE software package [29], [30]. It provides detailed results of energy systems' performance in the long-term perspective. In order to supplement case study results with energy security measure (indicator), the energy systems resistance to various disruptions is investigated by the Model for Energy Security Coefficient Assessment (MESCA) built in the OSeMOSYS modelling generator [31], [32] . This regional modelling activity, using forward and backward links, is harmonized with modelling of energy system development and functioning conducted in the REEEM project on the EU level (using the TIMES PanEU mathematical model). Harmonization (see 4.1 paragraph) is accomplished by iterative adjustments of model input parameters according to the results of other models.

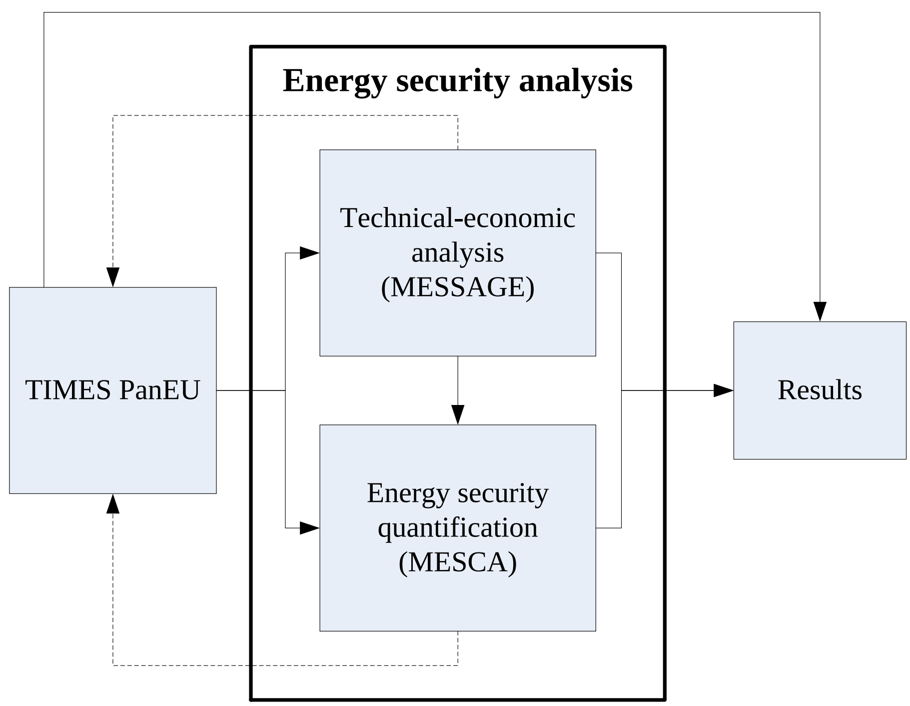


Figure 3.1. Involvement of mathematical models into analysis of energy security.

The technical-economic analysis of the development and operation of energy systems is a key activity in the energy security analysis. The impact of global factors (derived from TIMES PanEU) on the energy systems under consideration are taken into account in this study, as well as measures to ensure energy security are selected. The mathematical model of the technical-economic analysis of the development and operation of energy systems does not differ in essence from other mathematical models used for this purpose. However, much more attention is paid to the more detailed representation of operation regimes of the energy system, reservation needs and means, diversification of energy supply chains and so on. More details on the distinctive features of the analysis of the development and functioning of the energy system will be discussed in section 3.1. Chapter 3.2 will focus on the methodological principles of resistance testing of the planned energy system.

3.1 Methodological principles of the energy system development and operation analysis

3.1.1 Structure of the mathematical model

The principal structure of the regional mathematical model for the technical-economic analysis of the energy sector development and operation is shown in Figure 3.2~~Figure 3.2~~. The structure of the energy system model of a particular country is provided in Fig. 3.3.

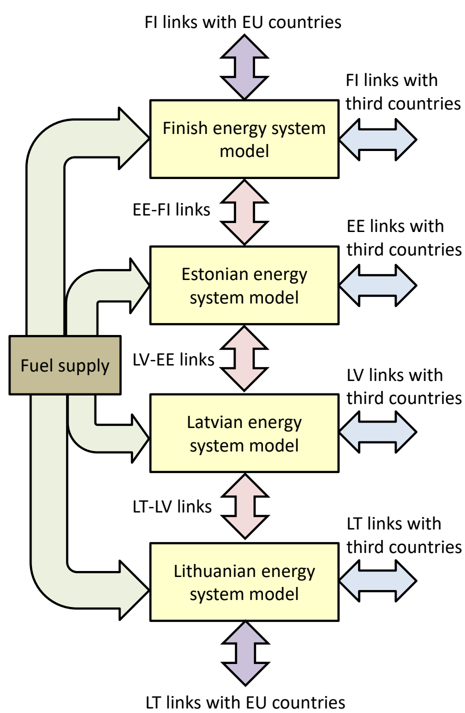


Figure 3.2. Structure of the mathematical model used in the analysis

The model presented in Fig. 3.2 and Fig. 3.3 covers electricity, district heating and fuel supply systems in three Baltic States (i.e. Estonia, Latvia and Lithuania) and Finland. All existing and possible new condensing power plants are included into the electricity system. Electricity transmission and distribution grids, as well as all energy accumulation means (hydro pumped storage plants, electric batteries) are also included into this system. The main technical-economic parameters of all the elements of the model are placed in the database of the REEEM project. Electricity system links between countries in the region, as well as links with energy systems of the third countries are represented by the throughput capacities of the power lines. Throughput capacities of these international lines change in time due to expected reorientation of the Baltic power systems from synchronous operation with IPS/UPS towards synchronous operation with power systems of the Continental Europe. Throughput capacities can be also extended if corresponding investments are made. Correct representation of international lines is very important not only for modelling of electricity flows between countries but also for a proper assessment of reservation options of large generating and transmitting units that may be introduced into the comparatively small system of the Baltic States. In this relation, reservation options of large units (power plant or international line) were seriously analysed by putting into mathematical model special approaches designed for explicit modelling of frequency containment reserve, frequency restoration reserve and replacement reserve (see Chapter 3.1.3 for a greater details).

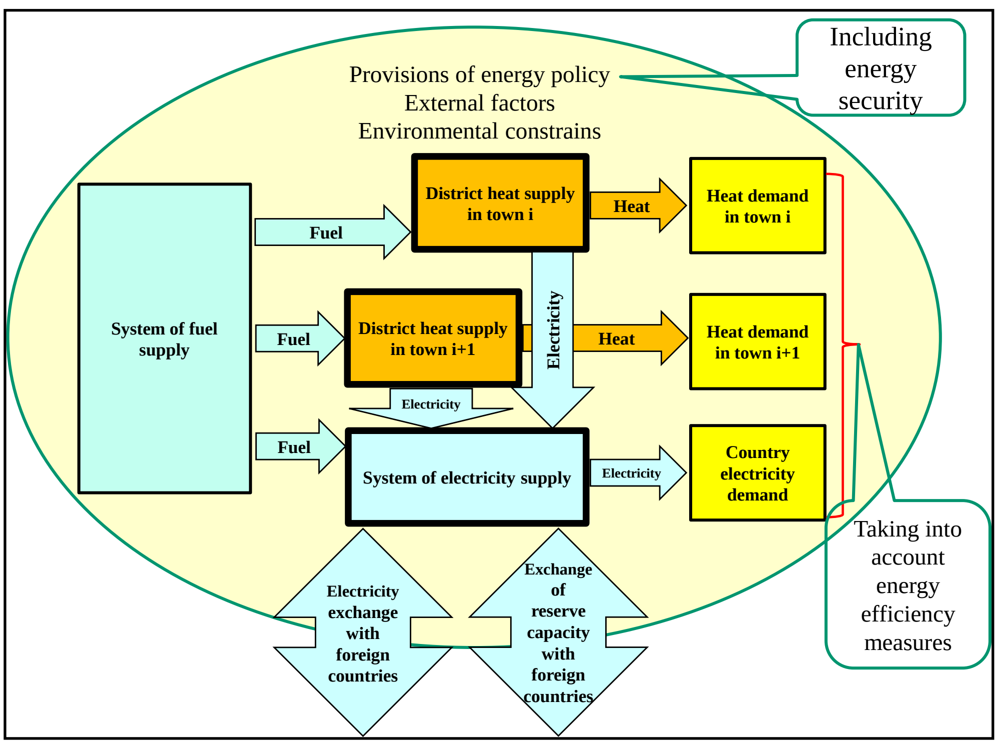


Figure 3.3. Structure of the country energy system model.

District heating systems in all Baltic countries and Finland are tightly coupled with the electricity system. Combined heat and power plants (CHP) supply or can supply a large share of the required district heat in the largest towns. In this relation, analysis of power system development cannot be done separately from analysis of CHP contribution to the future district heat supply. Supply of district heat in Lithuania is modelled for 12 separate towns and one additional option is devoted to the rest of the country. For Estonia, district heating markets are modelled for Tallinn and Viru regions, as well as for the rest of the country. District heat market in Finland is divided into three parts: very large systems representing the broader Helsinki region (Helsinki, Espoo and Vantaa cities), large district heating systems which cover all the remaining towns and industrial district heat supply systems. For Latvia, only two district heat supply markets are foreseen – for Riga city and for the rest of the country. District heating systems contain all existing and possible new heat production technologies, combined heat and power plants, heat accumulation means and heat transmission-distribution networks.

3.1.2 Modelling of electricity trade between countries

Exchange of electricity between the countries within the region and neighbouring countries is determined by taking into account the throughput capacities of lines, electricity production cost in the region and exogenously given electricity prices in neighbouring countries. Therefore in the case where electricity generation cost at a certain moment of time in the region under consideration is lower than the electricity price in the neighbouring countries, electricity is generated locally and even exported. In opposite cost/price situation – electricity is imported from the neighbouring country in which electricity price is the lowest and throughput capacity of the line allows.

The future electricity prices in the neighbouring markets are one of the important factors which could influence the development path of the electricity sector in the Baltic region. Electricity price in Scandinavian countries (Nord Pool price) will have a major impact because Baltic countries and Finland belong to this electricity market. The electricity prices in the Nordic region have historically been low due to a large share of cost-effective hydropower and nuclear in the total electricity generation balance. The average annual wholesale prices of electricity in the Nord Pool Spot exchange are shown in Fig. 3.4.

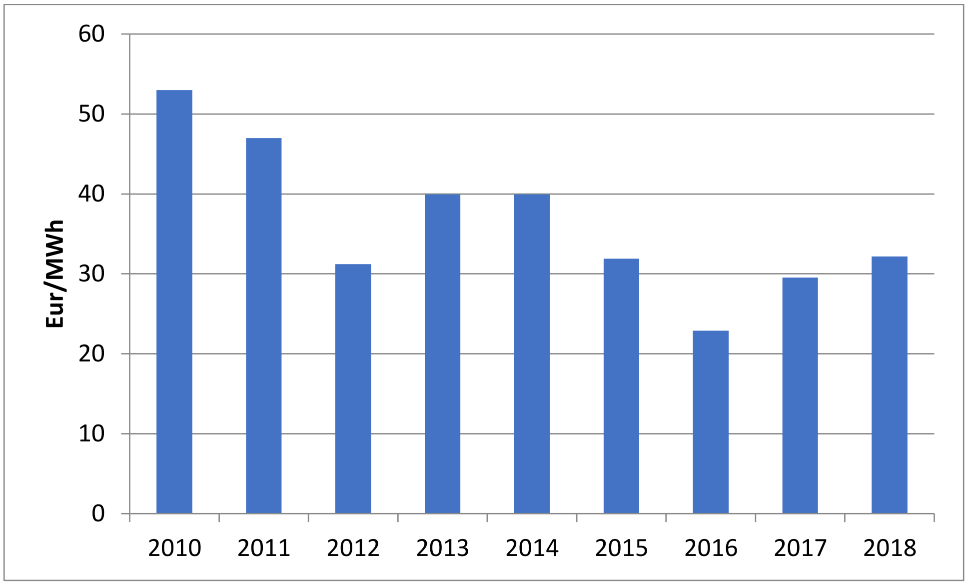


Figure 3.4. Dynamics of electricity prices in Nord Pool Spot exchange. (Yearly averages. Own calculation based on statistical data taken from https://www.nordpoolgroup.com/historical-market-data/).

Future electricity prices for energy security analysis have to be taken from models analysing the energy sector development on a much broader scale (for example, EU or even broader). Currently assumptions regarding future electricity price in neighbouring countries were based on available forecasts and statistical data about price variation within a year. Thus, yearly average electricity prices in Scandinavian countries were assumed to be grooving from 40 Eur/MWh to 50 Eur/MWh in time period 2020-2030 with further growth up to 56 Eur/MWh by 2050. Based on own investigation, the average annual price in Poland was assumed to be 4% higher and price in Russia 2% lower compared to long-term average electricity price in Scandinavian countries.

Seasonal and daily electricity price variations are taken from Nord Pool statistical data and represented in the model correspondingly to the requirements of the MESSAGE model (*Load regions for prices*). Variations of electricity prices in this representation are shown in Fig 3.5.

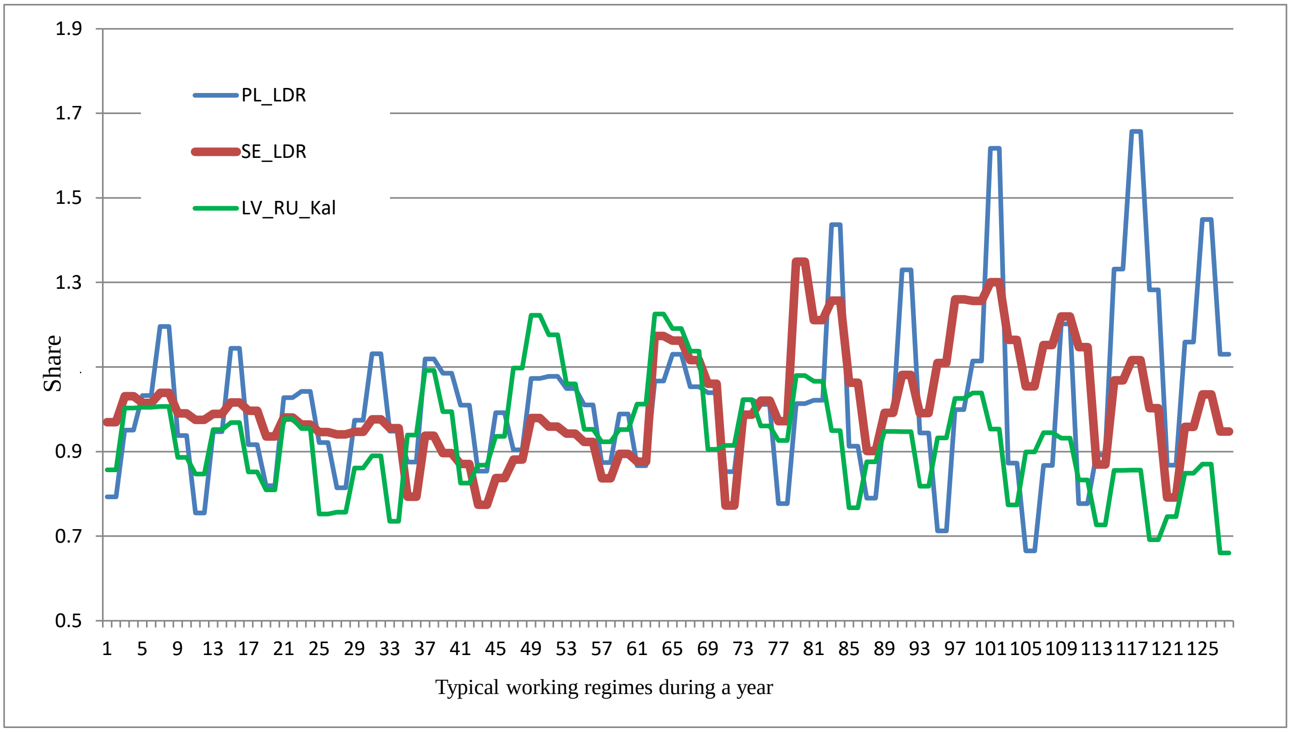


Figure 3.5. Variation of electricity prices in neighbouring countries.

3.1.3 Use of power plants and international power supply lines for supply of necessary reserve capacities

From time to time, power plants or interconnectors operating in a particular energy system go out of order. In order to avoid disruptions in generation and consumption balance and to guarantee stable operation of the system, reserve capacities are necessary to compensate those, who go out of order. The greater possible disturbance in the system occurs, the bigger need for reserve power is required. Large energy units inevitably cause reservation problems: the larger unit fails, the more reserve capacity must start operating to replace it. Power reservation principle and requirement of reserve capacities are shown in Fig. 3.6.

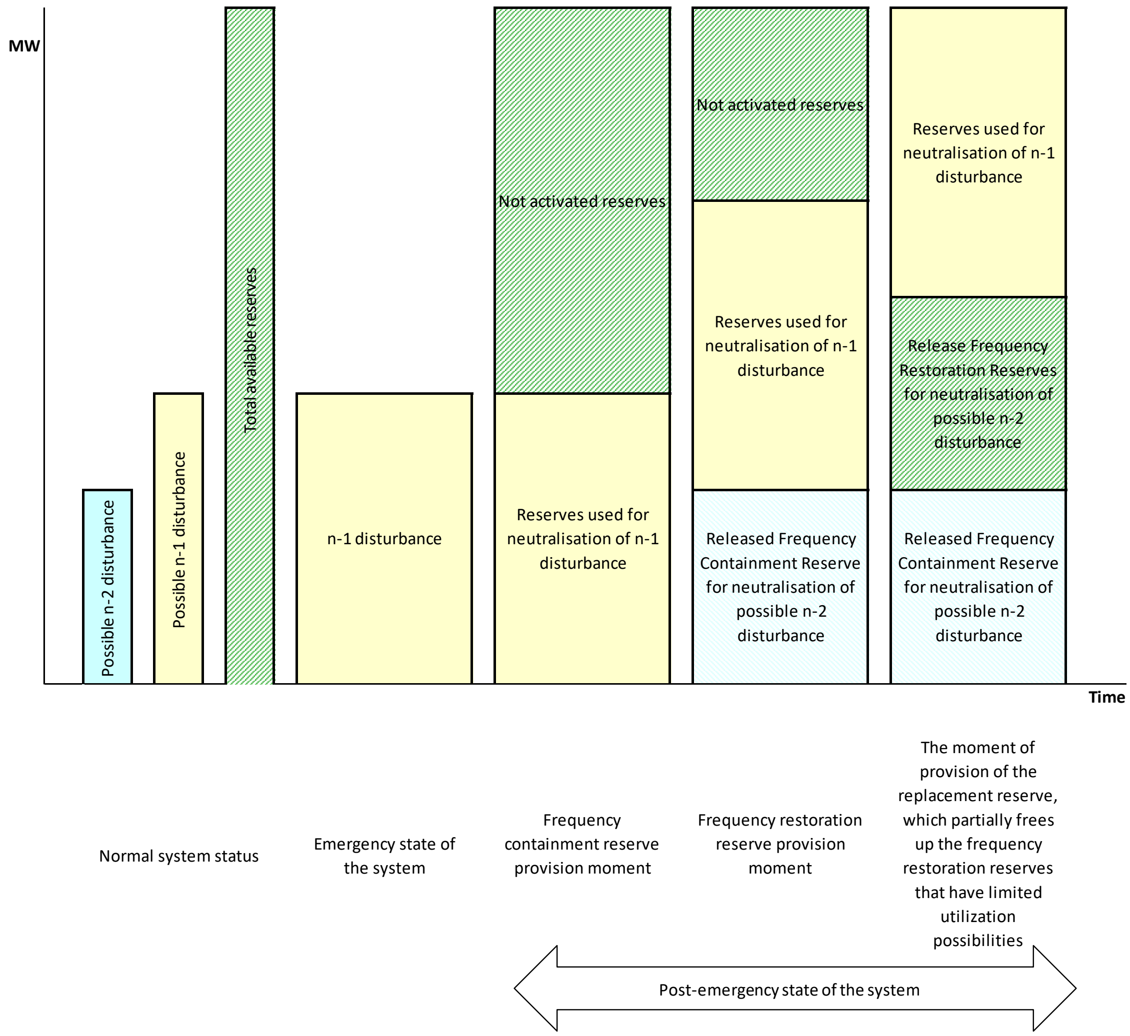


Figure 3.6. Reserve requirements for reservation of large units in power systems.

Disturbance “n-1” in Fig. 3.6 indicates the possible outage of the “largest unit” (power plant or interconnector) that operates in the system at a given moment of time. Similarly, disturbance “n-2” indicates the possible outage of the “second largest unit” that operates in the same moment of time. If, for some reason, the largest unit suddenly stops working, its power has to be immediately replaced by power from other units, which can offer frequency containment reserve (FCR) (here it should be noted that units, which offer different reserves, differ in manoeuvring abilities, installed capacities, efficiency, etc.). These power plants, for a short time period, can increase output of electrical power. Reserve requirement is of the same size as the unit, which went out of order. In this case, the frequency containment reserve equals the power of the largest unit (power plant or interconnector depending on which of them stopped working).

Frequency containment reserve within a limited time has to be replaced by a frequency restoration reserve (FRC), and then released to be able to respond to another possible disturbance. So, the size of the frequency restoration reserve is also equal to the size of the largest unit. After activation of the replacement reserve (RR) the frequency restoration reserve has to be also released to be able to respond to the possible n-2 disturbance Therefore, the total size of the reserve power should be approximately three times the power of the largest unit (more ~~precicesly~~precisely, it has to be equal to the power of n-1 disturbance plus 2*power of the n-2 disturbance). If the system operates isolated from others, all this reserve has to be deployed inside the system. Hence the total installed capacity of power plants in isolated system has to exceed the consumers' maximum demand by approximately three times the biggest unit (disturbance) capacity. If the system is connected with neighbouring power systems, reserve services (by contract) can be obtained via cross-border lines. Of course, in this case the required reserve must exist in neighbouring countries and the cross-border lines have to be able to transmit the required reserve capacity.

Currently the biggest possible n-1 disturbance in the Baltic States may occur due to outage of the fully loaded Lithuania-Sweden interconnector (700 MW). The higher n-1 disturbance in future can happen due to possible construction of large nuclear unit or due to commissioning of larger interconnector (for example, cable between Lithuania and Poland). In Finland the biggest n-1 disturbance can happen due to outage of Olkilouto NPP (1600 MW), operation of which will start soon. Currently, the biggest n-2 disturbance in Baltic countries can be related to outage of the Estonia-Finland interconnector (650 MW). In Finland the biggest n-2 disturbance can happen due to outage of fully loaded 880 MW nuclear unit.

A special reservation modelling approach was used in the REEEM energy security study in order to implement the above described reservation principle into the mathematical model used for energy system development and operation analysis in the Baltic States and Finland. For this reason all power plants, which usually are represented in energy system planning models as having only one main output – electricity, here have three additional outputs (see Fig. 3.7). Each of them is appointed to represent reserve supply: frequency containment reserve, frequency restoration reserve and replacement reserve.

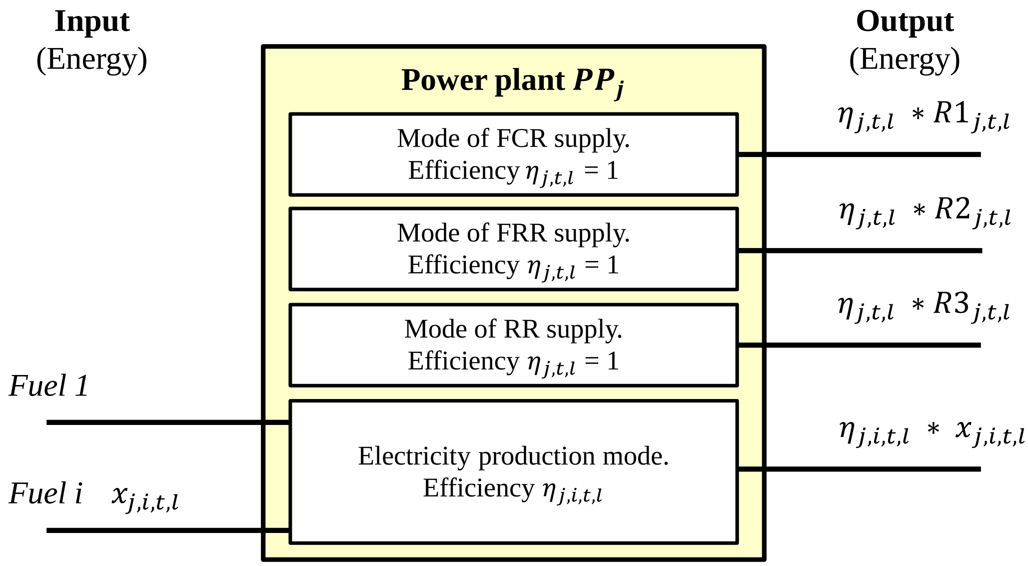


Figure 3.7. Representation of the ordinary power plant in energy system model.

Interconnectors may also be used for providing reservation services. Their representation in the mathematical model (see Fig. 3.8) is even more complicated in comparison to an ordinary power plant. In the case where the interconnector is used for electricity import, supply of reserve power can be possible due to not fully utilized throughput capacity for commercial electricity flow. In the case where the interconnector is used for electricity export, the interconnector can be used for reserve provision due to stopped export and reversed energy flow through it in the emergency situation. Therefore an interconnector, besides the electricity import and export flows (alternative operation modes) in the mathematical model is represented as having the reserve provision options both for electricity import and export modes.

Ability of reserve supply from energy storages (for example, by hydro pumped storage power plants) in the model is represented very similarly as for interconnectors because storage units can provide reservation services in generation and charging operation modes. (For example, reserve can be obtained due to interrupted charge).

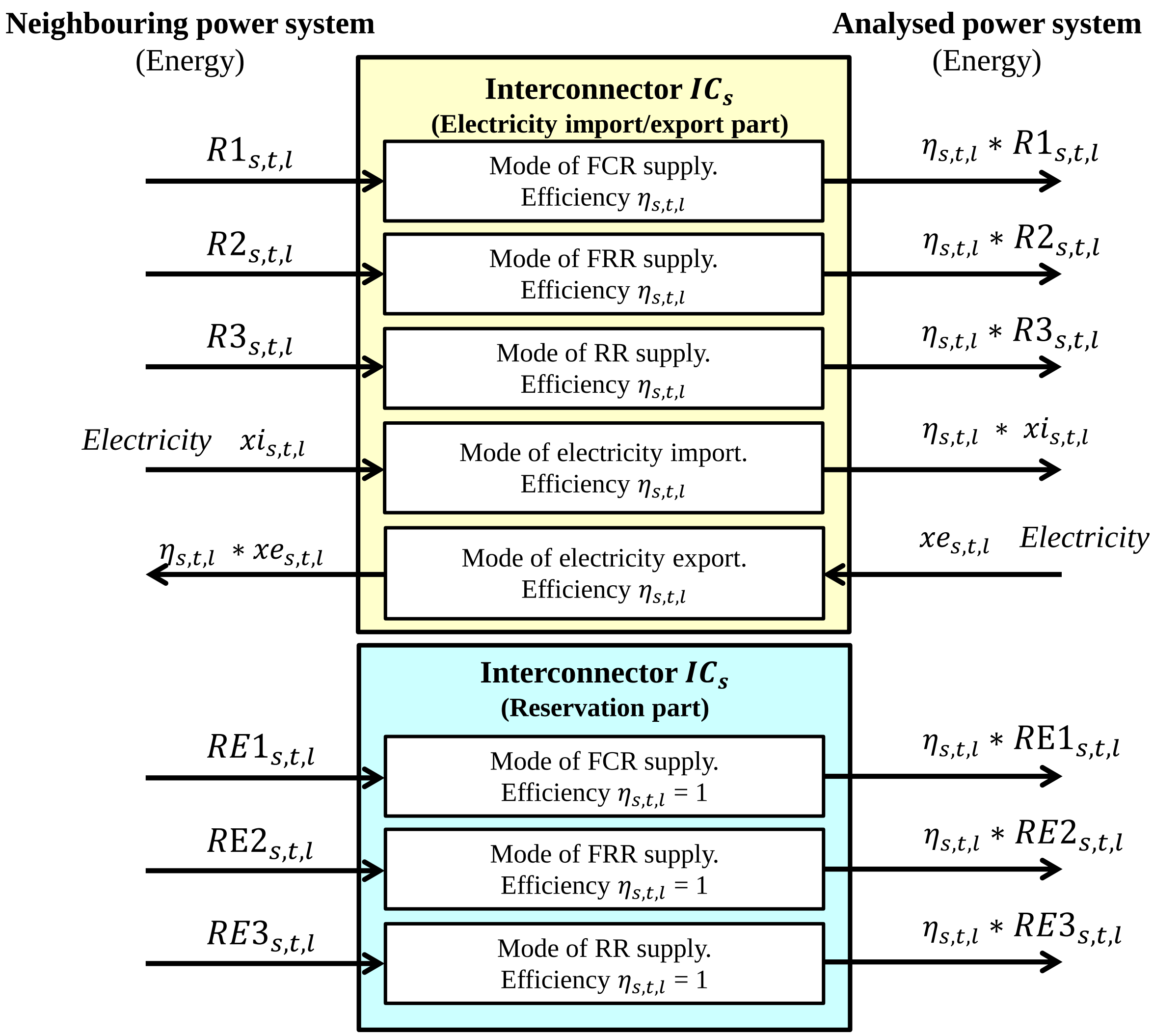


Figure 3.8. Representation of interconnector in the energy system mathematical model.

Detailed description of reservation modelling principles is given in [33].

3.1.4 Balancing of intermittent electricity generation from RES

In the mathematical models of the energy sector development and operation analysis, time is divided into time intervals, in which everything remains relatively constant. The time division into intervals is based on many factors: demand for energy of different forms, availability of energy resources, energy prices and so on. Energy demand is one of the most important factors in this time division. The actual energy demand variation within a day can be well approximated with a 5-7 staircase curve. This approximation principle assumes that for each section of the curve, the energy demand and all other parameters of the energy system remain unchanged, and the duration of one separate section is several hours. Typical days are used to reflect process variations in individual seasons. In this way, a specific time interval in a day is used to represent the change of the daytime processes of that season in the same time of day. This principle is well suited to reflect the change of inert processes. The change of energy demand in the system (not a separate user) is also a rather inert and cyclical process. However, this cannot be said about the possibilities of using wind energy for electricity generation. One day the wind can be strong, the next day of the same season weak and so on. Even during the same day, the wind can change dramatically. Thus, this principle of depicting process changes in the energy system is not suitable for the correct representation of electricity generation from wind and for the estimation of balancing capacities for variable wind generation.

In order to eliminate this deficiency, this study used the enhanced principle for modelling of wind electricity generation and for estimation of balancing capacities for compensation of its variation. The essence of this principle is that for each typical time interval of the day (for each segment of the approximation curve) representing energy demand, a probability curve of wind availability is prepared. The latter is formed from the data of perennial wind speeds that existed at the time of the day in a particular season. So, from multi-annual statistical wind speed data, there are so many probability curves of wind availability prepared as many time steps are used for representation of energy demand. For example, if there are 4 seasons in a year, two typical days (work day and weekend) are used to represent each season, and each typical day is divided into 5 time intervals totally it will make 40 time intervals over the year. The same number of wind probability curves is prepared. Having these wind probability curves and technical characteristics of the wind turbine the corresponding electricity generation probability curves are elaborated. Electricity generation probability curves converts wind speed into electricity generated for the particular type of wind turbine. The elaborated modelling principle for two consecutive time intervals is shown in Fig. 3.9.

Electricity generation probability curves are also approximated be stepwise curves. Approximation gives information on what power $P_{\tau i}$ and how long (τi) it can be generated from wind in each particular time interval t that represent one particular step of the stepwise demand approximation curve. After splitting time intervals t into sub-intervals the final splitting of time into time slices τi is obtained. This final splitting is used in mathematical model. In this case for the same demand few cases of wind electricity generation are modelled. When wind generation is big, no balancing power is required. However, when wind speed is low additional balancing power plants have to operate in order to cover unchanged demand. Thus, this modelling approach gives an opportunity to find an optimal solution taking into account actual wind availability, required balancing capacities, demand and other variations in the system, technical – economic characteristics of energy generation technologies and other requirements defined for the system.

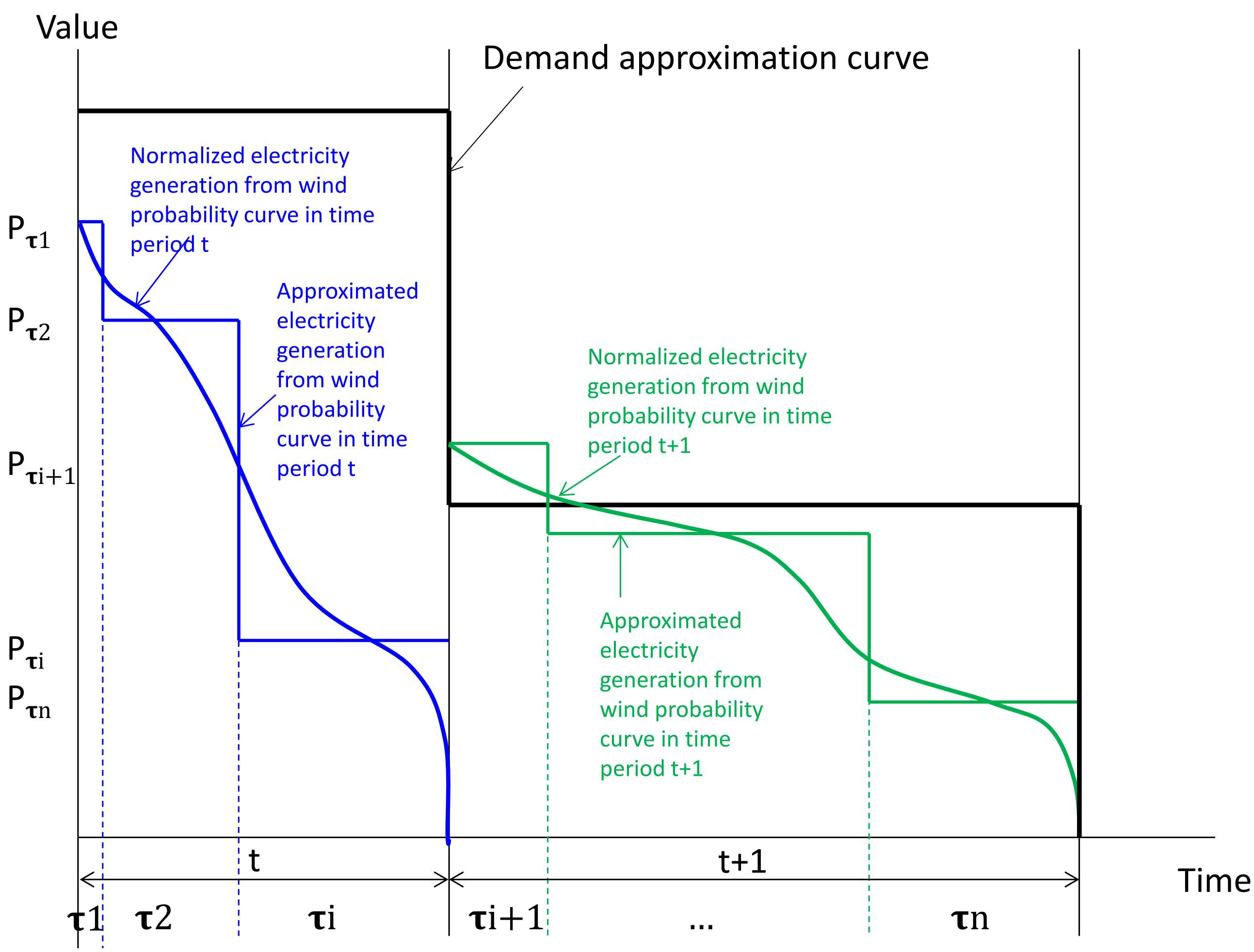


Figure 3.9. Representation of wind power generation in two consequent time intervals of the particular day.

3.2 Energy Security Coefficient

The methodology presented in this subsection aims to expand the capabilities of conventional energy system modelling tools in order to assess energy security comprehensively and proposes an energy security metric in terms of energy system resilience. The energy system model is built in the Open Source Energy Modelling System

(OSeMOSYS) generator, which is further described in subsection 3.2.3. The methodology is implemented step by step as illustrated in the schematic overview in Fig. 3.10.

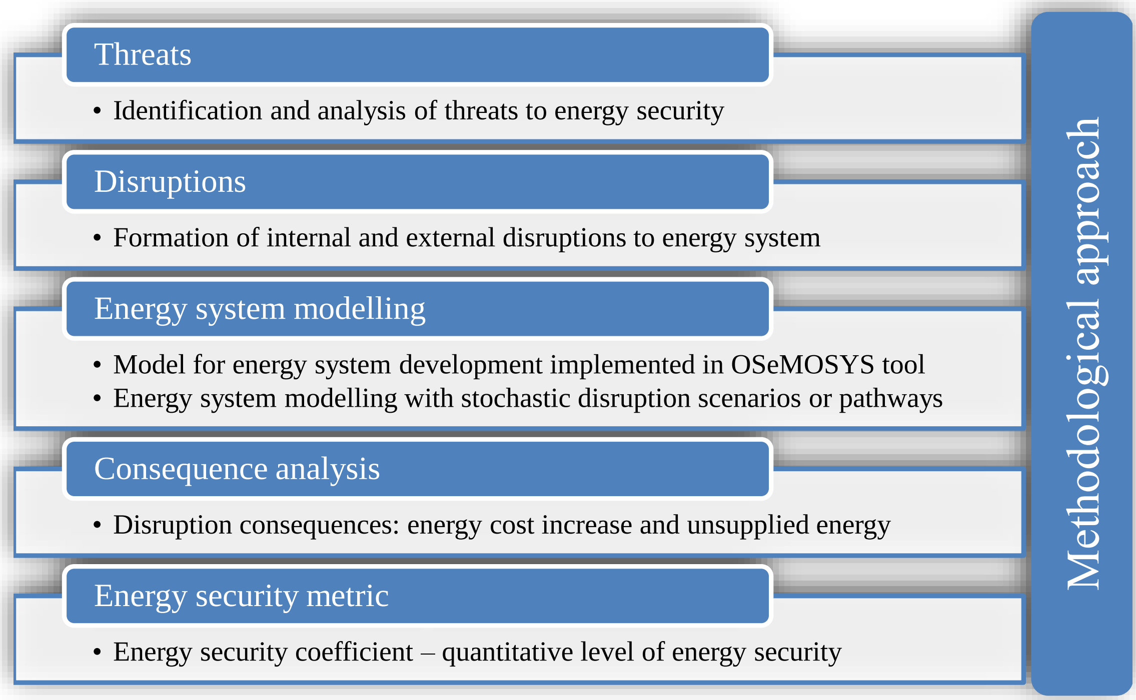


Figure 3.10. Methodology framework for the energy security analysis.

The methodology is based on the analysis of various emerging threats, disruptions arising from threats and associated consequences to energy system. It seeks to quantitatively estimate energy security for future development scenarios or pathways. Energy system modelling is employed to determine the ability of the energy system to cope with or resist the emerging disruptions. An integral characteristic of disruption consequences (energy cost increase and unserved energy) is considered as *energy security coefficient* (ESC) of the analysed energy development scenario. It enables the comparison of various energy development scenarios in terms of energy system resilience and to assess the impact of individual energy projects on energy security. Each step of the methodology framework (Fig. 3.10) is presented further in more detail.

3.2.1 Threats to energy security

Every energy system is surrounded by a variety of threats of various origins. A threat is defined as any potential danger that exists within or outside the energy system and that has a potential to result in some kind of disruption of that system. Threats depend on the country where the energy system exists, its geographic and political region/context. The manifestation of threats to energy security can cause damage and reduce the energy security level. In general, threats usually may be of two types: malicious and non-malicious. Threats can be provoked by specific subjects (the state, energy companies, terrorist organisations, individuals), who can change the conditions of the energy sector and cause damage by their actions, decisions or inactivity. Such kind of threats are referred as malicious. Threats in the majority also appear as non-intentional accidents, which are referred as non-malicious. These threats include accidents, natural disasters and other threats.

Both malicious and non-malicious threats to energy security also can roughly be divided into several types according to the sources of threats: technical, natural and socio-political. Technical threats exist due to accidents and damages that occur due to technical reasons and may cause serious disruptions in the energy system or even a total cut-off of energy supply. Most common threats are natural, which depend on the local seismic, climate and other geographic conditions and some of natural threats are posed by climate change. Due to their complex nature, socio-political threats are hard to predict and covers various factors. Such type of threats usually are described by qualitative parameters. Thus, various available sources should be used in order to identify and evaluate threats and their likelihood. For example, detailed statistical analysis, documentation of technical equipment exploitation, reliability assessments, meteorological phenomena databases, expert assessments, analysis of energy strategies, political and sociological studies of threats or other available sources should be used to estimate the likelihood of threats.

Types of threats include intentional and non-intentional threats, have different probabilities of occurring and would entail different scales of consequences for energy systems. Threats to energy security also depend on the existing national and international factors, change in time and space, so the complete list of threats is unique for each energy system or country at a certain period of time. Such list of threats as the outcome of the first step of the presented methodology should be composed in order to define the energy system disruptions. The main energy security threats for Baltic countries and Finland are discussed in subsection 4.3.2.

3.2.2 Disruptions in the energy system

Threats to energy security may manifest or be realised by causing various energy system disruptions. Disruptions in the energy system may be referred to as natural or man-made phenomena that may disrupt the functioning of energy system or operation of some elements of the system. Disruptions can affect the whole energy sector, from fuel sources, infrastructure to end-users.

Usually, disruptions occur in the energy supply or when energy prices increase. Thus, in this methodology, disruption is considered not only a physical supply disruption as determined by the IEA [34], but also this concept includes the price increase of energy sources.

However, disruptions by their nature may be divided into two key types. Each type depends on where the disruption occurs: if within the energy system, then it is called internal disruption; if outside the energy system, then it is called external disruption. This forms the basis for characterizing disruptions by a variety of parameters, such as the start, duration and extent of disruption, interruption or complete cut-off of energy supply, price increase of energy sources, availability of technology, which function was disrupted, etc. Since disruptions in reality are of stochastic nature, parameters of disruptions should be described by probabilistic distributions. This enables the generation of a set of disruption scenarios that is used for modelling of energy system.

In this methodology, the disruption start parameter is described by uniform distribution since the disruption can occur at any time moment during the modelling period. The disruption duration parameter follows an exponential distribution since the disruption can last for a very short time to several years or even decades. The extent of disruption is characterized by normal or lognormal distribution, depending on which kind of disruption is being considered. If the supply interruption is analysed, then it is distributed according to the lognormal distribution, since the probability of a severe disruption is usually very low. If the price increase is analysed, this disruption follows the normal distribution since it has a wider spread of probabilities and higher occurrence of severe price increases. The frequency of occurrence parameter is based on the logarithmic probability scale, and therefore is not described by any specific probability distribution. Distribution fitting software [35], detailed studies [36]–[44], catalogues of technologies [45], reports [46]–[48] and other sources were also used to define suitable distributions.

The values for disruption parameters are selected in such a way that each parameter can be divided into three equal parts. The rationale behind this is equivalent to the 3-point Likert scale used in social sciences. According to that, such boundaries of values are defined also as equal parts, except values for duration parameter, which were defined by expert assessment. Boundaries for qualitative and quantitative values are also based on studies of risks to energy [38] and detailed project reports[46], [47]. In addition, the values of disruption parameters and their probability distribution parameters are time-dependent and can vary over time. A detailed list of disruption parameters and their relationship with probability distributions are presented in Table 3.1.

Table 3.1. Parameters of internal and external disruptions

<table>
<tr><th rowspan="2">Disruption</th><th rowspan="2">Parameter</th><th rowspan="2">Probability distribution</th><th colspan="2">Value</th></tr>
<tr><th>qualitative</th><th>quantitative</th></tr>
<tr><td rowspan="12">Internal:
• Restriction of technology availability due to technology reliability and outage rate
• Change of technology or energy project initial investment (capital cost) due to risk of investment for the candidate technology
External:
• Interruption or complete cut-off of energy supply
• Price increase of energy sources</td><td>Start</td><td>Uniform</td><td>–</td><td>From modelling first year to end year</td></tr>
<tr><td rowspan="3">Duration</td><td rowspan="3">Exponential</td><td>Short-term</td><td>≤ 1 year</td></tr>
<tr><td>Medium-term</td><td>> 1, ≤ 3 year</td></tr>
<tr><td>Long-term</td><td>> 3 year</td></tr>
<tr><td rowspan="3">Extent</td><td rowspan="3">Normal, lognormal</td><td>Small</td><td>≤ 33%</td></tr>
<tr><td>Medium</td><td>> 33, ≤ 66%</td></tr>
<tr><td>Large</td><td>> 66%</td></tr>
<tr><td rowspan="3">Frequency of occurrence</td><td rowspan="3">–</td><td>Low</td><td>≤ 0.01</td></tr>
<tr><td>Medium</td><td>> 0.01, ≤ 0.1</td></tr>
<tr><td>High</td><td>> 0.1</td></tr>
<tr><td>Technology or energy source</td><td>–</td><td>Any energy supply, production or transportation technology or any energy source in the energy system</td><td>–</td></tr>
</table>

A set of disruptions is generated with different values of disruption parameters using the Monte-Carlo method. Each set of disruption parameters corresponds to a different energy system scenario. Such a set of scenarios consists of various combinations of energy system disruptions.

Each Mote-Carlo simulation generates *n* number of scenarios with various disruption combinations, which forms a set of disruption scenarios. Such a set of scenarios with different disruption combinations is used further for modelling energy system.

3.2.3 Modelling of disrupted energy system

The main step in methodology presented herein is the modelling of the energy system. The energy system model is built in the Open Source Energy Modelling System (OSeMOSYS) generator. However, other modelling tools can also be used in the employed methodology if properly and correctly applied, i.e. the selected tool should be adapted to simulate various disruptions and model the energy system in the environment of these stochastic disruptions. The main reasons for choosing OSeMOSYS as the main modelling tool in the methodology is the fact that it is flexible, easy to apply and modify.

OSeMOSYS is a tool developed by KTH Royal Institute of Technology in collaboration with a range of other institutions [31]. OSeMOSYS is used for long-run integrated assessment and energy planning and is designed as a tool to inform the development of local, national or multi-regional energy strategies. It has been employed to develop energy systems models from the scale of continents down to the scale of countries, regions and villages. OSeMOSYS may cover all or individual energy sectors, including heat, electricity and transport. It is a deterministic linear optimisation model. However, mixed integer programming may be applied to certain functions.

The objective function of OSeMOSYS is to minimize the total discounted costs (TDC) of the energy system to meet the given demand(s) for energy services, which can be met through a range of technologies. The total cost includes fixed and variable cost, capital investment, technology emissions penalty, storage cost and excludes salvage value. Refer to [31], [32] for a full description and implementation of the OSeMOSYS tool.

In the presented methodology, model of energy system is applied to be modelled in *n* runs with various stochastic disruption scenarios using Monte-Carlo method. In order to do so, the model was expanded by adding supplementary equations to calculate consequences caused by disruptions to the energy system. Two main consequences are evaluated regarding energy security: unserved energy and energy cost increase, which demonstrate if the energy system is resilient.

A new dummy variable of unserved energy has been added to the model. This variable represents produced energy at an extremely high cost. The reason of introducing this variable is determined by the calculation principle used in the OSeMOSYS, which is demand driven modelling generator. Therefore, if the demand is not met, the model cannot find a feasible solution. Thus, the share of unserved energy in the total energy demand can be calculated in two ways as follows:

$$UE = 1 - (Production\ /\ Demand), \tag{1}$$

or

$$UE = UEA\ /\ Demand, \tag{2}$$

where *UE* is a variable, which demonstrates what part of the required energy is unserved. Variable *UE* can also be expressed as a percentage and has a range from 0% to 100%. For example, if *UE* = 0.4, then 40% of demanded energy is unserved for an analysed time period. This variable can be calculated either in each time slice (parameter *l* in OSeMOSYS) or in each year (parameter *y* in OSeMOSYS). Variables *Production* and *Demand* are OSeMOSYS model variables that correspond to the generation of any technology and energy demand, respectively. Variable *UEA* is a dummy variable that calculates the amount of unserved energy measured in energy units, for example, MWh, PJ or other. However, if unserved energy occurs in more than one sector in the analysed energy system, for example, electricity and heat, then values for variable *UEA* should be added.

Calculation of another consequence caused by disruptions to energy system takes into account the result of the objective function. Energy cost increase in particular disruption scenario is based on total discounted cost in the case of analysed scenario and cost in the case of the baseline scenario. The part of energy cost increase is calculated in the following manner:

$$ECI = (FC - BC)\ /\ BC, \tag{3}$$

where *ECI* is a variable, which demonstrates how much energy cost has increased in the case of analysed disruption scenario in comparison with the cost of the baseline scenario. This variable can also be expressed as a percentage and acquires values ≥ 0%. For example, if *ECI* = 0.2, then the cost of the analysed disruption scenario is 20% higher than the cost of the baseline scenario. Variables *FC* and *BC* refer to the total cost of the scenario under consideration and baseline scenario, respectively. In this methodology, the baseline scenario is considered a scenario without any disruptions with the lowest total cost of analysed scenarios.

For this reason, modelling of an energy system should be carried out in two steps. Firstly, any analysed scenario is modelled without disruptions to get results and total costs for each scenario. The scenario with the lowest total costs is considered as the baseline scenario. Second, each scenario is modelled with various disruption combinations in *n* runs and in post-modelling phase calculation of equations (1~~(1~~)–(3~~(3~~) is performed. A more detailed characterization of modelling algorithm is provided in subsection 3.2.5.

Energy disruption consequences to energy system can be used to determine a measure of resilience to disruptions which directly refers to energy security. Thus, energy security is measured quantitatively by an energy security metric developed by the authors.

3.2.4 Energy security metric

The methodology as one of the outputs proposes a quantitative energy security metric, so-called *energy security coefficient* (ESC). This metric complements the outputs of conventional energy system modelling tools. The coefficient aims to evaluate the consequences of disruption scenarios in the energy system in terms of energy system resilience to disruptions. The energy security coefficient can be calculated for different scenarios in each time slice or on a yearly basis as follows:

$$ESC = \exp(-a_1 \times UE \times \exp(YS) - a_2 \times ECI \times \exp(YS)), \quad (4)$$

where variables *UE* and *ECI* directly refer to disruption consequences, which are estimated by formulas (2~~(2~~) and (3~~(3~~) respectively, exp – exponential function, a_1, a_2 – weights indicating the importance of consequences. Usually, unserved energy is considered as having higher importance than energy cost increase and to that end has a higher weight. This assumption is based on the severity of the consequences of each variable. However, it largely depends on the analysed energy system. The empirical basis for the weights should be a particular energy system analysed using the employed methodology. *YS* refer to the OSeMOSYS parameter *YearSplit*, which splits the year into time slices. *YS* measures the duration of a modelled time slice as a fraction of the year and allows to split the year into, for example, different seasons, days or nights, ~~wokdays~~ workdays or holidays, etc. In formula (4~~(4~~) *YS* stands for the duration of consequences and estimates how long these consequences lasted.

In this case, energy security is evaluated in terms of the ability of the energy system to overcome or resist the resulting disruptions. Thus, the energy security coefficient, calculated by the formula (4~~(4~~), indicates the level of energy system resilience to disruptions. The ESC is calculated from the consequences of disruptions, which directly reveals the vulnerability of the energy system. Values of the ESC have a range from 0 to 1:

- if *UE* = 0% and *ECI* = 0%, then the analysed energy system is resilient to disruptions and *ESC* = 1 (maximum ESC);

- if *UE* = 100% or *ECI* ≥ 100%, then the analysed energy system is not resilient to disruptions and *ESC* = 0 (minimum ESC).

The energy security coefficient enables a comparison of energy system development scenarios from an energy security perspective. Dependence on disruption consequences and their duration is exponential rather than linear. For example, estimated consequences of being without energy for two days will be much higher than twice than being without energy for one day. Therefore, the exponential function is used in the formula of energy security coefficient. Another empirical justification of the formula is its values vary between 0 and 1. Such scale of the ESC is the most comprehensible and easiest to interpret the result as it also can be expressed in percentage (0–100%).

3.2.5 Modelling algorithm

In order to employ the methodology for calculating ESC due to its specificity, the modelling of energy system should be carried out in two steps. Flowchart of the modelling algorithm, presented in Fig. 3.11, demonstrates the implementation of modelling in one particular scenario of all analysed scenarios.

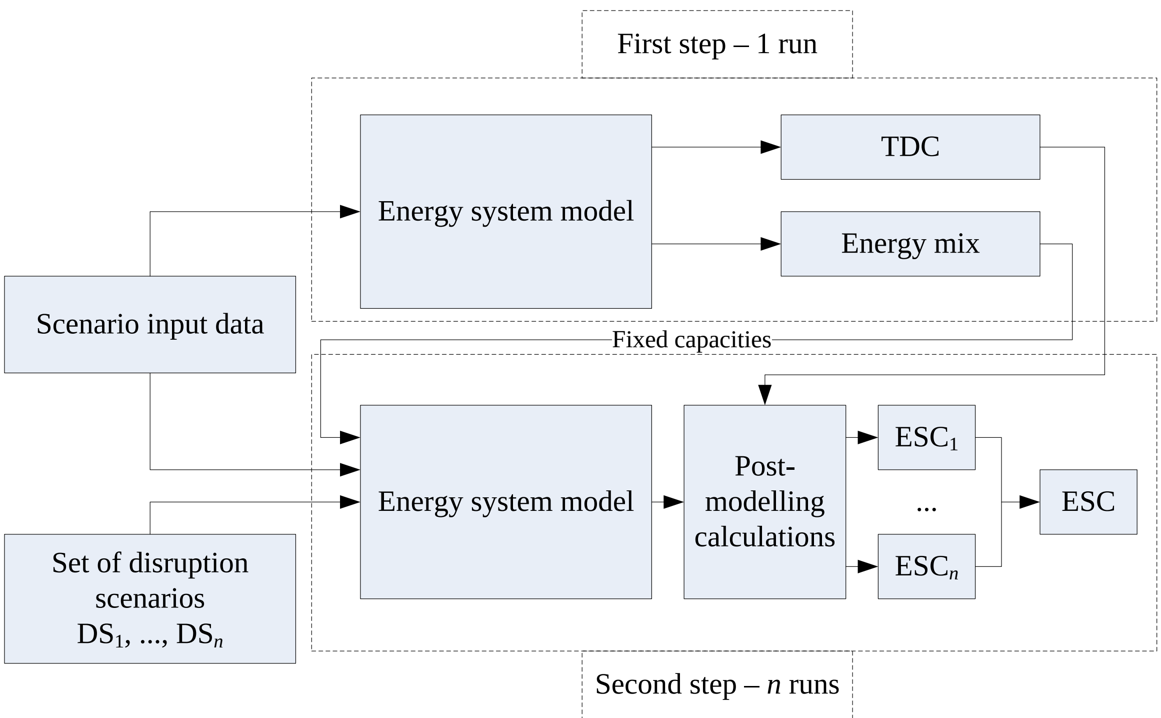


Figure 3.11. Algorithm flowchart of the energy system modelling in one particular scenario.

In the first step, the energy system model is run in the usual way and modelling does not differ from the modelling with conventional energy system modelling tools. The key input data ~~paramaters~~ parameters are energy demand, technology performance and cost data, generation constraints, etc. considering the assumptions of the analysed scenario. Key outputs of this step are the optimal energy mix with installed capacities and total discounted costs since these are used further in the next step. Furthermore, all the analysed energy system scenarios in the first step of the algorithm (Figure 3.11) are modelled to define which scenario of the analysed ones is defined as the baseline scenario. In the presented methodology, after the implementation of the first step, the scenario with the lowest total discounted cost is considered as the baseline scenario.

In the second step, the same energy system model is run separately under the analysed scenarios, however, with additional inputs. Firstly, installed capacities of technologies should be fixed using the output from the first step. Secondly, the energy system is modelled in *n* runs using a set of scenarios with different disruption combinations (provided in subsection 3.2.2). The main output of this step is the energy security coefficient of each run, calculated by (4(4) formula. The ESC can be presented and analysed in various ways: in each year during the modelling period, for the whole modelling period, in each run, etc. Since *n* runs are performed using the algorithm (Figure 3.11), the employed methodology also provides an uncertainty framework. In general, the output of the model enables the analysis of the ESC distribution within the runs, provides the range of the ESC at some probability level and may estimate the probability that the ESC measure will exceed a specific threshold value. Furthermore, output results may be used to make general inferences, such as estimating the mean, standard deviation, median, quartiles and many other statistics of the ESC. However, in order to provide an integral metric of the ESC, coefficients of *n* runs can be averaged in order to easily compare the results of different scenarios. In such a way, performed modelling gives the value of the energy security coefficient for the analysed scenario of energy system and tests how well the energy system copes with or resists the disruptions in this scenario. In order to compare the results with other scenarios, the modelling algorithm, in the same way, is applied for each of the analysed scenarios.

The reason for fixing capacities of some technologies in the second step, is that the energy system is modelled with various disruptions, which is provided to the model as input data. Since the model might “know” or “suspect” in advance when the disruption occurs, it might install new capacities to avoid disruption in the future, although in the normal case this would not be necessary. Thus, fixing capacities avoids installation of unnecessary new technologies.

4 Modelling assumptions, scenarios, results

4.1 Harmonisation of the Baltic energy security study with the research on energy sector development on EU level in the REEEM project

Harmonization of the energy security analysis in the Baltic States and Finland with the global analysis of energy system development at the European Union level in the REEEM project, is based on exchange of ideas among researches on the modelling principles, exchange of initial information about energy systems, result analysis of the TIMES PanEU model and feedback provided. This was organized in a form of discussions during project meetings and information exchange via e-mails. However time limitations and differences in modelling focus did not allow reaching the level of full harmonization.

The main factors defining energy sector development pathways in the TIMES PanEU model are emissions of greenhouse gases (GHG) and use of renewable energy sources. The emission reduction target for the emission trading sector (ETS) was set for the entire European Union. It was assumed that GHG emissions in the ETS should be reduced by 21% in 2020, by 43% in 2030 and by 83% in 2050. All reduction rates are compared to the 2005 emission level.

The GHG emission targets for non ETS were slightly different among member states. These targets for countries covered in the energy security study are presented in Table 4.1.

Table 4.1. Emission reduction targets for non ETS, %.

	Targets for 2020	***Targets for 2030***	***Target for 2050***
Finland	-16%	-39%	-80%
Estonia	11%	-13%	-60%
Latvia	17%	-6%	-60%
Lithuania	15%	-9%	-60%

The highest GHG emission target is set for Finland (80% reduction), while for all the Baltic countries it stands at only 60%. In addition, emission increase at the beginning of the study period is allowed for the Baltic countries.

In TIMES PanEU, the assumed targets for the use of renewable energy sources are given in Table 4.2.

Table 4.2. Renewable energy targets, share.

	2020	**2030**	**2040**	**2050**
Finland	38%	50%	68%	85%
Estonia	25%	38%	56%	75%
Latvia	40%	49%	62%	75%
Lithuania	23%	36%	56%	75%

Thus, by 2050, the share of RES in final electricity consumption should reach 85% in Finland and 75% in the Baltic countries.

The above mentioned targets, especially for GHG emissions, could not be transferred directly to mathematical models used for energy security analysis because of different coverage. Energy sector operation and development models used for security study cover electricity, heating and fuel supply systems while the TIMES PanEU model covers more sectors of economic activity. Therefore it was assumed that energy security analysis in the Baltic countries and Finland will be harmonized with results taken from TIMES PanEU model. The main focus will be given to the share of RES in electricity and district heat production because GHG emission reduction for these sectors is not presented in TIMES PanEU results.

The two pathways considered here are Base which represents current trends, and High RES that assumes higher renewable energy generation targets [49]. The data representing the share of RES in electricity and district heat production under both pathways are given in Table 4.3.

Table 4.3. Electricity and district heat produced from RES, share from total production.*

Country	*Scenario*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
Electricity produced from RES									
Finland	Base	0.44	0.42	0.59	0.75	0.82	0.87	0.92	0.93
	High RES	0.44	0.42	0.59	0.75	0.81	0.87	0.92	0.92
Estonia	Base	0.29	0.22	0.26	0.89	0.86	0.88	0.89	0.90
	High RES	0.29	0.22	0.26	0.69	0.83	0.86	0.92	0.95
Latvia	Base	0.61	0.87	0.67	0.80	0.77	0.85	0.89	0.90
	High RES	0.61	0.86	0.72	0.82	0.82	0.88	0.93	0.98
Lithuania	Base	0.39	0.70	0.72	0.86	0.80	0.33	0.26	0.29
	High RES	0.39	0.69	0.63	0.81	0.76	0.65	0.80	0.94
District heat produced from RES									
Finland	Base	0.44	0.46	0.47	0.61	0.90	0.90	0.94	0.99
	High RES	0.45	0.46	0.47	0.57	0.89	0.90	0.86	0.97
Estonia	Base	0.74	0.95	0.91	0.75	0.73	0.76	0.52	0.61
	High RES	0.71	0.95	0.91	0.74	0.75	0.71	0.50	0.72
Latvia	Base	0.25	0.53	0.49	0.52	0.49	0.62	0.60	0.61
	High RES	0.25	0.51	0.60	0.58	0.60	0.69	0.78	0.96
Lithuania	Base	0.13	0.57	0.69	0.81	0.74	0.91	0.95	0.98
	High RES	0.13	0.57	0.59	0.71	0.69	0.91	0.96	0.96

*Calculations are based on results from files 2018-12-20_Base_TIMESPanEU_FrameworkV1_DataV4_Output (1).xlsx and 2018-12-20_HighRES_TIMESPanEU_FrameworkV1_DataV4_Output.xlsx

The data presented in Table A_4.3 shows very similar shares of electricity produced from RES in Finland, Estonia and Latvia in both the Base and the High RES scenarios. A significant difference between the Base and the High RES scenario is recorded only for Lithuania (probably influenced by the construction of a new nuclear power plant in the Base scenario). Shares of district heat production from RES in both scenarios are very similar for Finland, Estonia and Lithuania. Significant difference is visible for Latvia, especially for the end of the study period. The reason for these differences is not explained.

Assuming the Baltic States as one region, electricity production from RES in different TIMES PanEU scenarios would be as presented in Fig. 4.1. Similar data for district heat production are given in Fig. 4.2.

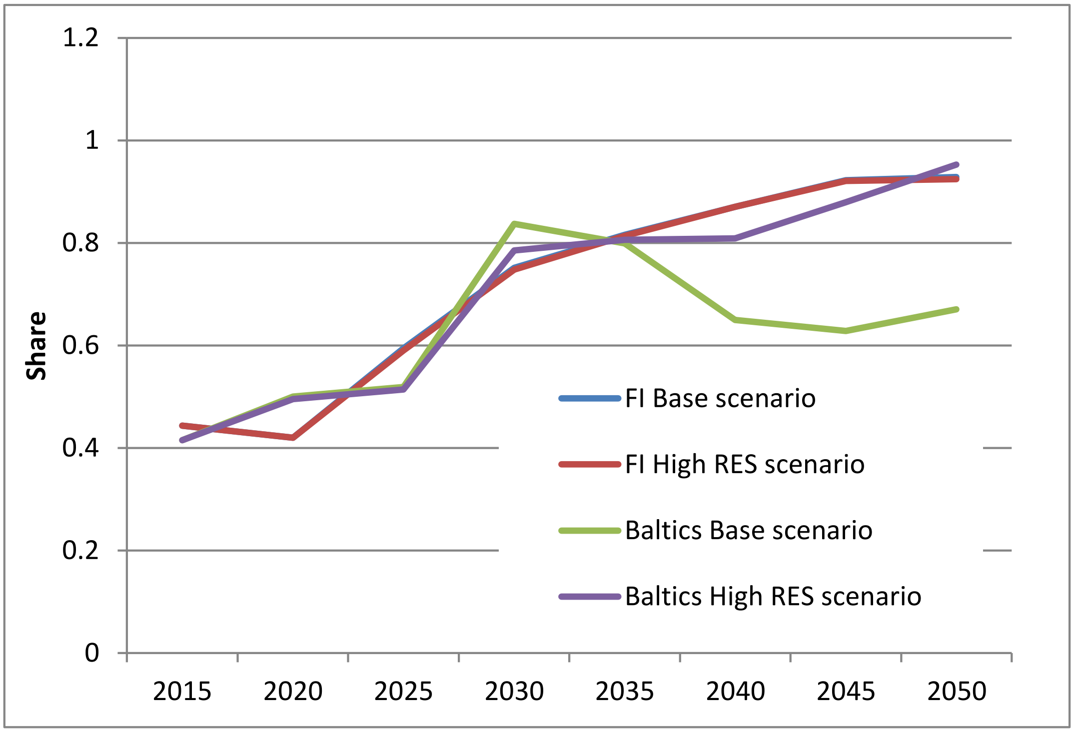


Figure 4.1. Electricity production from RES in Baltic States and Finland in different TIMES PanEU scenarios.

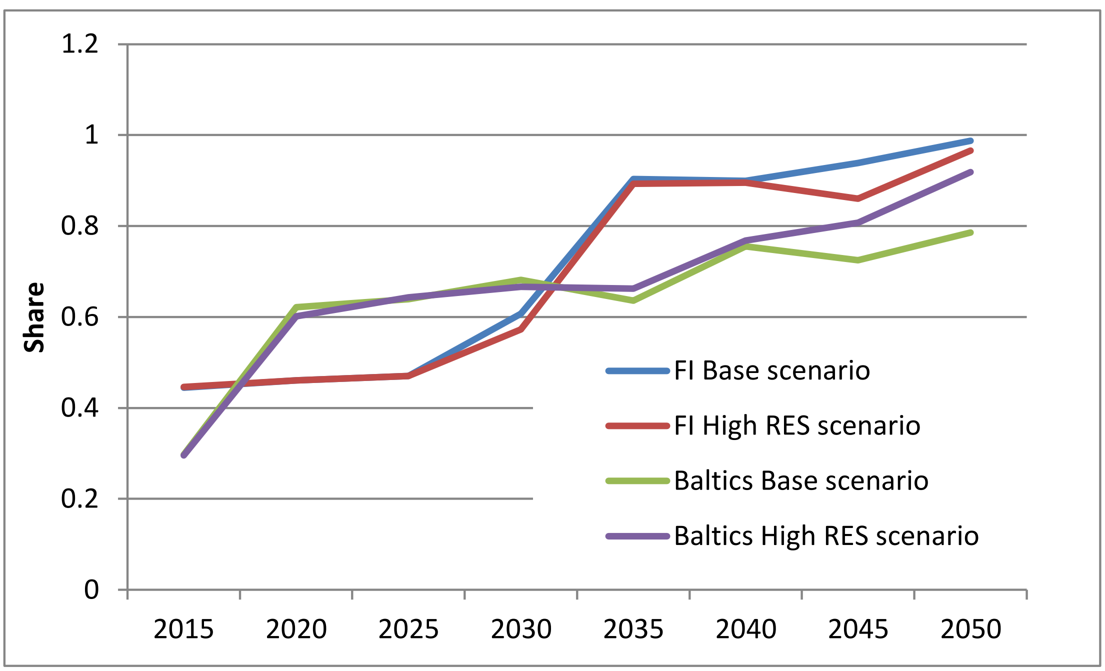


Figure 4.2. Heat production from RES in Baltic States and Finland in different TIMES PanEU scenarios.

From the data presented in Fig. 4.1, it is evident that electricity production from RES in the Baltic States and Finland is very similar in the High RES scenario while it is different in the Base scenario. On the contrary, shares of RES based district heat production (Fig. 4.2) are similar in the Base and the High RES scenarios but differ among Finland and the Baltic states. Having no very clear justification of why these differences occur, it was assumed that for the energy security case study, a common target for RES based energy generation will be used for the entire region, i.e. common target for Finland and the Baltic States. In addition for simplicity reasons this target was converted into RES share in total use of primary energy sources for electricity and district heat production. Therefore, for the purpose of harmonization of the energy security research with the research carried out using TIME PanEU the RES target shares given in Table 4.4 were considered.

Table 4.4. RES target shares in primary energy consumption for electricity and district heat production.

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
TIMES PanEU Base scenario	0.326	0.329	0.432	0.594	0.672	0.697	0.742	0.758
TIMES PanEU High RES scenario	0.327	0.329	0.430	0.581	0.672	0.742	0.819	0.852

The CO_2 prices taken from the TIMES PanEU model results, are also harmonized across the two studies. These prices are presented in Table 4.5.

Table 4.5. CO_2 prices, Eur/t.

Scenario	***2015***	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
TIMES PanEU Base	0	0	1.6	28.9	32.2	27.6	52.8	501.1
TIMES PanEU High RES	0	0	0	25.1	29.7	24.1	30.1	489.1
Additional	0	10	89.8	169.7	249.6	329.4	409.3	489.1

4.2 Scenarios analysed

Energy security in Baltic States and Finland was analysed for three scenarios, which are based ~~of~~ on Base and High RES pathways defined in the REEEM project. Base and High RES scenarios in the energy security case study have the same CO_2 prices and RES targets as the same scenarios used in TIMES PanEU model. However, additional scenario (BaseCO2Lin) was constructed from Base scenario with different CO_2 prices, as specified in Table 4.5. Characteristics of these scenarios is given in Table 4.6.

Table 4.6. Characteristics of scenarios selected for energy security study in Baltic States and Finland

Scenarios	***RES share in primary energy consumption***	***CO_2 prices***
Base	According to TIMES PanEU Base scenario	According to TIMES PanEU Base scenario
High RES	According to TIMES PanEU High RES scenario	According to TIMES PanEU High RES scenario
BaseCO2Lin	According to TIMES PanEU Base scenario	Linear growth from 10 Eur/t in 2020 up to value estimated in TIMES PanEU Base scenario for 2050

4.3 Model for Energy Security Coefficient Assessment

In this Subsection, the Model for Energy Security Coefficient Assessment (MESCA) built in OSeMOSYS and its main modelling assumptions are briefly described. This modelling exercise is performed in order to demonstrate energy security dynamics for future development of country energy system within different scenarios. Since the detailed technical and economic analysis of energy systems future performance for the Baltic countries and Finland was carried out using MESSAGE model, this modelling exercise concentrates on the energy security coefficient results. To better understand the structure of the models of the Baltic countries and Finland energy systems and results achieved, the model structure, main modelling assumptions and scenarios analysed are briefly provided further.

4.3.1 Structure of the MESCA and modelling assumptions

The mathematical models of the energy system for each of the analysed countries (i.e. Estonia, Latvia, Lithuania and Finland) were built in OSeMOSYS as single country models that work independently. However, existing and planned transmission lines with neighbouring countries are included. It should be noted that in this analysis, only electricity and district heating energy systems are under consideration.

Also, to keep the country model as simple as possible, different energy generation, transportation and other technologies are aggregated into technology types and are considered the same for each country. This needs to be done since modelling of each energy system is done in *n* runs with different stochastic disruptions for each analysed scenario (for example, 500 runs for each scenario were performed in this analysis), which requires a lot of effort in terms of computation time.

In order to construct the energy system models and to perform the energy security analysis, it is necessary to make fundamental assumptions that might have a big influence on the model itself as well as on the results of the conducted analysis.

The mathematical model for energy system in each of the analysed countries is constructed including fuel supply for electricity and heat production and electricity and district heating systems for the whole country. The energy system basically is characterized by various types of existing and candidate technologies, e.g. power plants fuelled with different types of fuels, transmission and distribution networks, local and imported fuel, imported electricity, etc. Also, each technology is described by technical and economic parameters, e.g. efficiency, installed capacity, costs, etc.

The aggregated fuel groups that are defined in the model are the following: coal (also includes lignite), oil, oil shale (only for Estonia), natural gas, waste, biomass and nuclear fuel. Sources of fuel supply are split into two categories – local and imported. Two main factors for defining the set of technologies available are the fuel and the form of the energy production. Three types of technologies which use fuel for energy (electricity and heat) generation are defined according to the form of energy conversion – power plant (PP), combined heat and power (CHP) plant and heat only boiler (HOB). Only natural gas fired plants have a fourth type – combined cycle (CC) power plant. Also, for nuclear, only one power plant option was considered. Nevertheless, these types of technologies are considered for each fuel type, however, only for fuel fired technologies. Also, the following types of technologies were defined and implemented in the model: hydro, wind PP (onshore and offshore), solar PP, electricity storage (batteries), solar thermal, heat pumps, electricity import, transmission and distribution network, unserved energy (only in the disruption scenarios).

The analysis period is considered from 2015 to 2050. The initial data and some assumptions for the modelling are taken from various available sources. However, in order to keep the model data synchronized as much as possible with the main model within Work Package 6[2] (WP6) of the REEEM project, the main data for technology technical and economic parameters (e.g. costs, efficiency, lifetime and other) were taken from the TIMES PanEU model, which is the key model within WP6 as well as within the whole REEEM project. In addition, some data, such as year division into time slices, electricity consumption patterns, availability and capacity of RES were derived from the Open Source Energy Model Base for the European Union (OSeMBE) [50], which is the model implemented in the OSeMOSYS tool and developed as an open source engagement model within REEEM project and reported in the deliverable D7.3. Important parameters in the energy security analysis are total installed capacity of existing technologies and new installed capacities of new technologies. Data for these parameters as well as for the final energy demand was derived from the MESSAGE model results within WP6. Such data exchange with other models in the project approach facilitates coherence in the energy security case study and WP6.

[2] The main objective of WP6 "Energy Systems Integration" in REEEM project is to develop an Integrated European Energy System Model which holistically represents energy resources, supply and demand technologies and related infrastructure. It enables the analysis of demands, as well as environmental, social and economic impacts. A special focus is the impact of technological development and innovation on the energy system and the modelling of related EU policy measures.

4.3.2 Energy security threats for the Baltic countries and Finland

In this energy security case study, an attempt was made to list threats to energy security that would be common for each of the analysed countries (Finland, Estonia, Latvia and Lithuania). However, some threats are more or less country specific, which are also briefly discussed. Common threats to energy security include the country political instability, the coercive manipulation of energy supplies, the competition over energy sources as a trigger for conflict, attacks on supply infrastructure, as well as accidents, natural disasters, terrorism, reliance on foreign countries for energy sources and other [51]–[62]. The main threats common for analysed countries are listed in Table 4.7~~Table 4.7~~.

Table 4.7. Common threats to energy security of the analysed countries

Category	Examples of threats
Technical	• technical problems or accidents in the energy production, resource extractions and transportation, energy transmission infrastructure and processing enterprises, • attacks on supply infrastructure.
Natural	• extreme temperature, wind, rainfall and other extreme meteorological phenomena or natural disasters.
Socio-political	• corruption, poor or inadequate management and investments in energy sector, • low government effectiveness and regulations, • high energy market concentration or formation of monopolies, • political instability of the consumer, supplier and transit countries, • the coercive manipulation of energy supplies, • increasing possibility of terrorist attacks and cyber-attacks, • increasing probability of armed conflict in the region, • international political and economic crises, • security concerns affecting the future of renewable energy, • shift in stability of European Union affecting the investments on strategic large-scale energy projects.

Increased tension between Russia and the West, Finnish energy import dependence, active (Russian) presence on the Finnish market and political tensions, increasing CHP heat taxation and loss of CHP pose the main threats to energy security of **Finland**. Other threats relevant to Finland's energy security are the following: environmental standards and regulations which create an obstacle for new large hydro power plants; public policy failure to create reliable markets, short-sightedness and populism in policy; withdrawal of PP capacity from the market (permanent has already taken place in 2015, about 900 MW dismantling). Society resistance to strategic energy projects is the reason of delays in wind PPs and NPP constructions and many local wind PPs projects have been cancelled. International energy market price shocks are seen as a threat, e.g. oil price shocks mainly hit transportation entrepreneurs in Finland. A conflict in the Baltic Sea region would impact Finland as well, e.g. oil exporter area conflicts have impacted via higher global market prices. Storms cause frequently electricity outages in rural areas of Finland. In extreme cold periods over large areas lack of electricity capacity is observed.

Estonia faces technical problems in the oil shale mining as well as high tariffs for resource extraction and consumption. Nevertheless, peatland management strategy is seen as a risk to biodiversity in Estonia. Geopolitical threats are stemmed from Russia's sphere of influence, e.g. control of Narva basin, impeded development of offshore windfarms due to security concerns, etc. Outdated environmental standards and regulations are also seen as a threat. Other threats relevant to Estonia's energy security are as follows: formation of monopolies – high electricity market concentration – low heat market concentration; society resistance to strategic energy projects, domination of state–owned companies on oil shale operations, aggressive policy of supplier states against the consumer states and interruption of energy resource due to disorders in the transit chain.

Latvia remains highly dependent on imports for petroleum products and natural gas, which poses a major threat to energy security.

The Astravets NPP in Belarus and the possible resumption of the Baltiyskaya NPP in Kaliningrad region are seen as threats to **Lithuania**'s energy security. These projects serve as Russia's tool to retain dominance over the regional energy market and impede the region's integration into Western Europe energy system [57]. Russia might seek to affect the decisions regarding the synchronization of the Baltic's energy system with the European Continental Network (ECN), which poses a threat to energy security as well as interest to recover its positions in the Lithuanian gas sector.

As for the other analysed countries, strong winds and extreme snowfalls may cause breaking the lines, extreme temperatures in winters and summers are the main cause of high demand.

4.4 Results and discussion

4.4.1 Electricity generation

Electricity generation in Finland for the Base scenario is summarized in Fig. 4.3 and Table 4.8. As it is possible to see from the data presented, nuclear fuel is currently dominant in the Finnish electricity generation. Electricity generation in nuclear power plants makes about 30% from total electricity requirement in 2015. After commissioning of the Olkiluoto NPP this share increases to 36-37%. The peak of electricity generation from nuclear plants is expected during period 2020-2035. In later years, with the decommissioning of existing nuclear units, the share of electricity generation from nuclear fuel will start declining and at the end of the study period will make only about 15% from total electricity requirement.

Electricity generation from hydro power plants is expected to remain stable contributing about 13-19% to the total electricity requirement. Some generation decline can happen in the middle of the study period due to rehabilitation of existing plants, which according to the results of the analysis is an economically attractive option for all the countries in the region under analysis.

Increasing requirements for climate change mitigation will stipulate growing electricity generation from wind power plants. This generation is expected to exceed 15 TWh per annum by 2050 and will cover nearly 18% of the total electricity requirements in Finland. It is also expected that a significant increase of electricity generation from wind power plants will occur in line with the declining electricity generation from nuclear plants. In other words, it is possible to say that wind power plants will significantly contribute to the carbon free electricity generation to a great extent, substituting another carbon free generation, that of nuclear power plants.

Electricity generation by manoeuvrable gas turbine CHP will be growing in parallel with growing electricity generation from wind power plants. This phenomenon can be explained by the necessity for balancing of intermittent electricity generation from wind power plants. Manoeuvrable gas turbine CHP will make significant contribution to balancing of intermittent generation by exploiting the balancing capabilities provided by the grid. Electrical batteries will also contribute to balancing of variable electricity generation at wind power plants. Their annual electricity output will wary in a range of 2.9-5.9 TWh. This will cover ~3.8-7.5% of the total electricity requirements in Finland.

Growing electricity import to Finland will contribute to balancing of variable wind generation. It also will substitute the declining electricity generation from power plans running on fossil fuel, as well as declining generation from nuclear plants. Thus, the electricity import/export balance is expected to increase from about 19% in 2015 to about 32% in 2050.

Summarizing, it is possible to say that electricity supply in Finland is and will remain sufficiently diversified both in terms of primary energy sources and supply channels. Nuclear fuel, hydro, wind resources, gas and biomass can be mentioned in case of primary energy sources are concerned. Electricity import is also possible from different countries (Sweden, Norway, Estonia and Russia), i.e. from different suppliers. This makes a good basis for energy security, whose quantitative characteristics will be discussed in Chapter 4.5.

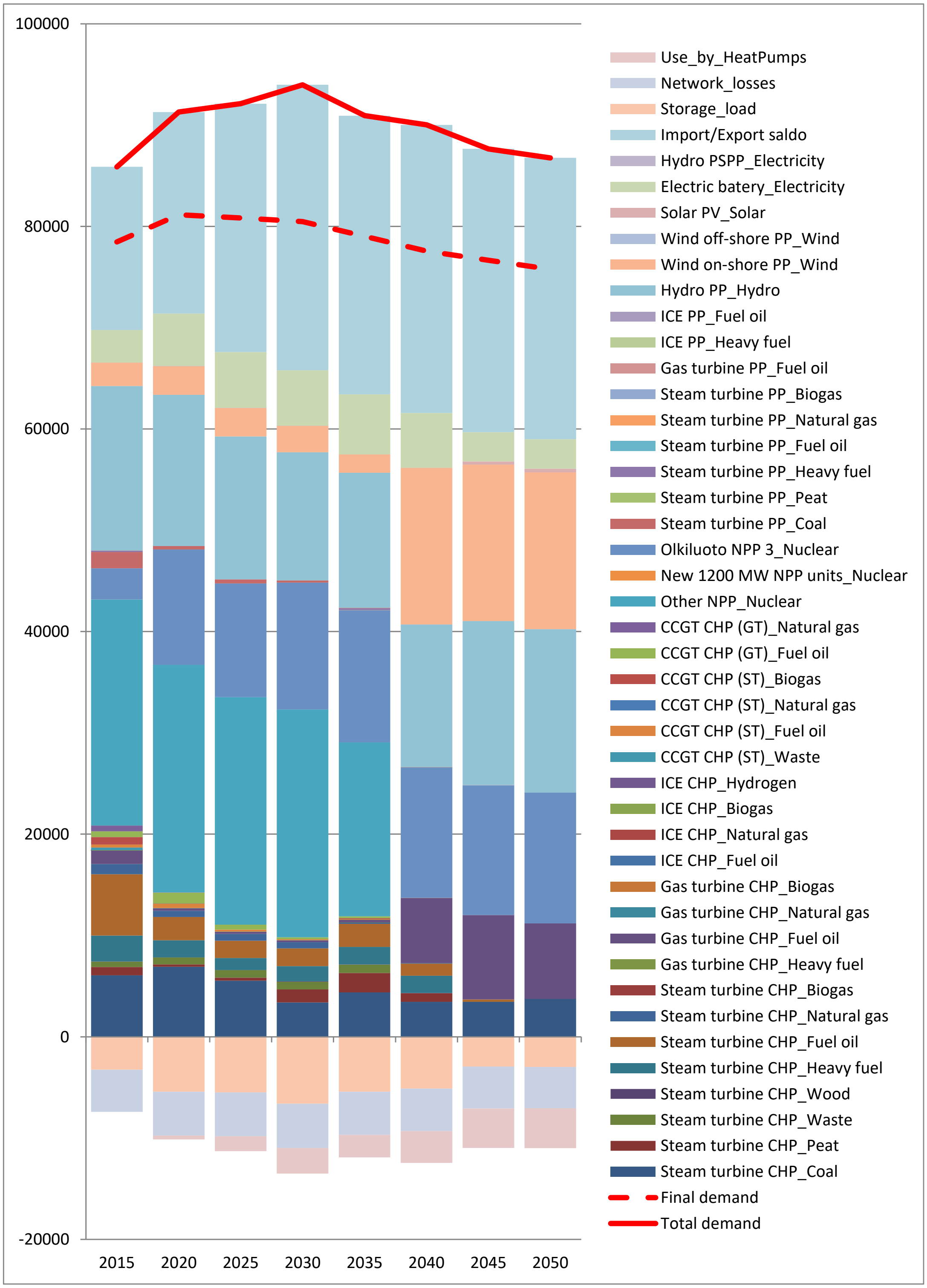


Figure 4.3. Electricity production by technology type and main fuel in Finland in the case of Base scenario.

Table 4.8. Electricity production by technology type and main fuel in Finland in Base scenario, GWh

	2015	2020	2025	2030	2035	2040	2045	2050
Steam turbine CHP_Coal	6070	6905	5531	3387	4384	3460	3449	3757
Steam turbine CHP_Peat	827	236	296	1281	1916	844	0	0
Steam turbine CHP_Waste	527	695	762	769	812	0	0	0
Steam turbine CHP_Wood	10	10	10	35	23	5	0	0
Steam turbine CHP_Heavy fuel	2563	1678	1178	1509	1747	1717	0	0
Steam turbine CHP_Fuel oil	6053	2291	1710	1752	2259	1205	229	0
Steam turbine CHP_Natural gas	997	616	678	596	148	56	0	0
Steam turbine CHP_Biogas	0	0	0	0	5	4	0	0
Gas turbine CHP_Heavy fuel	0	0	0	0	3	0	0	0
Gas turbine CHP_Fuel oil	1334	250	213	198	254	6414	8330	7425
Gas turbine CHP_Natural gas	0	0	0	0	2	0	0	0
ICE CHP_Fuel oil	8	0	0	0	0	0	0	0
ICE CHP_Biogas	36	10	11	11	0	0	0	0
ICE CHP_Hydrogen	1	0	0	0	0	0	0	0
CCGT CHP (ST)_Waste	245	10	0	0	0	0	0	0
CCGT CHP (ST)_Fuel oil	297	434	197	83	68	4	0	0
CCGT CHP (ST)_Natural gas	0	3	0	0	0	4	0	0
CCGT CHP (ST)_Biogas	742	20	0	7	77	0	0	0
CCGT CHP (GT)_Fuel oil	567	1060	471	199	199	0	0	0
CCGT CHP (GT)_Natural gas	568	21	0	0	0	0	0	0
Other NPP_Nuclear	22326	22469	22469	22469	17167	0	0	0
Olkiluoto NPP 3_Nuclear	3067	11398	11229	12537	13034	12887	12816	12921
Steam turbine PP_Coal	1601	340	395	218	0	0	0	0
Steam turbine PP_Peat	2	0	0	0	5	3	0	0
Steam turbine PP_Heavy fuel	164	0	0	0	193	14	0	0
Steam turbine PP_Natural gas	2	0	0	0	6	3	0	0
Gas turbine PP_Fuel oil	0	0	0	0	38	0	4	2
Hydro PP_Hydro	16224	14935	14113	12647	13344	14079	16209	16133
Wind on-shore PP_Wind	2320	2815	2807	2607	1811	15453	15439	15473
Wind off-shore PP_Wind	7	7	7	7	0	0	0	0
Solar PV_Solar	10	10	10	8	5	3	316	359
Electric batery_Electricity	3199	5175	5509	5474	5909	5424	2884	2923
Import/Export saldo	16106	19891	24504	28181	27514	28439	27964	27769
Storage_load	-3264	-5420	-5482	-6617	-5428	-5105	-2943	-2982
Network_losses	-4144	-4325	-4332	-4363	-4262	-4199	-4124	-4078
Use_by_HeatPumps	0	-382	-1472	-2519	-2213	-3154	-3916	-3946
Final demand	78463	81153	80820	80478	79024	77561	76659	75756

Electricity generation in the Baltic states for the Base scenario is summarized in Fig. 4.4 and Table 4.9. Electricity import and its generation from oil shale is dominant in the Baltic countries (Estonia, Latvia and Lithuania) at the beginning of the study period. The share of imported electricity cover ~29% of the total electricity requirements in the Baltic states. Electricity generation from oil shale is valued at ~26% level. It is expected in the future electricity import and electricity generation from oil shale will be declining to ~7% and less that 1% by 2050. Electricity import will be mainly declining due to expressed energy policy will. The electricity generation from oil shale will decline due to environmental concerns. On the opposite side, electricity generation from wind and gas will be growing in order to compensate these reductions. Thus, electricity generation from wind power plants is expected to be reaching ~2.8 TWh in 2030 and more than 19 TWh in 2050. This will cover ~7.5% and ~40% of the total electricity requirements in the region correspondingly.

Electricity generation from gas in the Base scenario will grow from ~20% in 2015 to ~32% in 2050. As it is the case in Finland, these power plants will significantly contribute to balancing of variable electricity generation from wind power plants. However, electricity grid (i.e. varying electricity import/export from/to neighbouring countries) will make the major contribution to balancing of variable wind generation in the Baltic states. Use of hydro pumped storage power plant in comparison to aforementioned options is economically less attractive option used for balancing electricity supply and demand due to comparatively big losses.

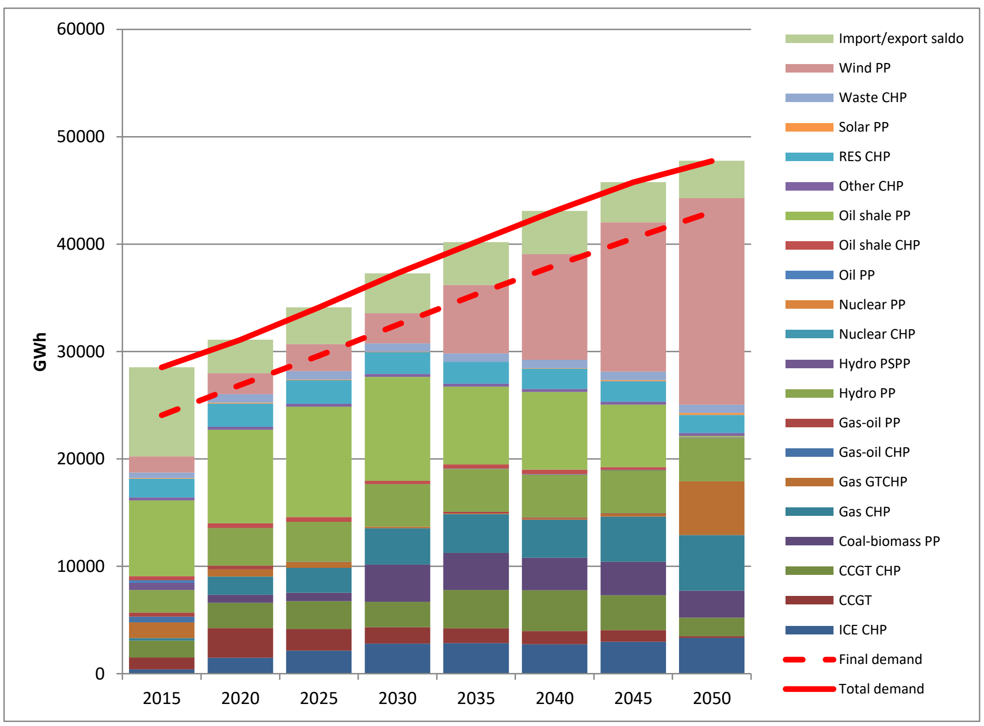


Figure 4.4. Electricity production by technology type in Baltic States in the case of Base scenario

Table 4.9. Electricity production by technology type in Baltic States in the case of Base scenario, GWh.

Technology type and main fuel	2015	2020	2025	2030	2035	2040	2045	2050
ICE CHP	421	1498	2146	2802	2853	2743	2982	3347
CCGT	1086	2761	2016	1534	1386	1237	1088	165
CCGT CHP	1583	2352	2598	2361	3563	3801	3245	1719
Coal-biomass PP	0	743	778	3475	3466	3022	3124	2508
Gas CHP	233	1702	2325	3381	3603	3530	4183	5164
Gas GTCHP	1466	666	571	143	56	101	223	5027
Gas-oil CHP	522	6	25	0	0	0	0	0
Gas-oil PP	375	351	0	0	143	109	87	0
Hydro PP	2110	3492	3686	3964	4006	4003	4007	4008
Hydro PSPP	675	8	10	14	34	47	66	51
Nuclear CHP	0	0	0	0	0	0	0	0
Nuclear PP	0	0	0	0	0	0	0	0
Oil PP	233	0	0	0	0	0	0	0
Oil shale CHP	391	438	438	290	374	407	227	0
Oil shale PP	7052	8710	10266	9677	7254	7249	5817	158
Other CHP	264	275	275	275	275	275	275	274
RES CHP	1737	2168	2185	2026	2031	1878	1913	1683
Solar PP	73	75	75	43	0	54	107	188
Waste CHP	500	775	771	770	785	785	785	764
Wind PP	1516	1964	2539	2804	6380	9825	13913	19223
Import	18189	38797	37063	48612	48138	48569	48156	45482
Export	-9896	-35688	-33651	-44881	-44150	-44542	-44430	-42003
Final demand	24069	26893	29597	32488	35310	37986	40544	42991
Total demand	28531	31094	34115	37289	40195	43093	45767	47733
Import/export saldo	8293	3110	3412	3730	3988	4028	3727	3480

Electricity generation in each Baltic county in the Base scenario is presented in Fig. 4.5-4.7 and Table 4.10-4.12.

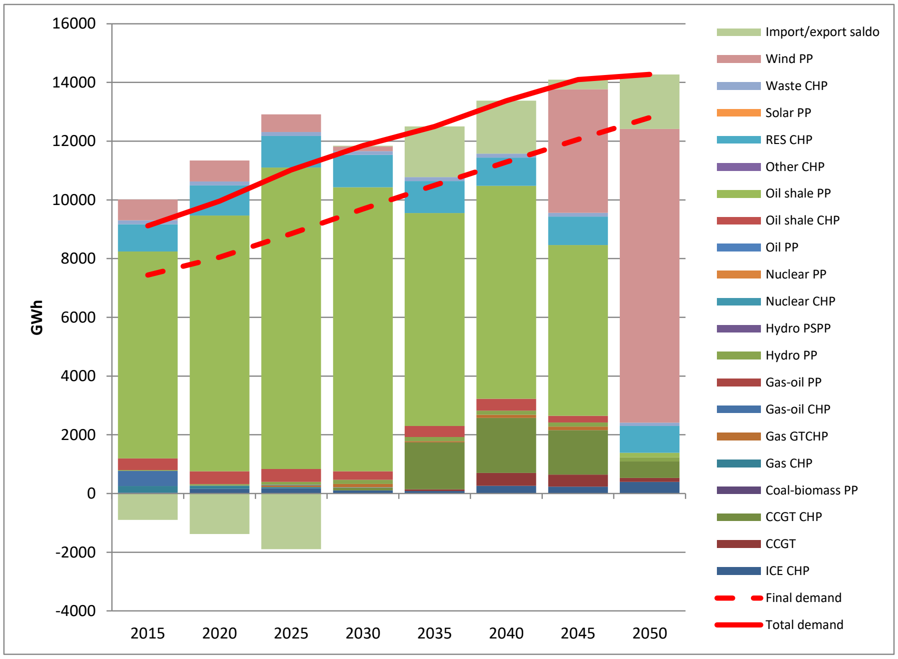


Figure 4.5. Electricity production in Estonia in the case of Base scenario.

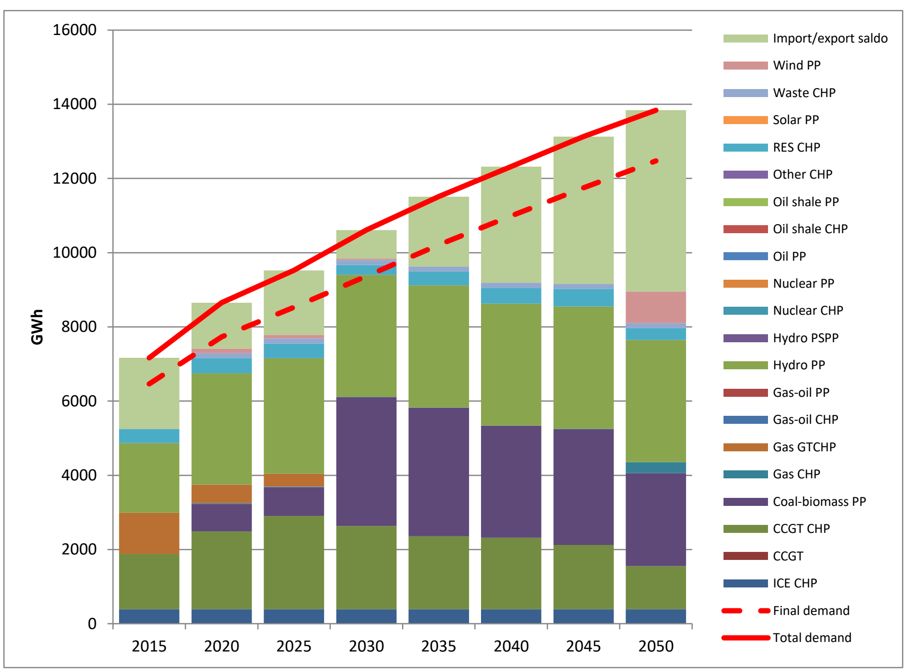


Figure 4.6. Electricity production in Latvia in the case of Base scenario.

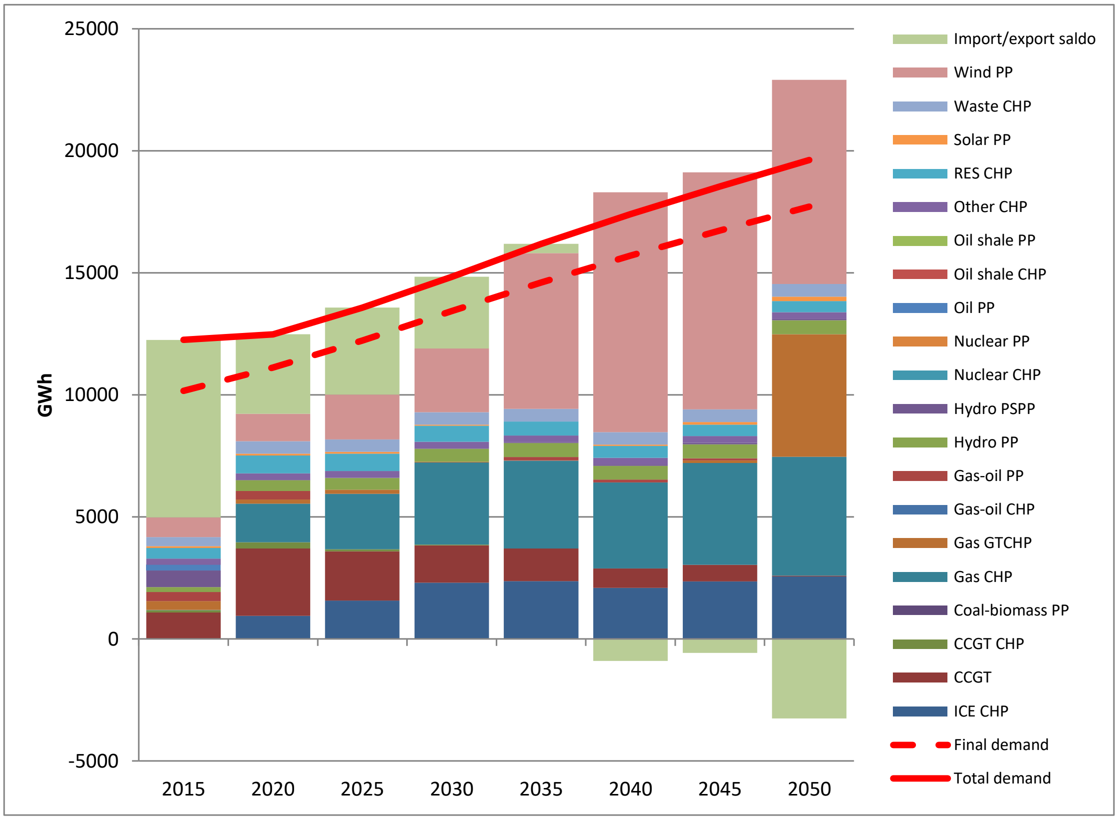


Figure 4.7. Electricity production in Lithuania in the case of Base scenario.

Table 4.10. Electricity production by technology type and main fuel in Estonia in the Base scenario, GWh

	2015	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
ICE CHP	29	164	178	109	88	259	232	395
CCGT	0	0	0	0	53	444	413	134
CCGT CHP	0	0	0	86	1597	1876	1514	559
Coal-biomass PP	0	0	0	0	0	0	0	0
Gas CHP	223	100	44	16	2	0	0	0
Gas GTCHP	0	0	54	111	44	101	120	0
Gas-oil CHP	522	6	25	0	0	0	0	0
Gas-oil PP	0	0	0	0	0	0	0	0
Hydro PP	28	47	95	142	142	142	142	142
Hydro PSPP	0	0	0	0	0	0	0	0
Nuclear CHP	0	0	0	0	0	0	0	0
Nuclear PP	0	0	0	0	0	0	0	0
Oil PP	0	0	0	0	0	0	0	0
Oil shale CHP	391	438	438	290	374	407	227	0
Oil shale PP	7052	8710	10266	9677	7254	7249	5817	158
Other CHP	0	0	0	0	0	0	0	0
RES CHP	926	1030	1080	1103	1087	964	964	912
Solar PP	0	0	0	0	0	0	0	0
Waste CHP	134	134	129	126	134	134	134	113
Wind PP	709	709	606	154	0	0	4205	10007
Import	5021	10994	8335	11954	11726	12260	11107	10892
Export	-5919	-12371	-10231	-11922	-10001	-10460	-10777	-9041
Final demand	7440	8047	8845	9689	10498	11290	12060	12801
Total demand	9117	9961	11019	11845	12500	13376	14096	14270

Table 4.11. Electricity production by technology type and main fuel in Latvia in the Base scenario, GWh

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
ICE CHP	391	391	391	391	391	391	391	391
CCGT	0	0	0	0	0	0	0	0
CCGT CHP	1489	2095	2513	2241	1966	1925	1731	1160
Coal-biomass PP	0	743	778	3475	3466	3022	3124	2508
Gas CHP	0	24	16	7	4	0	10	297
Gas GTCHP	1110	497	343	0	0	0	0	0
Gas-oil CHP	0	0	0	0	0	0	0	0
Gas-oil PP	0	0	0	0	0	0	0	0
Hydro PP	1879	2999	3114	3290	3294	3292	3292	3295
Hydro PSPP	0	0	0	0	0	0	0	0
Nuclear CHP	0	0	0	0	0	0	0	0
Nuclear PP	0	0	0	0	0	0	0	0
Oil PP	0	0	0	0	0	0	0	0
Oil shale CHP	0	0	0	0	0	0	0	0
Oil shale PP	0	0	0	0	0	0	0	0
Other CHP	0	0	0	0	0	0	0	0
RES CHP	378	411	396	266	370	425	478	316
Solar PP	0	0	0	0	0	0	0	0
Waste CHP	0	134	134	134	134	134	134	134
Wind PP	0	123	97	39	0	0	0	851
Import	5894	12107	12179	16401	17403	17962	18380	17956
Export	-3976	-10873	-10438	-15632	-15519	-14832	-14409	-13069
Final demand	6461	7732	8526	9368	10208	10993	11747	12475
Total demand	7165	8651	9523	10611	11510	12318	13130	13839

Table 4.12. Electricity production by technology type and main fuel in Lithuania in the Base scenario, GWh.

	2015	2020	2025	2030	2035	2040	2045	2050
ICE CHP	1	942	1577	2301	2374	2093	2359	2561
CCGT	1086	2761	2016	1534	1333	794	675	31
CCGT CHP	94	257	86	34	0	0	0	0
Coal-biomass PP	0	0	0	0	0	0	0	0
Gas CHP	10	1577	2265	3358	3597	3530	4173	4867
Gas GTCHP	356	169	173	32	11	0	104	5027
Gas-oil CHP	0	0	0	0	0	0	0	0
Gas-oil PP	375	351	0	0	143	109	87	0
Hydro PP	202	445	477	533	571	569	574	572
Hydro PSPP	675	8	10	14	34	47	66	51
Nuclear CHP	0	0	0	0	0	0	0	0
Nuclear PP	0	0	0	0	0	0	0	0
Oil PP	233	0	0	0	0	0	0	0
Oil shale CHP	0	0	0	0	0	0	0	0
Oil shale PP	0	0	0	0	0	0	0	0
Other CHP	264	275	275	275	275	275	275	274
RES CHP	433	727	708	658	574	489	471	455
Solar PP	73	75	75	43	0	54	107	188
Waste CHP	366	507	508	510	517	517	517	518
Wind PP	807	1133	1836	2612	6380	9825	9708	8365
Import	7274	15696	16549	20257	19008	18347	18669	16635
Export	-1	-12443	-12982	-17328	-18630	-19250	-19244	-19893
Final demand	10168	11114	12226	13431	14604	15703	16737	17714
Total demand	12249	12482	13573	14834	16186	17398	18541	19624

The presented data shows that electricity generation from oil shale is dominant in Estonia, almost during the entire study period. Only at the end of the period this is substituted by electricity generated from wind. The growing environmental burdens (CO_2 price, in particular) is the main cause of this change.

Three main types of power plants are used for electricity generation in Latvia; CCGT CHP running on gas, CHP's running on biomass and hydro power plants. The remaining part of electricity requirement is covered by electricity imports.

The electricity requirements to a large extent are met by electricity imports at the beginning of the study period. Local generation is deeply diversified both in terms of power plant and primary energy resources including gas, wind, biomass and municipal waste as the main ones. Over time, electricity generation from gas and wind will be growing in order to help implement the agreed energy policy provisions on the reduction of electricity imports. Significant increase of electricity generation from wind is expected after 2030.

Due to the sharp increase of electricity generation from wind in Estonia, the ability of the electricity grid and available manoeuvrable gas power plants will become insufficient to balance variable wind generation in the region. In the aftermath of that, significant increase of gas turbine CHP generation is expected in Lithuania at the end of study period.

4.4.2 Provision of reservation services

Provision of reservation services is very important for energy security. Modelling results regarding reserve provision in Finland for the Base scenario are summarized in Tables 4.13-4.15.

Table 4.13. Readiness of different suppliers for provision of frequency containment reserve in Finland, GWh.

	2015	***2020***	***2025***	***2030***	***2035***	***2040***	***2045***	***2050***
Steam turbine CHP_Coal	48	214	170	63	71	62	71	88
Steam turbine CHP_Peat	28	12	15	64	43	4	0	0
Steam turbine CHP_Waste	4	18	16	7	7	0	0	0
Steam turbine CHP_Wood	0	0	0	1	0	0	0	0
Steam turbine CHP_Heavy fuel	17	15	12	29	21	5	0	0
Steam turbine CHP_Fuel oil	25	61	49	48	52	12	2	0
Steam turbine CHP_Natural gas	4	23	31	13	2	0	0	0
Steam turbine CHP_Biogas	0	0	0	0	0	0	0	0
Gas turbine CHP_Heavy fuel	0	0	0	0	0	0	0	0
Gas turbine CHP_Fuel oil	0	10	8	5	10	168	315	273
Gas turbine CHP_Natural gas	0	0	0	0	0	0	0	0
Gas turbine CHP_Biogas	0	0	0	0	0	0	0	0
ICE CHP_Fuel oil	0	0	0	0	0	0	0	0
ICE CHP_Natural gas	0	0	0	0	0	0	0	0
ICE CHP_Biogas	0	0	0	0	0	0	0	0
ICE CHP_Hydrogen	0	0	0	0	0	0	0	0
CCGT CHP (ST)_Waste	0	0	0	0	0	0	0	0
CCGT CHP (ST)_Fuel oil	0	22	10	1	3	0	0	0
CCGT CHP (ST)_Natural gas	0	0	0	0	0	0	0	0
CCGT CHP (ST)_Biogas	1	1	0	0	4	0	0	0
CCGT CHP (GT)_Fuel oil	0	31	11	10	6	0	0	0
CCGT CHP (GT)_Natural gas	0	1	0	0	0	0	0	0

	2015	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
Other NPP_Nuclear	5	0	0	0	0	0	0	0
New 1200 MW NPP units_Nuclear	0	0	0	0	0	0	0	0
Olkiluoto NPP 3_Nuclear	0	13	23	11	1	0	1	2
Steam turbine PP_Coal	18	17	20	11	0	0	0	0
Steam turbine PP_Peat	0	0	0	0	0	0	0	0
Steam turbine PP_Heavy fuel	0	0	0	0	10	1	0	0
Steam turbine PP_Fuel oil	0	0	0	0	0	0	0	0
Steam turbine PP_Natural gas	0	0	0	0	0	0	0	0
Steam turbine PP_Biogas	0	0	0	0	0	0	0	0
Gas turbine PP_Fuel oil	0	0	0	0	2	0	0	0
ICE PP_Heavy fuel	0	0	0	0	0	0	0	0
ICE PP_Fuel oil	0	0	0	0	0	0	0	0
Hydro PP_Hydro	403	578	472	30	260	283	198	221
Wind on-shore PP_Wind	0	0	0	0	0	0	0	0
Wind off-shore PP_Wind	0	0	0	0	0	0	0	0
Solar PV_Solar	0	0	0	0	0	0	0	0
Electric batery_Electricity	144	530	550	605	567	377	95	68
Hydro PSPP_Electricity	0	0	0	0	0	0	0	0
AC interconnectors_Electricity	4485	9095	9095	10851	11347	11020	11355	12091
DC interconnectors1_Electricity	177	211	279	279	111	0	0	0
DC interconnectors2_Electricity	109	558	490	522	517	721	674	673
DC interconnectors3_Electricity	0	0	0	0	0	562	938	938
Total	5469	11411	11252	12549	13035	13215	13651	14354

Table 4.14. Readiness of different suppliers for provision of frequency restoration reserve in Finland, GWh.

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Steam turbine CHP_Coal	909	1005	1731	2265	1517	573	317	499
Steam turbine CHP_Peat	2432	575	1120	425	504	234	0	0
Steam turbine CHP_Waste	49	180	104	167	70	0	0	0
Steam turbine CHP_Wood	8	39	31	21	8	3	0	0
Steam turbine CHP_Heavy fuel	1523	1308	1460	1285	574	529	0	0
Steam turbine CHP_Fuel oil	1797	1097	2468	1495	1122	1064	129	147
Steam turbine CHP_Natural gas	69	223	209	205	27	15	0	0
Steam turbine CHP_Biogas	20	97	141	186	107	38	0	0
Gas turbine CHP_Heavy fuel	21	51	42	52	51	0	0	0
Gas turbine CHP_Fuel oil	240	591	417	449	288	3888	7043	7000
Gas turbine CHP_Natural gas	22	61	59	48	23	0	0	0
Gas turbine CHP_Biogas	1	2	0	0	0	0	0	0
ICE CHP_Fuel oil	0	3	4	4	3	0	0	0
ICE CHP_Natural gas	15	24	0	0	0	0	0	0
ICE CHP_Biogas	32	9	54	12	1	0	0	0
ICE CHP_Hydrogen	4	2	0	0	0	0	0	0
CCGT CHP (ST)_Waste	0	89	0	0	0	0	0	0
CCGT CHP (ST)_Fuel oil	566	326	638	116	122	54	0	0
CCGT CHP (ST)_Natural gas	21	157	212	57	39	42	0	0
CCGT CHP (ST)_Biogas	125	607	506	588	288	0	0	0
CCGT CHP (GT)_Fuel oil	3469	410	655	264	208	0	0	0
CCGT CHP (GT)_Natural gas	0	176	0	0	0	0	0	0
Other NPP_Nuclear	34	0	0	0	0	0	0	0
New 1200 MW NPP units_Nuclear	0	0	0	0	0	0	0	0
Olkiluoto NPP 3_Nuclear	0	585	890	293	0	0	0	0
Steam turbine PP_Coal	887	201	1157	743	0	0	0	0
Steam turbine PP_Peat	11	12	19	16	13	11	0	0
Steam turbine PP_Heavy fuel	252	273	468	205	356	75	0	0
Steam turbine PP_Fuel oil	67	40	0	0	0	0	0	0
Steam turbine PP_Natural gas	21	6	16	14	5	7	0	0
Steam turbine PP_Biogas	4	1	5	2	3	0	0	0
Gas turbine PP_Fuel oil	1121	389	1853	802	1056	0	8	13
ICE PP_Heavy fuel	7	0	0	0	0	0	0	0
ICE PP_Fuel oil	11	2	8	2	4	0	0	0

	2015	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
Hydro PP_Hydro	5352	280	517	0	156	177	375	314
Wind on-shore PP_Wind	212	0	0	0	0	0	0	0
Wind off-shore PP_Wind	0	0	0	0	0	0	0	0
Solar PV_Solar	0	0	0	0	0	0	0	0
Electric batery_Electricity	10261	1744	13075	4053	8481	4927	4946	3569
Hydro PSPP_Electricity	0	0	0	0	0	0	0	0
AC interconnectors_Electricity	2321	0	0	0	0	1451	4143	3053
DC interconnectors1_Electricity	141	1040	0	0	0	0	958	0
DC interconnectors2_Electricity	168	1946	0	0	0	1302	0	2409
DC interconnectors3_Electricity	0	0	0	0	0	0	0	0
Total	32191	13550	27860	13772	15024	14389	17920	17003

Table 4.15. Readiness of different suppliers for provision of replacement reserve in Finland, GWh.

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Steam turbine CHP_Coal	665	1261	1432	2495	2640	729	1142	1551
Steam turbine CHP_Peat	2233	594	2068	626	709	421	0	0
Steam turbine CHP_Waste	85	157	213	138	164	0	0	0
Steam turbine CHP_Wood	8	34	38	16	10	5	0	0
Steam turbine CHP_Heavy fuel	1357	1791	1675	1448	1289	909	0	0
Steam turbine CHP_Fuel oil	2043	1517	2653	2342	2681	2123	409	319
Steam turbine CHP_Natural gas	148	273	302	218	46	16	0	0
Steam turbine CHP_Biogas	42	138	135	130	185	65	0	0
Gas turbine CHP_Heavy fuel	16	50	56	79	74	0	0	0
Gas turbine CHP_Fuel oil	313	651	510	447	615	4690	5089	5238
Gas turbine CHP_Natural gas	26	79	60	62	54	0	0	0
Gas turbine CHP_Biogas	1	2	0	0	0	0	0	0
ICE CHP_Fuel oil	0	2	5	3	6	0	0	0
ICE CHP_Natural gas	13	46	0	0	0	0	0	0
ICE CHP_Biogas	28	12	48	21	2	0	0	0
ICE CHP_Hydrogen	2	3	0	0	0	0	0	0
CCGT CHP (ST)_Waste	0	101	0	0	0	0	0	0
CCGT CHP (ST)_Fuel oil	547	424	403	221	257	90	0	0
CCGT CHP (ST)_Natural gas	21	168	197	66	118	84	0	0
CCGT CHP (ST)_Biogas	316	555	597	454	719	0	0	0
CCGT CHP (GT)_Fuel oil	1944	656	867	398	306	0	0	0
CCGT CHP (GT)_Natural gas	0	187	0	0	0	0	0	0
Other NPP_Nuclear	104	0	0	0	0	0	0	0
New 1200 MW NPP units_Nuclear	0	0	0	0	0	0	0	0
Olkiluoto NPP 3_Nuclear	0	678	893	194	0	148	218	112
Steam turbine PP_Coal	859	282	1010	963	0	0	0	0
Steam turbine PP_Peat	13	5	26	19	25	32	0	0
Steam turbine PP_Heavy fuel	443	381	684	409	506	201	0	0
Steam turbine PP_Fuel oil	82	65	0	0	0	0	0	0
Steam turbine PP_Natural gas	9	8	22	23	19	28	0	0
Steam turbine PP_Biogas	3	2	4	4	5	0	0	0
Gas turbine PP_Fuel oil	2305	400	4392	2117	2833	0	41	38
ICE PP_Heavy fuel	8	0	0	0	0	0	0	0
ICE PP_Fuel oil	12	4	12	9	14	0	0	0

	2015	2020	2025	2030	2035	2040	2045	2050
Hydro PP_Hydro	2958	149	470	0	103	708	725	679
Wind on-shore PP_Wind	151	0	0	0	0	257	353	101
Wind off-shore PP_Wind	0	0	0	0	0	0	0	0
Solar PV_Solar	0	0	0	0	0	0	0	0
Electric batery_Electricity	0	0	0	0	0	0	0	0
Hydro PSPP_Electricity	0	0	0	0	0	0	0	0
AC interconnectors_Electricity	2283	0	0	0	0	1781	6890	2019
DC interconnectors1_Electricity	111	1017	0	0	0	0	948	0
DC interconnectors2_Electricity	497	1740	516	0	0	2270	0	5214
DC interconnectors3_Electricity	0	0	0	0	0	0	0	0
Total	19648	13435	19288	12903	13379	14555	15815	15270

Reservation service amount expressed in GWh does not mean actually provided service. This shows the ability of the plan for provision of the service, if such would be required. In other words, this shows readiness of plants and international lines for service provision. The presented data clearly shows that the major part of frequency containment reserve is provided by interconnectors, especially AC lines. Depending on the year, they cover 80-87% of the total requirements of frequency containment reserve. This implies that certain throughput capacity of lines should be always available for reservation services and that not full capacity can be used for commercial electricity trade. Results of this study show that on average only 56% -72% of installed throughput capacity of interconnectors is used for commercial electricity flows.

Provision on frequency restoration reserve is much more diversified and can be obtained from the majority of power plants. Contribution of interconnectors varies in a range up to 32% of the total requirements. This is also the case with the provision of replacement reserves in Finland where power plants are the main contributors to this kind of reserve.

Reserve requirements in Lithuania are illustrated for one randomly selected year. This illustration is presented in Fig. 4.8-4.10. In principle, it gives similar results as it does for Finland. Practically all frequency containment reserve is provided by interconnectors, and all the requirements for frequency restoration and replacement reserves are fulfilled by power plants, located within the region. Therefore, if all capacity expansion options (see chapter 4.4.4) are implemented, the electricity systems of Finland and the Baltic States will have sufficient reserves in order to withstand n-1 disturbance and be ready to overcome disturbance n-2. There is no single time slice within the long time period analysed in which there would be not enough reserve capacities in the system. Thus, in theory, the power systems should not encounter any serious disruptions. However, in practice, certain elements that ensure the provision of reservation services may not be implemented or their functioning may not correspond to the real threats. Therefore, the disruption of the operation of an important element (line or generator) may cause a major disturbance to the entire power system, especially in the case where throughput capacity of interconnectors was reduced due to various reasons. Looking at the current situation [63], the biggest problems are related to the provision of frequency containment and replacement reserves.

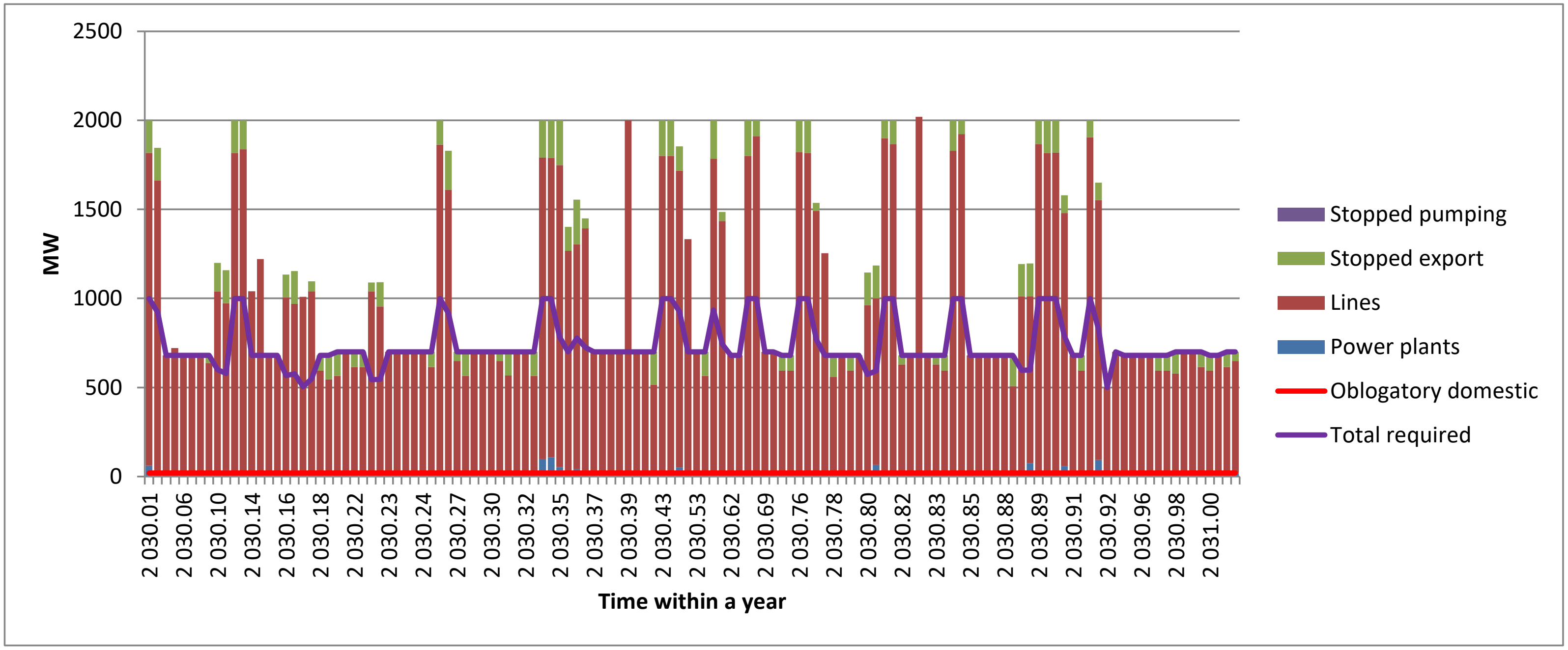


Figure 4.8. Provision of frequency containment reserve in Baltic countries in the case of Base scenario.

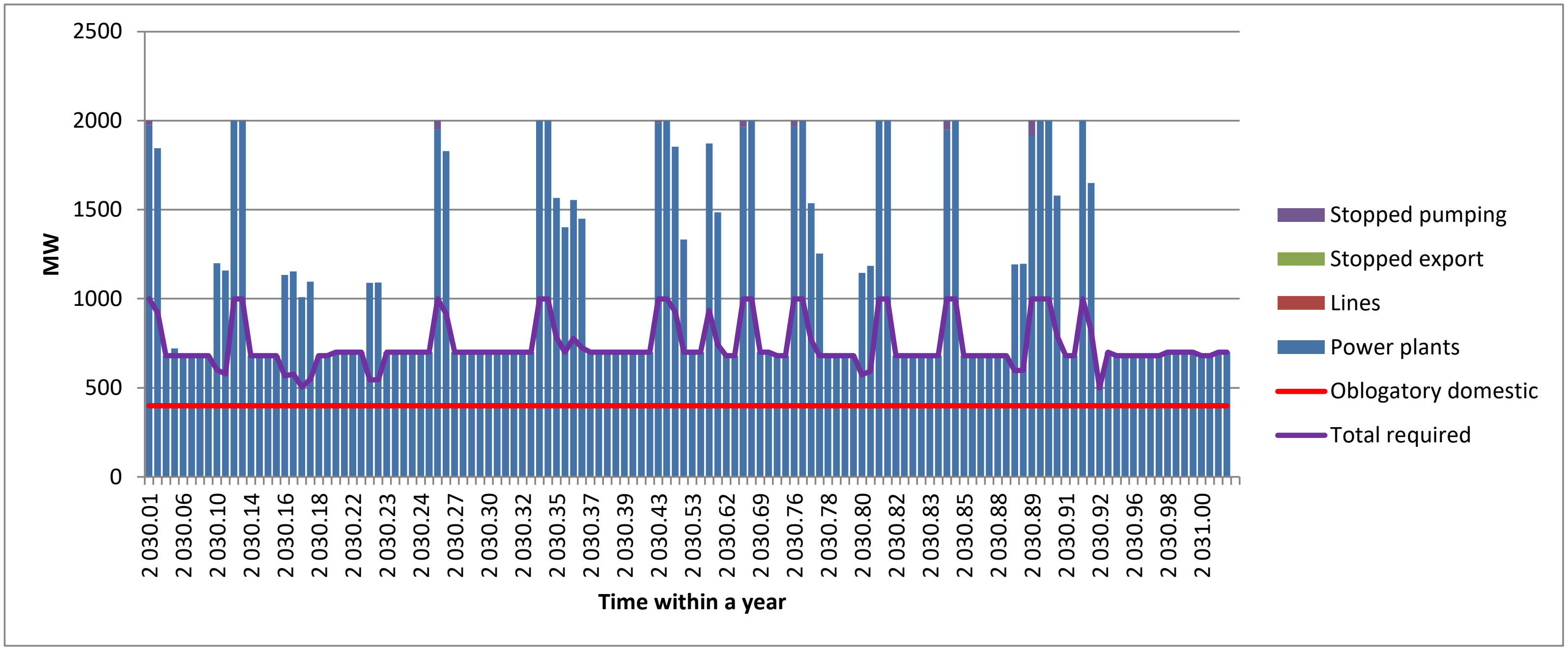


Figure 4.9. Provision of frequency restoration reserve in Baltic countries in the case of Base scenario.

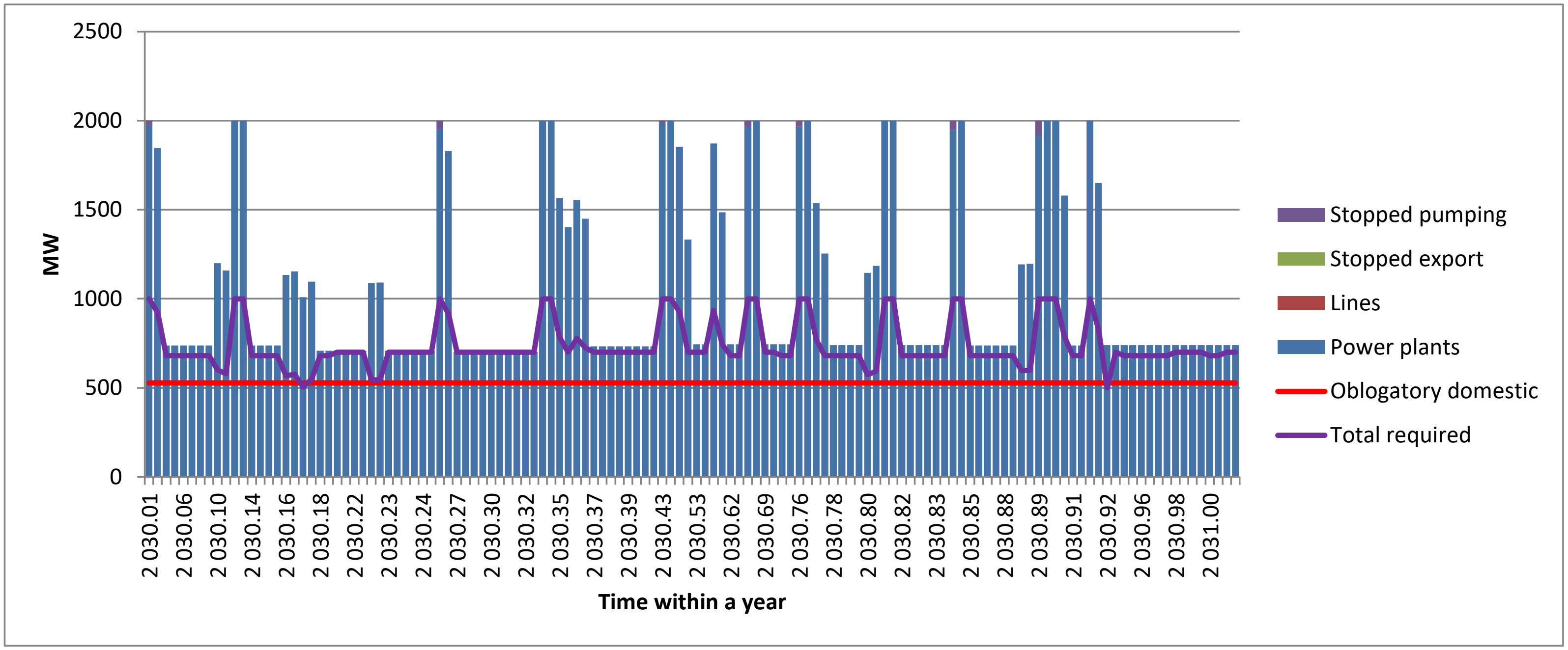
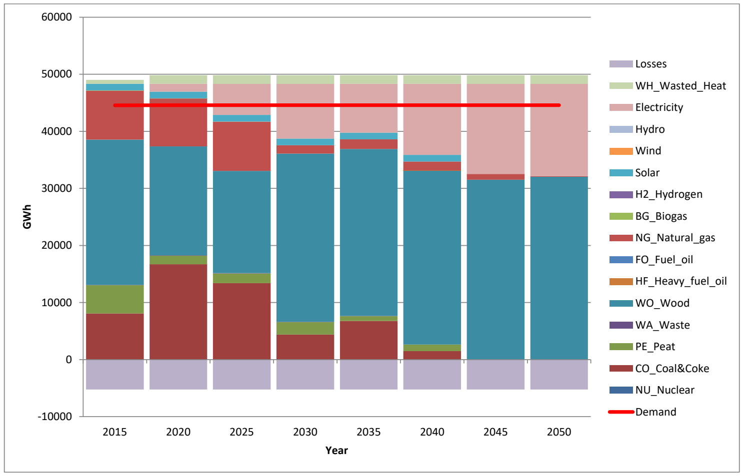


Figure 4.10. Provision of replacement reserve in Baltic countries in the case of Base scenario.

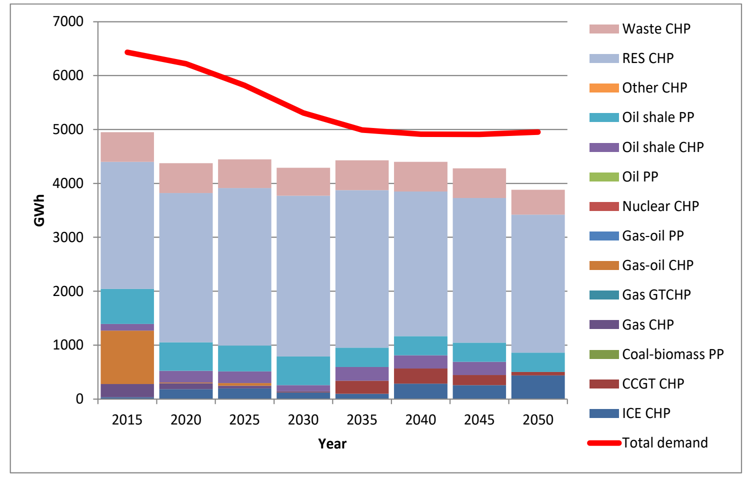
4.4.3 Heat generation

Dynamics of heat generation in Finland and the Baltic states for the Base scenario are shown in Fig. 4.11.

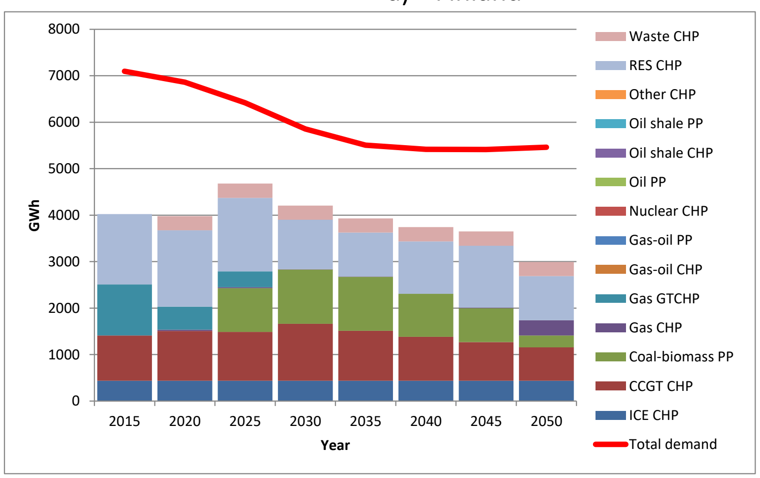
In the Baltic states, the remainder between heat demand and heat provided by CHP is covered by biomass boilers. The presented data shows large biomass contribution to district heat production. Depending on the year and the country, biomass based heat production varies in a range of 58-75% of the total heat generation. Share of biomass based heat production in particular towns reaches even 100%. Looking from the energy security point of view, such a big dominance of one kind of fuel can lead to distortions of competition and cause rise of heat prices. From the other point of view, large quantities of wood fuel burned in towns lead to increased emissions of particulates. In addition, preparation of large quantities of biofuel requires sustainable development of the forestry sector. Large use of wood fuel may turn into not sustainable process in forestry if not sufficient attention is paid to planting new forests for future energy needs.



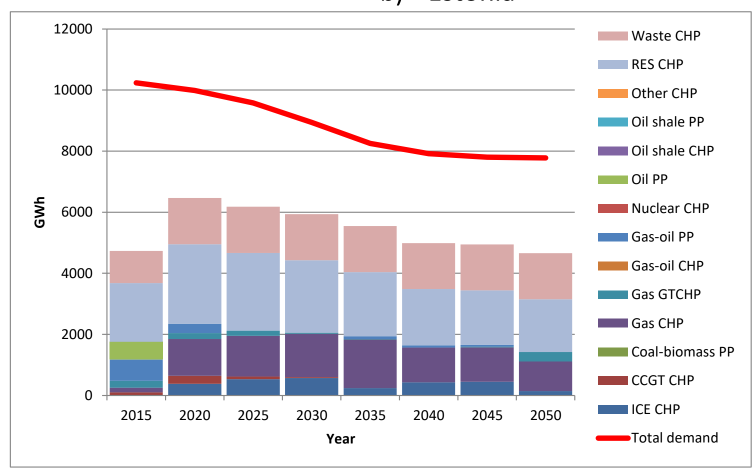
a) Finland



b) Estonia



c) Latvia



d) Lithuania

Figure 4.11. Production of district heat in the case of Base scenario..

4.4.4 Installed capacity

Installed capacities of power plants and interconnectors in Finland for the Base scenario are presented in Fig. 4.12 and Table 4.16.

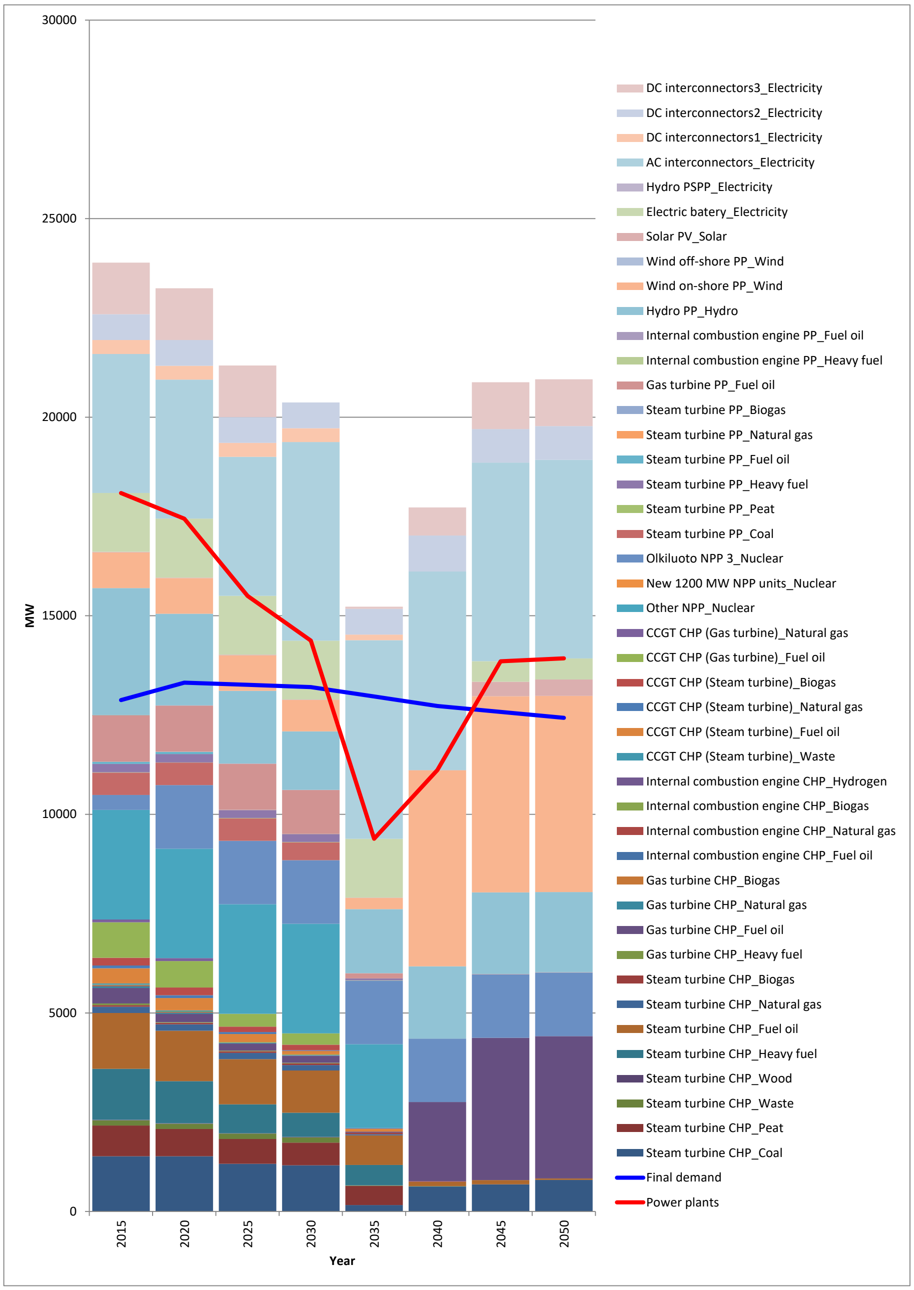


Figure 4.12. Installed capacity of electricity generation sources in Finland.

Table 4.16. Installed capacity of electricity generating technologies in Finland, MW.

	2015	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Steam turbine CHP_Coal	1390	1390	1198	1162	164	617	681	794
Steam turbine CHP_Peat	773	686	626	570	483	0	0	0
Steam turbine CHP_Waste	135	135	135	135	8	0	0	0
Steam turbine CHP_Wood	13	13	10	9	5	1	0	0
Steam turbine CHP_Heavy fuel	1283	1059	727	609	512	18	0	0
Steam turbine CHP_Fuel oil	1405	1270	1139	1066	743	108	108	38
Steam turbine CHP_Natural gas	159	159	159	135	30	0	0	0
Steam turbine CHP_Biogas	40	40	40	40	40	16	0	0
Gas turbine CHP_Heavy fuel	42	17	17	17	0	0	0	0
Gas turbine CHP_Fuel oil	389	207	178	178	25	1995	3582	3582
Gas turbine CHP_Natural gas	42	27	17	16	0	0	0	0
Gas turbine CHP_Biogas	2	1	0	0	0	0	0	0
ICE CHP_Fuel oil	1	1	1	1	0	0	0	0
ICE CHP_Natural gas	18	13	0	0	0	0	0	0
ICE CHP_Biogas	19	17	17	16	0	0	0	0
ICE CHP_Hydrogen	4	1	0	0	0	0	0	0
CCGT CHP (ST)_Waste	30	30	0	0	0	0	0	0
CCGT CHP (ST)_Fuel oil	381	312	203	87	74	0	0	0
CCGT CHP (ST)_Natural gas	67	67	49	20	20	0	0	0
CCGT CHP (ST)_Biogas	198	198	138	138	0	0	0	0
CCGT CHP (GT)_Fuel oil	889	665	322	288	0	0	0	0
CCGT CHP (GT)_Natural gas	72	72	0	0	0	0	0	0
Other NPP_Nuclear	2758	2758	2758	2758	2107	0	0	0
New 1200 MW NPP units_Nuclear	0	0	0	0	0	0	0	0
Olkiluoto NPP 3_Nuclear	0	1600	1600	1600	1600	1600	1600	1600
Steam turbine PP_Coal	565	565	565	452	0	0	0	0
Steam turbine PP_Peat	7	7	7	7	7	0	0	0
Steam turbine PP_Heavy fuel	212	211	200	200	46	0	0	0
Steam turbine PP_Fuel oil	52	52	0	0	0	0	0	0
Steam turbine PP_Natural gas	6	6	6	6	6	0	0	0
Steam turbine PP_Biogas	1	1	1	1	1	0	0	0
Gas turbine PP_Fuel oil	1160	1160	1160	1100	127	0	8	8
ICE PP_Heavy fuel	5	0	0	0	0	0	0	0
ICE PP_Fuel oil	8	3	3	3	0	0	0	0
Hydro PP_Hydro	3196	2311	1833	1477	1615	1818	2053	2021

	2015	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
Wind on-shore PP_Wind	898	898	896	790	282	4940	4940	4940
Wind off-shore PP_Wind	2	2	2	2	0	0	0	0
Solar PV_Solar	11	11	11	9	6	2	364	413
Electric batery_Electricity	1482	1482	1482	1482	1482	0	518	531
Hydro PSPP_Electricity	0	0	0	0	0	0	0	0
AC interconnectors_Electricity	3500	3500	3500	5000	5000	5000	5000	5000
DC interconnectors1_Electricity	350	350	350	350	140	0	0	0
DC interconnectors2_Electricity	650	650	650	650	650	906	846	846
DC interconnectors3_Electricity	1300	1300	1300	0	57	705	1179	1179
Final power demand	12875	13316	13261	13205	12966	12727	12578	12430

The presented results show a substantial drop in installed capacity of power plants in the time period until 2035. This is related to the decommissioning of existing capacities after end of their technical life time and expected low electricity price in the market. Low electricity price in the market does not guarantee enough return on investments for new power plants. In such circumstances new investments are postponed. Absence of other instruments that could encourage new investments (for example, capacity market) may lead to a situation where energy security may decrease. In such situation, existing fossil fuel power plants that currently are not competitive in the electricity market might still be a cost-effective option to provide reserve services and ensure energy security. It is necessary to keep this in mind when decision about decommissioning of existing plants is made. The changing role of existing technologies can be considered as an important aspect of flexibility that increases energy security. Such cost-effective solutions may accelerate a real energy transition by ensuring energy security at a lower cost.

Shrinking diversity of fuels used by power plants is observed with the decommissioning of old plants. At the beginning of the study period, power plants were running on nuclear fuel, coal, peat, biomass, fuel oil, hydro and wind energy. By the end of the study period the most polluting fuels like coal and peat disappeared from the list of fuels. Nevertheless, even at the end of the study period electricity production is based on four major primary energy forms – nuclear fuel, fuel oil, wind and hydro energy. In addition, smaller contribution comes from biomass and solar energy.

Growth of installed capacity in Finland is expected with the rapid development of wind power plants followed by fast penetration of manoeuvrable gas turbine CHP. Gas turbine CHPs are used for balancing of variable wind generation.

It is also necessary to mention that dynamics of available power in the system will significantly differ from the installed capacity shown in Fig. 4.12, especially after 2035. , The difference between available power and installed capacity will appear because the available power of wind power plants and balancing power plants cannot be added together arithmetically while installed capacities can be summed.

Another important factor that should be mentioned is the increasing throughput capacity of international lines. This is linked to the growing capacity of wind power plants and increasing demand for balancing services in the system. Study results show that the total throughput capacity of international links in 2040 is already ~14% higher than in 2015 and in future it will be growing up to ~21% in 2045 and later years.

Dynamics of installed capacity of power plants and interconnectors providing electricity to the Baltic countries are shown in Fig. 4.13 and Table 4.17.

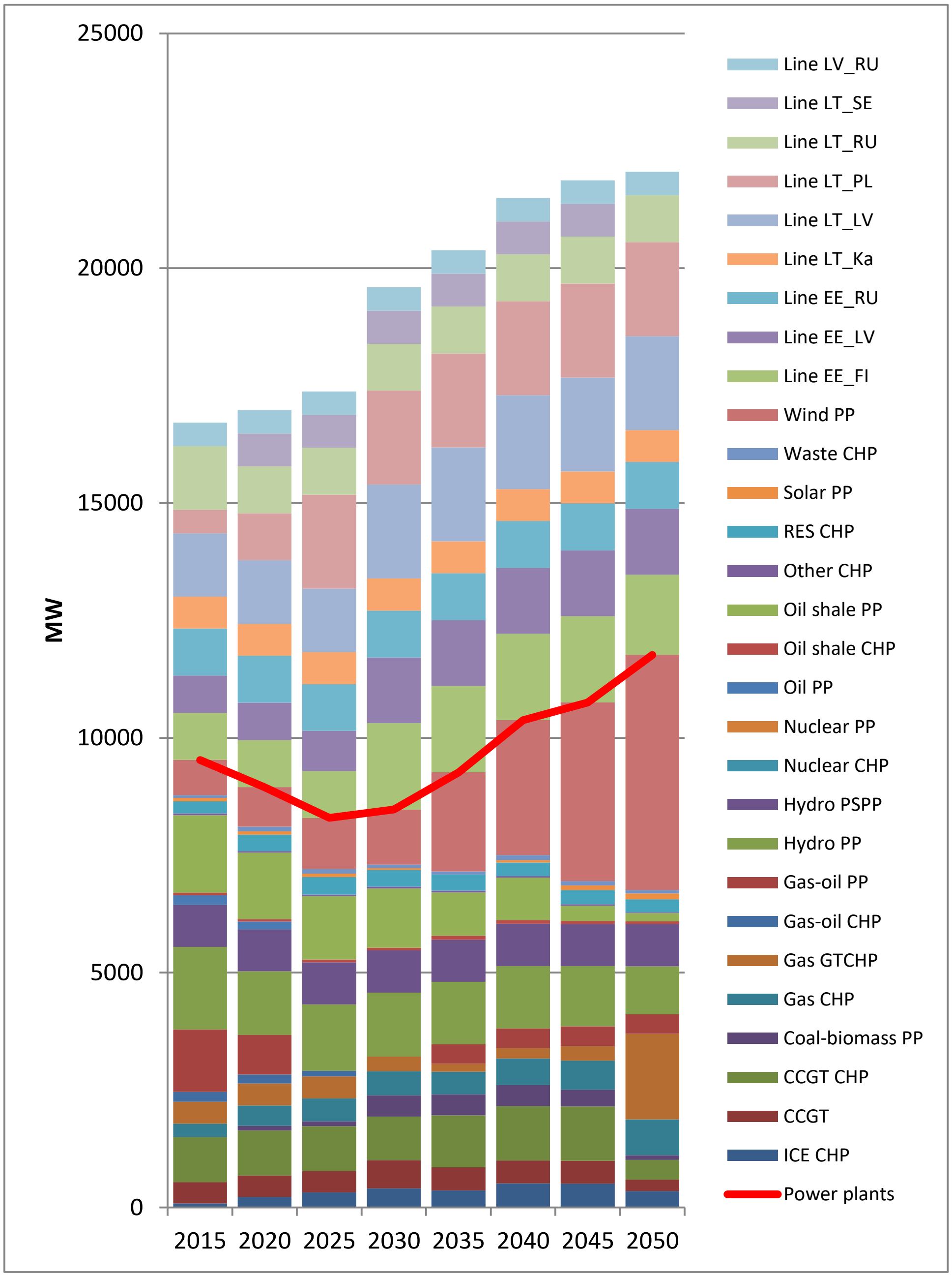


Figure 4.13. Installed capacity of electricity generation sources in Baltic States in the case of Base scenario.

Table 4.17. Installed capacity of electricity generating technologies in Baltic States in Base scenario, MW.

	2015	2020	2025	2030	2035	2040	2045	2050
ICE CHP	86	224	322	406	362	517	509	352
CCGT	455	455	455	599	495	486	486	241
CCGT CHP	964	964	954	933	1104	1157	1157	421
Coal-biomass PP	0	94	108	449	449	449	355	101
Gas CHP	283	433	484	519	480	563	619	761
Gas GTCHP	468	468	468	306	168	222	309	1821
Gas-oil CHP	210	192	120	0	0	0	0	0
Gas-oil PP	1330	842	0	0	420	420	420	420
Hydro PP	1752	1355	1411	1362	1325	1328	1284	1018
Hydro PSPP	900	900	900	900	900	900	900	900
Nuclear CHP	0	0	0	0	0	0	0	0
Nuclear PP	0	0	0	0	0	0	0	0
Oil PP	200	160	0	0	0	0	0	0
Oil shale CHP	56	56	56	56	84	79	62	62
Oil shale PP	1652	1412	1352	1266	922	900	322	172
Other CHP	35	35	35	35	35	35	35	17
RES CHP	259	350	373	356	344	293	304	278
Solar PP	70	70	70	40	0	50	100	125
Waste CHP	64	99	99	72	68	105	91	69
Wind PP	746	842	1087	1175	2108	2874	3799	5008
Line EE_FI	1000	1000	1000	1839	1839	1839	1839	1706
Line EE_LV	800	800	852	1400	1400	1400	1400	1400
Line EE_RU	1000	1000	1000	1000	1000	1000	1000	1000
Line LT_Ka	680	680	680	680	680	680	680	680
Line LT_LV	1350	1350	1350	2000	2000	2000	2000	2000
Line LT_PL	500	1000	2000	2000	2000	2000	2000	2000
Line LT_RU	1350	1000	1000	1000	1000	1000	1000	1000
Line LT_SE	0	700	700	700	700	700	700	0
Line LV_RU	500	500	500	500	500	500	500	500
Total	16708	16980	17376	19592	20384	21497	21871	22052

The presented data shows big diversification among power plant types but lower diversity among primary energy forms used for electricity generation. The major part of installed capacity of power plants, especially at the end of the study period, comes from wind power plants and plants which are running on natural gas. Hydro power plants and power plants running on various types of biomass also make significant contribution.

It is also expected that the total installed capacity of power plants in the Baltic states will start growing from 2025-2030. The major contribution is expected from wind power plants, CHP using natural gas and CHP running on biomass.

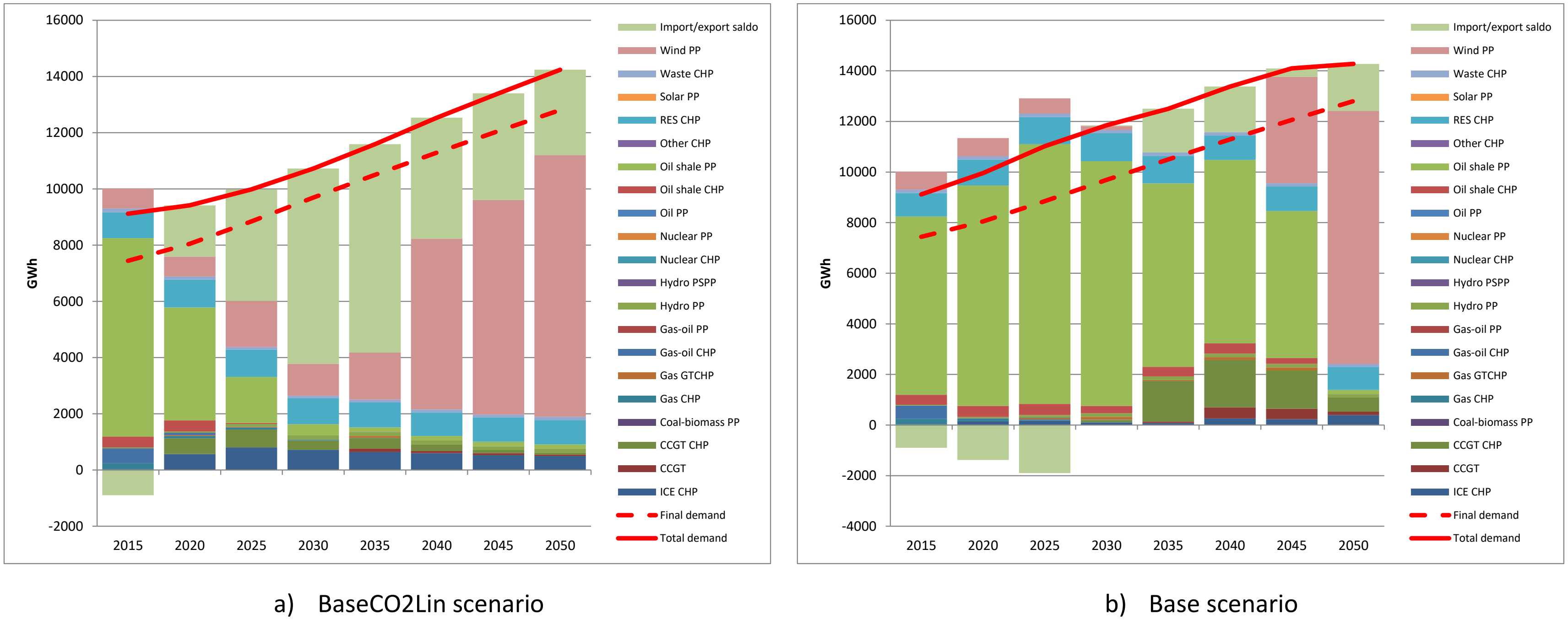
The analysis also shows that increased throughput capacity on international lines and lines linking the Baltic countries with each other would be beneficial. This is illustrated by the growing throughput capacity of the links between Lithuania and Poland, Estonia and Finland, as well as between Lithuania and Latvia, Latvia and Estonia. This growth is especially important for provision of sufficient reservation services and balancing intermittent wind generation.

4.4.5 Energy system expansion and operation peculiarities in other analysed scenarios

Results related to the energy system development and operation in the High RES scenario fully correspond to the results in the Base scenario. This happened because CO_2 prices have a more significant impact to the system development in comparison to the RES target. In this relation, the higher RES target considered in the High RES scenario was already reached in the Base scenario.

Differences of energy system development and operation are observed between the BaseCO2Lin and the Base scenario. In the middle of the study period, the higher CO_2 price considered in the BaseCO2Lin scenario had an impact on the operation of power plants running on ~~poluting~~polluting fuels. In this relation the biggest differences are observed in the Estonian energy system. Reduced electricity generation from oil shale power plants is substituted by electricity imports and higher generation by wind power plants.

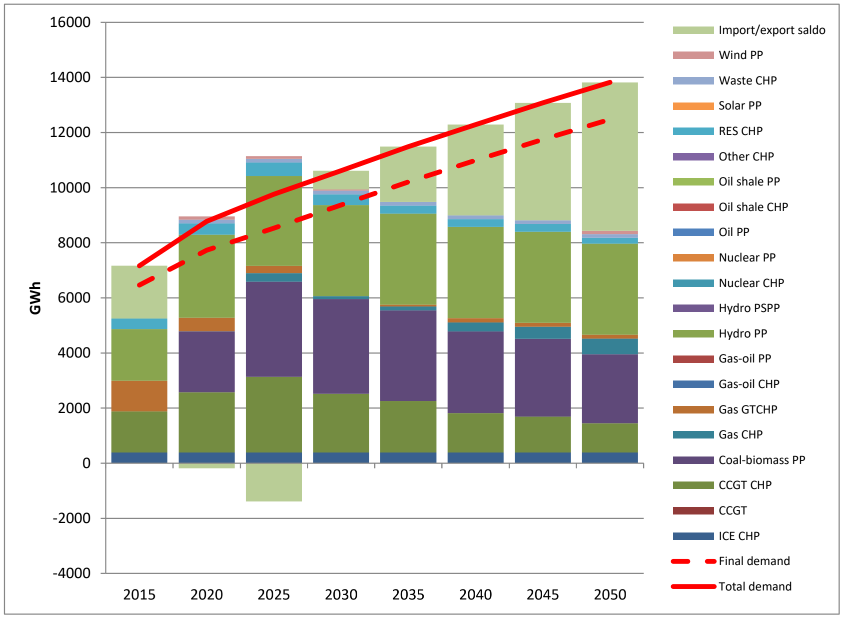
Dynamics of electricity generation in Estonia in the case of the BaseCO_2Lin scenario and a comparison with the Base scenario are shown in in Fig. 4.14. The same information for Latvia, Lithuania and Finland is provided in Fig. 4.15-4.17.



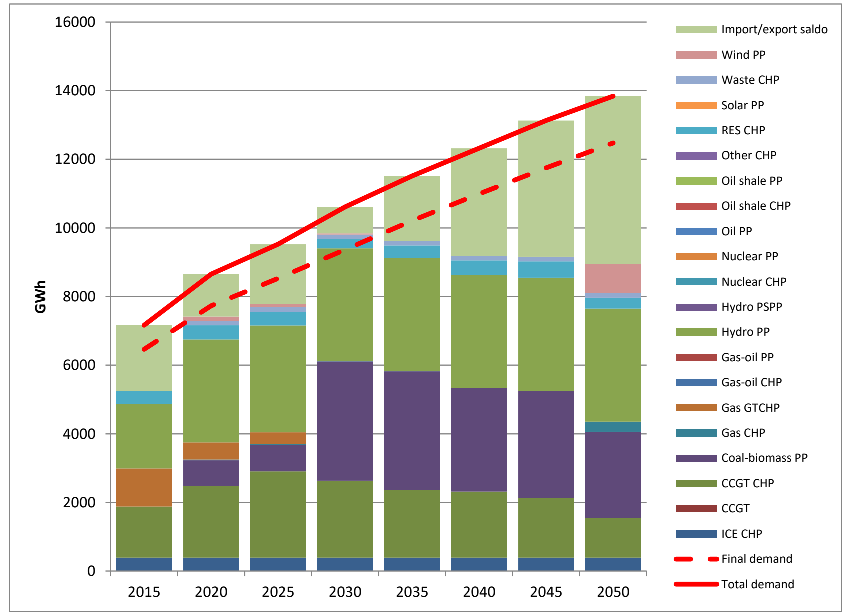
a) BaseCO2Lin scenario

b) Base scenario

Figure 4.14. Dynamics of electricity production in Estonia in BaseCO2Lin and Base scenarios.

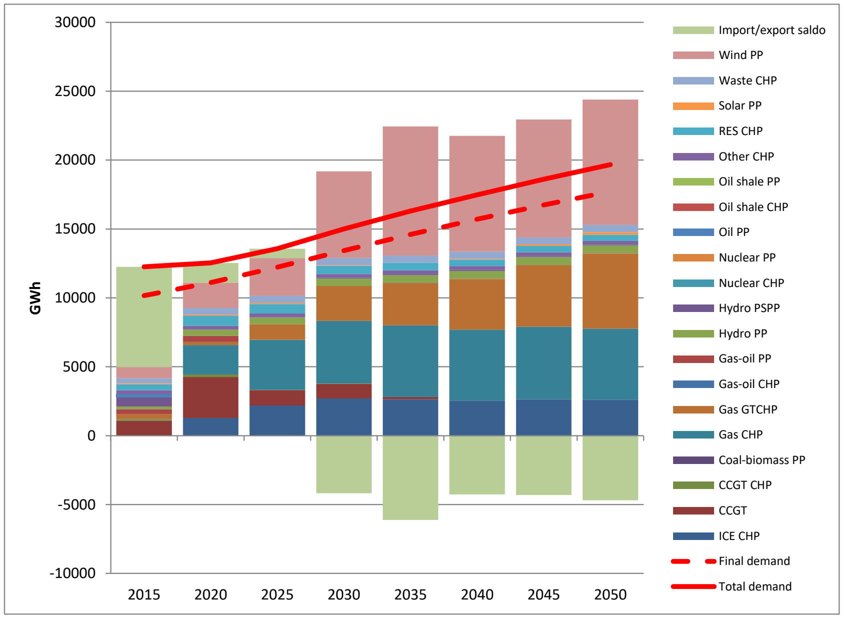


a) BaseCO2Lin scenario

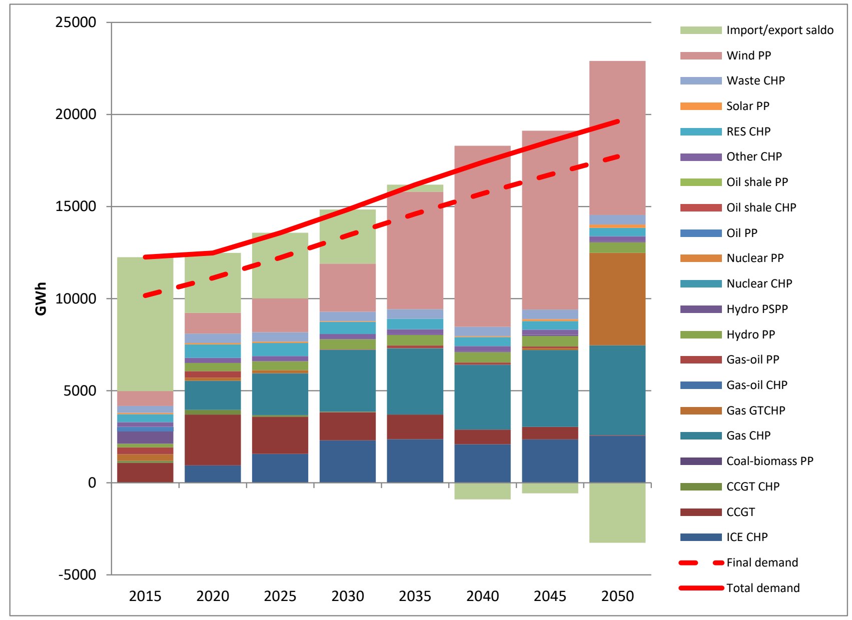


b) Base scenario

Figure 4.15. Dynamics of electricity production in Latvia in BaseCO2Lin and Base scenarios.

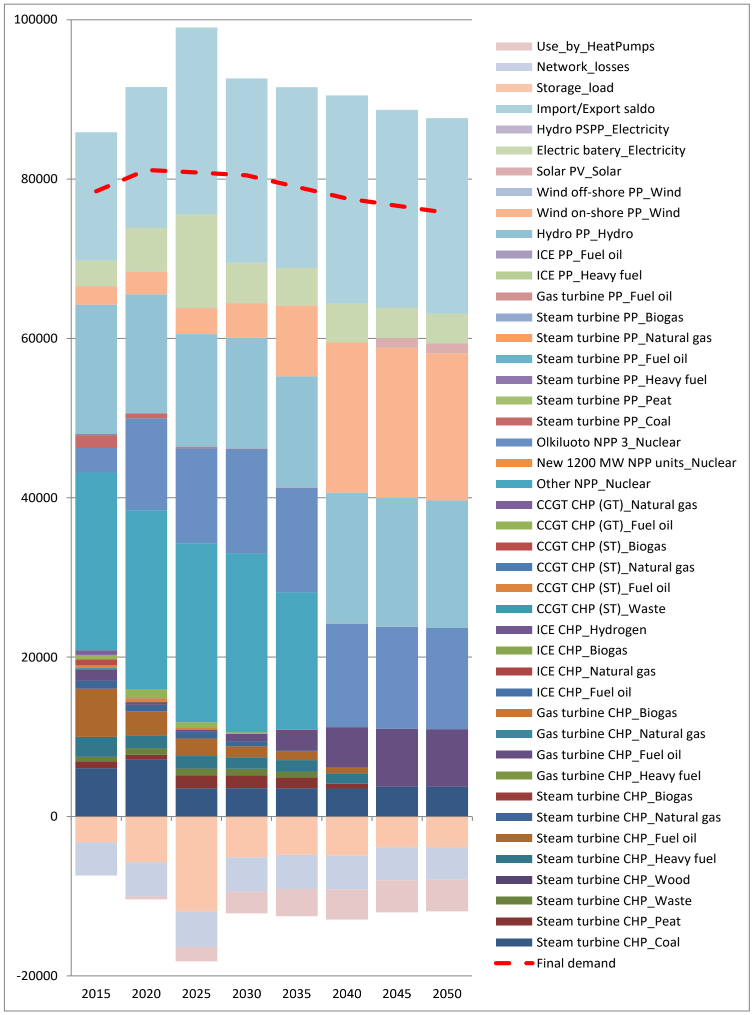


a) BaseCO2Lin scenario

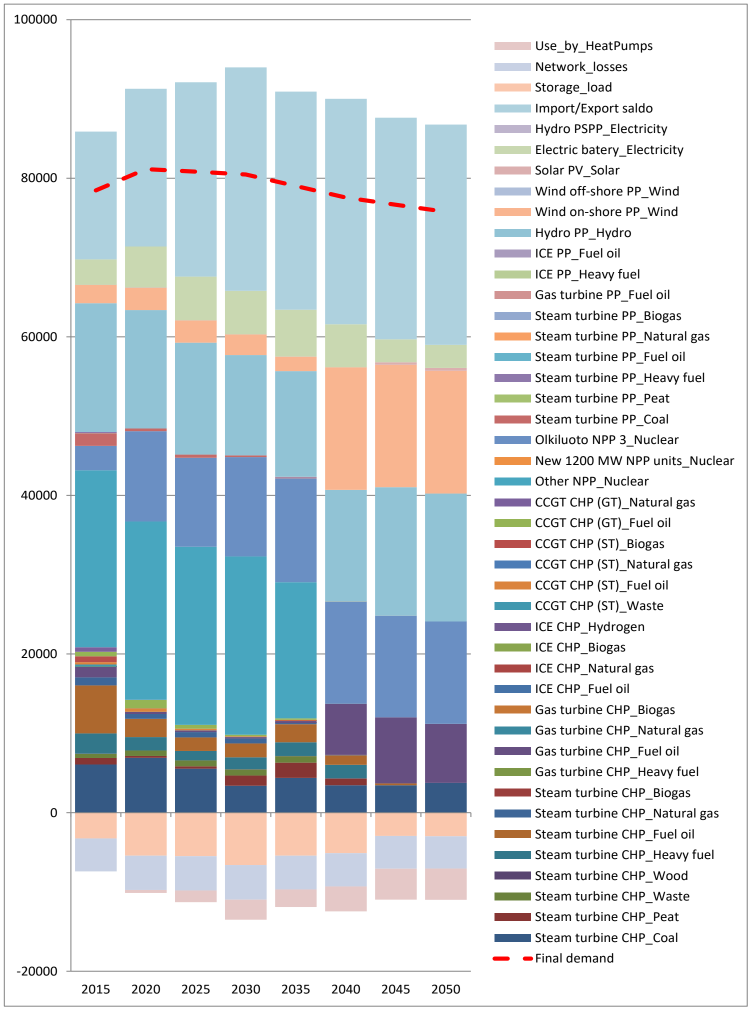


b) Base scenario

Figure 4.16. Dynamics of electricity production in Lithuania in BaseCO2Lin and Base scenarios.



a) BaseCO2Lin scenario



b) Base scenario

Figure 4.17. Dynamics of electricity production in Finland in BaseCO2Lin and Base scenarios.

Electricity generation changes in neighbouring countries are much lower in comparison to changes in Estonia. Higher electricity generation from biomass burning power plants in Latvia would be observed in years 2020-2025. This additionally produced electricity would be exported partly to Estonia. Higher electricity generation from CCGT CHP would be also expected in Lithuania, as well as additional electricity exports to Estonia.

Reduced electricity generation from Estonian oil shale power plants has only a minor impact on electricity ~~genration~~generation in Finland, as well as to net electricity imports to Baltic countries. The fact that the impact on electricity imports/exports is minor in this case can be explained by the energy policy target for decreasing electricity imports to the Baltic counties which is common for all scenarios analysed.

The full set of modelling results for all the scenarios is stored in the REEEM project database (publicly available after the relevant deliverable is approved).

4.5 Results of Energy Security Coefficient

This subsection highlights the main results obtained from the modelling exercise performed with the model for energy security coefficient assessment (MESCA). The main goal of the calculations is to measure how energy security level relates to different future, energy development projects. One of the most important energy security assurance requirements is the capacity of the energy system to withstand potential disruptions. Therefore, a significant parameter for the result interpretation is the total installed capacity of energy technologies in the energy system. For the future perspective, it demonstrates when certain technologies reach their lifetime, resulting in capacity decreases, and when installation of new technologies might be considered by the model. In addition, the ratio of the total installed capacity to the final capacity demand also plays a considerable role when analysing energy security assurance, thus, under the result interpretation process, this parameter is also considered.

The energy security coefficient dynamics during the modelling period, for each country are presented with insights and interpretation of the impact on energy security. Having analysed the results, the major energy security assurance measures were determined within different scenarios. Since in every year during the modelling period, many different events occur and significant energy projects are implemented towards the development of the energy system, the analysis of the obtained results includes only the most significant ones, which have an impact on the variation of energy security coefficient for each of the analysed countries.

4.5.1 Finland

Fig. 4.21 demonstrates the yearly average energy security coefficient in the analysed scenarios during the modelling period 2015-2050 in Finland.

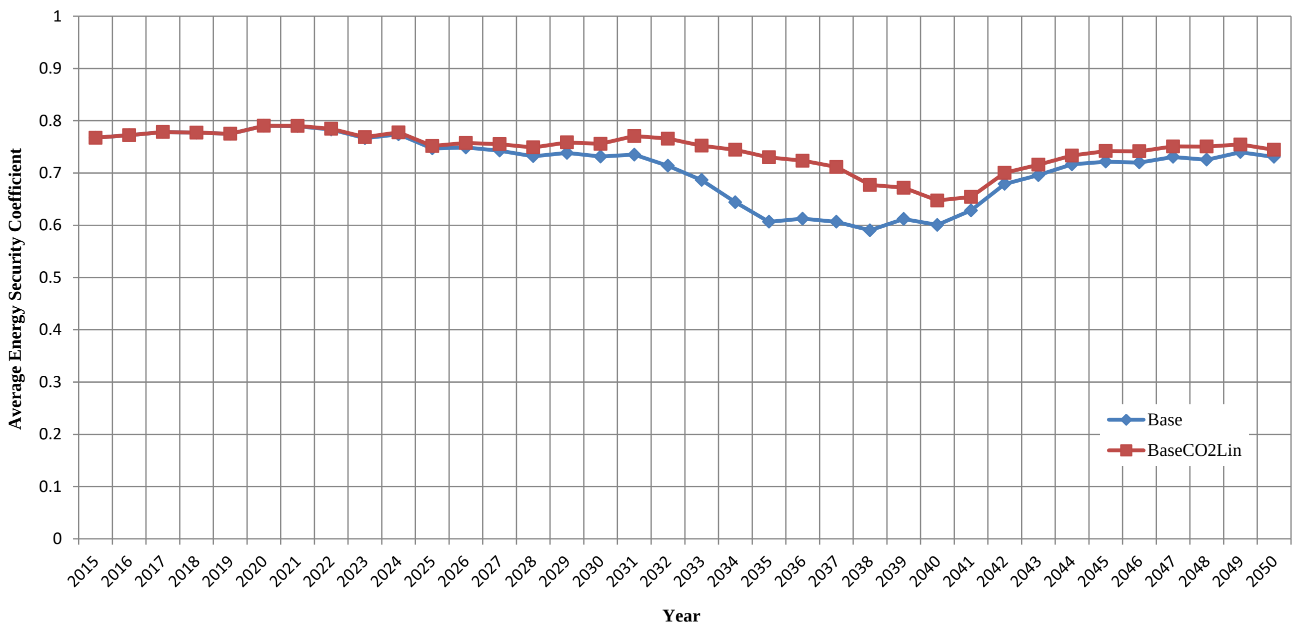


Figure 4.18. Energy security coefficient in the analysed scenarios for energy system of Finland.

Until 2025, the energy security coefficient is at the same level with the start of the modelling period, quite stable and relatively high in both analysed scenarios. It is also observed, that the installed capacity of energy generation does not differ until 2025 between the two scenario. The capacity of fossil fuel fired PPs is gradually been reduced in both cases; however, nuclear power (also new unit of Olkiluoto NPP from 2020) allows the system to maintain the ESC at the same level.

From 2025 to 2030, in the Base case, loss of capacity is observed, while in the BaseCo2Lin scenario, lost capacity is replaced mostly by biomass and wind technologies. Thus, a difference in the ESC is also recorded. However, a quite unique situation is observed in the Base scenario from 2030 to 2035 when a significant amount of capacity is faced out and practically none is installed to compensate in this period. As a result, in 2035, the total installed capacity of energy generation technologies is even 27% lower than the final capacity demand (ratio *total installed capacity/final capacity demand* = 0.73), while in the BaseCO2Lin scenario, ratio is equal to 1 during the same time. This significantly decreases the ESC in the Base case since the system becomes vulnerable to various disruptions mainly due to lack of generation capacity. In the BaseCo2Lin scenario, loss of capacity is also recorded, but not to as large extent as in the Base case. Also, the significantly increased capacity of power connection lines with Sweden allows partially to compensate generation capacity losses. From 2035, mostly wind power is installed in the energy system, which stabilizes the ESC to 2040 and increases from 2040 to the end of the modelling period in the Base scenario. From 2040, new wind power plants also appear in the BaseCO2Lin scenario and the performance of the ESC is relatively higher in comparison with the Base scenario. The main reason is that the Base scenario does not reach the same level of capacity as in the second scenario. But as it can be seen from Fig. 4.21, the difference is insignificant in terms of energy security assurance.

4.5.2 Estonia

The average energy security coefficient for the analysed scenarios, during the modelling period 2015-2050 in Estonia is presented in Fig. 4.18.

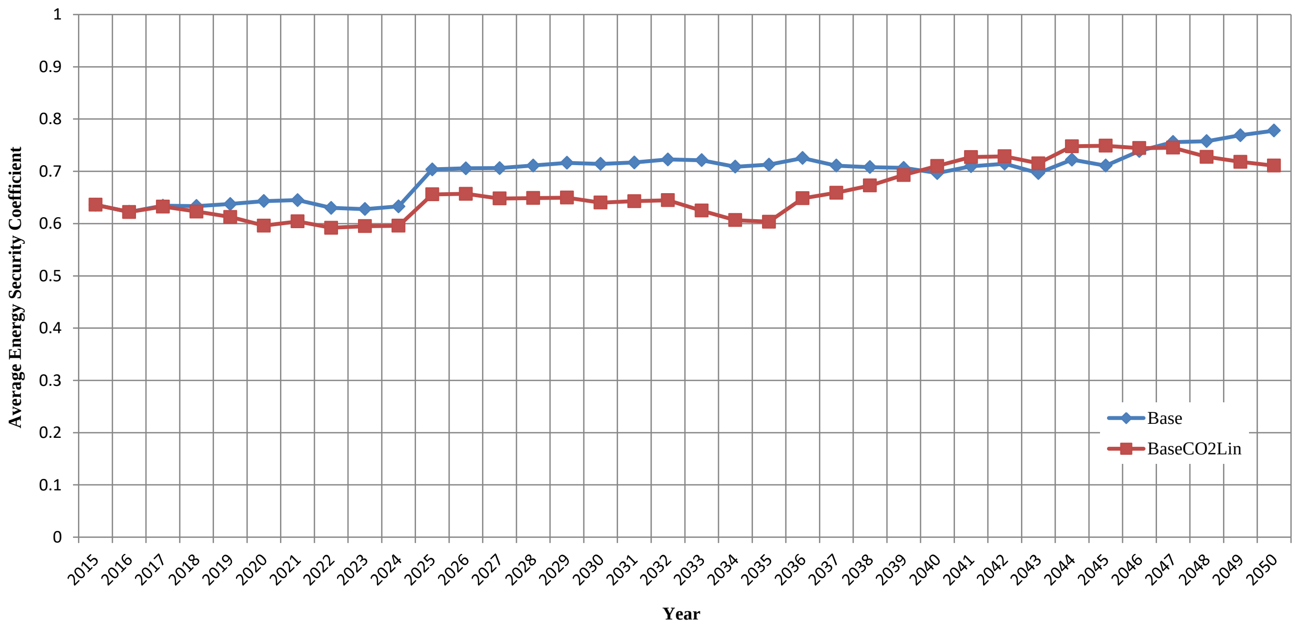


Figure 4.19. Energy security coefficient in the analysed scenarios for energy system of Estonia

In each year within the energy system, a variety of factors that influence the energy security may appear or disappear. However, due to their excessive amount, only the key factors are discussed further in the results.

The energy security coefficient in the Base scenario is quite stable until 2025, since no major events appear in the Estonian energy system, electricity generation from oil shale dominates in the country with some additions from renewable energy sources. Also, the total installed capacity (mostly of fossil fuel power plants) gradually decreases. However, a quite unique situation is observed in the BaseCO2Lin scenario. The ESC in this scenario is lower since high CO_2 prices lead to a sudden decrease of oil shale power plant capacity. In addition, this lost capacity is not suddenly replaced by other alternatives of the same type but rather by wind and biomass CHP plants. This in fact means that the actual replacement is much lower since wind power plants on average can operate approximately three times lower of its capacity than oil shale power plants. For a country that has a high share of power generation from a local fuel source, switching to other alternatives in a short-term period under market conditions is unbearable. Thus, not always the emergence of new installed technologies in this situation is feasible without promotion. Therefore, loss of capacity during 2017-2025 in the BaseCO2Lin is the main cause of lower ESC.

One of the most characteristic years in the analysed period is 2025, where a significant increase in the ESC is observed. This is related to the synchronization of Estonian, Latvian and Lithuanian power systems with the

European Continental Network (ECN) through Poland. Disconnection of the Baltic power system from synchronous work with the IPS/UPS and synchronization with the ECN or implementation of other technical measures which ensure reliable and stable work of the power system, is mandatory for energy security assurance in the Baltic countries. This would prevent from a possible total “black-out” of the power network of the Baltic States or unreliable work of the network and would remove possible geopolitical threats from the Eastern countries, which manifest themselves through disruptions in the power system. The frequency of the electricity systems of the Baltic States is currently controlled from a central dispatch centre in Moscow. Such possible geopolitical threat would be eliminated after the synchronization. Once the Baltic states synchronize with the ECN, they will not only operate their systems on that region’s frequency, but also apply its common rules. Since such low probability threats but with severe consequences are taken into account in the assessment, the ESC in 2025 is improved significantly in both scenarios (Fig. 4.18).

From 2025 to 2045, the ESC in the Base scenario remains similar with relatively slight fluctuations due to various minor factors, e.g. relatively small loss of capacity is replaced by new. Nevertheless, from 2045, the ESC is improved due to additional renewable (mostly wind power) capacity installed, which ensures more diversified electricity generation during the period 2045-2050.

In the BaseCO2Lin scenario, the ESC during 2025-2035 slightly decreases due to loss of capacity and in 2035 reaches its lowest point when there is no oil shale capacity left at all and the total installed capacity of energy generation technologies is only 6% higher than the final capacity demand (ratio *total installed capacity/final capacity demand* = 1.06), while in the Base scenario this ratio is 35% at the same time (not taking into account the capacity of interconnectors, but only local generation technologies). In the period of 2035-2045, the ESC in the BaseCO2Lin scenario performs much better when the energy system starts to install new wind power capacity. However, in 2045-2050, wind power is dominant in the total installed capacity which cannot ensure stable power generation and diversity, while in the Base scenario, the energy mix is more diversified and ensures slightly higher ESC in the end of the modelling period. Since the energy costs are also considered when calculating the ESC, the rapid emergence of wind power in the BaseCO2Lin scenario significantly increases the system costs, which in turn negatively affects energy security. These energy security measures enable the energy system to keep a moderate ESC and the system is able to withstand severe disruptions, which might occur simultaneously. In addition, from 2020 to 2030 power transmission capacity with Latvia increases from 800 to 1400 MW, and from 2025 power transmission capacity with Finland increases by 900 MW, which also enables the system to maintain a stable ESC in the case of loss of other capacities. Strengthened power lines with other countries allow higher diversification of energy supply sources.

4.5.3 Latvia

Only minor differences between the different scenarios are observed when analysing the Latvian energy security coefficient in this case study. Fig. 4.19 demonstrates the average energy security coefficient in each year for the analysed scenarios during the modelling period 2015-2050 in Latvia.

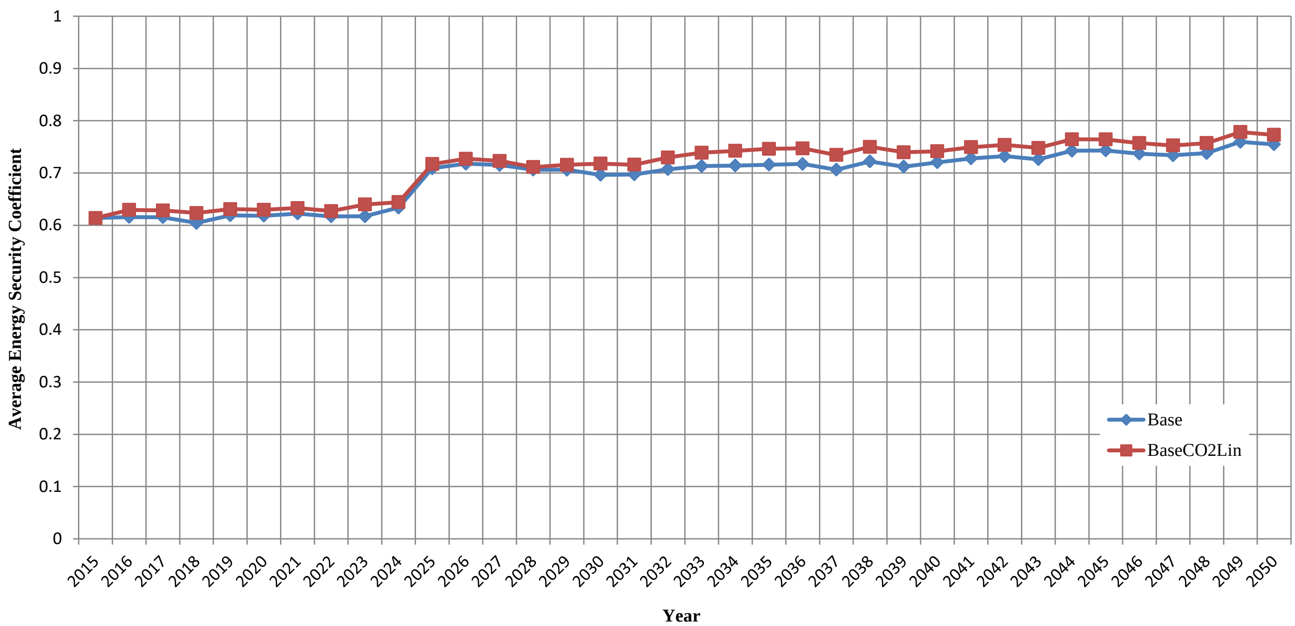


Figure 4.20. Energy security coefficient in the analysed scenarios for energy system of Latvia.

The energy security coefficient is quite stable until 2025 since no major events appear in the Latvian power system. Electricity generation is mainly based on hydro power ~~complemmented~~complemented by natural gas fired plants and electricity imports. Increased CO_2 prices in the BaseCO2Lin scenario does not drastically change the mix of the energy system; only some additional capacity of hydro and biomass CHP technologies are observed during the modelling period.

As in the case of Estonia, 2025 is the year in which the synchronization of Baltic power system with the ECN is implemented and energy security is improved. The justification for this matter is detailed in the case of Estonia. As a result, for Latvia, the ESC during the period 2025-2050 remains almost at the same level with a slight increasing trend. As it was mentioned in subsection 4.5.1, the capacity of power lines with Estonia is increased, which also has a significant impact on maintaining the ESC at a certain level. The total installed capacity of energy generation technologies is on average 114% higher (more than twice) than the final capacity demand during the modelling period in the Base case, which seems to be sufficient. When taking into account the capacity of power lines with other countries, this ratio increases to approximately 400% on average. For the BaseCO2Lin scenario, these numbers are even slightly higher.

4.5.4 Lithuania

Fig. 4.20 demonstrates the average energy security coefficient in each year for the analysed scenarios during the modelling period 2015-2050 in Lithuania.

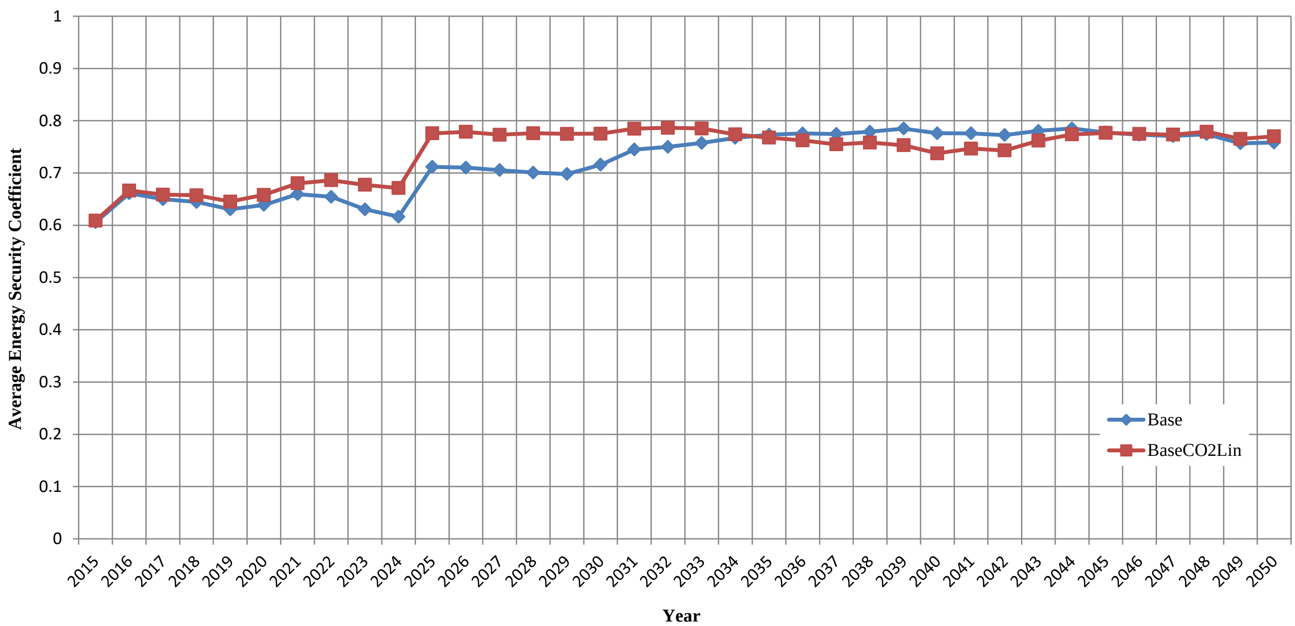


Figure 4.21. Energy security coefficient in the analysed scenarios for energy system of Lithuania.

The energy security coefficient in both analysed scenarios show a sudden rise in 2016, which is caused by new power connections with Sweden and Poland. Starting exploitation of new power lines in 2016 has exerted a positive impact upon the ESC, mainly due to improved resilience of energy system in the case of electricity supply disruptions. In addition, diversification of electricity import routes and electricity market was improved.

Until 2025, the BaseCO2Lin scenario performs better in terms of energy security in comparison to the Base scenario, since loss of capacity is observed in the Base case while this capacity is replaced mainly by biomass CHP and wind power plants and remains stable in the BaseCO2Lin case.

However, in 2020 and 2021, both scenarios show a slight increase in the ESC due to the increased capacity of power lines with Poland; also Gas Interconnection Poland-Lithuania starts its operation. On the one hand, new gas interconnection diversifies natural gas supply sources and routes, integrates gas market of isolated Baltic countries into the common EU gas market, ensures natural gas supply security and reliability in Lithuania and may contribute to the rational use and availability support of the LNG terminal. On the other hand, with the ~~decomission~~decommission of old power units, the power system has become more vulnerable due to the lack of provision of proper electricity reserves and technical disruptions. Therefore, due to lost capacity, the ESC during 2022-2024 decreases in the Base scenario and remains at a quite low level compared with the historical ESC. However, this is not the case in the BaseCO2Lin scenario where lost capacity is replaced in the same period by new technologies. Due to high CO_2 prices, the wind technology penetrates the system much earlier than it is done in the Base case.

A significant increase of the ESC is observed in 2025, when the synchronization of power systems of the Baltic countries with the European Continental Network is implemented and related to that, the capacity of the power connection lines in Lithuania with Poland are significantly increased (up to 2000 MW in total). These projects improves the ESC as well as resilience of Lithuanian energy system in the case of electricity supply disruptions. Other aspects of the impact of the synchronization on energy security are explained in the case of Estonia.

From 2025 onwards, in both scenarios installed capacity (mainly wind PP and gas CHP due to balancing) increases, however, at different level, which allows to ensure a stable ESC. In the Base case, starting from 2030, more rapid development of wind PPs is observed, which increases the ESC to a certain level and maintains it till the end of the modelling period. In the BaseCO2Lin scenario from 2034, the ESC has a minor decrease until 2042 mainly due to the slight loss of capacity during this period. However, the ESC in both scenarios equalizes due to a similar energy mix in the end of the modelling period.

The total installed capacity of energy generation technologies is on average 155% higher than the final capacity demand during the modelling period in the Base case, while in the BaseCO2Lin scenario is 200%. The Lithuanian energy system in this modelling exercise in both scenarios has a quite stable and increasing capacity of energy generation in the whole modelling period. Nevertheless, the system remains diversified and not dependent only on single energy source or supply.

The modelling exercise on the evaluation of energy security coefficient for the Baltic countries and Finland revealed that the ESC performance is highly dependent on generation adequacy in the country. Since old generation technologies are facing decommissioning during the modelling period, in order to maintain energy security, new technologies need to be installed. Lack of capacity might lead the energy system to face some failures and renders it insufficient to cope with technical and other disruptions. However, not always the emergence of these technologies under market conditions is feasible without promotion. In fact, too large penetration of new capacity in a short-term period might also lead to problems since there is a huge economic burden for the energy system to cope with severe consequences of economic risks due to over-investment risk.

Diversification of energy supply sources is also a significant measure to increase energy security. This measure might also be implemented through power interconnectors with other countries by increasing capacity of power lines. It also enables higher power market integration and diversification of supply routes, which helps to further enhance energy security.

5 Conclusions

Measures that ensure energy security have to be foreseen already at the energy planning stage and timely put into practice. The selection and implementation of energy security measures should be carried out in accordance with the real conditions of the functioning of the energy system. Environmental restrictions associated with climate change mitigation as well as country specific and international policy trends also have to be taken into account.

In energy security analysis, the energy planning models (MESSAGE, TIMES, Balmorel, OSeMOSYS, etc.) should be employed with additional features that allow both the assessment of changes in the system and foreseeing necessary energy security measures. The major enhancements presented in this study are related to the detailed modelling of reservation services in the system, balancing of intermittent electricity generation from renewable energy sources, as well as to detailed representation of energy system operation regimes. For the proper assessment of reservation services, the need and supply of frequency containment reserves, frequency restoration reserves and replacement reserves are modelled in detail. Balancing of variable electricity generation from renewable energy sources is based on renewable energy generation probability curves. For detailed representation of operation regimes increased seasonal, diurnal and spatial resolution, as well as modelling of multiple fuel use in power plants and boiler houses is used.

Energy system modelling with various disruptions using the probabilistic method allows to evaluate the energy system's resilience to these disruptions. It enables to compare different energy system scenarios in terms of the energy security quantitative measure (the energy security coefficient).

Refurbishment of existing hydro power plants, construction of wind power plants, CHPs running on biomass and municipal waste, CHPs running on natural gas and biogas are the most attractive electricity generation options in the Baltic States and Finland. Biomass boilers and heat pumps are economically more preferable for heat production. The development of other technologies in the near future is economically less justifiable, due to electricity import driven by the relatively low electricity market prices and environmental limitations.

Energy security issues in the Baltic States are largely related to the electricity system. Although positive from the diversification point of view, a significant share of intermittent electricity generation (in particular from wind) also imposes additional energy security challenges as it requires the power system to maintain sufficient balancing capacities.

The most economically attractive balancing options in the Baltic States and Finland are: a) generation compensation obtained via interconnectors from available sources in neighbouring countries; b) gas turbine CHPs; c) gas turbine power plants and plants with internal combustion engines; d) electricity storages (hydro pumped storage power plant, electric batteries).

The Baltic States have powerful electrical connections with neighbouring power systems from which they import large amount of required electricity. The capacity of a separate power line may exceed 30-50% of each country's total power demand. The possible malfunctions of such a line may cause significant energy security problems if required reserve capacities are not available.

Study results show that in theory the power system should not face any serious disruptions. However, in practice, certain elements that ensure the provision of reservation services may not be implemented or their functioning may not correspond to the real threats that can appear due to failure of a powerful line, especially in the case where throughput capacity of interconnectors could be reduced due to various reasons. Looking at the current situation, the biggest problems are related to the provision of frequency containment and replacement reserves.

The modelling exercise on the evaluation of the energy security coefficient for the Baltic countries and Finland in Base and BaseCO2Lin scenarios during the modelling period 2015–2050 revealed that:

- The energy security coefficient (ESC) for Estonia changes over time from 0.62 (minimum) to 0.78 (maximum) while the average ESC during the whole modelling period is 0.7 in the Base scenario. The performance of the ESC in the BaseCO2Lin scenario demonstrates worse results in comparison to the Base scenario. Accordingly, minimum ESC is 0.59, maximum – 0.75 and the average – 0.66. High CO_2 prices and the outcome of that radical decommissioning of oil shale technologies reduce the ESC, especially from 2019 to 2035, and only from 2035 new capacities are commissioned.
- Latvia's energy security seems to be the most stable in both scenarios in comparison to other countries and differences between scenarios are insignificant. However, the ESC does not reach relatively high values. Minimum ESC is 0.6 and 0.61, maximum – 0.76 and 0.78, average – 0.69 and 0.1 in the Base and the BaseCO2Lin scenario respectively.
- The ESC in Lithuania strongly is enhanced from 2025 (as well as in Estonia and Latvia, but not to the same extent), and reaches the same minimum (0.61) and maximum (0.79) in both scenarios. However, the minimum is observed in the beginning of the modelling period (2015) while the maximum is observed in different years, i.e. 2044 in the Base case and 2032 in the BaseCO2Lin case. The average estimate of the ESC for both scenarios is 0.72 and 0.74 respectively.
- Finland's energy system has the highest ESC in the beginning of the modelling period comparing with the other analysed countries, since it demonstrates diversified energy generation and supply in both scenarios. The peak of the ESC (0.79) in both scenarios is reached in 2020. However, from 2030 onwards especially, in the Base case, the ESC decreases gradually while in 2038 it demonstrates the lowest ESC (0.59) in the whole modelling period. In the BaseCO2Lin scenario, the minimum of ESC is not so drastic (0.65) due to additional requirements of CO_2 prices and commissioning of new capacities. The average performance of ESC is 0.71 and 0.74 respectively in both scenarios.
- The highest increase in the ESC for Baltic countries is observed when the synchronization of power system of the Baltic countries with the European Continental network through Poland is

implemented in 2025. Additional energy security measures for all the analysed countries might be increasing the capacity of power lines with other countries, RES development or other.

- When comparing the ESC performance between countries within different scenarios, it was observed that the highest average ESC is recorded in the BaseCO2Lin scenario for Finland and Lithuania (0.74) while the lowest ESC is observed in the BaseCO2Lin scenario for Estonia (0.66). In addition, all the analysed scenarios in this case study demonstrate that the average ESC is higher than 0.65.

The choice of energy security measures is a challenging task due to both the broad variety of threats to be addressed and the need to ensure that the costs of energy security measures are exceeded by the benefits for the national economy due to increased energy security. Moreover, the implementation of energy security measures is a challenge itself, since some measures require additional policy measures or market mechanisms to be implemented. In this relation policy and market mechanisms have to be looked through in order to find a way for implementation of the foreseen energy security measures in practice.

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Appendix A: Qualitative values of disruption parameters

Estonia

Restriction of energy supply

Restriction of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas supply from Russia	High	Low	Low	High	Medium	Low
gas supply from Lithuania LNG terminal	Low	Low	Low	Medium	Low	Low
oil / fuel oil supply	Medium	Low	Low	High	Medium	Low
biofuel supply	Medium	Low	Low	Medium	Medium	Low
waste supply	Medium	Low	Low	Medium	Medium	Low
coal supply	Medium	Low	Low	Medium	Medium	Low
oil shale / shale oil / shale oil gas supply	Medium	Low	Low	Medium	Low	Low
peat supply	Medium	Medium	Low	Medium	Medium	Low
firewood supply	Medium	Low	Low	Medium	Medium	Low
electricity import from Finland	Medium	Low	Low	Medium	Low	Low
electricity import from Latvia	Medium	Low	Low	Medium	Low	Low
termination of electricity supply to consumers	Low	Low	Low	High	Medium	Low

Price change of energy source

Price change of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas from Russia	High	High	Medium	High	High	High
gas from Lithuania LNG	Medium	Low	Low	High	Medium	Medium
oil / fuel oil	Medium	Low	Low	High	High	High
biofuel	High	Medium	Low	High	Medium	Medium
waste	High	Medium	Low	High	Medium	Medium
coal	High	Medium	Low	High	Medium	Medium
oil shale/shale oil/shale oil gas	Low	Low	Low	High	Medium	Medium
peat	High	Medium	Low	High	Medium	Medium
firewood	High	Medium	Low	High	Medium	Medium
electricity import from Finland	High	Medium	Low	High	Medium	Low
electricity import from Latvia	High	Medium	Low	High	Medium	Low

Latvia

Restriction of energy supply

Restriction of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas supply from Russia	High	Low	Low	High	Medium	Low
oil/fuel oil supply	Medium	Low	Low	High	Medium	Low
biomass supply	Medium	Medium	Low	Medium	Medium	Low
waste supply	Medium	Medium	Low	Medium	Medium	Low
coal supply	High	Medium	Low	High	Medium	Low
electricity import	High	Medium	Low	High	Medium	Low
termination of electricity supply to consumers	Low	Low	Low	High	Medium	Low

Price change of energy source

Price change of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas from Russia	High	High	Medium	High	High	High
oil/fuel oil	Medium	Low	Low	High	High	High
biomass	High	Medium	Low	High	Medium	Medium
waste	High	Medium	Low	High	Medium	Medium
coal	High	Medium	Low	High	Medium	Medium
electricity import	High	High	Medium	High	High	High

Lithuania

Restriction of energy supply

Restriction of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas supply from Russia	High	Low	Low	High	Medium	Low
gas supply from LNG terminal	Low	Low	Low	Medium	Low	Low
oil/fuel oil supply	Medium	Low	Low	High	Medium	Low
biomass supply	Medium	Low	Low	Medium	Medium	Low
waste supply	Medium	Low	Low	Medium	Medium	Low
nuclear fuel supply	Medium	Low	Low	Medium	Low	Low
coal supply	Medium	Low	Low	Medium	Medium	Low
electricity import from Russia	High	Medium	Low	High	Low	Low
electricity import from Kaliningrad	High	Medium	Low	High	Low	Low
electricity import from Latvia	Medium	Low	Low	Medium	Low	Low
electricity import from Poland	Medium	Low	Low	Medium	Low	Low
electricity import from Sweden	Medium	Low	Low	Medium	Low	Low
termination of electricity supply to consumers	Low	Low	Low	High	Medium	Low

Price change of energy source

Price change of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas from Russia	High	High	Medium	High	High	High
gas from LNG terminal	Medium	Low	Low	High	Medium	Medium
oil/fuel oil	Medium	Low	Low	High	High	High
biomass	High	Medium	Low	High	Medium	Medium
waste	High	Medium	Low	High	Medium	Medium
nuclear fuel	Medium	Low	Low	Medium	Medium	Medium
coal	High	Medium	Low	High	Medium	Medium
electricity import from Russia	High	High	Medium	High	High	High
electricity import from Kaliningrad	High	High	Medium	High	High	High
electricity import from Latvia	High	Medium	Low	High	Medium	Low
electricity import from Poland	High	Medium	Low	High	Medium	Low
electricity import from Sweden	High	Medium	Low	High	Medium	Low

Finland

Restriction of energy supply

Restriction of:	Size			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas supply from Russia	Low	Low	Low	Low	Low	Low
gas supply from LNG terminal	Low	Low	Low	Low	Low	Low
oil/fuel oil supply	Low	Low	Low	Low	Low	Low
biofuel supply	Low	Low	Low	Low	Low	Low
waste supply	Low	Low	Low	Low	Low	Low
nuclear fuel supply	Low	Low	Low	Low	Low	Low
coal supply	Low	Low	Low	Low	Low	Low
electricity import from Russia	Medium	Medium	Medium	Medium	Medium	Medium
electricity import from Sweden	Medium	Medium	Medium	Medium	Medium	Medium
electricity import from Estonia	Medium	Medium	Medium	Medium	Medium	Medium
electricity import from Norway	Low	Low	Low	Low	Low	Low
termination of electricity supply to consumers	High	Medium	Low	High	Low	Low

Price change of energy source

Price change of:	Extent			Duration		
	Small	***Medium***	***Large***	***Short-term***	***Medium-term***	***Long-term***
	Probability					
gas from Russia	Medium	Medium	Low	Low	Low	Medium
gas from LNG terminal	Medium	Low	Low	Low	Low	Medium
oil/fuel oil	Medium	Medium	Medium	Low	Medium	High
biofuel	Medium	Medium	Low	Low	Medium	Medium
waste	Low	Low	Low	Low	Low	Low
nuclear fuel	Low	Low	Low	Low	Low	Medium
coal	Medium	Medium	Low	Medium	Medium	Medium
electricity import from Russia	Medium	Medium	Medium	Medium	Medium	Medium
electricity import from Sweden	High	High	Medium	Medium	Medium	Medium
electricity import from Estonia	Medium	Medium	Low	Medium	Medium	Low
electricity import from Norway	Low	Low	Low	Low	Low	Low

Appendix B: Conversion tables for converting from qualitative to quantitative values

Size of supply restriction			
Qualitative parameter	Small	Medium	Large
Quantitative parameter (%)	0-33	34-66	67-100

Size of price change			
Qualitative parameter	Small	Medium	Large
Quantitative parameter (%)	0-33	34-66	> 66

Disruption duration			
Qualitative parameter	Short-term	Medium-term	Long-term
Quantitative parameter (year)	≤ 1	> 1, ≤ 3	> 3

Probability			
Qualitative parameter	Low	Medium	High
Quantitative parameter (probability)	0.001-0.01	0.01-0.1	0.1-1