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Implications of carbon price paths on energy security in four Baltic region countries

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ABSTRACT

Energy security is one of the critical priorities of energy policy in the European Union and particularly in the Baltic region that is currently transforming itself from an isolated energy island to a highly interconnected area. In this paper, a comprehensive analysis of energy security in Estonia, Finland, Latvia, and Lithuania in the context of the energy transition is presented. The paper explores regional implications of two paths of carbon price (gradual and delayed carbon price increase). The analysis is performed by linking an energy system optimisation model with a probabilistic model of energy security. This modelling suite is used to assess the resilience of the planned energy system to possible disruptions. The results demonstrate that carbon price paths have a modest impact on energy security in Baltic countries if energy security measures are implemented in an optimal way. The research is based on the case study conducted in the framework of the European Union's Horizon 2020 project REEEM.

1. Introduction

Along with sustainability, affordability and efficiency, energy security is considered as one of the key issues in provision of energy services. Energy security is also one of the most important priorities of energy policy in the European Union (EU): European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy highlights energy security among overriding priorities [1]. Energy security is a crucial issue particularly in the Baltic region that is transforming itself from an isolated energy island to a highly interconnected area. The peculiarities of this region cover dependence on natural gas imports from Russia in Finland, power system synchronous operation with the area of the former Soviet Union in the case of Estonia, Latvia, and Lithuania (often referred to as the Baltic countries).

The development of energy systems in the region thus covers sometimes contradicting tasks to ensure cost-effectiveness, increase share of renewables, reduce greenhouse gas (GHG) emissions, maintain competitiveness of local industries, and increase energy security. Although providing many decarbonisation opportunities, the expansion of variable renewables causes certain technical challenges to the energy system [2]. High proportions of variable generation have considerable impacts on ancillary services required in a power system [3] but this aspect is often overlooked in both market design [4] and long-term energy planning models [5].

There is a wide variety of definitions of energy security [6] emphasising „low vulnerability of vital energy systems“ [7], availability, affordability, reliability, efficiency, little environmental impact, proactive governance, and social acceptability of energy services provided to end-users [8] and other aspects. The multidimensional and complex nature of energy security imposes difficulties in measuring energy security, and the number of proposed indicators is continually increasing. Moreover, a money-metric translation of changes in energy security indicators that could make these amenable for a rigorous economic cost-effectiveness assessment is also missing [9]. An essential part of such economic analysis is modelling of energy system development as it defines how the energy system adapts to the changing conditions, such as decarbonisation targets and increasing carbon prices. Moreover, single models are often unable to cover all the important dimensions of the changes and thus model linking and multi-model approaches are

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Abbreviations

CHP	Combined Heat and Power
ESC	Energy Security Coefficient
ETS	Emission Trading Sector
EU	European Union
FCR	Frequency Containment Reserve
FIBEM	Finnish-Baltic Energy Model
FRR	Frequency Restoration Reserve
GHG	Greenhouse Gas
HVDC	High-Voltage Direct Current
IPS/UPS	Integrated Power System/United Power System
MESCA	Model for Energy Security Coefficient Assessment
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
OSeMOSYS	Open Source Energy Modelling System
REEEM	Role of technologies in an energy efficient economy – model based analysis policy measures and transformation pathways to a sustainable energy system
RES	Renewable Energy Sources
RR	Replacement Reserve
TIMES	The Integrated MARKAL-EFOM System

used to provide new insights on the development of energy [10] and related systems [11]. In this research, energy security is defined as 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 reasons [12]. Such definition is in line with the approaches proposed by Cherp and Jewell [7] as well as Valentine [13] who distinguishes availability, affordability and resilience criteria.

Previous energy security-related research covering Baltic region countries paid primary attention to generation adequacy, the roles played by cogeneration and imports, energy security evaluation applying various methodologies, and sustainability of energy development. Generation adequacy topics cover modelling the resilience of the system in case one or more major power system components fail at the peak time [14], evaluating the impacts of a severe drought [15] and Monte-Carlo simulations in adequacy assessments [16]. Due to climatic conditions and existing district heating infrastructure, cogeneration technologies are particularly attractive power production option in the cities of the region [17]. On the contrary, possible decommissioning of cogeneration plants might have negative energy security impacts that need to be neutralised by new generation capacities and interconnections [18]. Biomass-based cogeneration is seen as a replacement of fossil fuels in electricity production [19], but certain limits on biomass quantity are imposed by sustainability and ecosystem impacts [20].

To ensure generation adequacy, continuous investments to generation sources are needed, but the current market conditions are not favourable for new investments as electricity import is more attractive than majority of local generation sources [21]. For instance, most of electricity consumed in Lithuania is imported from neighbouring countries [22]. The dependence on energy imports is a widely discussed topic in energy security literature. Bompard et al. developed a framework with methodologies to assess the electricity independence of the Baltic countries [23], Jääskeläinen et al. analysed energy trade between Finland and Russia and whether Finland's notable dependence is an energy security threat [24]. The studies of Lithuanian case concluded that maintaining installed capacities are preferred as an energy security measure [21] while an economically unjustified increase of domestic electricity generation would have negative economy-wide impacts [25].

Indicator approach which is based on various energy security indexes is the most common when evaluating energy security in general. Indexes particularly for the Baltic countries are evaluated across different dimensions by Zeng et al. [26], Augutis et al. [27], World Energy Council [28], World Economic Forum [29], Wang and Zhou [30], Radovanović et al. [31], Erahman et al. [32], Le Coq et al. [33], Badea et al. [34] and other. Although energy security evaluation based on historical data dominates in the energy security literature, there is a clear need to foresee measures that ensure energy security at the planning stage to be able timely put them into practice. Also, the selection and implementation of energy security measures need to be carried out following 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 shall also be considered. Therefore, research on energy security implications of increasing carbon prices within different paths is especially relevant from the practical point of view.

Practical relevance is further strengthened by the diverse current situation in four inter-connected Baltic countries under consideration. The Finnish energy system is very dependent on imports from Russia: Finland imported 64.0% of its primary energy in 2016 and 63.0% of this amount originated in Russia [24]. There are two important high-voltage direct current (HVDC) connections between Finland and Estonia, and in recent years, electricity imports from Finland to the Baltic region have been significant. Finland is also growingly dependent on electricity imports: in 2018 23% all consumed electricity was imported, about 13 TWh from Sweden and about 8 TWh from Russia. In 2018, the total production of electricity in Lithuania amounted to 3.2 TWh while the total consumption for electricity was 12.1 TWh. Thus, 73% of consumed electricity was imported, the largest import share being from Russia (4.6 TWh) [35]. In Latvia, total consumption of electricity in 2018 was 7.4 TWh, electricity import constituted 12% [36]. In 2018, Estonia's electricity production was 18% higher than consumption and it was a net electricity exporter [36].

In this paper, a comprehensive analysis of energy security in the Baltic region (Estonia, Latvia, and Lithuania) and Finland in the context of energy transition and carbon price paths is presented. Energy security analysis in this study is based on the enhanced mathematical model of prospective energy sector development and functioning linked with a simplified probabilistic model used to assess resilience of the planned energy system to possible disruptions. The usage of the simplified probabilistic model is considered as a solution to overcome computational limitations that could appear in case if a detailed model is used to reflect a broad variety of possible energy security threats.

The research is based on Baltic energy security case study conducted in the framework of the EU Horizon 2020 project REEEM [37]. As shown by literature review, energy security in the region is in most cases considered either as additional argument in the analysis of energy system development or as a phenomenon that is analysed separately from the development of energy sector. In the present study, we focus on energy security in Finland and the Baltic countries as an important determinant of energy development and analyse it in line with the modelling of energy development scenarios. The analysis mainly focuses on electricity system that is the most vulnerable in the region; however, it takes into account district heating and fuel supply systems as they are tightly coupled with electricity. Such approach allows not only analysing energy security under certain energy development paths but also integrating energy security measures to energy development scenarios. For this, the models used in the analysis are 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 paper are related to the modelling of reserve provision in the system (the need and supply of frequency containment reserves, frequency restoration reserves and replacement reserves are modelled in detail), balancing of intermittent electricity generation from renewable energy sources (modelling is based on renewable energy generation probability curves), as well as to detailed representation of energy system operation regimes. Different carbon price paths are analysed and the impact on energy security is discussed as well.

The remaining part of the paper is structured as follows: Section 2 discusses the research methodology and two models used; Section 3 presents scenarios analysed and relation of the present study with European energy development scenarios; the modelling results are discussed in Section 4. Conclusions in Section 5 summarize the main findings of the conducted study.

2. Methodology for energy security analysis

Study of energy security is based on mathematical modelling of the development and operation of energy systems in Finland, Estonia, Latvia and Lithuania, and subsequent testing of energy systems to determine their resilience to various disruptions using the probabilistic model. Resilience in the methodology is defined as the ability of energy system to absorb, limit or defeat the impact of the disruption. The technical-economic analysis of the development and operation of energy systems (see Fig. 1, where solid lines represent direct links, while dashed lines show indirect and soft relations) is performed by the Finnish-Baltic Energy Model (FIBEM) created in the environment of the MESSAGE software package [38,39]. 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 system resilience to various disruptions is examined by the Model for Energy Security Coefficient Assessment (MESCA) mainly built in the Open Source Energy Modelling System (OSeMOSYS) modelling generator [40,41]. The MESCA is the probabilistic model of energy security, which using Monte Carlo simulations in many runs determines the ability of energy system to resist disruptions, generated in a probabilistic way. This regional modelling activity, performed with FIBEM and MESCA models, is harmonized with modelling of energy system development and functioning conducted in the REEEM project [42] on the EU level using the TIMES PanEU model [43]. It should be noted that modelling with TIMES PanEU is not done in this energy security study but only assumptions from the modelling results are taken as input parameters to the FIBEM and MESCA models (Fig. 1). Harmonization (see Section 3) is accomplished by iterative adjustments of model input parameters according to the results of other models.

Technical-economic analysis of the development and operation of energy systems carried out with the FIBEM is a key activity in energy security analysis. The mathematical model of technical-economic analysis of the development and operation of energy systems FIBEM does not differ in essence from other mathematical models used for this purpose and built in an environment of MESSAGE, TIMES or MARKAL programming packages. However, much more attention is paid to more detailed representation of operation regimes of the energy system, reserve provision needs and means, diversification of energy supply chains, electricity trade between countries, balancing of intermittent electricity generation from the renewable energy sources (RES), energy security ensuring measures, etc. The links with the TIMES PanEU model is made by using similar technical-economic parameters for energy technologies, as well as using RES targets and CO2 prices from mentioned model as an input parameter in FIBEM and MESCA. Additionally, MESCA probabilistic model enables to determine the energy security quantitively, which directly refers to the energy system resilience measure.

2.1. *The structure of the energy system model FIBEM*

Principal structure of regional mathematical model for technical-economic analysis of the energy sector development and operation FIBEM is shown in Fig. 2.

The model covers electricity, district heating and fuel supply systems in three Baltic countries (i.e. Estonia, Latvia and Lithuania) and Finland. The supply of different fuels to each country is modelled taking into account country peculiarities of fuel supply infrastructures and other country-specific factors. All existing and new power plants, electricity transmission and distribution grids, energy accumulation options (hydro pumped storage plants, electric batteries) are included into the electricity system. The main technical-economic parameters of all elements of the model as well as modelling outputs are stored in the database of Open Energy Platform [44]. Electricity system links between countries in the region as well as links with energy systems of the third countries are represented by throughput capacities of the power lines. They change in time due to reorientation of the Baltic power systems from synchronous operation with IPS/UPS towards synchronous operation with power systems of the Continental Europe. The IPS/UPS is a wide area synchronous transmission grid consisting of Independent Power Systems of 12 countries bordering Russia and the Unified Power System of Russia. Throughput capacities can also be extended if corresponding investments are made. Correct representation of international lines is very important not only for modelling electricity flows between countries, but also for proper assessment of reserve provision options of large generating and transmitting units that already exist or may be introduced into the relatively small system of the Baltic countries. In this

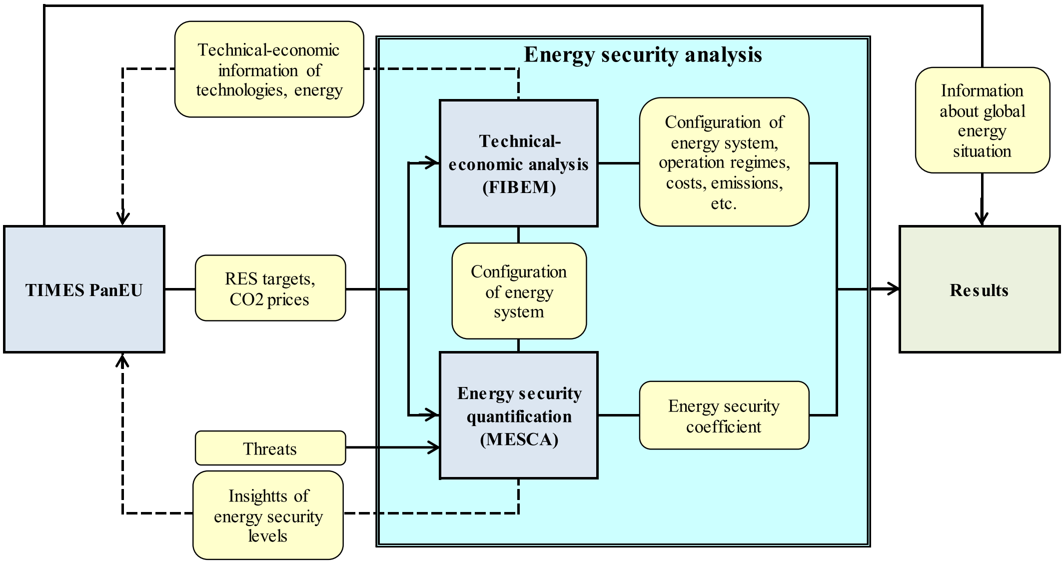


Fig. 1. Involvement of mathematical models into energy security analysis.

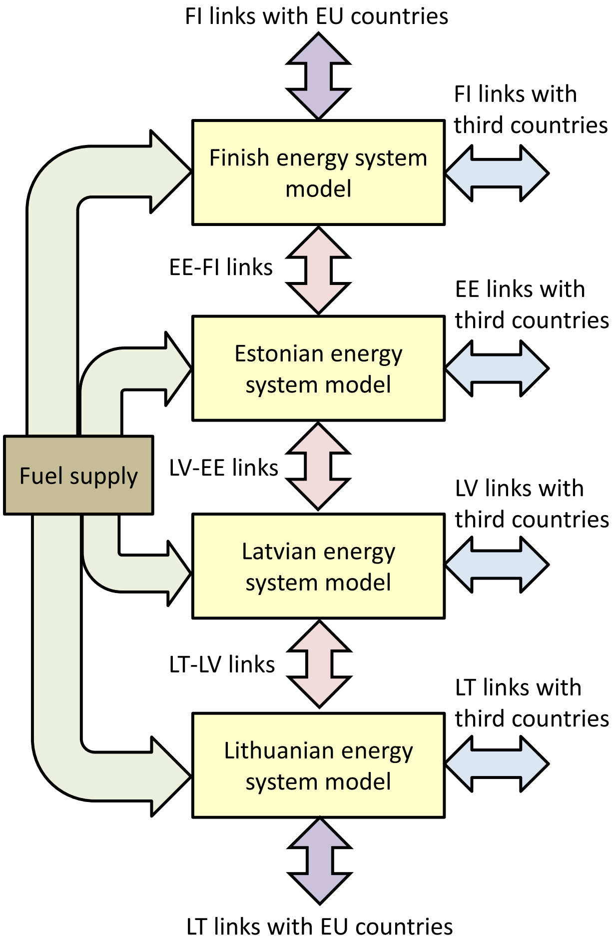


Fig. 2. Structure of the FIBEM used in the energy security analysis.

relation, reserve provision options of large units were analysed in detail by putting into mathematical model special approaches designed for explicit modelling of reserves, which in more detailed is discussed in Subsection 4.3.

District heating systems in the analysed countries are tightly coupled with the electricity system. Combined heat and power (CHP) plants supply or can supply a large share of the required district heat in the largest towns. At the same time, they may supply corresponding amount of electricity to the national electricity grid. In this relation, the analysis of power system development cannot be done separately from analysis of CHP contribution to the future district heat supply. Therefore, modelling of development of district heating systems was analysed in parallel with analysis of electricity system development. The close integration of these systems makes it possible to assess their potential interoperability in real-time and to provide rational solutions at State level. Taking into account the local character of district heating systems (individual district heating systems of particular towns do not have physical connections) supply of district heat is modelled explicitly for each larger town within the analysed countries, while district heating systems of smaller towns were aggregated into one equivalent system of particular country. District heating systems contain all existing and possible new heat production technologies, CHP plants, heat accumulation means and heat transmission-distribution networks. The development of these heat generating technologies is selected taking into account the costs of heat production, and the cases of cogeneration plants are additionally evaluated for their competitiveness in the electricity system.

2.2. Reserve modelling in FIBEM

In order to avoid disruptions in generation and consumption balance and to guarantee stable operation of the energy system, reserve capacities are necessary to compensate those, who go out of order. Most of existing scientific literature dealing with power reserves focus on operating reserves and balancing of renewable generation. It has been shown that operating reserves are important cost determinants of renewables integration [45] which has to be considered at the planning stage to avoid sub-optimal solutions and shortages of flexible resources [46].

Fluctuations of electricity production from renewables can be represented by increasing time granularity in long-term energy planning models (it allows getting realistic capacity and generation structures). More specific case is the provision of reserves against extraordinary disturbances that is especially relevant in case of large units (big thermal plants, wind parks, transmission lines). Large energy units inevitably cause reserve problems: the larger unit fails, the more reserve capacity must start operating to replace it.

Power reserve provision principle and requirement of reserve capacities are shown in Fig. 3.

Disturbance "n-1" in Fig. 3 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 (maximum within 30 s) [47] replaced by power from other units, which can offer frequency containment reserve (FCR). These power plants, for a short time period, can increase the output of electrical power. Reserve requirement is of the same size as the unit, which went out of order. In this case, the FCR equals the power of the largest unit (power plant or interconnector depending on which of them stopped working).

The FCR within 15 min has to be replaced by a frequency restoration reserve (FRR), and then released to be able to respond to another possible disturbance. Thus, the size of the FRR is also equal to the size of the largest unit. After (in 12 h) activation of the replacement reserve (RR) the FRR 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 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, 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 largest unit capacity. If the system is connected with neighbouring power systems, reserve provision 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 countries may occur due to the outage of fully loaded Lithuania-Sweden interconnector (700 MW). The higher "n-1" disturbance in the future can happen due to possible construction of large nuclear unit or due to commissioning of larger interconnector. In Finland, the biggest "n-1" disturbance can happen due to the outage of Olkiluoto NPP (1600 MW), operation of which is planned to start soon. Currently, the biggest "n-2" disturbance in the Baltic countries can be related to the 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.

Introduction of reserve provision to long-term energy planning models is a challenging task not only due to their temporal aggregation as it is the case with intermittent renewables [48,49] but also because of the lack of prevailing market design for ancillary services [50,51]. Despite of their importance on for both development and operation of

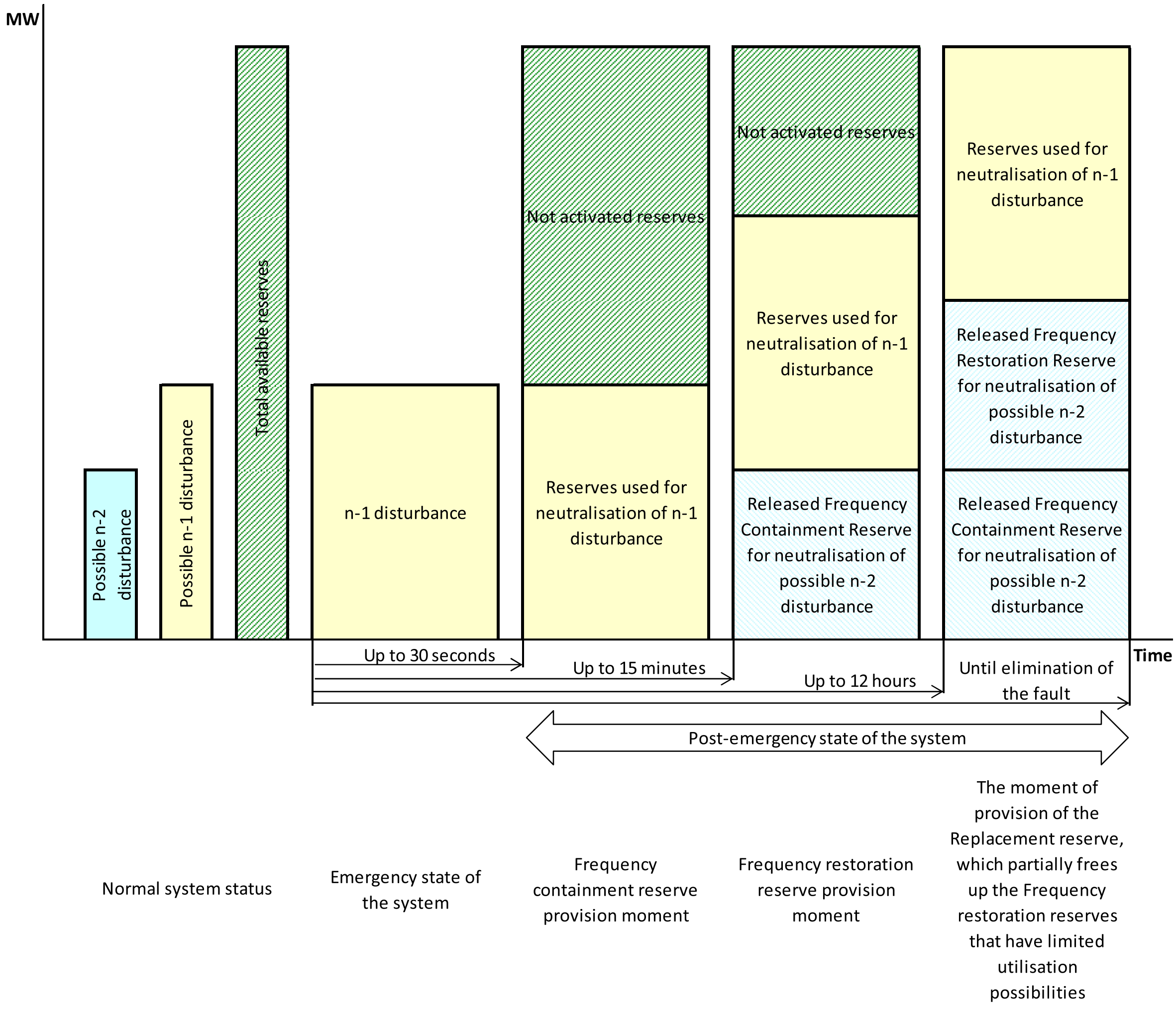


Fig. 3. Reserve requirements for large units in power systems.

energy systems, reservation issues are still neglected in the most of energy planning models. A specific modelling approach [52] was used in this energy security study in order to implement the above-described reserve provision principle into the mathematical model. In contrast to other studies that assume certain reserve margins based on yearly averages or extreme days [53], FIBEM determines reserve requirements dynamically for each time-slice modelled. To model reserve provision, all power plants, which usually are represented in energy system planning models as having only one main output – electricity, have three additional outputs to represent reserve supply in FIBEM: FCR, FRR and RR. Reserve provision options reflect technology peculiarities and ability to provide reserves [54]. Interconnectors are also considered for reserve provision. To analyse the benefits and possibilities of cross-border reserve procurement [55], it was assumed that all kinds of reserves can be provided by HVAC. The maximum value of each type of reserve size, in this case, was limited by the line throughput capacity unused for commercial electricity import. Similarly, the maximum value of each type of reserve size was limited by the value of exported power if electricity is exported through the line. For HVDC lines additional limitations were assumed – the value of each type of reserve was limited by 10% from commercial power flow thorough the line. This assumed limitation is based on the operational practice of power companies. In addition, in 2025 synchronization of Estonian, Latvian and Lithuanian power systems with the European Continental Network (ECN) is foreseen. It was assumed that status of some interconnectors linking power systems of Baltic States with the power system of Continental Europe and former IPS/UPS is changing in 2025 due to planned resynchronisation process.

2.3. Energy security coefficient

The methodology for quantitative assessment of energy security aims to expand 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. In this step, the scenario results of the FIBEM are checked in terms of energy security by an uni-directional soft link with the MESCA probabilistic model, introduced in Section 2.

The methodology is based on the analysis of various emerging threats, disruptions arising from threats and associated consequences to energy system in the case of potential disruptions. It seeks to quantitatively estimate energy security for future development scenarios. Energy system modelling is employed to determine the ability of the energy system to overcome or resist the emerging disruptions. An integral characteristic of disruption consequences is represented by energy security coefficient (ESC), which is a quantitative metric of energy security derived from the cost of energy generation and unserved energy. Detailed description of the methodology used in the MESCA model and quantitative justification of ESC is provided in the study [12], therefore, will not be discussed in detail further in this paper.

The ESC aims to evaluate the ability of the energy system to overcome resulting disruptions and indicates the level of energy system resilience to these disruptions. The ESC is calculated from the consequences of disruptions, which directly reveals vulnerability of the energy system:

$$ESC = \exp(- w_1 \cdot c_1 \cdot \exp(t) - w_2 \cdot c_2 \cdot \exp(t))$$

where w_1 and w_2 indicate weights of each consequence, c_1 and c_2 indicate disruption consequences (unserved energy and energy cost increase respectively), t refers to OSeMOSYS parameter *YearSplit*.

Values of the ESC are estimated within the range from 0 to 1. If the ESC is equal to 1 (maximum ESC), then the energy system is considered as resilient to disruptions with high energy security level. If the ESC is equal to 0 (minimum ESC), then the energy system is considered as not resilient (vulnerable) to disruptions with low energy security level. In short, higher ESC value indicates higher energy security level. The ESC enables the comparison of energy system development scenarios from energy security perspective taking into account energy system resilience measure.

3. Assumptions and scenarios

To reflect the European energy development trends, the assumptions about carbon prices and renewable energy targets were synchronised with the outputs of TIMES PanEU [43] model runs. Data harmonization in this study was done for both FIBEM and MESCA models (Fig. 1). It should be noted that in this study no modelling is carried out using TIMES PanEU model. As indicated in Fig. 1, the energy security analysis was carried out using FIBEM and MESCA models. However, the initial assumptions concerning carbon prices and RES targets from the TIMES PanEU model results are used as input parameters to FIBEM and MESCA models.

The main factors defining energy sector development pathways in the TIMES PanEU model are emissions of greenhouse gases (GHG) and use of RES. The emission reduction target for the emission trading sector (ETS) was set for the entire EU. 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. The highest GHG emission target for 2050 is set for Finland (80% reduction), while for all the Baltic countries it stands at 60%. Regarding the RES targets, by 2050, the share of RES in final electricity consumption should reach 85% in Finland and 75% in the Baltic countries.

Two initial pathways are considered in the TIMES PanEU model: *Base*, which represents current trends, and *High RES* that assumes higher RES generation targets [43]. Following the results and assumptions of the abovementioned pathways, it was assumed in this study that a common target for RES based energy generation will be used for the entire region, i.e., common target for Finland and the Baltic countries. 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 1 were considered.

The CO_2 prices taken from the TIMES PanEU model results, are also harmonized across the two studies and are presented in Table 2.

As it is presented in Table 2, TIMES PanEU Base and TIMES PanEU High RES scenarios result in very similar carbon prices, having a considerable jump in 2050. Therefore, it was decided that faster carbon price growth will be represented by additional BaseCO2Lin scenario.

To sum up, further analysis includes the Base scenario, which has the same CO_2 price and RES targets as the Base used in TIMES PanEU model, and the BaseCO2Lin, which assumes linear growth from 10 EUR/t in 2020 up to value estimated in TIMES PanEU High RES scenario for 2050.

4. Results and discussion

In order to illustrate the situation in the Finnish and Baltic energy sectors corresponding to the scenarios under consideration, this section will first review the dynamics of installed capacities in the analysed countries, the modelling results showing expected changes in power generation and reserve provision while Subsection 4.4 will provide energy security assessment for the scenarios considered. The results of installed capacity, electricity generation and provision of reserve services are presented for Finland and Baltic countries (all together) while results of energy security coefficient are presented for each analysed country separately.

4.1. Installed capacity

Installed capacities of power plants and interconnectors in Finland are presented in Fig. 4.

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 the end of their technical lifetime and expected low electricity price in the market, which does not guarantee enough return on investments for new power plants. In such circumstances, new investments are postponed. The absence of other instruments that could encourage new investments may lead to a situation where energy security may decrease (see Subsection 4.4 for more information). In such situation, existing fossil fuel power plants that currently are not competitive in the electricity market might still be a cost-effective option for reserve provision and ensuring energy security. It is necessary to keep this in mind when a decision about the 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 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, a smaller contribution comes from biomass and solar energy.

Growth of installed capacity in Finland is expected with rapid development of wind power plants followed by fast penetration of manoeuvrable gas turbine CHP. Gas turbine CHPs are used for the 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, especially after 2035. The difference between available power and installed capacity will appear because available power of wind power plants and balancing power plants cannot be added together arithmetically while installed capacities can be summed.

Another important factor is increasing throughput capacity of international lines. This is linked to growing capacity of wind power plants and increasing demand for balancing services in the system. Study

Table 1
RES target shares in primary energy consumption for electricity and district heat production.

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

Table 2
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 (BaseCO2Lin)	0	10	89.8	169.7	249.6	329.4	409.3	489.1

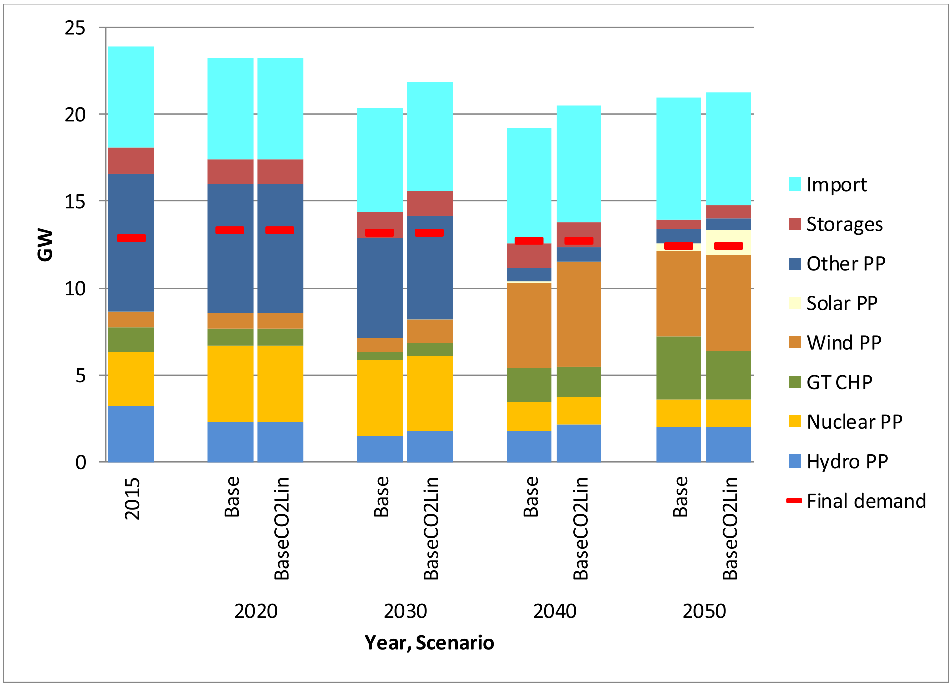


Fig. 4. Installed capacity of electricity generation sources in Finland in analysed scenarios.

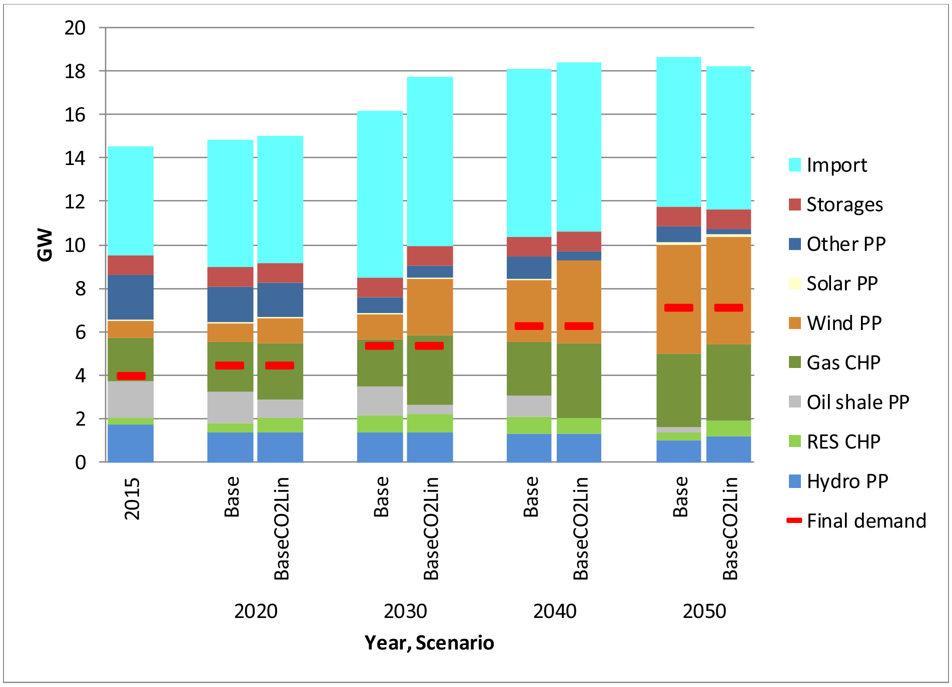


Fig. 5. Installed capacity of electricity generation sources in the Baltic countries.

results show that total throughput capacity of international links in 2040 is already ~14% higher than in 2015 and in the 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. 5.

Modelling results demonstrate high diversification among power plant types but lower diversity among primary energy forms used for electricity generation. Major part of installed capacity of power plants, especially at the end of the study period, comes from wind power plants and plants which run on natural gas. Hydropower plants and power plants running on various types of biomass also make a notable contribution. It is also expected that total installed capacity of power plants in the Baltic countries will start growing from the period 2025–2030. Major contribution is expected from wind power plants, CHP using natural gas and CHP running on biomass.

The analysis also revealed that increased throughput capacity on international lines and lines linking the Baltic countries with each other would be beneficial. This growth is especially important for provision of sufficient reserves and balancing intermittent wind generation.

4.2. *Electricity generation*

Electricity generation in Finland for the Base and the BaseCO2Lin scenarios is presented in Fig. 6. Due to high utilization of installed capacity 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 the period 2020–2035. In later years, with 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 hydropower plants is expected to remain stable contributing about 13–19% to the total electricity requirement. Some generation decline occurs in the middle of the study period due to the rehabilitation of existing plants, which according to the results of the analysis is an economically attractive option for all countries in the region under analysis. In addition, higher CO_2 prices (BaseCO2Lin scenario) result in earlier retrofitting of some hydroelectric plants and increasing their efficiency, which results in earlier increase of electricity production in these plants.

Increasing requirements for climate change mitigation will stipulate the growth of electricity generation in 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 significant increase of electricity generation from wind power plants will occur in line with the declining electricity generation from nuclear plants. As in the case of hydropower, higher CO_2 prices (BaseCO2Lin scenario) lead to faster development of wind power plants over the period 2030–2050, which allows for more than 20% increase in power generation in these plants, compared to the Base scenario.

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 necessity for balancing intermittent electricity generation from wind power plants. Manoeuvrable gas turbine CHP will make a significant contribution to balancing of intermittent generation after 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. The utilization of these technologies is very similar for both scenarios considered.

Growing electricity import to Finland will contribute to the balancing of variable wind generation. It also will substitute the declining electricity generation from power plants 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. However, electricity import after 2030 in the BaseCO2Lin scenario is 12–18% lower than in the Base scenario. This is explained by the increased electricity production in hydro and wind power plants, as well as the reduced utilization of installed capacities of interconnectors due to their higher utilization for reserve provision services and balancing of variable wind power generation.

Summarising, electricity supply in Finland is and will remain sufficiently diversified both in terms of primary energy sources and supply

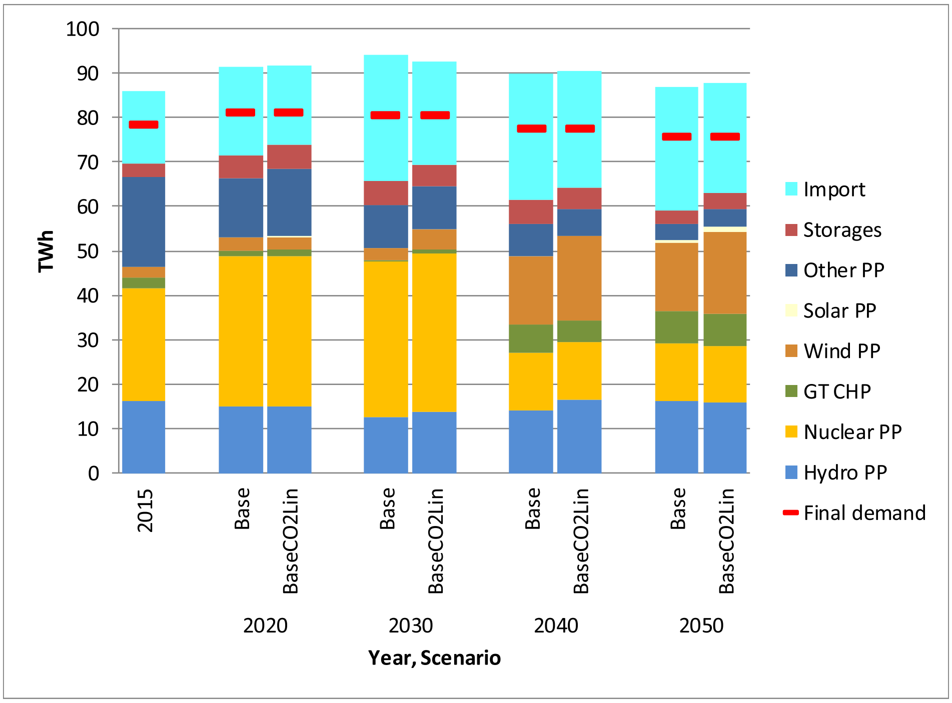


Fig. 6. Electricity production in Finland in analysed scenarios.

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-suppliers (Sweden, Norway, Estonia and Russia). This makes a good basis for energy security, whose quantitative characteristics are discussed in Subsection 4.4.

Electricity generation in the Baltic countries for analysed scenarios is summarized in Fig. 7. Electricity import and generation from oil shale are dominant in the Baltic countries at the beginning of the study period. The share of imported electricity covers ~29% of the total electricity requirements in the Baltic countries. 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 than 1% by 2050, correspondingly. Electricity import will be mainly declining due to expressed energy policy, while electricity generation from oil shale will decline due to environmental concerns. Therefore, a much faster decline is observed in the BaseCO2Lin scenario in which CO_2 prices are significantly higher in the middle of the study period, if compared with the price in the Base scenario. On the opposite side, electricity generation from wind and gas will be growing in order to compensate these reductions. Thus, depending on scenario, electricity generation from wind power plants is expected to be reaching ~2.8–7.5 TWh in 2030 and about 19 TWh in 2050. This will cover ~7.5–20% and ~40% of the total electricity requirements in the region correspondingly.

Electricity generation from gas will grow from ~20% in 2015 to ~32–33% in 2050. As it is the case in Finland, these power plants will significantly contribute to the balancing of variable electricity generation from wind power plants. However, electricity grid (i.e. varying electricity import/export from/to neighbouring countries) will make major contribution to balancing of variable wind generation in the Baltic countries. Use of hydro pumped storage power plant in comparison to the aforementioned options is an economically less attractive option used for balancing electricity supply and demand due to comparatively big losses.

As far as individual Baltic countries are concerned, oil shale-based electricity production is typical for Estonia. In the Base scenario, 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. In the BaseCO2Lin scenario, this electricity generation source practically disappears already in 2030. The growing environmental burdens (CO_2 price, in particular) are the main cause of this rapid change. Reduced electricity generation from Estonian oil shale power plants has only a minor impact on electricity generation in Finland, as well as to net electricity imports to the Baltic countries. Energy policy target can explain the fact that the impact on electricity imports/exports is minor in this case for decreasing electricity imports to the Baltic countries which is common for both scenarios analysed.

Three main types of power plants are used for electricity generation in Latvia: CHP running on gas, CHPs running on biomass and hydropower plants. The remaining part of electricity requirement is covered by electricity imports. Higher CO_2 prices (BaseCO2Lin scenario) would lead to higher electricity generation from biomass burning power plants. This increase is mainly observed in period 2020–2025. Additionally, produced electricity is partly exported to Estonia.

The electricity requirements in Lithuania 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 plants 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 in electricity generation from wind is expected after 2030. Higher CO_2 price (BaseCO2Lin scenario) has the biggest impact on electricity generation from CCGT CHP in Lithuania. Higher electricity generation at these power plants is observed since 2030. Part of this additionally produced electricity is exported to Estonia which has electricity supply shortage due to the earlier closure of oil shale power plants.

Climate change mitigation associated with growing CO_2 prices results in the transition from fossil fuel-based to carbon-free electricity generation that comes from domestic resources (wind, solar, domestically produced biomass). Growing share of domestic energy resources in total primary energy consumption has a positive impact on energy security. In addition, existing fossil fuel power plants that currently are not competitive in the electricity market often are a cost-effective option for reserve provision. Thus, energy security can be also increased by keeping these power plants for reserve provision purposes instead of building

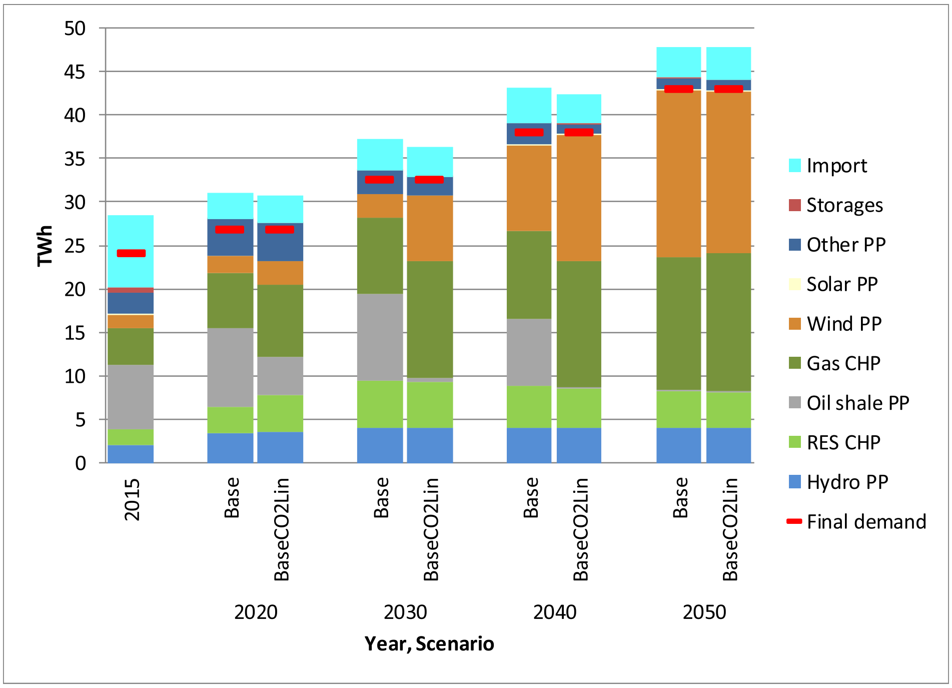


Fig. 7. Electricity production in Baltic countries in analysed scenarios.

new ones.

4.3. Provision of reserve services

Reserve provision services play an important role in energy security. Modelling results regarding possible reserve provision in Finland and the Baltic countries for the Base scenario are summarized in Table 3 and Table 4 respectively.

Reserve provision amount expressed in GWh (ordered reserve capacity multiplied by order time) does not mean actually activated reserves. This shows the ability of plants for provision of the reserves if such would be required or, in other words, the readiness of plants and international lines for reserve provision. Total reserves of particular type provided by power plants and interconnectors together, according methodology applied, are always greater or equal to the utilized power of the largest unit. Therefore, the neutralisation of n-1 disturbance is always guaranteed.

The results clearly show that major part of FCR is provided by interconnectors, especially AC lines. Depending on the year, even in Finland, where the contribution of power plants plays bigger role, FCR provided by interconnectors cover 80–87% of the total requirements of FCR. This implies that certain throughput capacity of lines should be always available for reserve provision services and that not full capacity can be used for commercial electricity trade. Modelling results show that on average only 56%–72% of installed throughput capacity of interconnectors is used for commercial electricity flows.

Provision of FRR is much more diversified and can be obtained from majority of power plants. In Finland, the contribution of interconnectors varies in a range of up to 32% of the total FRR requirements. This is also the case with the provision of RR in Finland, where power plants are the main contributors to this kind of reserve.

Regarding the provision of reserves, Baltic countries, in principle, give similar results as it does for Finland. Practically all FCR is provided by interconnectors, and all the requirements for FRR and RR are fulfilled by power plants, located within the region. As implied by the modelling methodology (see Subsection 2.2), if all capacity expansion options (see Subsection 4.1) are implemented, the electricity systems of Finland and the Baltic countries 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 reserve 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.

4.4. Energy security coefficient

This subsection highlights main results obtained from the modelling exercise performed with the probabilistic model MESCA (Fig. 1). The ESC dynamics during the modelling period, for each country are presented with insights and interpretation of the impact on energy security. Having analysed the results, major energy security assurance measures were determined within different scenarios. The modelling results are presented for each of the analysed countries separately, comparing the ESC within different scenarios. Fig. 8 demonstrates the yearly average ESC in the analysed scenarios during the modelling period in the analysed countries. Since Base and High RES scenarios give practically the same results in terms of energy security, the ESC results only for Base and BaseCO2Lin scenarios are presented in this Subsection.

4.4.1. Finland

Until 2025, the ESC is at the same level as at the start of the study period, quite stable and relatively high in both analysed scenarios. The installed capacity of energy generation does not differ until 2025 between the scenarios. 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 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, total installed capacity of energy generation technologies is even 27% lower than final capacity demand. This significantly decreases the ESC in the Base case since the energy 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 such large extent. Also, significantly increased capacity of power connection lines with Sweden allows to partially 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 PPs also appear in the BaseCO2Lin scenario and performance of the ESC is relatively higher in comparison with the Base scenario (Fig. 8. (a)).

4.4.2. Estonia

The ESC 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 with some additions from RES. Also, total installed capacity (mostly of fossil fuel PPs) gradually decreases. However, in the BaseCO2Lin scenario the ESC is lower since high CO_2 prices lead to a sudden decrease of oil shale PP 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. 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.

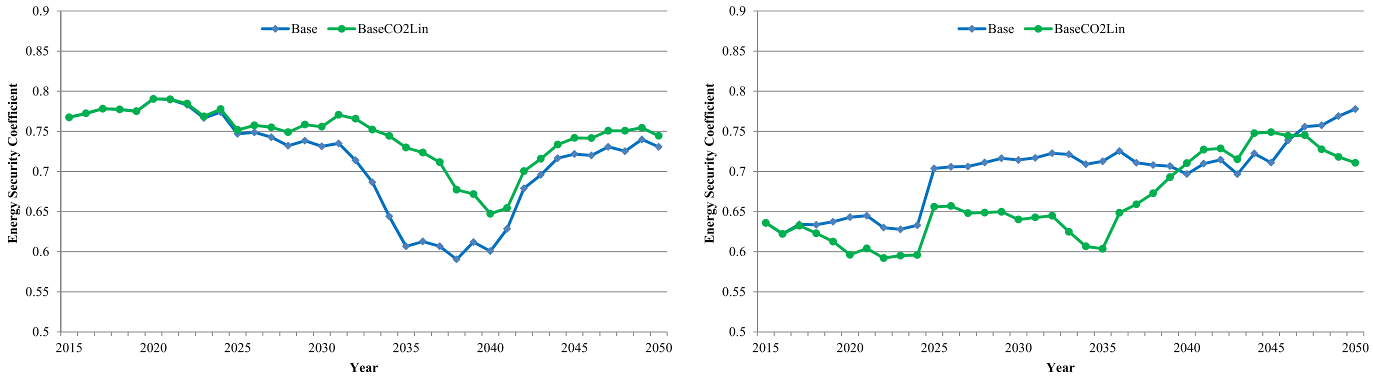
One of the most characteristic years in the analysed period is 2025, where significant increase in the ESC is observed (Fig. 8. (b)). This is related to synchronization of Estonian, Latvian and Lithuanian power systems with the ECN. This measure ensures higher energy security since this would prevent from a possible total "black-out" of power network of the Baltic countries or unreliable work of the network and would remove possible geopolitical threats from the Eastern countries. Fig. 8.

Table 3
Reserve provision in Finland for the Base scenario (GWh).

Type of reserve	Reserve provided by	2020	2025	2030	2035	2040	2045	2050
FCR	Power plants	1547	1387	897	1059	913	684	652
	Interconnectors	9864	9864	11652	11976	12302	12967	13702
FRR	Power plants	10565	27860	13772	15024	11636	12819	11541
	Interconnectors	2985	0	0	0	2753	5101	5462
RR	Power plants	10678	18772	12903	13379	10504	7977	8037
	Interconnectors	2757	516	0	0	4051	7839	7233

Table 4
Reserve provision in the Baltic States for the Base scenario (GWh).

Type of reserve	Reserve provided by	2020	2025	2030	2035	2040	2045	2050
FCR	Power plants	34	29	23	22	24	25	22
	Interconnectors	762	971	1121	1094	1081	1094	1059
FRR	Power plants	796	1001	1128	1109	1086	1107	1082
	Interconnectors	0	0	0	0	0	0	0
RR	Power plants	1070	1034	1153	1151	1132	1156	1139
	Interconnectors	0	0	0	0	0	0	0



(a) Finland (b) Estonia

(c) Latvia (d) Lithuania

Fig. 8. Energy security coefficient in the analysed scenarios.

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 RES (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 total installed capacity of energy generation technologies is only 6% higher than final capacity demand, while in the Base scenario this ratio is 35% at the same time. From 2035 to 2045, the ESC in the BaseCO2Lin scenario performs much better when energy system starts to install new wind power capacity. However, in 2045–2050, wind power is dominant in 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 study period.

4.4.3. Latvia

Only minor differences between the scenarios are observed when analysing the ESC of Latvian energy system (Fig. 8. (c)). The ESC is quite stable until 2025 since no major events appear: electricity generation is mainly based on hydro power complemented by natural gas fired plants and electricity imports. Increased CO_2 price in the BaseCO2Lin scenario does not drastically change the mix of energy system; only some additional capacity of hydro and biomass CHP technologies is observed during the study period.

As in the case of Estonia, 2025 is the year in which synchronization of the 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. The ESC during the period 2025–2050 remains almost at the same level with a slight increasing trend. 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. When taking into account 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.

4.4.4. Lithuania

The ESC in both scenarios for Lithuania is increased in 2016 by introducing new power connections with Sweden and Poland (Fig. 8. (d)). Interconnectors have 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 PPs and remains stable in the BaseCO2Lin case. However, in 2020 and 2021, both scenarios show a slight increase in the ESC due to increased capacity of power lines with Poland; also, Gas Interconnection Poland-Lithuania starts its operation.

Significant increase of the ESC is observed in 2025 when synchronization of power systems of the Baltic countries with the ECN is implemented and related to that, the capacity of the power connection lines in Lithuania with Poland is significantly increased. Aspects of the impact of 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 a 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 study 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 at 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 study 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 study period. In addition, the system remains diversified and not dependent only on a single energy source or supply.

The modelling exercise on the evaluation of ESC 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 study period, in order to ensure 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 the 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

The research presented in this paper demonstrates that coupling detailed energy system model with the probabilistic model allows not only to foresee energy security measures depending on the developments of carbon price paths and other relevant factors but also to evaluate the energy system's resilience to various disruptions and compare different energy system scenarios in terms of the energy security quantitative measure.

The obtained results indicate that faster increase of carbon price (BaseCO2Lin carbon price path) has the most significant impact on the development of Estonian energy system due to the phase-out of existing oil shale power plants. 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 countries and Finland regardless of the carbon price path. Biomass boilers and heat pumps are economically preferable for heat production. The development of other technologies in the nearest future is economically less justifiable, due to electricity import driven by relatively low electricity market prices and environmental limitations.

Energy security issues in the Baltic countries are mainly related to 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 countries 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 countries 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. Possible malfunctions of such line may cause significant energy security problems if required reserve capacities are not available.

In theory, the power system should not face any serious disruptions. However, in practice, certain elements that ensure the provision of reserve services may not be implemented or their functioning may not correspond to the real threats that can appear due to failure of 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.

Climate change mitigation targets associated with higher CO_2 prices result in earlier decommissioning of power plants using oil shale, coal and oil, faster growth of installed capacities and electricity production of wind power plants, earlier upgrade of hydropower plants and increased their efficiency, increased installed capacity of interconnectors and more intensive their use for balancing intermittent generation in RES plants.

Existing fossil fuel power plants that currently are not competitive in the electricity market often are a cost-effective option for reserve provision and ensuring energy security. The changing role of such existing technologies is an important aspect of flexibility that increases energy security and accelerate the transition from fossil fuel-based to carbon-free electricity generation.

When comparing the performance of energy security coefficient between countries within analysed carbon price paths, it was observed that the highest average (in terms of modelling period) ESC is recorded in the BaseCO2Lin scenario for Finland and Lithuania (0.74) while the lowest average (in terms of modelling period) ESC is observed in the BaseCO2Lin scenario for Estonia (0.66). In addition, all analysed scenarios in this case study demonstrate that the average ESC is higher than 0.65. The results demonstrate that carbon price paths have modest impact on energy security in Baltic countries if energy security measures are implemented in optimal way. An acceptable energy security level can be maintained despite the carbon price path.

The choice of energy security measures is a challenging task due to both 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 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 foreseen energy security measures in practice.

Declaration of competing interest

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

CRediT authorship contribution statement

Arvydas Galinis: Conceptualization, Methodology, Software, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Linas Martišauskas:** Conceptualization, Methodology, Software, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. **Jaakko Jääskeläinen:** Data curation, Writing - original draft. **Ville Olkkonen:** Data curation, Writing - original draft. **Sanna Syri:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing. **Georgios Avgerinopoulos:** Writing - original draft, Writing - review & editing. **Vidas Lekavičius:** Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing, Supervision, Project administration.

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