KAUNAS UNIVERSITY OF TECHNOLOGY

LITHUANIAN ENERGY INSTITUTE

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INVESTIGATION OF ENERGY SYSTEMS DISTURBANCES IMPACT ON ENERGY SECURITY

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (06 T)

2014, Kaunas

Doctoral dissertation was prepared during the period of 2009–2013 at Lithuanian Energy Institute, Laboratory of Nuclear Installation Safety.

The research was funded by the Research Council of Lithuania.

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The official defence of the dissertation will be held at the public session of the Board of Energetics and Power Engineering Science Field at 10:00 a.m. on 19 September 2014 in Dissertation Defence Hall at Lithuanian Energy Institute (Breslaujos str. 3-202, Kaunas).

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The Summary of the Dissertation was sent on 19 August 2014.

The dissertation is available at the libraries of Lithuanian Energy Institute (Breslaujos str. 3, Kaunas) and Kaunas University of Technology (K. Donelaičio str. 20, Kaunas).

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ENERGETIKOS SISTEMŲ TRIKDŽIŲ ĮTAKOS ENERGETINIAM SAUGUMUI TYRIMAS

Daktaro disertacijos santrauka
Technologijos mokslai, energetika ir termoinžinerija (06 T)

2014, Kaunas

Disertacija rengta 2009–2013 metais Lietuvos energetikos instituto Branduolinių įrenginių saugos laboratorijoje.

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Disertacija ginama viešame Energetikos ir termoinžinerijos mokslo krypties tarybos posėdyje, kuris įvyks 2014 m. rugsėjo 19 d. 10 val. Lietuvos energetikos instituto posėdžių salėje (Breslaujos g. 3-202, Kaunas).

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Disertacijos santrauka išsiųsta 2014 m. rugpjūčio 19 d.

Su disertacija galima susipažinti Lietuvos energetikos instituto (Breslaujos g. 3, Kaunas) ir Kauno technologijos universiteto (K. Donelaičio g. 20, Kaunas) bibliotekose.

INTRODUCTION

The energy sector is a particularly important segment of the economy, on which depend not only production, but also the efficient functioning of the infrastructure – directly or indirectly with the production, import, export or transportation of energy sources are related almost all areas of the economy. On the functioning of the energy systems depend industry, transport, agriculture and other sectors. Due to the increasing energy demand in the world, unstable energy prices, potential energy supply disruptions energy security has become one of the priority issues for most of Europe and world countries. Energy security is usually understood as a sufficient, reliable, accessible energy supply at an affordable price, but assessing energy security it is important not only those aspects, but also the ability of energy systems to resist energy supply disruptions and price increases arising due to various reasons.

Energy security, which assurance must be provided in the national energy strategy, in Lithuania is named as one of most important general objectives of energy policy [1]. An energy security issue, especially in recent years is highly relevant in Lithuania as the country is dependent on a single external energy supplier, has no electricity and gas connections with Western Europe. The country‘s electricity networks are integrated and function in a single system with Russian and Belarusian electricity networks. After the closure of the Ignalina Nuclear Power Plant (NPP) from 2010 country‘s energy balance has significantly changed, increased dependence on imported energy sources and Lithuania from the electricity exporting country has become an electricity importer. Security of energy supply is one of the country‘s primary energy priorities, which is an integral part of national security. Energy security has become the general priority of Lithuania and European Commission (EC), which identifies Lithuania among the most vulnerable countries in the European Union (EU) for the security of energy supply [2].

Many studies are performed in the field of energy security, but there are yet no universally accepted criteria or methodologies to quantitatively evaluate the country‘s or region‘s energy security, its level variation over time and to perform energy security analysis or assessment. Single separate methods or models are used, but many of these works and studies performed in various countries are confidential and not freely available to the public. However, the objective of energy security research may be twofold. First, it is to ascertain all the factors that affect energy security and to determine their interdependent relationship. It is necessary to create models capable of showing the impact that different disturbances originating from various threats have on energy systems. In addition, it is important to assess probabilities of the occurrence of such disturbances and how to eliminate their consequences. Once these objectives are achieved, developed models would enable to assess the level of national energy security, its variation over time and would determine, which development projects of the energy sector and impact they have on energy security. It would enable to compare the energy security level with other, in particular, neighbouring countries' energy security.

Relevance of the work. An adequate level of energy supply security is vital to the functioning of an economy and is one of the main guarantees of national security since reliable energy supply is needed for the industry's activity assurance and to meet the needs of people. Lithuania currently imports main energy sources and practically 80 % is energy dependent on one country supplier. In order to improve Lithuania's energy security, the development of the energy sector must be implemented, but the development decisions of energy sector are based not only on the technical and economic parameters, but also the socio-political and geopolitical aspects. For this reason, methods must be developed that enable simultaneously take into account indicated limitations as well as used arguments of decision makers, which are based on the modelling results of different scenarios and optimisation calculations.

Currently worldwide used methods of energy security assessment are either only deterministic or only stochastic, but energy security by its very nature is a process involving both these properties. Therefore, from the scientific point of view, there is a great need to develop an energy security assessment and analysis tools, incorporating the deterministic and stochastic processes into one unit in order to assess the energy security in various ways simultaneously.

The aim of the work. To create the methodology for modelling of energy systems disturbances and energy security assessment, and carry out energy security analysis of the Lithuanian energy sector.

Tasks of the work. Tasks to achieve the aim of the work are the following:

1. To create the probabilistic model of energy security threats realisation to disturbances and develop the probabilistic model of disturbance parameters;
2. To create energy security metric (measurement and assessment methodology) and the assessment model of energy systems disturbances impact on energy security;
3. To assess energy security of the development scenarios of Lithuanian energy sector at the current time and its variation over time and compare scenarios in terms of energy security;
4. To carry out uncertainty and sensitivity analysis of the model results and parameters.

Scientific novelty of the work. A new methodology for the assessment of energy security, combining the deterministic economic-optimisation modelling methods of energy systems, probabilistic methods of disturbance formation evaluation and threat assessment techniques based on expert assessment, is created. The application of the developed methodology enables modelling of perspective development of the energy sector with stochastic disturbances and more precisely to define energy security. The results of the study and created scientific knowledge supplement energy security theory with new methods and models.

Practical significance of the work. The created methodology enables the assessment of the current energy security of energy sector, the comparison of various energy sector development scenarios impact on energy security and determination of optimal development scenario in terms of energy security. A new energy security measure – energy security coefficient, which enables quantitatively evaluate energy security, is proposed. The methodology is applied to Lithuanian energy sector, and its energy security variation until 2030 is assessed as well as energy security of various development scenarios of the Lithuanian energy sector is compared. Using the obtained results the recommendations are proposed what measures should be taken to improve energy security.

Defensive propositions of the dissertation:

1. The created probabilistic model of energy security threats realisation to disturbances enable the assessment of probabilistic parameters of disturbances influencing energy security;
2. The created methodology and metric for the assessment of energy security enable the assessment and measurement of current energy security of energy systems, its variation over time and the comparison of various development scenarios of the energy sector in terms of energy security;
3. Energy security of the development scenarios of Lithuanian energy sector systems based on various energy production technologies is different and depends on energy production and import ratio.

Approbation of the work. One publication on the theme of doctoral dissertation has been published in the journal of Institute for Scientific Information database “ISI Web of Science” with citation index and one publication in the journal referred in other international scientific databases. Research results were published in ten international conference proceedings.

Scope and structure of the work. The dissertation consists of introduction, three main sections, covering literature review, methodology and research results, and conclusions. The dissertation contains 116 pages (without appendixes), including 32 figures, 12 tables, 165 references and list of publications on the theme of dissertation.

1. METHODOLOGY FOR THE ASSESSMENT OF ENERGY SECURITY

In order to assess energy security comprehensively, the methodology must be developed, which takes into account the aspects of energy security definition: reliable energy supply, energy price increase and energy system resistance to disturbances. This dissertation presents the created new methodology for the assessment of energy sector energy security, which is detailed in this Section.

1.1. Threats and disturbances to energy systems

For each energy system, a variety of threats can arise. A threat could be defined as any potential danger that exists within or outside the energy system and that has a potential to result into some kind of disruption of that system functioning. Usually essential threats to energy security are distinguished, which can cause two types of disturbances: supply interruptions and the increase in the price of energy sources[1]. Threats can roughly be divided into several groups: natural, technical, economic, socio-political and geopolitical threats.

Threats by their severity according to their potential impact on the energy systems are divided into four states: 0 – no threat impact, 1 – low threat impact, 2 – medium threat impact, 3 – high threat impact.

For the purpose of qualitative assessment of threat realisation or disturbance occurrence frequencies, the following logarithmic gradation may be observed: very low frequency threats – less than 10^{-3} (at least one from more than 1000 possible cases), low frequency threats – from 10^{-3} to 10^{-2} (at least one from 100 possible cases), medium frequency threats – from 10^{-2} to 10^{-1} (at least one from 10 possible cases), and high frequency threats – more than 10^{-1} (at least one from less than 10 possible cases).

Threats to energy systems may realise by causing various energy system disruptions, called disturbances that can disrupt the functioning of energy systems that occur in energy supply disruptions or energy price increases. Disturbances by their nature are divided into several groups. The first group related to the duration disturbances can be very different and depend on the type of energy. To energy security important are disturbances, which are long-term or neutralization of their consequences is long lasting. Therefore, energy security analysis mainly takes into account disturbances arising from the long-term threats.

Another group of disturbances depends on where the disturbance occurs: within the energy systems (internal disturbance) or outside the systems (external disturbance). Both external and internal disturbances are independent.

[1] Energy sources include both primary energy (oil, natural gas, coal, nuclear fuel, local and renewable energy sources) and secondary energy (electricity and heat).

Disturbances can also be classified according to the disturbances' causes or nature. Natural, technical, economic, socio-political, geopolitical and other reasons are included in this group. It should be noted that all disturbance groups may overlap.

In order to model random disturbances' impact on energy systems, disturbances should be characterized by parameters of a stochastic nature. Description of disturbance parameters and determination of their values as well as probability distributions enable to define a probabilistic model of the disturbance formation. External disturbances due to all the possible threats usually cause two types of disruptions: energy supply interruptions or terminations and energy price increases.

1.2. Disturbance parameters

This dissertation proposes a method of deviation from the basic scenario for the description and modelling of energy disturbances. The basic scenario describes the situation of the energy sector from the present day until 2030 assuming that energy supply disturbances do not exist, whereas fuel and energy sources are supplied as it was predicted by the demand for electricity and heat production.

Since the disturbance parameters have probabilistic characteristics, it is necessary to determine their probability distributions and to provide a complete set of disturbance scenarios, which is used for modelling functioning of energy systems. It should be noted that some of the disturbances are dependent. Therefore, their distributions of the parameters depend on the parameters of other disturbances. Furthermore, values of the disturbance parameters are changing over time and parameters of their probability distributions also depend on the time t.

Parameters of external disturbance:

1) *Part of energy supply deviation from the basic supply scenario*; here $\delta(t) = \{\delta_i(t) \mid i = 1, 2,..., N_\delta\}$ and N_δ is the number of parameter acquired values. Supply deviation parameter includes both supply restriction and complete termination. Parameter acquires values from 0 to 100 % compared with the amount of supply in the basic scenario during an appropriate period.

2) *Price deviation of energy sources from the projected price in the basic scenario*; here $\omega(t) = \{\omega_i(t) \mid i = 1, 2,..., N_\omega\}$ and N_ω is the number of parameter acquired values. The upper value of this parameter is not limited. Price variation in the disturbance analysis usually means the price increase.

For each of the major parameters of external disturbance have to be identified other external disturbance parameters, which describe when the disturbance began, how long it lasted and what energy source has been disrupted:

a) *Energy source, which supply was restricted or its price has increased*; here $\varphi(t) = \{\varphi_i(t) \mid i = 1, 2,..., N_\varphi\}$ and N_φ is the number of energy sources in the analysed energy systems.

b) *Starting moment of the external disturbance*; here $\tau^{ext} = \{\tau_i^{ext} \mid i = 1, 2,..., N_\tau^{ext}\}$ and N_τ^{ext} is the number of parameter acquired values.

c) *Duration of energy sources supply or price deviation*; here $\phi^{ext}(t) = \{\phi_i^{ext}(t) \mid i = 1, 2,\ldots, N_\phi^{ext}\}$ and N_ϕ^{ext} is the number of parameter acquired values. This parameter indicates how long deviation of energy sources supply or price has lasted.

Parameters of internal disturbance:

1) *Reliability characteristic of energy production, transmission or distribution technology* in this methodology is expressed as *technology availability*; here $\kappa(t) = \{\kappa_i(t) \mid i = 1, 2,\ldots, N_\kappa\}$ and N_κ is the number of parameter acquired values.

As in the case of the external disturbance, parameter κ is defined with internal disturbance starting moment, duration, and technology, which availability has been reduced.

a) *Energy production, transmission or distribution technology*, which activity has been disturbed; here $\psi(t) = \{\psi_i(t) \mid i = 1, 2,\ldots, N_\psi\}$ and N_ψ is the number of parameter acquired values.

b) *Starting moment of the internal disturbance*; here $\tau^{int} = \{\tau_i^{int} \mid i = 1, 2,\ldots, N_\tau^{int}\}$ and N_τ^{int} is the number of parameter acquired values.

c) *Duration of the internal disturbance*; here $\phi^{int}(t) = \{\phi_i^{int}(t) \mid i = 1, 2,\ldots, N_\phi^{int}\}$ and N_ϕ^{int} is the number of parameter acquired values.

Meaning of the parameters τ^{int} and ϕ^{int} is the same as the parameters τ^{ext} and ϕ^{ext} respectively, but the values of the parameters may be different, i.e. internal and external disturbances may occur at different periods, have a different duration and can be independent. Disturbance parameters and their probability distributions are summarized in Table 1.1.

It is necessary to analyse threat realisation frequencies and transition probabilities from threats to disturbances in order to assess the probability distributions of the disturbance parameters. For this reason, a mathematical apparatus, which is based on the network system of the states of threats and disturbances, is employed by the author to create the probabilistic model of disturbance formation from the threats.

Table 1.1. Characteristics of disturbance parameters

Disturbance parameter	Probability distribution	Parameters of probability distribution
Starting moment of the external or internal disturbance	Uniform $U(a, b)$	a – the beginning of the modelling period b – the end of the modelling period
Part of energy supply deviation from the basic supply scenario	Lognormal Log-$N(\mu, \sigma)$; here $\mu = \ln\left(\frac{v^2}{\sqrt{d+v^2}}\right)$, $\sigma = \sqrt{\ln\left(1+\frac{d}{v^2}\right)}$	v – average supply deviation d – dispersion of supply deviation
Price deviation of energy sources from the projected price in the basic scenario		v – average price deviation d – dispersion of price deviation
Duration of the external or internal disturbance	Exponential $Exp\ (\lambda)$; here $\lambda = \lambda(\delta, \omega)$ in the case of the external disturbance and $\lambda = \lambda(\kappa)$ in the case of the internal disturbance	λ – parameter, depending on the average duration of the disturbance
Technology availability	Beta $Be(\alpha, \beta)$	α, β – distribution shape parameters depending on the level of technology availability

1.3. Probabilistic model of threats realisation to disturbances

In a system, which consists of Z number of blocks, each of the blocks BL_j may be described by one of G_j different states ST_i ($i = 1, 2,\ldots, G_j$); here BL_j ($j = 1, 2,\ldots, Z$) is the block under analysis, Z – the number of blocks in the system, G_j – the number of states in block BL_j. The time moments when the states change, i.e. when the transition from the states of one block to those of another block is probable, is denoted by $z = 1, 2,\ldots, Z$. The number of states G_j in each block BL_j can be different.

It is necessary to calculate probabilities $P(BL_z(i))$, $i = 1, 2,\ldots, G_z$, $z = 1, 2,\ldots, Z$ in order to determine the probability distributions of the states of each block. Equation is used to calculate these probabilities:

$$P\big(BL_{z+1}(j)\big) = \sum_{i=1}^{G_z} P\big(BL_z(i)\big) \cdot P\big(BL_{z+1}(j) \big| BL_z(i)\big), \tag{1.1}$$

$$j = 1, 2, \ldots, G_{z+1},\ z = 1, 2, \ldots, Z-1.$$

Threat block is the initial block in the analysed probabilistic model. Each block state represents a threat, which can also occur in different severity level. Each realisation of a threat is described with its frequency of occurrence. Initial block-state frequency vector $\boldsymbol{\pi}$ of threats is defined by calculating its elements according to equation:

$$\pi_i(t) = P(BL_1(i;t)) = f_i(t), \; i = 1, 2, \ldots, G_1(t); \tag{1.2}$$

here $G_1(t)$ – the number of threat states in the threat block BL_1 at time moment t, $f(t)$ – frequency determined from the threat realisation effect severity.

This gives the initial frequency vector of threat realisation $\pi(t) = \left(\pi_1(t) \;\; \pi_2(t) \;\; \ldots \;\; \pi_{G_1(t)}(t)\right)^T$; here $\pi_i(t)$ indicates i^{th} threat realisation frequency in the threat block BL_1 at time moment t. The disturbance probabilistic assessment is possible when the initial distribution of threat realisations is defined. Disturbances resulting from all possible threats can be divided into the following types:

- restriction or termination of the energy sources supply;
- price increase of the energy sources.

Disturbances can arise from threats to energy systems and probabilistic transition from the states of threat block to the states of disturbance block is possible. However, the realisation of threats into disturbances faces barriers that can reduce or completely eliminate the risk of threat realisation. Barrier block BL_2 is defined in the system, where each state of the threat corresponds to the entire set of barriers that are identified by $BR_i^k(t)$; here the indices $i = 1, 2,\ldots, G_1(t)$ and $k = 1, 2,\ldots, K_i(t)$ indicate the numbers of threat block states and barrier at time moment t respectively, and $K_i(t)$ denotes the number of barriers in the block BL_2 of the i^{th} state.

Scheme of the network system of threats, barriers and disturbances block states is shown in Fig. 1.1. Threats in the system are defined by their realisation frequencies from elements of (1.2) equation composing vector $\boldsymbol{\pi}$. Activation or non-activation of the barriers are assessed respectively with the probabilities $P(BR_i^k(t))$ or $1 - P(BR_i^k(t))$. In order to calculate the disturbance formation probabilities $P_j(t)$ (here $j = 1, 2,\ldots, G_3(t)$), it is needed to assess probability matrix of the transition from threats to disturbances $\mathrm{C}(t) = \begin{pmatrix} c_{11}(t) & c_{12}(t) & \ldots & c_{1G_3}(t) \\ c_{21}(t) & c_{22}(t) & \ldots & c_{2G_3}(t) \\ \vdots & \vdots & \ddots & \vdots \\ c_{G_1 1}(t) & c_{G_1 2}(t) & \ldots & c_{G_1 G_3}(t) \end{pmatrix}$, where elements of this matrix denote the transition from threat block states to disturbance block states probability at time moment t. But between these blocks, barrier block is defined, and it reduces probabilities of the disturbance formation. These probabilities are calculated according to the formula:

$$P_j(t) = \sum_{i=1}^{G_1(t)} f_i(t) \cdot c_{ij}(t) \cdot \prod_{k=1}^{K_i(t)} \left(1 - P\left(BR_i^k(t)\right)\right); \tag{1.3}$$

here $P_j(t)$ – j^{th} disturbance probability at time moment t, $f_i(t)$ – a realisation frequency of threat i at time moment t, $c_{ij}(t)$ – transition from threat i to disturbance j probability at time moment t, $P(BR^k{}_i(t))$ – probability of threat i of barrier k at time moment t, $j = 1, 2,\ldots, G_3(t)$.

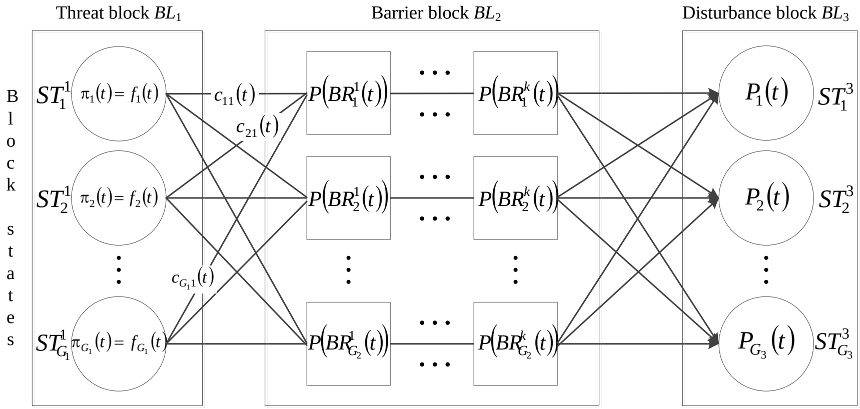


Fig. 1.1. Scheme of the probabilistic model of disturbances formation from the threats

Presented probabilistic model enable the assessment of likelihood of threats realisations to disturbances, which depend on the threat realisation frequency and probability of barrier activation. Taking into account the estimated probabilities and probability distributions of disturbance parameters, a set of disturbance scenarios is generated randomly. With this set energy sector and its development scenarios are modelled. The result of the developed probabilistic model is the assessment of the disturbances probabilities and formation of the set of disturbance scenarios, which is used for modelling functioning of energy sector with stochastic disturbances using economic-optimisation model presented further.

1.4. Economic-optimisation model of energy sector

Energy sector modelling tools and mathematical models are used to simulate and analyse economic and technological development of energy sector systems. These tools with the help of mathematical equations describe the real energy systems, i.e. their structure, technical and economic parameters, various processes, fuel, energy and financial flows.

Linear programming (optimisation) method for modelling of disturbed energy systems optimised perspective development is used in this dissertation. The Open Source Energy Modeling System (OSeMOSYS) [3, 4] is used as energy systems modelling tool. OSeMOSYS model is adjusted and adapted for energy system stochastic disturbance scenarios modelling.

The equations of the model are divided into those used to meet the capacity and activity constraints, fuel supply, capital investment, salvage values, operating costs, and total discounted cost. Indices used in the equations include all their sets of values from each set, i.e. $r \in R$ *(region)*, $y \in Y$ *(year)*, $t \in T$ *(technology)*, $l \in L$ *(time slice)*, $f \in F$ *(fuel)*, $m \in M$ *(mode of operation)* and $e \in E$ *(emission)*.

The objective function of the model is to minimize the total discounted cost of energy systems to meet the given demand(s) for the energy sector. It is summarized in equation:

$$\text{Minimize } \sum_{y}\sum_{t}\sum_{r} TDC_{y,t,r} \text{ , } \forall y,t,r \text{ ,} \tag{1.4}$$

$$TDC_{y,t,r} = DOC_{y,t,r} + DCI_{y,t,r} + DTEP_{y,t,r} - DSV_{y,t,r}\text{, } \forall y,t,r \text{ ;} \tag{1.5}$$

here $TDC_{y,t,r}$ – total discounted cost, $DOC_{y,t,r}$ – discounted operating cost, $DCI_{y,t,r}$ – discounted capital investment, $DTEP_{y,t,r}$ – discounted technology emissions penalty, $DSV_{y,t,r}$ – discounted salvage value.

Full description of original OSeMOSYS model can be found [3, 4].

However, functions that describe functioning of cogeneration power plants (CHP) are not realised in the model. Since the technology used in the model can be described in various parameters, the author has modified so that it can be used for modelling of CHP plants, i.e. at the same time can describe both electricity and heat production. Methodologies from the European Parliament and the Council Directive 2012/27/EU Annex I [5] and CHP plants Manual [6] are used to integrate modelling of the CHP plants. This with the help of additional equations in OSeMOSYS original model is included the possibility to model CHP plants.

Additional model block of disturbances

The author of the dissertation created a new additional block of the model for disturbance scenario analysis and modelling in order to adapt the original model to the energy systems modelling with the stochastic disturbances. To integrate the new block, new variables, parameters, and sets as well as all other variables matched existing definitions were added to the basic model. The full description of the energy disturbance block is not presented, but the main equations are described further.

The main constraints to the disturbance parameters are due to limitations of their acquired values and the modelling period. The new model block introduces the capability to restrict technologies' capacity according to energy demand. This is very useful, for example, to restrict the import of electricity, depending on the demand. This limitation is described mathematically as follows:

$$TMaxC_{y,t,r}^{\mathrm{AN}} \le RC_{y,t,r} \cdot \left(DEM_{y,f,r}^{\mathrm{AN}} / CAU_{t,r}\right),\ \forall y, f, t, r\,; \tag{1.6}$$

here $TMaxC_{y,t,r}^{\mathrm{AN}}$ – total annual maximum capacity, $RC_{y,t,r}$ – technology constraint coefficient, $DEM_{y,f,r}^{\mathrm{AN}}$ – specified annual demand of energy source, $CAU_{t,r}$ – capacity to activity unit.

Energy supply restriction parameter δ is associated with the model parameter *TAMaxC* and changes its initial values by equation:

$$TMaxC_{y,t,r}^{\mathrm{AN}} = TMaxC_{y,t,r}^{\mathrm{AN}} - TMaxC_{y,t,r}^{\mathrm{AN}} \cdot \delta_{y,t,r} / 100\,,\ \forall y, t, r\,. \tag{1.7}$$

Another external disturbance parameter ω describing the potential energy price increase is associated with the model parameter *VOC* and changes the initial values by equation:

$$VOC_{y,t,m,r} = VOC_{y,t,m,r} + VOC_{y,t,m,r} \cdot \omega_{y,t,r} / 100\,,\ \forall y, t, m, r\,; \tag{1.8}$$

here $VOC_{y,t,m,r}$ – variable cost.

The values of the internal disturbance parameter ψ compose a subset of set *T*, which include those model technologies, whose activity can be disturbed. Technology availability parameter κ of the internal disturbance changes model technology availability factor by equation:

$$AF_{y,t,r} = AF_{y,t,r} \cdot \kappa_{y,t,r}\,,\ \forall y, t, r\,; \tag{1.9}$$

here $AF_{y,t,r}$ – availability factor. Moreover $0 \le \kappa \le 1$.

The amount of unsupplied energy due to disturbances in every time slice is calculated in the following manner:

$$UE_{y,l}^{\mathrm{TS}} = \sum_{t}\sum_{f}\sum_{r} PT_{y,l,t,f,r}^{\mathrm{TS}} / \sum_{f}\sum_{r} DEM_{y,l,f,r}^{\mathrm{TS}} \cdot 100\,,\ \forall y, l\,; \tag{1.10}$$

here $UE_{y,l}^{\mathrm{TS}}$ – the amount of unsupplied energy in each time slice (%), $PT_{y,l,t,f,r}^{\mathrm{TS}}$ – production of technology in each time slice, $DEM_{y,l,f,r}^{\mathrm{TS}}$ – energy demand in each time slice.

The energy cost increase due to disturbances is calculated as the difference between the cost of the basic scenario and the cost of the disturbance scenario. To calculate it, it is necessary to determine the cost of energy systems without disturbances. Then it is possible to calculate the energy cost increase due to disturbances by equation:

$$FCC_{y,l}^{\mathrm{TS}} = \left(FC_{y,l}^{\mathrm{TS}} - BSC_{y,l}^{\mathrm{TS}}\right) / \, BSC_{y,l}^{\mathrm{TS}} \cdot 100 \,, \; \forall y,l \,; \qquad (1.11)$$

here $FCC_{y,l}^{\mathrm{TS}}$ – the increase of energy cost in each time slice (%), $FC_{y,l}^{\mathrm{TS}}$ – energy cost in each time slice, $BSC_{y,l}^{\mathrm{TS}}$ – energy cost of the basic scenario in each time slice.

The equation (1.11) is correct only in the case of 100 % of required energy is supplied. In order to assess unsupplied energy costs, the costs of supplied energy should be calculated and if there are amounts of unsupplied energy in the systems, then the assessment of expected costs of unsupplied energy should be carried out. Then estimated costs are included in the expected costs, with which were expected to supply energy, and expected energy costs are obtained. This is realised by equation:

$$FCE_{y,l}^{\mathrm{TS}} = \left(FC_{y,l}^{\mathrm{TS}} / \sum_{t} \sum_{f} \sum_{r} PT_{y,l,t,f,r}^{\mathrm{TS}} \right) \cdot \sum_{f} \sum_{r} DEM_{y,l,f,r}^{\mathrm{TS}} \,, \; \forall y,l \,; \qquad (1.12)$$

here $FCE_{y,l}^{\mathrm{TS}}$ – the expected energy costs in each time slice.

Described disturbance block of the energy systems model is used as an additional block in the basic OSeMOSYS model. Disturbance scenarios in the energy systems can be modelled using the created tool. The set of these scenarios is generated randomly using the probabilistic model described in 1.3 Subsection. This is carried out by joining the probabilistic disturbance formation model and economic-optimisation analysis model of energy sector development into single, described in the disturbance block of the model. The disturbance consequences to the energy systems are obtained after the modelling: energy price increase and the amount of unsupplied energy.

1.5. Measurement of energy security

The author of the dissertation has proposed a new way to measure energy security and assess its variation over time. It is a metric, which is characterized by energy security coefficient (ESC) calculation. This created integral characteristic can define energy security coefficient of the energy systems both at the current time and its variation over time. ESC enables the assessment of the consequences of disturbance scenarios in the energy systems from the energy security point of view. ESC depends on the amounts of the unsupplied energy, the increase in the energy price, and how long it lasted in each disturbance scenario. ESC for each disturbance scenario s in each time slice l is calculated as follows:

$$ESC^{\mathrm{TS}}_{y,l,s} = \exp\left(-w_1 \cdot FCC^{\mathrm{TS}}_{y,l,s} \cdot \exp\left(w_2 \cdot YS_{y,l}\right) - w_3 \cdot UE^{\mathrm{TS}}_{y,l,s} \cdot \exp\left(w_4 \cdot YS_{y,l}\right)\right), \quad \forall y,l,s; \tag{1.13}$$

here $ESC^{\mathrm{TS}}_{y,l,s}$ – energy security coefficient of disturbance scenario s in each time slice l, $\exp(\cdot)$ – exponential function e^x, $YS_{y,l}$ – year split, w_j – weight coefficients indicating the importance of unsupplied energy against the price increase ($j = 1, 2, 3, 4$).

According to the (1.13) formula, energy security coefficient of the energy systems can be assessed annually, during the whole modelling period and for the whole set of disturbance scenarios calculating the average ESC values.

Energy security coefficient indicates the level of energy systems resistance to disturbances. ESC is calculated from the disturbance consequences (unsupplied energy and energy price increase), which directly reveals the vulnerability of the systems. This feature of the energy systems is the opposite of systems resistance to disturbances feature, which is evaluated with energy security coefficient. The ESC value varies from 0 to 1. ESC is equal to 1 (maximum ESC) if the energy systems are resistant to disturbances and there are no price increase and unsupplied energy amounts. ESC is equal to 0 (minimum ESC) if the energy systems are not resistant to disturbances and price increase is equal or more than 100 % or the amount of unsupplied energy reaches 100 %.

Summary of the Section

The developed methodology for the assessment of energy sector energy security in terms of energy systems resistance to disturbances was presented in this Section. This methodology includes several different models:

- probabilistic model for the formation analysis from threats to disturbances in energy systems;
- economic-optimisation model for energy sector development optimisation with stochastic disturbance scenarios;
- energy security metric intended to measure and assess energy security calculating energy security coefficient, which indicates the level of energy systems resistance to disturbances.

Energy security assessment by the developed methodology can be implemented step by step and its scheme is presented in Fig. 1.2. The first step is designed to the assessment of threats that arise in the energy system from outside as well as inside. Each threat can realise in one or another energy system disturbance that could do potential damage to the energy systems of the energy sector. Since the threats and disturbances are of a stochastic nature (Subsections 1.1 and 1.2), the probabilistic model is used for analysis of threat realisation to disturbances (Subsection 1.3). In the second step energy sector with the development scenarios are modelled using economic-optimisation model of energy sector prospective development (Subsection 1.4). The energy sector is modelled with a set of many stochastic disturbance scenarios, where parameters and disturbance occurrence probabilities are determined using the above mentioned probabilistic model. In the third step energy security and its variation over time of all disturbance scenarios are assessed. Energy security coefficient (ESC) is determined according to the disturbance consequences: unsupplied energy and energy price increase. ESC evaluates the level of energy system resistance to disturbances (Subsection 1.5). Energy security in different periods of each energy sector development scenario is obtained calculating values of energy security coefficient. Sensitivity and uncertainty analysis of model parameters is carried out in the fourth step.

The developed methodology can be applied to any energy sector, which consists of individual energy systems such as electricity, heat, natural gas supply, petroleum products supply, renewable energy sources, etc. This may be energy sector of both individual country and whole region. It should be independent, separate from other sectors and able to function independently.

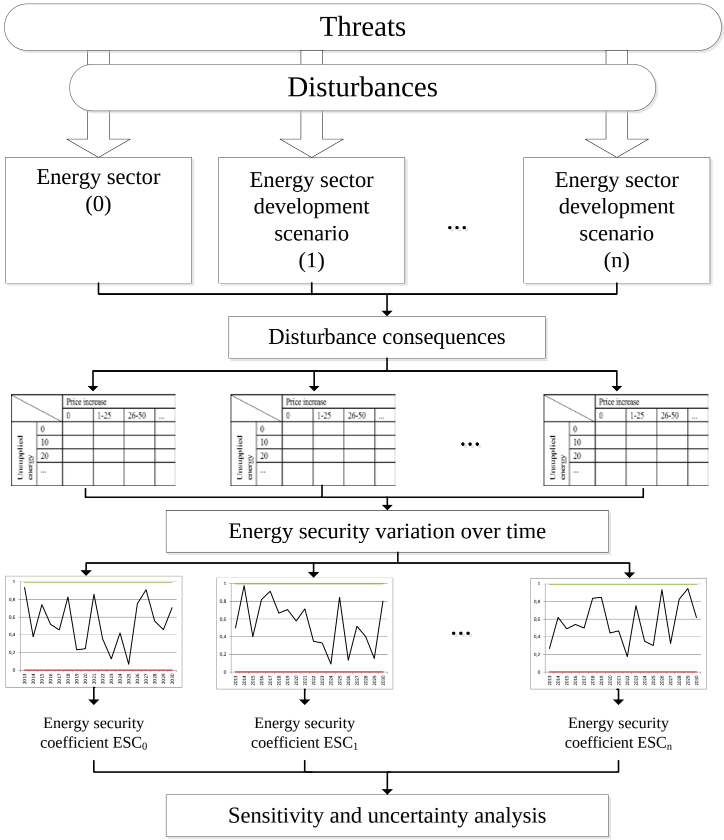


Fig. 1.2. Scheme of the methodology for the assessment of energy sector energy security and its development scenarios

The main difference compared to other existing methods is that usually optimisation-economic models of energy sector development take into account only one of the criteria – price. The developed methodology assesses not only the price impact, but also other aspects that comprehensively characterize energy security, such as potentially unsupplied energy to consumers due to unreliable supply and energy system ability to resist such disturbances.

2. ENERGY SECURITY STUDY OF THE LITHUANIAN ENERGY SECTOR

2.1. Lithuanian energy sector model

Lithuanian energy sector is the object of the study of the developed methodology for the assessment of energy security. The application of the methodology has been tested in various development scenarios of the energy sector. The whole Lithuanian energy sector consists of a number of main energy systems: electricity, heat, natural gas, petroleum products, etc. These systems are closely related, but the most important is the electricity system.

Modelling scenarios are presented in the dissertation considering all planned or already implemented development projects of the Lithuanian energy sector. The main highlight of the results is that are taken into account not only the energy costs of the development scenarios, but also energy security criteria, i.e. how energy systems in each scenario are able to resist to disturbances that occur both within the systems and outside them, but can have an impact. In such way variation over time of energy security of the Lithuanian energy sector in each scenario is assessed. The results also depend on the modelling assumptions, which in many scenarios are the same up to a certain year as in the basic scenario, but from then they vary according to the simulated scenario.

New threats to Lithuania's energy security are not identified in this work, but are used from the previous studies in this area. Threats to Lithuania's energy security are listed in the studies of LEI and VMU Energy Security Research Centre [7, 8] and other studies [9]. These threats are used in the dissertation, and in more detail will not be analysed.

The set of 500 disturbance scenarios is composed with a random generation method after disturbance occurrence from the threats probabilities and parameters of probability distributions of disturbance parameters are assessed. Lithuanian energy sector and its development scenarios are modelled with generated set of stochastic disturbances.

2.2. Modelling assumptions and analysed scenarios

Lithuanian energy sector as one region is modelled from 2013 to 2030. Electricity and heat energy systems are modelled indicating energy demand forecasts of electricity and heat in the future. Oil, natural gas and RES systems are used for fuel supply for both electricity and heat production (natural gas, fuel oil and biofuel). The time dimension is subdivided into two levels within year: seasons and time segments within a season. The modelling step is one year. The forecasts of electricity demand are based on the most probable scenario [10]. The forecasts of heat demand are based on the assumptions used in Kaunas city district heat supply strategy [11]. The forecasts of fuel and energy price are taken from the annual publications [12, 13], mentioned strategy [11] and assumptions of the session [14]. The information about the new installed capacity development and investments is received from the National Energy Independence Strategy [15]. The emissions into the environment of materials are not modelled. Discount rate is 5 %.

The development scenarios of the Lithuanian energy sector

Basic scenario. This scenario is considered as the main scenario, in which the Lithuanian energy sector is developing as it is intended until 2030. Major events and development projects in this scenario are as follows:

- 9^{th} gas fired combined cycle (CC) unit of Lithuanian Power Plant (LPP) (455 MW) in 2013.
- LNG terminal (maximum annual capacity 3,000 Mm^3) in 2015.
- LitPol Link electricity connection: 500 MW in 2015 and 1 000 MW in 2020.
- NordBalt electricity connection (700 MW) in 2016.
- RES development as projected [15] (annual additional capacities about 60 MW_{el} and 100 MW_{th}).
- The old units of LPP gradually are shut down until 2025:
  - 3^{rd} and 4^{th} units (300 MW) in 2013.
  - 1^{st} and 2^{nd} units (300 MW) in 2016.
  - 5^{th} and 6^{th} units (600 MW) in 2018.
  - 7^{th} and 8^{th} units (600 MW) in 2025.
- The old cogeneration plants in the main cities are shut down in 2025.
- Electricity import is not limited and satisfies the remaining electricity demand.

All these mentioned assumptions are the same in all analysed development scenarios and do not vary. Analysis consists of total five major development scenarios of Lithuanian energy sector including the basic scenario. The first scenario (SC1) corresponds to the basic scenario, but it is already possible disturbances affecting energy systems. In this scenario, major planned development projects as outlined above are implemented, but the majority of electricity is imported, especially after the closure of the old units of Lithuanian power plant. Since nothing new is done and energy sector is developing as the basic scenario, electricity import is dominating to meet the electricity demand in this scenario.

In the second scenario (SC2), assumptions are the same as in the basic scenario until 2023 when a new nuclear power plant starts exploitation. Share of the unit capacity and investments are considered only for Lithuania, which according to the market is 47.5 %, while capacity is 657 MW.

Installed capacity of renewable energy sources in the third scenario (SC3) in 2018 begins rapidly increasing until 2025 achieves a level that is twice higher than is predicted for that year. RES are subsidized until 2025.

In the fourth scenario (SC4), until 2018 all assumptions are the same as in the basic scenario, but this scenario is characterized by the fact that from 2018 closed old 5th and 6th units of Lithuanian power plant are replaced by a new 450 MW capacity combined cycle unit. Since 2025, the last old 7th and 8th units of LPP are replaced by the second new gas fired CC unit with the same capacity as the first case in 2018.

The fifth scenario (SC5) is characterized by the combination of SC2 and SC4 scenarios: from 2018, old 5th and 6th units of LPP are replaced by a new 450 MW capacity CC unit and in 2023, a new NPP is constructed, where capacity of the unit and investments are considered only for Lithuania share.

2.3. Analysis of the results

Variation over time of the average energy security coefficient is defined calculating average ESC in each year of the set of all disturbance scenarios in the modelling period in the development scenarios of energy sector (Fig. 2.1).

The obtained results reveal that energy security coefficient of the Lithuanian energy sector in 2013 is 0.62. The implementation of planned and under development projects would allow energy security coefficient to achieve the value of 0.83 in 2016–2017, which would be peak of the period 2013–2030. LNG terminal would have a significant impact on this offering a natural gas supply alternative to natural gas import from Russia. Furthermore, during this period (2016–2017) Lithuanian power system would have a sufficient amount of installed capacity that could even result in excess production of electricity as well as strong links with neighbouring power systems. However, most of the produced electricity of the country power plants cost would be too high to be able to compete with imported electricity price. After the implementation of the above mentioned development projects and stopping further investments in the energy sector, energy security would gradually decrease. It should be noted that until 2018, the development of the energy sector would be the same in all analysed scenarios and from 2018, the development would start vary.

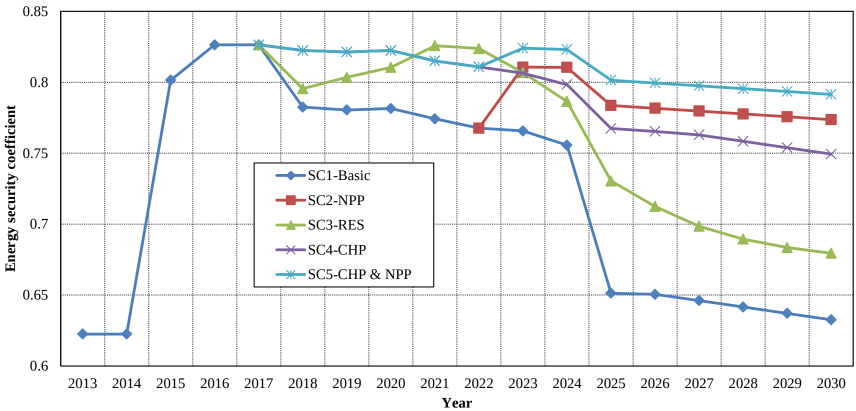


Fig. 2.1. Variation over time of energy security coefficient of the analysed Lithuanian energy sector development scenarios

In the case of the first, i.e. the basic scenario, which is characterized by electricity import, nothing doing further without investing in new technologies of the energy sector, but only meeting the electricity demand of almost the whole of it importing, would create a situation that energy security coefficient would start to fall. The first significant coefficient decrease in 2018 would be due to the 5th and 6th units of LPP end of exploitation (Fig. 2.1). Every year installing only about 60 MW of RES power plants and about 100 MW of RES for heat generation and in 2025 completely shutting down the old Lithuanian power plant units, Lithuanian ESC would be reduced to 0.65 and would be decreasing further. Very sudden drop in energy security in 2025 would be felt due to complete closure of the old LPP units and the closure of old cogeneration power plants in the main cities for the electricity production. After 2025, very dangerous situations would arise in the cases of no possibility to import electricity, which could lead to both technological and geopolitical reasons.

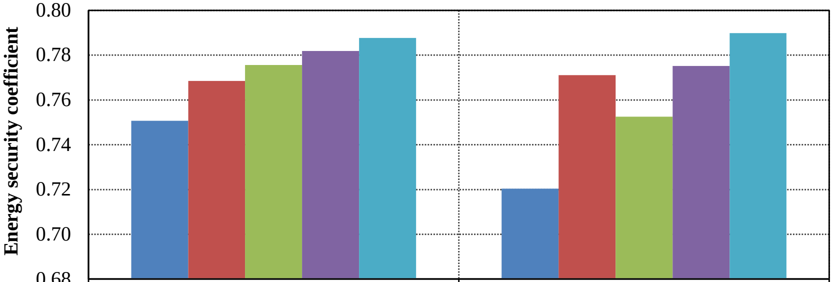
In the scenario of a new nuclear power plant, developing nuclear energy, i.e. in 2023 starting exploitation of a new nuclear power plant unit and considering a capacity share of the Lithuania about 657 MW, energy security coefficient in 2023 would rise to 0.81 (Fig. 2.1). Since 2025 completely closing the old LPP units, ESC would fall to 0.78, but unlike the first scenario, would last practically at the same level until 2030. ESC for a long time would be maintained at a similar level since the new NPP would increase the diversification of electricity generation technologies and uncertainty of forecasts of nuclear fuel price is not as high as forecasts of natural gas price.

In the case of the third, i.e. rapid development of renewable energy sources, scenario in 2018 due to the old LPP unit shutdown, energy security coefficient would not decrease as much as in SC1 due to a start of rapid development of RES in this year (Fig. 2.1). ESC in the beginning of the RES development would increase to 0.83 and when achieved its peak value in 2021 would start slowly, but from 2025 rather drastic decrease. Increasing the share of RES in energy production, ESC would further fall and in 2030 would be 0.68. That would be the lowest value of the ESC in this year of the analysed scenarios, except SC1. In SC3, the threat of monopolies in biofuel market would increase, which would reduce energy security. Once the implementations of such plans over time would be done, ESC would decrease and return Lithuania to 2013 year situation.

In the fourth, i.e. gas fired combined cycle units, scenario in 2018 closing the 5th and 6th units of Lithuanian power plant and replacing them with a new 450 MW gas fired CC unit would stop the drastic decrease in energy security coefficient, and it would remain in the interval [0.80; 0.82] until 2024 (Fig. 2.1). Since 2025 completely shut downing the last old LPP units (7th and 8th) and replacing them with a new 450 MW gas fired CC unit, ESC would fall to 0.77, but this decrease would be much less than in the case of the first scenario and ESC in 2030 would be 0.75.

In the case of the fifth scenario, in 2018 installing new CC unit instead of old LPP units, ESC would not decrease drastically and would remain between 0.81 and 0.82 until 2023. From this year starting exploitation new NPP, ESC would rise to 0.82, i.e. would return practically to the same level as it was in 2016–2017 when the ESC value was the highest. Even higher value of ESC would not be achieved due to the very significant additional investments (in this scenario). In 2025 again due to the last old LPP units’ closure ESC would fall to 0.80, but would last at a similar level (0.79) until 2030 (Fig. 2.1). This is the highest ESC value in all the analysed scenarios.

In order to compare the development scenarios with each other not only from ESC variation over time point of view, but also with one integral characteristic, an integral average ESC of the whole modelling period is calculated. After the average values of ESC in the analysed scenarios are defined, an advantage of the fifth scenario is noticed, compared to other scenarios, because the ESC value of the fifth scenario is the highest of all the modelled scenarios in the period 2013–2025 as well as in the period 2013–2030 (Fig. 2.2). These results also unfold the importance of time moment of the implementation of development project in the energy sector.



	ESC 2013–2025	ESC 2013–2030
SC1	0.751	0.720
SC2	0.769	0.771
SC3	0.776	0.753
SC4	0.782	0.775
SC5	0.788	0.790

Fig. 2.2. The comparison of energy security coefficient of the analysed Lithuanian energy sector development scenarios in different periods

2.4. Results of uncertainty and sensitivity analysis

For the energy security model of the Lithuanian energy sector uncertainty and sensitivity analysis was carried out for the external disturbance parameters of the model. Probability distributions of the ESC values are assessed for each year in the modelling period. ESC 90 % level confidence interval limits each year over time are also defined. Such confidence level is chosen because the confidence interval would not be excessively wide.

Level of the confidence interval defines the probability of real value of ESC falling into this interval. It is important to emphasize that the disturbance parameters are time-dependent and their variance over time is changing (usually increasing). Due to this reason uncertainty of the disturbance parameters is increasing over time and the confident interval of the ESC values is widening every year. The analysis of ESC and its uncertainty variation over time in all five development scenarios revealed that during the period of 2015–2025 scatter of the ESC values is less due to the implementation of the development projects in the Lithuanian energy sector.

Not only variation of ESC uncertainty over time, but also uncertainty of the final scenario result is important, i.e. uncertainty of average ESC, which is calculated for a particular period. Model basic uncertainty analysis statistical characteristics of all five development scenarios during two analysed periods are presented in Table 2.1.

Table 2.1. Basic statistical characteristics of the uncertainty analysis of the analysed scenarios in different periods

Period	Scenario	Min	Max	Mean	Standard deviation	0.90 level confidence interval limits
2013–2025	SC1	0.5466	0.8755	0.7506	0.0545	Upper: 0.7785 Lower: 0.7298
	SC2	0.5610	0.8772	0.7685	0.0498	Upper: 0.7943 Lower: 0.7483
	SC3	0.5555	0.8832	0.7756	0.0500	Upper: 0.8009 Lower: 0.7555
	SC4	0.5917	0.8713	0.7818	0.0492	Upper: 0.8051 Lower: 0.7614
	SC5	0.5943	0.8731	0.7877	0.0487	Upper: 0.8106 Lower: 0.7673
2013–2030	SC1	0.5519	0.8519	0.7204	0.0567	Upper: 0.7561 Lower: 0.6928
	SC2	0.6221	0.8760	0.7711	0.0498	Upper: 0.8010 Lower: 0.7463
	SC3	0.5888	0.8847	0.7525	0.0480	Upper: 0.7866 Lower: 0.7275
	SC4	0.5738	0.8628	0.7752	0.0427	Upper: 0.8031 Lower: 0.7503
	SC5	0.6503	0.8725	0.7899	0.0403	Upper: 0.8170 Lower: 0.7650

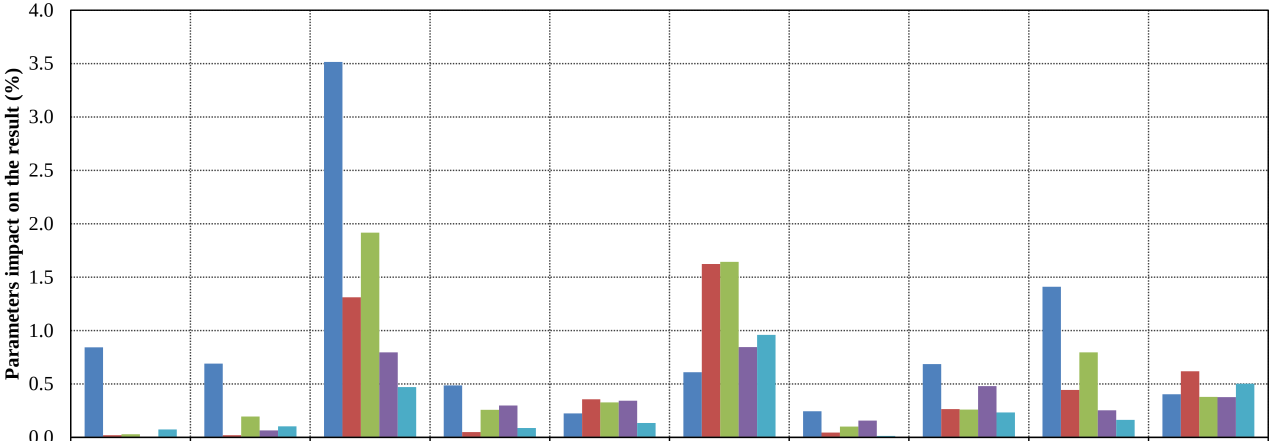
The obtained results reveal that in the fifth scenario uncertainty impact on the results of disturbance parameters is the lowest in both periods, because the ESC value change interval is narrowest and in addition, the standard deviation is the lowest of all analysed scenarios. In order to determine which model external disturbance parameters have the highest impact on uncertainty of energy security coefficient, sensitivity analysis of the parameters is performed. Additional model calculations with different sets of parameter combinations are carried out. In order to perform sensitivity analysis it is necessary to select the most important disturbance parameters that potentially have the highest impact on the model result. In the case of energy security investigation of the Lithuanian energy sector ten disturbance parameters, which can have the highest impact on ESC, were selected by the expert method. The main characteristics of these parameters of each development scenario are presented in Table 2.2.

Table 2.2. The most important disturbance parameters used in the sensitivity analysis

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Parameter</th><th colspan="3">Period</th></tr>
<tr><th>SC1</th><th>SC2</th><th>SC3–SC5</th></tr>
<tr><td>1</td><td>Natural gas supply from the East</td><td rowspan="6">2013–2030</td><td rowspan="10">2023–2030</td><td rowspan="10">2018–2030</td></tr>
<tr><td>2</td><td>Natural gas price from the East</td></tr>
<tr><td>3</td><td>Electricity import from the East</td></tr>
<tr><td>4</td><td>Electricity import price from the East</td></tr>
<tr><td>5</td><td>Biofuel supply</td></tr>
<tr><td>6</td><td>Biofuel price</td></tr>
<tr><td>7</td><td>Natural gas supply from LNG terminal</td><td rowspan="2">2015–2030</td></tr>
<tr><td>8</td><td>Natural gas price from LNG terminal</td></tr>
<tr><td>9</td><td>Electricity import through NordBalt connection</td><td rowspan="2">2016–2030</td></tr>
<tr><td>10</td><td>Electricity import price through NordBalt connection</td></tr>
</table>

In order to determine the impact of each disturbance parameter on the result (ESC), parameter quantitative sensitivity analysis was performed. Each initial reference values of all ten parameters were increased by 20 % and the parameter impact on the result was defined in percentage.

Parameters sensitivity analysis of the energy security model of the development scenarios of the Lithuanian energy sector revealed that in the first scenario, the highest impact on energy security coefficient has the third parameter – deviation of electricity import from the East (Fig. 2.3). This parameter also in other scenarios is one of the dominants. Electricity import through NordBalt connection also has a significant impact on ESC in SC1. Obviously, in SC1, where electricity import is dominating in satisfying electricity demand, the highest impact on energy security have exactly parameters that are associated with imported electricity. Biofuel price parameter has the highest impact on the result uncertainty in SC2 and SC3. This is due to the increase of RES share in the total energy balance and production. In SC2 and SC5 scenarios, the highest impact having parameters are more related to energy prices rather than energy supply. It is because disruptions of supply (import) due to disturbances would become not so sensitive as in the power system would be installed new sources of electricity production. Parameters, related to the natural gas import and the price, have higher impact only in the first scenario and a scenario of electricity production in new gas fired CC units (SC4). The impact of uncertain parameters on the result is the lowest in SC5 of all analysed development scenarios.



	Natural gas supply from the East	Natural gas price from the East	Electricity import from the East	Electricity import price from the East	Biofuel supply	Biofuel price	Natural gas supply from LNG terminal	Natural gas price from LNG terminal	Electricity import through NordBalt connection	Electricity import price through NordBalt connection
SC1	0.84	0.69	3.52	0.49	0.23	0.61	0.24	0.69	1.41	0.40
SC2	0.02	0.02	1.31	0.05	0.36	1.62	0.04	0.26	0.44	0.62
SC3	0.03	0.19	1.92	0.26	0.33	1.64	0.10	0.26	0.80	0.38
SC4	0.00	0.07	0.79	0.30	0.34	0.85	0.16	0.48	0.25	0.38
SC5	0.07	0.10	0.47	0.09	0.14	0.96	0.01	0.23	0.16	0.50

Fig. 2.3. Sensitivity comparison of the most important disturbance parameters in the Lithuanian energy sector development scenarios

It is also important that the impact of the parameters is changing over time.

Impact variation on the result over time of parameters having the highest impact in each development scenario is presented in Fig. 2.4.

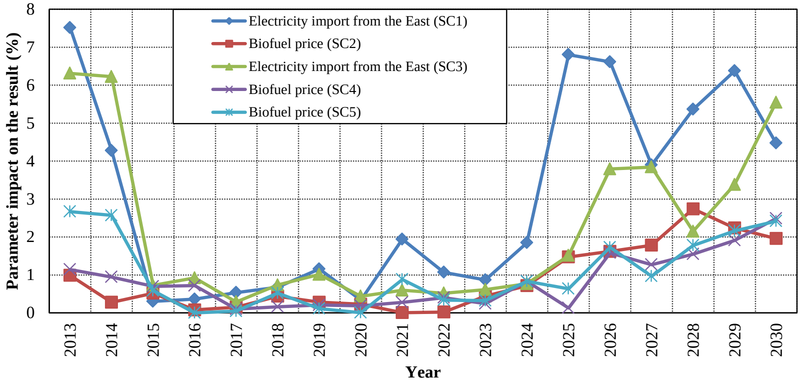


Fig. 2.4. Impact variation on the result over time of parameters having the highest impact in analysed scenarios in 2013–2030

The comparison of analysed scenarios reveals that the highest parameter impact on the result over time is until 2015 and from 2025. This is due to the implementation of new development projects in the energy sector and the closure of old LPP units.

The impact of the parameters can be assessed by ranks for easier comparison of uncertain parameter sensitivity on the modelling results in all development scenarios. The numerical value of the rank is lower, the parameter rank is higher, and this parameter has higher impact on the modelling result. The comparison of sensitivity of the most important parameters of the analysed development scenarios is presented in Table 2.3. Results reveal that the assessment of average rank of each parameter in all development scenarios gives the highest impact of parameters associated with electricity import from the East (average rank is 1.8) and biofuel price (average rank is 2.2). Electricity import through NordBalt connection and imported electricity price parameters (both average rank is 4.2) also have a significant impact on energy security coefficient, but it is more than two times lower than the parameter with the highest impact on the result.

Sensitivity analysis on energy security of the Lithuanian energy sector pointed out that in order to reduce the uncertainty of energy security coefficient it is necessary to increase the accuracy of the disturbance parameters related to electricity import and fuel prices.

Table 2.3. The comparison of parameters sensitivity analysis of the analysed development scenarios

Parameter	**Scenario**										Average rank
	SC1		**SC2**		**SC3**		**SC4**		**SC5**		
	Impact %	Rank	Impact %	Rank	Impact %	Rank	Impact %	Rank	Impact %	Rank	
Natural gas supply from the East	0.84	3	0.02	10	0.03	10	0.001	10	0.07	9	8.4
Natural gas price from the East	0.69	4	0.02	9	0.19	8	0.07	9	0.10	7	7.4
Electricity import from the East	3.52	1	1.31	2	1.92	1	0.79	2	0.47	3	1.8
Electricity import price from the East	0.49	7	0.05	7	0.26	7	0.30	6	0.09	8	7
Biofuel supply	0.23	10	0.36	5	0.33	5	0.34	5	0.14	6	6.2
Biofuel price	0.61	6	1.62	1	1.64	2	0.85	1	0.96	1	2.2
Natural gas supply from LNG terminal	0.24	9	0.04	8	0.10	9	0.16	8	0.01	10	8.8
Natural gas price from LNG terminal	0.69	5	0.26	6	0.26	6	0.48	3	0.23	4	4.8
Electricity import through NordBalt connection	1.41	2	0.44	4	0.80	3	0.25	7	0.16	5	4.2
Electricity import price through NordBalt connection	0.40	8	0.62	3	0.38	4	0.38	4	0.50	2	4.2
Total	9.12		4.75		5.91		3.61		2.74		

CONCLUSIONS

New methodology for the assessment of the energy sector energy security, which consists of the probabilistic model of energy systems threats realisation to disturbances, economic-optimisation model of energy sector development and energy security metric, is presented in the dissertation. The application of the developed methodology was carried out to assess energy security coefficient (scale from 0 to 1) of the Lithuanian energy sector with a number of various development scenarios. The first – characterized by the dominant electricity import, the second – an operation of the new nuclear power plant, the third – rapid development of renewable energy sources, the fourth – gradual change of the old units of Lithuanian power plant with the new combined cycle units, the fifth – involves both the new combined cycle unit instead of the old units of Lithuanian power plant and the new nuclear power plant. The performed investigation leads to the following conclusions:

1. Probabilistic model of threats realisation to disturbances enabling to assess probabilistic characteristics of disturbance parameters is developed, and it has been found that in the case of the Lithuanian energy sector, the highest impact on energy security have electricity and natural gas import decrease and their price increase disturbances.
2. The application of the created methodology and metric for the assessment of energy security enables more accurate evaluation and measurement of current energy security of the energy sector, its variation over time and the comparison of various development scenarios of the energy sector from the energy security point of view.
3. Performed energy security study of the Lithuanian energy sector revealed that energy security coefficient in 2013 was 0.62 and after the implementation of development projects (LNG terminal, NordBalt and LitPol Link electricity connections, the development of RES) in 2016–2017 energy security coefficient would achieve the value of 0.83.
4. Energy security assessment and comparison of the Lithuanian energy sector development scenarios revealed that in 2030 in the first scenario energy security coefficient would be 0.63 (1 % higher than in 2013), in the second – 0.77 (15 % higher), in the third – 0.68 (6 % higher), in the fourth – 0.75 (13 % higher) and in the fifth – 0.79 (17 % higher).
5. Performed uncertainty and sensitivity analysis revealed that energy security coefficient of the Lithuanian energy sector development scenarios is not sensitive to uncertainties of the model parameters (the difference between the lower and upper limits of the average 90 % level confidence interval is approximately 5 %) and the highest impact on uncertainty of energy security coefficient have electricity import from the East countries and biofuel price parameters.

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1. Augutis, Juozas; Krikštolaitis, Ričardas; Martišauskas, Linas; Pečiulytė, Sigita. Energy security level assessment technology // Applied Energy. Amsterdam, Netherlands : Elsevier. ISSN 0306-2619. 2012, Vol. 97, spec. iss., p. 143–149. [Science Citation Index Expanded (Web of Science)].

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REZIUMĖ

Darbo aktualumas. Pakankamas energijos tiekimo saugumo lygis yra gyvybiškai svarbus ekonomikai funkcionuoti ir yra vienas pagrindinių valstybės saugumo garantų, nes pramonės veiklai užtikrinti, gyventojų poreikiams patenkinti reikalingas patikimas energijos tiekimas. Šiuo metu Lietuva importuoja pagrindinius energijos išteklius ir praktiškai 80 % energetiškai priklauso nuo vienos šalies tiekėjos. Norint Lietuvoje pagerinti energetinį saugumą, reikia plėtoti energetikos sektorių, tačiau energetikos plėtros sprendimai yra priimami atsižvelgiant ne tik į techninius ir ekonominius parametrus, bet ir į sociopolitinius ir geopolitinius aspektus. Todėl turi būti sukurti metodai, leidžiantys vienu metu atsižvelgti į nurodytus apribojimus ir taip pat vertinti sprendimų priėmėjų naudojamus argumentus, kurių priėmimas turi būti pagrįstas įvairių scenarijų modeliavimo rezultatais ir optimizaciniais skaičiavimais.

Šiuo metu pasaulyje taikomi energetinio saugumo vertinimo metodai yra arba tik deterministiniai, arba tik stochastiniai, o energetinis saugumas savo prigimtimi yra procesas, apimantis vienu metu abi šias savybes. Todėl moksline prasme yra didelis poreikis sukurti energetinio saugumo vertinimo ir analizės priemones, jungiančias deterministinius ir stochastinius procesus į vieną visumą, kad būtų galima įvertinti energetinį saugumą daugeliu aspektų vienu metu.

Darbo tikslas. Sukurti energetikos sistemų trikdžių modeliavimo ir energetinio saugumo tyrimo metodiką bei atlikti Lietuvos energetikos sektoriaus energetinio saugumo analizę.

Darbo uždaviniai. Darbo tikslui pasiekti suformuluoti šie uždaviniai:

1. Sudaryti energetinio saugumo grėsmių realizavimosi į trikdžius ir jų parametrų tikimybinį modelį;

2. Sukurti energetinio saugumo metriką (matavimo ir vertinimo metodiką) ir energetikos sistemų trikdžių įtakos energetiniam saugumui vertinimo modelį;
3. Įvertinti Lietuvos energetikos sektoriaus sistemų plėtros scenarijų esamą energetinį saugumą ir jo kitimą bėgant laikui bei palyginti scenarijus energetinio saugumo prasme;
4. Atlikti modelio rezultatų neapibrėžtumo ir parametrų jautrumo analizę.

Mokslinis darbo naujumas. Sukurta nauja energetinio saugumo vertinimo metodika, sujungianti deterministinius ekonominius-optimizacinius energetikos sistemų modeliavimo metodus, tikimybinius trikdžių susiformavimo vertinimo metodus ir ekspertinius grėsmių vertinimo būdus. Taikant sukurtą metodiką energetikos sektoriaus perspektyvinę plėtrą galima modeliuoti su stochastiniais trikdžiais ir tiksliau nustatyti energetinį saugumą. Darbo rezultatai ir sukurtos mokslo žinios papildo energetinio saugumo teoriją naujais metodais ir modeliais.

Praktinė darbo vertė. Sukurta metodika leidžia įvertinti esamą energetikos sektoriaus energetinį saugumą, palyginti įvairių energetikos sektoriaus plėtros scenarijų įtaką energetiniam saugumui bei nustatyti optimalų plėtros scenarijų pagal energetinio saugumo kriterijus. Pasiūlytas naujas energetinio saugumo nustatymo rodiklis – energetinio saugumo koeficientas, leidžiantis kiekybiškai įvertinti energetinį saugumą. Metodikos pritaikymas atliktas Lietuvos energetikos sektoriui ir įvertintas energetinio saugumo kitimas iki 2030 m. bei palyginta Lietuvos energetikos sektoriaus įvairių plėtros scenarijų įtaka energetiniam saugumui. Naudojantis atliktų mokslinių tyrimų rezultatais pateiktos rekomendacijos ir pasiūlymai, kokių priemonių reikia imtis energetiniam saugumui pagerinti.

Ginamieji disertacijos teiginiai:

1. Sudarytas energetinio saugumo grėsmių realizavimosi į trikdžius tikimybinis modelis leidžia įvertinti energetinį saugumą įtakojančių trikdžių tikimybinius parametrus;
2. Sukurta energetinio saugumo vertinimo metodika ir metrika leidžia įvertinti ir nustatyti energetikos sistemų esamą energetinį saugumą, jo kitimą bėgant laikui bei palyginti įvairius energetikos sektoriaus plėtros scenarijus energetinio saugumo prasme;
3. Lietuvos energetikos sektoriaus sistemų plėtros scenarijų, pagrįstų įvairiomis energijos gamybos technologijomis, energetinis saugumas skiriasi ir priklauso nuo energijos gamybos ir importo proporcijų.

Darbo aprobavimas. Disertacinio darbo tema paskelbta viena publikacija mokslinės informacijos instituto duomenų bazės „ISI Web of Science“ leidinyje, turinčiame citavimo indeksą, ir viena publikacija kitų tarptautinių duomenų bazių leidinyje. Tyrimų rezultatai pristatyti 10 tarptautinių konferencijų.

Darbo apimtis ir struktūra. Disertaciją sudaro įvadas, trys pagrindiniai skyriai, apimantys literatūros apžvalgą, metodologiją ir atliktų tyrimų rezultatus, bei išvados. Disertacijos apimtis 116 puslapių (be priedų), juose 32 paveikslai, 12 lentelių, 165 cituojamų literatūros šaltinių ir mokslinių publikacijų disertacijos tema sąrašai.

IŠVADOS

Disertacijoje pristatyta nauja energetikos sektoriaus energetinio saugumo vertinimo metodika, susidedanti iš energetikos sistemų grėsmių ir trikdžių susiformavimo tikimybinio modelio, energetikos sistemų plėtros ekonominio-optimizacinio modelio ir energetinio saugumo metrikos. Metodika pritaikyta Lietuvos energetikos sektoriui, įvertinant jo energetinio saugumo koeficientą (skalė nuo 0 iki 1) įvairiais plėtros scenarijais. Pirmasis – pasižymi vyraujančiu elektros energijos importu, antrasis – naujos atominės elektrinės darbu, trečiasis – itin sparčia atsinaujinančių energijos išteklių plėtra, ketvirtasis – senųjų Lietuvos elektrinės blokų laipsnišku pakeitimu naujais kombinuotojo ciklo blokais, penktasis – apima tiek naują kombinuotojo ciklo bloką vietoj senųjų Lietuvos elektrinės blokų, tiek naują atominę elektrinę. Atliktų mokslinių tyrimų pagrindu galima daryti šias išvadas:

1. Sudarytas grėsmių realizavimosi į trikdžius tikimybinis modelis, leidžiantis įvertinti trikdžių parametrų tikimybines charakteristikas ir nustatyta, kad Lietuvos energetikos sektoriaus atveju didžiausią įtaką energetiniam saugumui turi elektros energijos ir gamtinių dujų importo sumažėjimo ir jų kainų padidėjimo trikdžiai.
2. Taikant sukurtą energetinio saugumo tyrimo metodiką ir metriką galima tiksliau įvertinti ir nustatyti energetikos sektoriaus esamą energetinį saugumą, jo kitimą bėgant laikui bei palyginti įvairius energetikos sektoriaus sistemų plėtros scenarijus energetinio saugumo prasme.
3. Atlikus Lietuvos energetikos sektoriaus energetinio saugumo tyrimą nustatyta, kad energetinio saugumo koeficientas 2013 m. buvo 0,62 ir įgyvendinus vykdomus plėtros projektus (SGD terminalas, NordBalt ir LitPol Link elektros jungtys, AEI plėtra) 2016–2017 m. energetinio saugumo koeficientas pasiektų 0,83 reikšmę.
4. Lietuvos energetikos sektoriaus plėtros scenarijų energetinio saugumo įvertinimas ir palyginimas parodė, kad 2030 m. pirmajame scenarijuje energetinio saugumo koeficientas būtų 0,63 (1 % didesnis nei 2013 m.), antrajame – 0,77 (15 % didesnis), trečiajame – 0,68 (6 % didesnis), ketvirtajame – 0,75 (13 % didesnis) ir penktajame – 0,79 (17 %

didesnis).

5. Atlikus rezultatų neapibrėžtumo ir parametrų jautrumo analizę nustatyta, kad Lietuvos energetikos sektoriaus plėtros scenarijų energetinio saugumo koeficientas nėra jautrus modelio parametrų neapibrėžtumams (skirtumas tarp vidutinio 90 % lygmens pasikliautinojo intervalo apatinės ir viršutinės ribų yra apie 5 %), o didžiausią įtaką energetinio saugumo koeficiento neapibrėžtumui turi elektros importo iš Rytų šalių ir biokuro kainos parametrai.

UDK 620.9 (043.3)

SL344. 2014-07-09, 2,5 leidyb. apsk. l. Tiražas 60 egz. Užsakymas 401.
Išleido leidykla „Technologija“, Studentų g. 54, 51424 Kaunas
Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, 51424 Kaunas