BENAS JOKŠAS

THE CRITICALITY ASSESSMENT OF ENERGY SYSTEMS CRITICAL INFRASTRUCTURE

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES, ENERGETICS AND POWER ENGINEERING (06T)

Kaunas
2015

KAUNAS UNIVERSITY OF TECHNOLOGY

LITHUANIAN ENERGY INSTITUTE

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INTRODUCTION

The economic and national security of the country is closely related to the effective functioning of the infrastructures that are interrelated accordingly and are closely dependent on each other on both the regional (domestic) and national scale. The objects of critical infrastructures (CI) are defined as public sector systems (elements), such as electricity systems, gas/oil systems, transportation systems, communication systems, and etc. that ensure the physical integrity of the country, energy security and economic stability. Since almost all sectors of the economy (industry, transport, agriculture, and other sectors), and social development of the country are directly or indirectly dependent on the import of sustainable energy, transportation, manufacturing and export, more and more attention is given to the problems of country energy critical infrastructure object protection. It is impossible to ensure the economic and social development or an acceptable political level of energy balance when the country's energy infrastructures are vulnerable and at risk, as their functional disturbance or disruption would endanger or cause damage to national security. The issues of evaluation and security of critical energy infrastructures have become one of the most urgent for all, large and small, countries of the world. In the process of analysis of critical energy infrastructures of the country, it is important to assess the interdependence among the elements of infrastructures and their criticality in respect to individual systems and countries. Such evaluation is important for the determination of the location in the infrastructure, which requires higher reliability and/or security. Therefore, critical energy infrastructures are defined as complex networked systems, where the elements of individual systems are connected (peer relationships) into a single networked system.

The European Commission's Green Paper on the *European Programme for Critical Infrastructure Protection* (European Commission, 2005) is a common reference for critical infrastructure list and a guideline for member countries, which regards the comparison and appointed priorities of critical infrastructures.

Accordingly, as all European Union countries, Lithuania has taken up the evaluation of national infrastructure and released a resolution by Lithuanian Government enacted on June 7th, 2010 (No. 717) on *The Approval of the Procedure for Recognition of Objects as National Significance Objects*. Also in Lithuania, NATO *Energy Security Centre of Excellence* is active in the evaluation of issues related to energy critical infrastructures and energy security.

There are quite a few scientific studies in the area of energy critical infrastructure evaluation; however, there are no universally accepted criteria or methodologies that would enable the quantification of the criticality of the country's critical energy infrastructure. Conducted research in different countries used separate (different) methods of evaluation. Nevertheless, many of these studies and the material are confidential, and the information related to critical infrastructure evaluation and protection is sensitive. The available research publications that usually provide evaluation methods for hypothetical systems, allow formulating the following critical energy infrastructure evaluation topics:

- Modeling and evaluation of infrastructure interrelations;
- Risk analysis of infrastructure systems;
- Identification and evaluation of critical infrastructures;
- Identification and evaluation of system infrastructure critical objects.

One of the main objectives in the evaluation of critical energy infrastructure is the identification of infrastructure critical items according to various evaluation criteria, such as peer relationships in the systems, the technical characteristics of the system infrastructure elements (capacity, reliability, etc.) and functional dependencies, as well as the influence of an impact regarding a country, a system, etc.

It is necessary to create the models of identification of critical elements in the energy infrastructure that allow the identification of critical infrastructures, their elements or groups of elements in the country’s energy system and the evaluation of the influence of these elements or their groups on consumers (the consumer can also be defined as different energy sector systems). The evaluation of the criticality of these elements or groups must be carried out with the regard of the integral energy systems as a whole taking into account random operation of the systems. The developed evaluation model would allow to assess the criticality of the country’s energy infrastructure, to compare the impact of various energy sector development projects on integrity and functionality of the country’s energy infrastructure, to identify critical elements of the energy infrastructure in the light of the actual functioning of the system (performance), and to compare the criticality of energy infrastructures in different countries.

The relevance of the research. In order to ensure economic and national security and development of the country, it is essential to ensure the integrity and functionality of the energy infrastructure.

As the country’s industrial development activities, the assurance of social essential functions, maintenance of safety and economic and social well-being is strongly dependent on appropriate (sustainable) functioning of the energy systems, which is especially true for countries such as Lithuania that imports most of its energy resources from one country.

Most of the existing energy critical infrastructure assessment models employ separate methods for the analysis of vulnerability and risk. The latter are at best deterministic models that deal with the impact of several infrastructures only fragmentarily. Other evaluation models only analyze interrelationships among infrastructures. Therefore, the problem of assessing the criticality of the country’s energy infrastructure is particularly relevant and, thus, it is necessary to evaluate not only the individual elements of the technical infrastructure indicators, but also take into account the integral of energy systems as a whole, and the existing within the infrastructures functional dependencies and influence on the consumers. This would allow assessing the criticality of the country's energy infrastructure in many aspects at the same time (that combines the methods of evaluation of the risks of energy systems, optimization modeling and functionality).

The relevance of the research is also foregrounded by the fact that the European Union (EU) members are obliged to perform the evaluation of criticality and to assure protection of the objects of critical infrastructures (CIO) according to the European Commission (EC) Council Directive 2008/114/EC on the *Identification and Accreditation of European Critical Infrastructure Objects and the Necessity to Improve their Protection*. EC Council Directive is one of the leading programmes that defines the most important areas to concentrate all efforts for the infrastructure prevention and protection. Also the creation and development of the methods for critical infrastructure evaluation is included in the Horizon 2020 directions. In Lithuania, NATO *Energy Security Centre of Excellence* is also active in the area of energy critical infrastructure evaluation and protection. Therefore, the dissertation research is relevant both practically and scientifically.

The aim of the research. To develop the methodology for the study of energy system infrastructure criticality and to investigate the criticality of Lithuanian energy system infrastructure.

The objectives of the research. To achieve the aim of the research the following objectives have been formulated:

1. To create a methodology for the measurement of functionality and criticality of energy system infrastructure.
2. To develop a mathematical evaluation model for the functionality and criticality of energy system infrastructure.
3. To apply the developed evaluation methodology for the evaluation of Lithuanian energy system infrastructure criticality.
4. To evaluate the impact of energy infrastructure scenarios on the criticality of energy systems.

Research novelty. This dissertation research helped to develop a new evaluation methodology of energy infrastructure systems criticality, which for the first time takes into account the interrelationships among the elements of the systems, the reliability, the risk, and random operation of the systems. The evaluation of criticality is carried out as regarded by the consumers.

The developed methodology and models helped to identify the Lithuanian energy system infrastructure elements (and their groups) that have the highest criticality for energy systems.

The designed methodology and models for the evaluation of criticality of critical energy infrastructures allow complete identification of the critical elements and their groups of the systems that have the highest criticality for energy systems, taking into account the random operation of the entire system.

The findings of the research complement the critical infrastructure (energy system) evaluation and modeling theory with new methods.

Practical significance of the research findings. The research findings allow to evaluate the criticality of energy infrastructure systems and to compare the impact of different energy development scenarios on infrastructure criticality. This allows determining the most critical elements of the energy infrastructure, as well as the interference processes in energy systems caused by these elements. On the basis of the findings, the criticality of Lithuanian energy system was evaluated, groups of critical elements were identified, and the impact of gas development scenarios on the criticality of energy systems was evaluated. The results obtained will contribute to the obligations of Lithuania to the implementation of EU Directive 2008/114 / EC.

Defended claims of the dissertation research:

- The creation of the evaluation methodology for the criticality of energy system critical infrastructures allows to identify the most critical elements of the systems according to their impact on consumers' energy needs, taking into account random operation of the systems.
- The reliability of energy system elements affects the criticality of separate elements and their groups.
- The logistic regression model is appropriate to assess the probability distribution of infrastructure elements or groups criticality.
- Additional natural gas supply system connectors reduce the criticality of both the electrical and the district heat systems.

Research approval. The topic of the dissertation was approved by a publication in the journal referred in Thomson Reuters "Web of Knowledge" database with citation index, and a publication in the journal of Thomson Reuters "Web of Knowledge" database without citation index. Study results were presented at six international conferences.

Research scope and structure. The dissertation consists of the introduction, three main chapters that include literature review, methodology, research findings, and conclusions. The scope of the dissertation is 113 pages (without annexes), including 35 figures, 12 tables, and the list of 115 referred to scientific literature sources and scientific publications relevant to the researched topic.

1. METHODOLOGY FOR THE ASSESSMENT OF THE FUNCTIONALITY AND CRITICALITY OF INFRASTRUCTURE ELEMENTS

In order to identify the critical elements of the infrastructure of energy system, a methodology has to be developed, which takes into account the reliability of the elements of the infrastructure and that will allow identifying the critical infrastructure elements in relation to the satisfaction of energy demands of the end consumer. This dissertation proposes to use criticality of the infrastructure element as a measure to assess the importance of considered element to the normal activity of all sectors of the infrastructure.

Energy sector is considered one of the most complicated due to complicated configuration and automatic generation control among all systems. The connections among systems are both physical, e.g., state electricity supply network connected with generation sources and regions distribution networks, and functional, such as thermal power plant, which connects gas-pipe, district heating network and electricity supply network, by transforming primary energy (e.g., natural gas) into heat and electricity, which is supplied to consumers. Also among energy systems, there exist reversible connections, such as natural gas supply to power plants so that electricity would be produced, which is correspondingly needed for proper functioning of natural gas transmission system.

The aim of energy system infrastructure criticality assessment is to assess criticality of each infrastructure element, which is based on simulating basic energy branches (electricity and heat, fuel) supply according to demand of the consumers. Therefore, according to element criticality, the existing connections among energy systems are estimated as well. For this purpose, in the assessment model system, infrastructures are decomposed at object level. Thus depending on system infrastructure decomposition particularity, the *N-th* element set may be possessed in the assessment model. Let us mark it as $\mathcal{K}:\{z_1, z_2, z_3, ..., z_N\}$.

Most often energy system connections are depicted as network systems (Fig. 1.1). The relations among the same infrastructure elements and different energy system infrastructure elements are expressed via element functionality with each other.

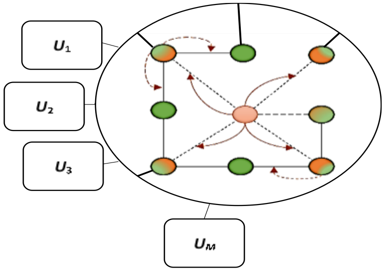

Fig. 1.1. Network model of the energy sector (U_M – M th consumer)

The elements of set consisting of *N-th* elements are composed of an object of gas supply network (main fuel for generation technologies), district heat generation technologies (combined heat and power plants with back-pressure units, boiler houses, biofuel boiler houses), power generation technologies (CHP with extraction units, hydro power plant, and wind power plants) and final consumers for heat and electricity in the developed mixed energy systems infrastructure model.

The elements of *N* mates set developed model analyses mixed energy systems infrastructure composed of gas supply network (main fuel for generation technologies), district heat generation technologies (combined heat and power plants with back-pressure units, boiler houses, biofuel boiler houses), power generation technologies (combined heat and power plant with extraction units, hydro power plant, and wind power plants) and final consumers for heat and electricity. The scheme of the model is presented in Fig. 1.2.

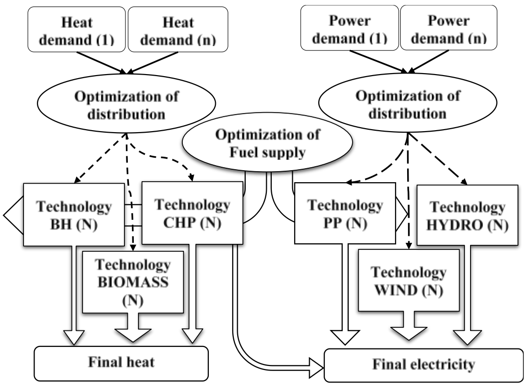

Fig. 1.2. Energy infrastructure model

The simulation of energy generation technologies was implemented by functional dependency in the model. The generation technology is depended on the availability rate, provided fuel type, installed capacity, efficiencies (which convert the primary energy), etc. All generation technologies are simulated by input-output method. Gas supply network is represented as a graph:

$$G = (\mathcal{V}, \mathcal{B}),\ \mathcal{V} = V_{FN} \cup V_{CN} \text{, there } V_{FN} \cap V_{CN} = \varnothing \text{,} \tag{1.1}$$

where V_{FN} – set of the final pipeline nodes of graph; V_{CN} – set of the pipeline connection nodes in graph; $\mathcal{B}$ – set of the edges (edge represents physical pipelines), which connect nodes $\mathcal{V}$.

The mathematical optimization model (optimization of maximum flow with goal programming) is used to simulate gas supply system. One of the model aims is to maximize the satisfaction of consumer demands. The maximum flow optimization method was used to achieve this goal. Simplex method of linear programming was used to find the maximum flow in the pipeline network. This mathematical model allows evaluating the quantities of supplied gas to the final nodes (consumers). Also the demands of heat and electricity are allocated for generation technologies by the Simplex optimization method. The optimization is performed to maximize energy generation in each of the analysed cities. This mathematical model allows distributing local heat demand to local generation technologies with the regard of the economic aspect. Preference is given to technologies using renewable energy sources (hydro power plants, wind power plants, etc.).

The created new methodology for the criticality assessment for energy infrastructure is presented in detail in this Section.

1.1. The criticality assessment of infrastructure elements

A critical infrastructure element will be defined as the functional activity of the element of infrastructure is fully stopped (the element is out of order), and the adaptive energy system is not working properly by the disruption, it means, that the consumers' energy demands are not satisfied (partially satisfied). The criticality of the k^{th} element may be estimated using the reliability indicators of final consumers obtained in case when k^{th} element is out of order. The weighted coefficient of the i^{th} final consumer within system (for instance, weighted coefficients are estimated with the regard of the energy demand of consumer, and they satisfy equality $\beta_1 + \ldots + \beta_M = 1$:

$$\beta_i(t) = \frac{V_i(t)}{\sum_{j=1}^{M} V_j(t)}, \tag{1.2}$$

here $V_i(t)$ – the demand of energy (MWh) of i^{th} final consumer within system, at the moment t; M – number of the final consumers in the energy system.

In general case, k-th infrastructure element criticality, per time unit, with moment t with respect to end users could be estimated according to expression:

$$c^k(t) = \left(1 - \sum_{i=1}^{M} \frac{S_i^k(t)}{V_i(t)}\right) \beta_i(t)\text{, } 0 \le c^k(t) \le 1, \tag{1.3}$$

here $S_i^k(t)$ – *i-th* consumer supplied energy amount (MWh) per time unit in the system after turning off the *k-th* element at the moment t; N – number of the elements in the energy system.

The system element criticality value is from interval [0; 1]. For example, $c^k(t) = 1$ means that disruption of the k^{th} element work stops the operation of all energy infrastructure at time moment t; let us assume the element criticality $c^k(t) = 0.35$, this means that at time moment t after disruption of *k-th* element operation, the demands of end users are not ensured by 35 % from the point of view of the analysed system.

In order to identify critical elements of energy system infrastructure in the primary selection part, the assessment of criticality of each infrastructure element should be carried out with the regard of the deterministic system, the assessment of such system elements is not conservative. However, a simple method application enables to quickly identify critical system elements with the regard of consumers. In the case of assessment of deterministic elements, an assumption is considered that infrastructure elements are completely reliable, i.e., their breakdown probabilities $p_i = 0$. The assessment of element criticality is carried out artificially after removing each of infrastructure elements according to principle N-1, N-2 and N-3.

1.2. The deterministic criticality assessment model for elements of energy system infrastructure

The deterministic criticality assessment model analysed separate elements of energy system infrastructure. This model does not assess the reliability of infrastructure. The assessment was performed with the assumption that only one element is out of order (ex. k^{th} element) and other elements of the infrastructure are functioning reliably.

After estimating criticality of each infrastructure element, their criticality set $\mathbb{C}_\tau^1$ (1.5 formula) is constructed. Since critical infrastructure element is selected, the criticality of such element with the regard of system end users is higher than the selected criticality level τ (when, $0 < \tau \leq 1$).

$$c^k(t) \geq \tau\,,\ k = 1, 2, \ldots, N\,,\ 0 < \tau \leq 1\,,\ c^k(t) \in \mathbb{C}_\tau^1\,. \tag{1.4}$$

Such critical element is defined as τ level critical infrastructure element. τ level critical infrastructure element set $\tilde{\mathbb{C}}_\tau^1$, which is formed from ranked in increasing order τ level critical infrastructure elements, is created.

$$\tilde{\mathbb{C}}_\tau^1 := \{c_1^{k_1}(t); c_2^{k_2}(t); c_3^{k_3}(t); \ldots; c_j^{k_i}(t); \ldots; c_m^{k_N}(t)\}\,,\ 1 \leq k_i \leq N\,, \tag{1.5}$$

here j – the position of element in ranked critical element set $j = 1, 2, \ldots, m$; k – forced turned off infrastructure element number in the oriented graph $k = 1, 2, \ldots, N$.

The criticality of removed element pairs k_i, k_j is estimated by formula (1.6). Thus the events of element pair removal are incompatible, i.e., at one time only one pair is removed with two infrastructure elements.

After evaluating criticality of each infrastructure element pair, their criticality set $\mathbb{C}_\tau^2$ is developed. From the latter τ level critical pair elements are selected, and their set $\tilde{\mathbb{C}}_\tau^2$ is created

$$c^{k_i,k_l}(t) \geq \tau\,,\ c^{k_i,k_l}(t) > \max_{1\leq k_i \leq k_l \leq N}\{c^{k_i}(t), c^{k_l}(t)\}\,,$$
$$c^{k_i}(t) \cap c^{k_l}(t) \in \widetilde{\mathbb{C}}_\tau^1\,,\ c^{k_i,k_l}(t) \in \mathbb{C}_\tau^2\,,\ 0 < \tau \leq 1\,,\ 1 \leq k_i \leq k_l \leq N\,, \tag{1.6}$$

$$\widetilde{\mathbb{C}}_\tau^2 := \{c_1^{\,k_1,k_2}(t);\, ...; c_j^{\,k_i,k_l}(t); ...; c_{m_1}^{\,k_{N-1},k_N}(t)\}\,,\ 1 \leq k_i \leq k_l \leq N\,, \tag{1.7}$$

here j – the position of element in ranked critical element set j = 1, 2, …, m_1; k – forced turned off infrastructure element number in the oriented graph k = 1, 2, …, N.

The assessment of elements criticality could be continued by analysis of three and four elements, which is out of order at the same time. In such case, the number of analysed elements combination significantly increases. The basic critical elements of energy system infrastructure are determined by this assessment method. However, this method does not represent realistic scenarios of system operation: failure probabilities of other system elements are not equal to zero, and the assessment criticality of elements is not conservative. Also various combinations of elements (which are out of order) could occur at any moment of the time.

1.3. The probabilistic criticality assessment model for energy systems infrastructure elements

The criticality assessment of infrastructure elements is performed with assumption that one element is out of order; the operating statement of other elements is defined with respect to their failure probability.

Both the analytical method and the digital simulation method of the system performance, Monte Carlo, may be applied to criticality assessment of the infrastructure of complex energy systems when analyzing not only the topological structure of the infrastructure, but also taking into account reliability indicators of infrastructure elements.

In order to identify critical elements of energy system infrastructure, when the activity of systems is random, depending on infrastructure element reliability, all possible energy system conditions are simulated using Monte Carlo simulation method. Criticality of energy systems is estimated by simulating random operation of systems by force not eliminating infrastructure elements. Calculations are performed according to the method presented in Fig. 1.3.

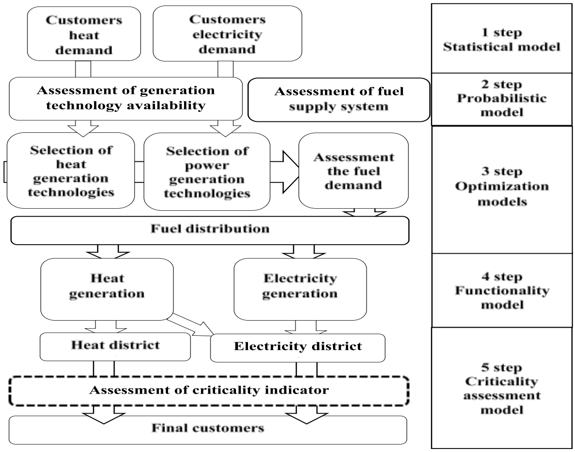

Fig. 1.3. Structural scheme of system criticality assessment method

The developed criticality assessment method consists of 5 steps:

step 1: analysis of statistical data and format input data for model;

step 2: Monte Carlo method is used to define the availability of system technologies that depend on statistical failure rate.

step 3: Simplex optimization method is used for the performing distribution of heat and electricity demands for generation technologies. Maximum gas flow distribution is performed as well.

step 4: generation technologies assess the amounts of productions dependent on supply system functionality.

step 5: the criticality assessment of electricity system and heat system is performed.

Basic systems criticality caused by the reliability of the infrastructure of the energy systems. The random operation of the systems is simulated while k^{th} element is out of order. The characteristics of average criticality value of k^{th} infrastructure element are estimated during the simulation of random operation of the systems.

$$c^{(k|\vec{\xi}_l)}(t) = 1 - \sum_{i=1}^{M} \frac{S_i^{(k|\vec{\xi}_l)}(t)}{V_i(t)} \beta_i(t), \; k = 1, 2, \ldots, N, \tag{1.8}$$

$$\bar{c}^k(t) = \frac{1}{N_{MC}} \sum_{l=1}^{N_{MC}} c^{(k|\vec{\xi}_l)}(t), \; k = 1, 2, \ldots, N, \tag{1.9}$$

here $\vec{\xi}_l$ – the indicator of infrastructure elements (random vectors), which is out of order during the l^{th} Monte Carlo simulation l = 1, 2, ..., N_{MC}; $c^{(k|\vec{\xi}_l)}(t)$ – the criticality value of k^{th} element (out of order) during the l^{th} Monte Carlo simulation (the system operation is random).

This approach could be used to obtain criticality results of more realistic situation. The value of system criticality becomes high when the higher number of elements is out of order at the same time in the energy systems.

1.4. The logistic regression model for the clustering critical elements

When energy system behaviour is described as random work, the elements of this system work randomly, one of the aims is to identify elements or group of elements whose disruption would affect the satisfaction of consumer energy demands.

The logistic regression model was designed to examine how functionality of the energy system infrastructure elements affects energy system criticality value by using probability scores as the predicted values of the dependent variable of energy system infrastructure. The purpose of this statistical analysis is to determine which elements of infrastructure influence high value of system criticality (statistical classification model) (Ozderim, 2011; Flahaut, 2004; Fang, Huang, 2012). Categorical variable Y is defined

$$Y = \begin{cases} 0, & c^{(k|\vec{\xi}_l)}(t) \notin C_\tau, \\ 1, & c^{(k|\vec{\xi}_l)}(t) \in C_\tau, \end{cases}, \tag{1.10}$$

here $c^{(k|\vec{\xi}_l)}(t)$ – criticality of system when operating statement of all elements is random with the regard of their failure probabilities; C_τ – analysed interval of criticality. The mathematical model is expressed as

$$P(Y=1\,|\,\vec{z}) = p_i = \frac{\mathrm{e}^{\hat{b}_0+\sum_{j=1}^{N}\hat{b}_j z_{ji}}}{1+\mathrm{e}^{\hat{b}_0+\sum_{j=1}^{N}\hat{b}_j z_{ji}}}, \ \forall j \in \mathcal{K}, \tag{1.11}$$

$$L = \prod_{i:y_i=1} p_i \prod_{i:y_i=0} \left(1-p_i\right), \tag{1.12}$$

here $i = 1, \ldots, n$, $j = 1,.., N$, p_i – probability that criticality value is from analysed interval C_τ $p_i = P(Y = 1)$, i – iteration; N – number of explanatory; z_i – the realization of system elements availability; b_j – coefficients of logistic regression.

When the logistic regression coefficients were estimated (the infrastructure elements whose failure affected the system criticality value), then it is awarded a set (cluster) of critical elements.

$$\tilde{\mathbb{C}}_\tau^{Log} = \{\vec{z}\ |\ P(Y=|\ \vec{z}) > 0.5\}, \tag{1.13}$$

here $\vec{z}$ – various combinations of out of order infrastructure elements at the same time.

This assessment allows establishing the critical infrastructure elements of all possible combinations (clusters) in each of the relevant criticality measure range C_τ.

1.5. The criticality assessment models of energy systems infrastructure

In this dissertation work, we analyze infrastructure of heat, power and gas supply systems. These systems are very important for every country so as to ensure the economic prosperity and national energy security, especially in cold period (extreme weather conditions). In order to ensure the social prosperity, it is necessary to guarantee uninterrupted heat and power supply for the consumers. Our model analyzes energy infrastructure composed of different types of energy generation technologies, such as boiler houses (BH), combined heat and power plants with back-pressure units (CHP), combined heat and power plants with extraction units (PP); renewable energy resources: hydro power plants (HP), wind villages (WP), biomass boiler houses and CHP. The generation technologies, such as CHP, BH and PP use natural gas as main fuel. Oil is used as alternative fuel in the CHP and PP. Each generation technology is defined as a functional unit with characteristic parameters and algorithms of operation. The system of heat, power and gas supply has internal functional relations. The function of the one subsystem depends on operating of other subsystems. The structural scheme of energy systems is presented in the Fig. 2.1. The disturbance occurred in any part of the system affects all subsystems (directly and indirectly). All generation technologies are simulated by input-output method. The demands of heat and electricity are allocated for generation technologies by the Simplex optimization method. The optimization is performed to maximize energy generation in each analysed city.

The demand of electricity is distributed for generation technologies by the same optimization model as heat demand. Preference is given to technologies using renewable energy sources (hydro power plants, wind power plants, etc.).
Gas supply network is represented as graph (1.1 equation). The mathematical optimization model (optimization of maximum flow with goal programing) is used to simulate gas supply system. One of the model aims is to maximize the satisfaction of consumer demands. The maximum flow optimization method was used to achieve this goal. Simplex method of linear programing was used to find the maximum flow in the pipeline network.

These optimization models enable the implementation of directives (economical, ecological, etc.) and emergency management plans. Monte Carlo method (MC) was used to obtain simulated data of the operation of the system. Operation statement of the system element was generated in each iteration to simulate the real system work. The estimates of failure probability of system elements were used from reports and journals (Security of supply of electricity market Lithuania monitoring report, 2014; Energy in Lithuania, 2012; EGIG, 2011).

Summary of the Section

The developed methodology for the assessment of criticality of infrastructure of energy systems was presented in this Section. The methodology is composed of several different assessment models:

- The criticality assessment metric of infrastructure elements (group of elements) is intended for assessing the criticality of infrastructure by the deterministic approach and probabilistic systems approach.
- The criticality value of the infrastructure element (group of elements) is indicated as the impact of consumer's energy demands satisfaction, when the element is out of order.
- The optimization models of energy system behavior, allowing the implementation of various energy system management strategies.

The main difference compared to other critical infrastructure criticality / vulnerability assessment methodologies is that the assessment analysis is performed for fairly detailed infrastructure, and this criticality assessment takes into account random operation of all energy systems and the satisfaction of consumers' energy demands.

2. THE RESEARCH OF CRITICALITY OF LITHUANIAN ENERGY SYSTEM

2.1. The model of Lithuanian energy systems

Lithuanian energy systems were selected as the object of study of developed methodology for the assessment of criticality of infrastructure elements. The most important Lithuanian energy systems have been selected for the study:

- Electrical;
- District heating;
- Natural gas supply (and oil products used as reserve fuel);
- Renewable energy.

The simulation period one time step (the quarter of the year) was selected for criticality analysis of infrastructure of Lithuanian energy systems. The criticality assessment of infrastructure and the identification of critical elements (combination of elements) are performed during this simulation period. In the developed aggregated energy system model country's electricity and six biggest cities' district heating system as well as natural gas supply system are analysed. Reliability indicators are used to evaluate gas pipe system reliability characteristics, submitted in database of EGIG (EGIG, 2011).

Since criticality assessment results of energy system infrastructure reveal the sensitive points of these systems estimating with the regard of end users demands insurance, thus the energy system infrastructure elements will be marked as codes: z_1, z_2, z_3, ..., z_N.

2.2. Modeling assumptions

Aggregated Lithuanian energy system infrastructure is modeled as a single region (closed energy sector). One of the assumptions is adopted in modeling infrastructure of energy systems and new infrastructure projects. This assumption is that the import of natural gas is fully guaranteed, i.e., does not analyze the potential political or economic disruptions in supply.

The cold time period (first quarter of the year) was selected for modeling and criticality analysis of energy systems, the reason is that the largest heat and electricity demand is required in this period. The criticality assessment was chosen for the cold season period (first quarter); the reason for that is that the largest heat and electricity demand is in this period.

The developed model analyzes energy infrastructure composed of gas supply network (main fuel for generation technologies), district heating system with heat generation technologies (combined heat and power plants with back-pressure units, boiler houses, biofuel boiler houses), power generation technologies (CHP with extraction units, hydro power plant, and wind power plants) and final consumers for heat and electricity. One of the model aims is to maximize the satisfaction of consumer demands. Heat energy demands were analysed in six largest cities of Lithuania: Vilnius, Kaunas, Klaipeda, Šiauliai, Panevėžys and Mažeikiai. The available statistical information was used to determine the heat demands of the largest cities (LŠTA, 2012; Ministry of Energy of the Republic of Lithuania, 2011). The simulations were performed using statistical indicator of energy demands in 2010–2011.

The infrastructure of district heating and power supply systems has not been analysed in detail, assuming that the heat and power supply is reliable. The reason for this is that these systems are complex and developed based on the *N*-1 reliability principle. Also the information about these systems is difficult to access.

The total country power demand was analysed during simulation. The other assumption is that total energy demands of the country must be generated and supplied by country energy system infrastructure. The priorities of energy generation are given to technologies, which use RES and for technologies that generate several types of energy, i.e., thermal power plants. The nuclear power is not considered in the modeling.

The natural gas is used as the main primary fuel for energy generation. The alternative fuel for energy generation is oil and biomass fuel. The supply of these fuels is ensured, and these supply systems are not analysed in more detail in the energy system model. Only main pipeline of natural gas system is considered in the simulation. The gas supply system is decomposed by separate segment of pipeline. The basic energy infrastructure system (M2) structure is similar to the Lithuanian energy sector. The new infrastructure projects of energy systems are analysed in order to reduce the criticality of energy systems. These new projects are related to improvements of natural gas supply system. The description of the energy system models, which are used in the criticality analysis, is given in the table below.

Table 2.1 The modifications of the Lithuanian energy system infrastructure model

The designation of infrastructure models	**The description of energy system models**
M1	The structure of infrastructure is similar to M2. The LNG terminal is not analysed to evaluate the impact of liquefied natural gas terminal for energy system criticality.
M2	Considered to be the basic energy infrastructure system model (similar to the structure in 2013–2014 situation).
M3	The structure of infrastructure is similar to M1. The project on increasing the capacity of gas interconnection between Latvia and Lithuania is analysed. The maximum capacity – up to 12 Mm^3 per day.
M4	The structure of infrastructure is similar to M1. Gas pipeline connection between Poland and Lithuania. The maximum annual capacity is 4.1 Bm^3.

Gas supply system is defined by graph of 89 main pipelines. The natural gas is supplied to the system from two sources: the debit of import from neighbor countries (two connections) is 31.2 Mm^3 per day and the other is 6.24 Mm^3 per day. The capacity of LNG is 3000 Mm^3 per year. Oil is used as an alternative fuel in the CHP. The assumptions of the system: closed energy system. The system was composed of 157 elements. The failure rates of CHP and PP are estimated by statistical data (Ministry of Energy of the Republic of Lithuania, 2011).

In order to determine elements of the critical infrastructure of power systems, criticality thresholds are selected. Evaluating by one element of the infrastructure, the criticality is higher than 0.1. When pairs of two elements of the infrastructure are analysed (when both fail simultaneously), the criticality threshold is 0.5. Analyzing combinations of infrastructure elements of three (when three elements fail simultaneously), the criticality threshold is 0.6. The elements of different systems are marked by the number of intervals. Gas supply system elements are from z^1 to z^{90}, the elements of the heat generation technologies in the cities (which used the natural gas as the main fuel) are from z^{91} to z^{126}. The elements of power plant are from z^{127} to z^{133}. The elements of technologies, which used renewable energy resources, are from z^{134} to z^{157}.

The topological structure of energy systems is presented in Fig. 2.1.

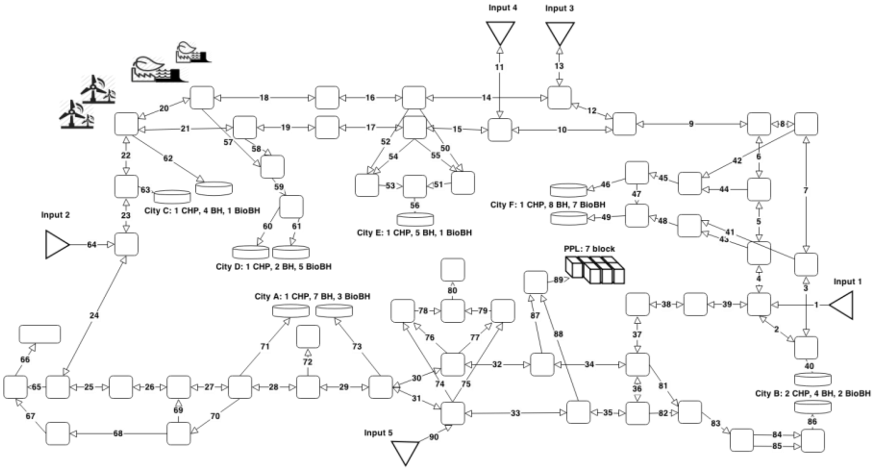

Fig. 2.1 The topological structure of energy systems

The basic energy infrastructure systems (M2) structure (the system composed of elements) is presented in Table 2.2 and Table 2.3 below.

Table 2.2 The list of electricity generation technology of the model

	Installed power capacity (MW)	Installed heat capacity (MW)
Hydro power plant	100.8	0
Small hydro power plant	25.7	0
Power plant 7 unit	1955	1752
Wind farm 2 unit	201.7	0

Table 2.3 The list of summed heat generation technology of the model

	The quantity of CHP	The quantity of BH	The quantity of biofuel boiler houses	Sum of installed power capacity (MW)	Sum of installed heat capacity (MW)
City A	1	7	3	170	1068.5
City B	2	4	2	384	2955
City C	1	4	1	30.8	1062
City D	1	2	5	186	732
City E	1	5	1	14	612
City F	1	8	7	35	741

2.3. Analysis of the results

The received criticality assessment results reveal energy infrastructure sites, which should be given extra attention, in order to reduce the criticality level of the analysed systems. The simulation was performed in a way that in each scenario, one element (different) of the system is out of order (*N*-1 principle). The criticality assessment results (the criticality value for final consumers of each system elements) of the power system are presented at first. This case was selected in order to investigate the main critical elements of the system (this assessment is not conservative).

Examining the criticality of infrastructure elements (by one element) with the regard of the power system, the number of critical elements is small (when the criticality of elements is higher than 0.1). During the evaluation, only one critical element z^{89} was identified, criticality estimate of $c^{89} = 0.326$. This element z^{89} is the element of gas supply system (the pipe connected the highest capacity electricity generation technology with the main natural gas supply system). This situation is natural, since the system is designed in accordance with the *N*-1 principle.

Examining the criticality of infrastructure elements with the regard of the power system of two and of three elements, the number of combinations of pairs of critical elements increases compared to the analysis, when the evaluation was performed by one element. A pair of elements is considered critical, when the criticality of elements is higher than 0.5. Twenty combinations of elements of two with the highest criticality are presented in Fig. 2.2.

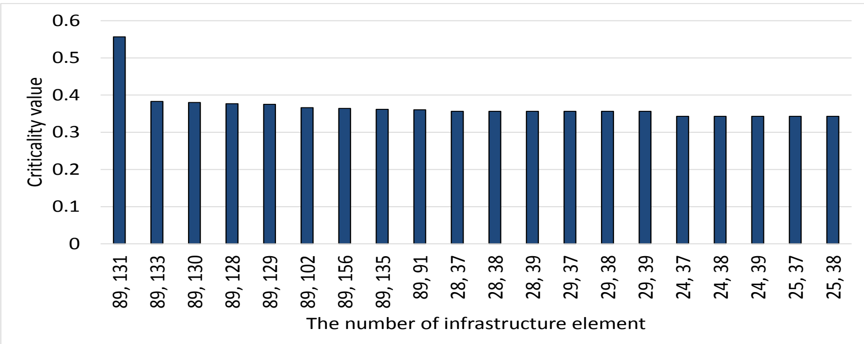

Fig. 2.2. Combinations (of three elements) of elements with the highest criticality to power system users

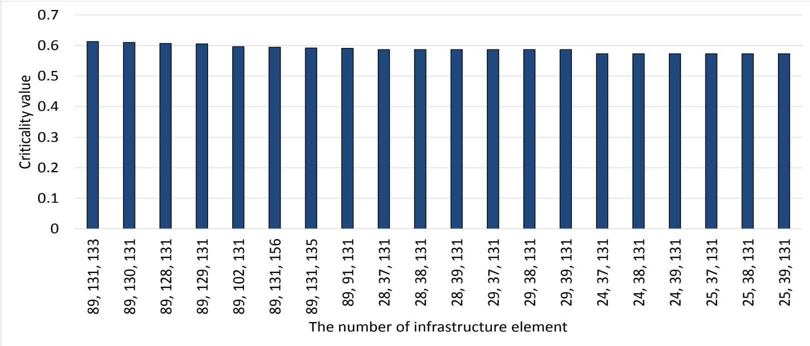

Fig. 2.3. Combinations (of three elements) of elements with the highest criticality to power system users

Examining the criticality of infrastructure elements of two elements, with the regard of power system users, 174 combinations with criticality have been identified (that is, 1.4% of all the examined combinations). Only one combination is determined as a critical pair (elements z^1 and z^{131}). The highest criticality 0.557 is reached upon simultaneous failure of the pair of elements z^{89} and z^{131}. When examining the criticality of pairs of elements of two elements for power system, it was reported that the formation of such pairs of critical elements has not been recorded when examining the criticality for power system of one element. Combinations were mostly made up of elements z^{24}, z^{25}, z^{26}, z^{28}, z^{29}, z^{37}, z^{38}, z^{39}. These elements are the elements of gas supply system, which are one-pipe natural gas supply section (where the two-pipe system moves into a one-pipe). Examining the criticality of infrastructure elements (of three elements), with the regard of the power system, the number of combinations of critical elements of three elements increased as compared to the analysis, when the evaluation was carried out for one or two elements. Twenty combinations of elements of three elements with the highest criticality are presented in Fig. 2.3, 15053 combinations with criticality have been identified (i.e., 2.3 % of the examined combinations), when the criticality is higher than 0.6. The highest criticality of the power system is caused by simultaneous failure of elements z^{89}, z^{131}, z^{133} ($c^{89,131,1353}$= 0.613). The elements of this combination are the elements of gas supply system and the heat generation technologies with the highest power capacity.

The criticality of infrastructure elements is also assessed with the regard of district heating supply systems of the country's six largest cities. During the cold period, these systems are of special importance, and their activity has to be flawless. The results obtained for the criticality of elements are presented with the regard of the two characteristic cities. City A has been selected, whose vast majority of the heat generating technologies uses natural gas, and City E, the city's generation technologies diversely use natural gas and biofuel.

After examination of the criticality of infrastructure elements of one element, with the regard of the district heating system of City A, it was obtained that the number of critical elements is not large (when the criticality of elements is higher than 0.1). The highest criticality for the City A district heating system is caused by gas supply system element z^{73} (c^{73} = 0.26). This element is the pipe connecting the highest capacity heat generation technologies with the main natural gas supply system. Combinations with the highest criticality of elements of two elements to the City A district heating system users are presented in Fig. 2.4, and to the City E district heating system are presented in Fig. 2.5.

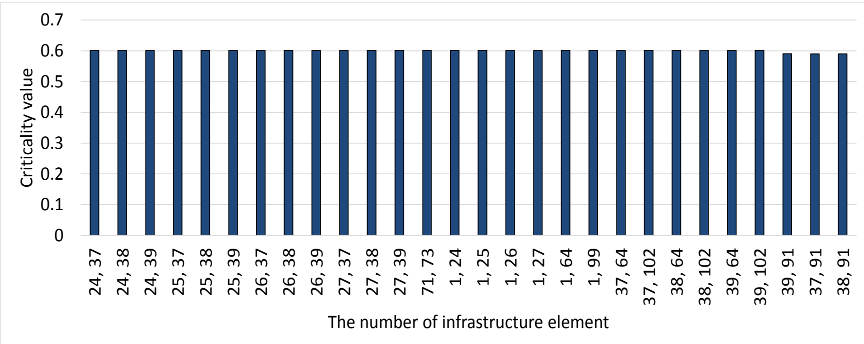

Fig. 2.4. Combinations (of two elements) of elements with the highest criticality to the City A district heating system users

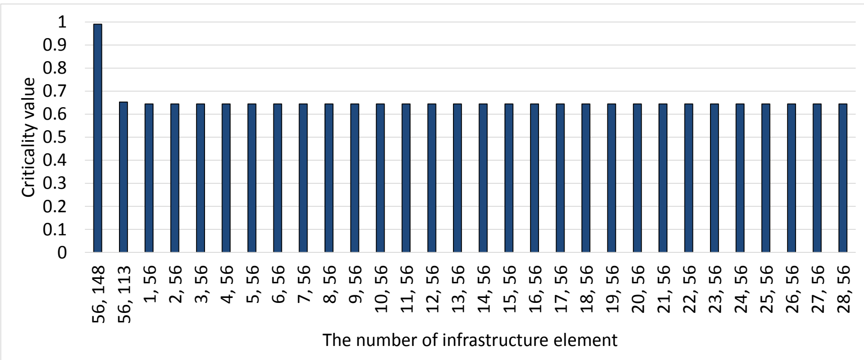

Fig. 2.5. Combinations (of two elements) of elements with the highest criticality to the City E district heating system users

Examining the criticality of infrastructure elements of two elements, with the regard of the district heating system of City A, 163 critical combinations have been identified (that is, 1.33% of all the examined combinations). Examining the criticality of infrastructure elements of three elements, 187 critical combinations have been identified (that is, 0.02% of all the examined combination). The highest and most frequently occurring criticality is obtained by combination of various elements by two with elements z^{1}, z^{24}, z^{25}, z^{26}, z^{27}, z^{37}, z^{38}, z^{39}, z^{64}, z^{73}, z^{91} z^{98}, z^{102}, z^{137}, z^{138}, z^{139} (these elements are the elements of gas supply system), except for items z^{91} z^{98}, z^{102}, z^{137}, z^{138}, z^{139}, which are the highest capacity heat generation technologies.

During assessment of the criticality of elements with the regard of the district heating system of City E, only one critical element z^{56} ($c^{56} = 0.644$) has been determined. This element is the pipe connecting the highest capacity heat generation technologies with the main natural gas supply system.

During criticality assessment of pairs of infrastructure elements with the regard of City E district heating system, 171 combinations with criticality have been identified, and only two combinations of critical element pairs, the criticality of which is higher than 0.5 (Fig. 2.5) ($c^{56,\ 148} = 0.991$ and $c^{56,\ 113} = 0.653$). The elements of this combination are the elements of gas supply system and the heat generation technologies with highest power capacity. This shows that the thermal energy demand for district heating system of City E has diversified from heat production of various types of heat generation technologies. Examining the criticality of infrastructure elements of three elements, 14270 combinations with criticality have been identified (that is, 2.2% of all the examined combinations). When assessing the criticality of infrastructure elements with the regard of consumers of district heating system of City E, only one combination of critical elements of three has been determined $\{z^{1}, z^{56}, z^{113}\}$, which completely disrupts district heating system activity. The criticality of these elements reaches the maximum value ($c^{1,\ 56,\ 113} = 1$). The elements of this combination are the elements of gas supply system and the heat generation technologies with highest power capacity. Such a difference in the amount of the determined critical elements and their combinations of district heating systems of the analysed cities is due to the fact that district heating system of City A mostly uses natural gas as the main fuel. Whereas in district heating system of City E, the majority of heat generation technologies use biofuel, in this way, the production is diversified depending on the type of fuel.

2.4. The analysis of influence of new infrastructure projects of energy systems in order to reduce the criticality of energy systems

The criticality assessment results of impact of new infrastructure development projects, when the energy system operation is random, are presented in this section. The systems and their modification M1, M2, M3, M4 were analysed during energy system simulation by the Monte Carlo method (the number of iteration is 1 000 000). It was observed that energy system infrastructure models M2 and M4 had the greatest impact of the systems criticality reduction (the implementation of new energy projects). This new energy projects are related to high natural gas transmission capacity infrastructure in the introduction of the energy sector. The results of influence of energy system development projects for the system criticality reduction are presented in Fig. 2.6.

Fig. 2.6. The influence of energy system development projects on the reduction of system criticality

The assessment results showed that the average criticality value of electricity system reduced by approximately 21%, and the average criticality value of district heating system of City A reduced by approximately 69% by gas pipeline connection between Poland and Lithuania (M4) energy system development project. The average criticality value was most reduced in the other DH systems of the analysed Cities by the LNG terminal (M2) energy system development project (percentage criticality value reduced from 25% to 88%).

2.5. The critical elements of energy system infrastructure identification by logistic regression model

To demonstrate the applicability of the criticality assessment methodology, when operation of the systems is random, was selected the M2 energy system infrastructure to identify the critical elements (the set of elements).

The system has been simulated using stochastic activity Monte Carlo simulations (iterations number is 100 000). The criticality assessment was performed when the analysed k^{th} element was out of order, operating statement of other elements was obtained using random number generator with respect to its failure probability. Obtained conditional probability distributions of elements criticality of electricity system, when k^{th} element is out of order and operating statements of other elements are random, are presented in Fig. 2.7.

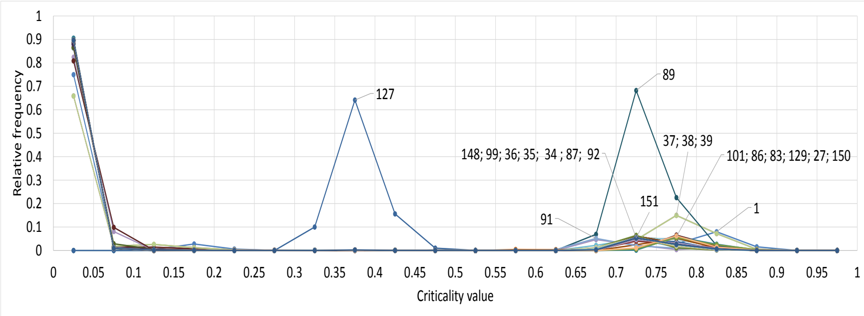

Fig. 2.7. The relative frequency distribution of k^{th} element criticality of the electricity system k = 1, …, 157^{th}

Such assessment of the criticality of infrastructure elements enables determining the elements with the highest criticality for power system, taking into account reliability indices of the system elements. When modeling system activity, various combinations of exhausted infrastructure elements formed together with forcedly removed element.

When analyzing modeling results, taking into account power system, three formed clusters of elements can be distinguished based on their criticality for this system consumers (as shown in Fig. 2.7) Elements and their combinations, according to their criticality, get into these clusters with different probabilities. The results are presented in Table 2.4.

Table 2.4 The results of criticality assessment by probabilistic assessment method

Power system			
The number of cluster	The range of criticality value	The range of probability value	Top 10 number of elements with highest probability to get in the criticality range
1 Cluster	[0; 0.05]	[0.65; 0.91]	All elements except 89 and 127
2 Cluster	[0.06; 0.225]	[0.0002; 0.09]	83, 86, 40, 39, 37, 38, 1, 30, 32, 87
3 Cluster	[0.625; 0.925]	[0.08; 0.28]	89, 39, 37, 38, 1, 27, 25, 26, 24, 28

The obtained results show that taking into consideration random operation of the systems, element z^{127} ($\bar{c}^{127} = 0.375$) obtains average criticality with the probability p = 0.64. Element z^{89} of the infrastructure could also be distinguished, because in case of random operation of systems, this element (just its failure is sufficient) with probability p = 0.68 obtains average criticality $\bar{c}^{89} = 0.775$ with the respect to power system consumers.

The obtained modeling results also allowed determining the criticality of which infrastructure elements (forced removal) in respect of power system reaches a high value and how often this happens. It would be possible to identify the set of critical elements (of one element), forced removal of which (switching off) from the system disrupts assurance of power consumers needs {z^{89}, z^{127}, z^{38}, z^{37}, z^{39}, z^{1}, z^{26}, z^{25}, z^{24}, z^{27}, z^{86}, z^{86}, z^{83}, z^{148}, z^{150}, z^{87}, z^{99}, z^{36}, z^{35}}. Infrastructure elements with the highest average criticality are presented in Fig. 2.8. It should be emphasized that frequent and high criticality of the elements also occurs due to random operation of the systems.

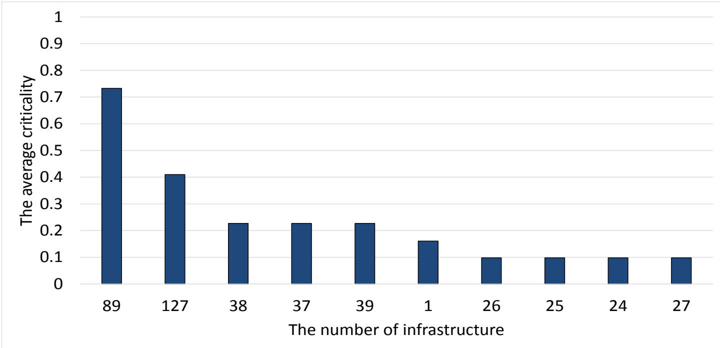

Fig. 2.8 The list of infrastructure elements with highest average criticality values for electricity system consumers

Similarly, when assessing the criticality of individual infrastructure elements of power systems, the criticality of these elements was also analysed in respect of district heating systems.

Analyzing the criticality of infrastructure elements in respect of district heating system of City A, four elements and clusters of their groups may be distinguished, when the access of elements into these clusters occurs with different probabilities. The results are presented in Table 2.5.

Table 2.5 The results of criticality assessment by probabilistic assessment method

DHS of City A			
The number of cluster	The range of criticality value	The range of probability value	Top 10 number of elements with highest probability to get in the criticality range
1 Cluster	[0; 0.04]	[0.75; 0.96]	all elements except 73
2 Cluster	[0.38; 0.5]	[0.0001; 0.12]	73, 38, 37, 39, 1, 28, 29, 34, 30, 32
3 Cluster	[0.5; 0.7]	[0.0004; 0.06]	1, 93, 94, 39, 37, 38, 64, 73, 88, 34
4 Cluster	[0.78; 0.86]	[$0.6\cdot10^{-4}$; 0.117]	37, 38, 39, 1, 26, 27, 24, 25, 71, 73

A part of elements of infrastructure do not pass the cluster (e.g., element z^{73}, which affects the needs of users of district heating system). The average criticality of this element reaches $\bar{c}^{73} = 0.42$ with probability of $p = 0.94$.

The similar situation occurs when criticality of the infrastructure elements is analysed in terms of city E district heating system.

In this case, only two clusters of elements on the basis of the criticality are formed (Table 2.6).

Table 2.6 The results of criticality assessment by probabilistic assessment method

DHS of City E			
The number of cluster	The range of criticality value	The range of probability value	Top 10 number of elements with highest probability to get in the criticality range
1 Cluster	[0; 0.04]	[0.799; 0.99]	all elements except 56
2 Cluster	[0.34; 0.42]	[0.03; 0.2]	56, 1, 9, 51, 53, 22, 23, 4, 5, 6

Results of the elements criticality assessment showed that needs of the final consumers of the system are not in case when the element z^{56} fails (it has the largest average criticality $\bar{c}^{56} = 0.38$ and it is obtained with probability $p = 0.97$). This z^{56} is the element of gas supply system (the pipe connected all heat generation technologies of City E with main natural gas supply system). It should be mentioned that the same average criticality for elements z^1 and z^9 is obtained with lower probabilities (respectively $\bar{c}^1 = 0.38$ $p = 0.2$). z^9 are the elements of gas supply system, which are one-pipe natural gas supply section (where the two-pipe system moves into a one-pipe), and z^1 is the pipe section of main import pipeline.

Comparing elements that obtained the largest average criticality in the systems of the two analysed cities district heating system, it was determined that elements of infrastructure have different criticality in terms of the analysed systems. The criticality of these elements also depends on the location in the infrastructure topology and the reliability of other elements of the infrastructure.

The simulation data for logistic regression analysis was obtained by M2 energy system infrastructure simulation by the Monte Carlo method (with 100000 repeats). The categorical variable Y is the interval of electricity system criticality, analysed in the logistic regression analysis $C_\tau = [0.6, 1]$ (Fig. 2.3). The statistically significant ($\alpha = 0.05$)

$$Y = \begin{cases} 0, & c^{(k|\vec{\xi}_l)}(t) \notin [0.6,1], \\ 1, & c^{(k|\vec{\xi}_l)}(t) \in [0.6,1]. \end{cases} \tag{2.1}$$

For clustering of such elements, logistic regression model is applicable (Ozderim, 2011; Flahaut, 2004; Fang, Huang, 2012). Developed logistic regression element classification model based on their criticality, enables to statistically significantly (level of significance $\alpha = 0.95$; 0.99) divide elements of the infrastructure into groups (clusters) in each measure range C_τ.

Based on logistic regression model, which enables to cluster elements of the infrastructure on their impact to the criticality to the system and assessing the probability, the cluster elements of the infrastructure and significant coefficients of logistic regression model were obtained. Element z^{89} was removed from the logistic regression model since the analysis showed that this particular element immediately falls into the cluster, i.e., in case of failure of the element z^{89} the criticality value falls into the range [0.6; 1] with probability $\hat{P}(Y=1|z^{89})_{C_\tau}=1$. The element is put into the set of critical elements.

Using the developed logistic regression model and selecting combinations of variables z^k (z^k=0, when k^{th} element is functioning z^k=1, when k^{th} element fails), the forecasted probability estimate $\hat{P}(Y=1|z^{89})_{C_\tau}=1$ that those elements combination in case of failure will fall into the range [0.6; 1] is obtained. The number of combinations of infrastructure elements falling into cluster (criticality range [0.6; 1] is presented in Table 2.7.

Table 2.7 The number of determined combinations in the cluster (criticality range [0.6; 1] in case of power system)

	Combinations with one out of order element	Combinations with two out of order elements	Combinations with three out of order elements	Combinations with four out of order elements	Combinations with five out of order elements
The number of combinations	1	3	56	661	4935

The generalization of the obtained results (Table 2.7) from the forecasted number of elements combinations, when those combinations consists of one, two, etc. elements, show how the number of critical element combinations increases when the sum of elements combinations number increases.

The highest forecasted probability of infrastructure elements combinations of two with critical elements failure in the range [0.6; 1] is not high. In total three combinations: elements z^{36} and z^{38}, with the forecasting probability $\hat{P}(Y=1|z^{36},z^{38})_{C_\tau}=0.73$ elements $z^{37}$and z^{38}, with the forecasting probability $\hat{P}(Y=1|z^{37},z^{38})_{C_\tau}=0.71$ and elements $z^{37}$and z^{39}, with the forecasting probability $\hat{P}(Y=1|z^{37},z^{39})_{C_\tau}=0.71$.

The highest predicted probability that the out of order combination of three elements will access into a cluster criticism is estimated with elements z^{37}, z^{38} and z^{37}. The predicted probability is $\hat{P}(Y=1|z^{37},z^{38},z^{39})_{C_\tau}=0.96$, when the criticality value is acquired in the interval [0.6, 1].

2.6. Important measurements and sensitivity analysis

The importance measures were estimated to compare the impact of gas supply system elements with the baseline scenario (all system element availability is random). Fussell-Vesely (*FV*) and Birnbaum importance (*BI*) measures of elements of analysed energy systems were estimated. The purpose of this analysis was to identify components with high value of *FV* and *BI*. When both importance measurements are high, the criticality can be reduced by decreasing the components unavailability or by improving the defense in depth against a failure of the component (Borst, Schoonakker, 2001; Kim, Han, 2009; Espiritu, Coit and Prakash, 2007; Baroud, et. al, 2014). The result (only with not null importance measurements) for the criticality of electricity and analysed DH systems is presented in Fig. 2.9-2.11.

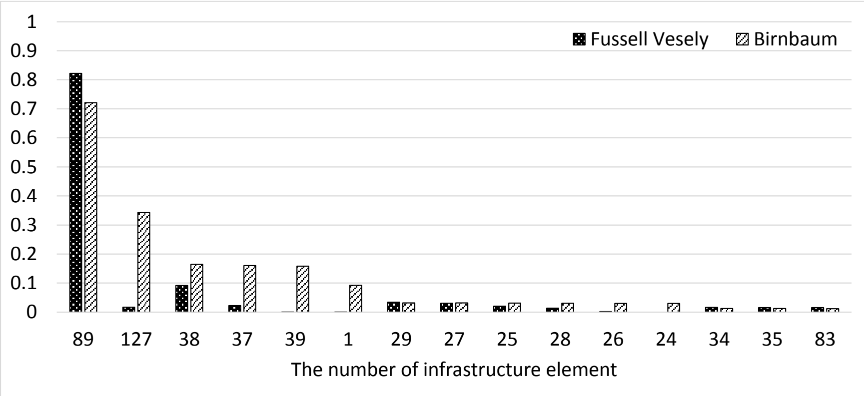

Fig. 2.9. The importance measurement of energy system infrastructure elements (in the electricity system)

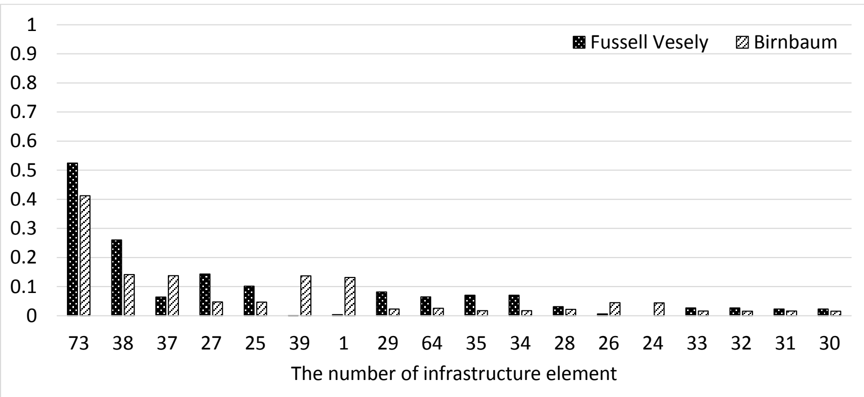

Fig. 2.10. Measure of infrastructure elements in case of City A district heating system

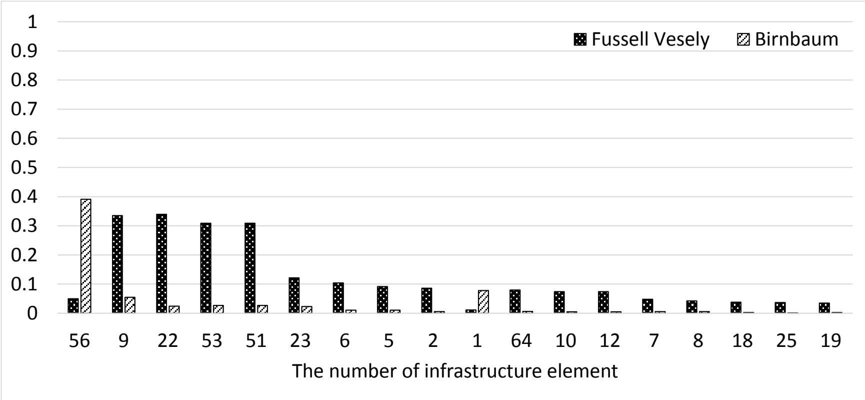

Fig. 2.11. Measure of infrastructure elements importance in case of City E district heating system

For the electricity system the following set could be defined for elements $\{z^{89}, z^{127}, z^{38}, z^{37}, z^{39}\}$, all these elements are the elements of gas supply system, expected the z^{127} is the generation technologies with highest power capacity. The results sensitivity of City A district heating system is based on elements $\{z^{73}, z^{38}, z^{37}, z^{39}, z^{1}\}$ all these elements are the elements of gas supply system, while in terms of City E district heating system – on elements $\{z^{56}, z^{1}\}$. Fussel-Vesely elements importance measures, which may be used for defining the elements the security of which could be improved in order to decrease the system criticality, correlate with elements criticality (in case of incidental operation of systems) identified by the results of critical elements.

CONCLUSIONS

In this research, a new methodology for the evaluation of the criticality in energy critical infrastructures has been developed. It has been designed to evaluate the criticality of both the overall system or its separate elements or groups with regard to the assurance of energy needs, and also to compare the impact of new infrastructure elements on the criticality of systems. Based on this methodology, a research of aggregated Lithuanian energy system infrastructures model (close systems) was carried out to evaluate the criticality of the existing energy systems and the impact of new energy infrastructures. The elements and groups, whose criticality beyond these parameters in the analysed energy systems, were determined depending on selected acceptability parameters of criticality level. The findings of the scientific research enalbe drawing the following conclusions:

1. The identification of critical elements of the energy system could be performed more accurately by the developed integral methodology for energy critical infrastructure assessment, than using only deterministic

methods. It was found that the deterministic approach identifies only three critical elements, and probabilistic methods – 10 critical elements in the case of analysed energy system.

2. The inclusion of reliability indicators of the infrastructure elements into mathematical model of criticality assessment enables to determine the overall system's criticality level, this is impossible without evaluation of the elements' reliability. In analysed energy systems cases it was shown that overall criticality of electricity system increases approximately by 7%, while in case of DHS- increases by 2%.
3. Following the evaluation of the criticality in energy system infrastructure it was found that:
   - The highest criticality for the electrical system has five elements, which range from 0.16 to 0.72. It was also found that one pair of elements (out of the 12246 combinations) has criticality higher than 0.5, and four triples of elements (out of 632 710 combinations) have criticality higher than 0.6.
   - With the regard of district heating systems in the examined urban areas, 7 separate elements were found with average criticality ranging from 0.1 to 0.42; 0.3% of elements pairs with higher than 0.5 criticality and 2.8% of element triples with higher than 0.6 criticality.
4. The criticality probability of the element or elements groups that will enter the selected criticality intervals could be determined by proposed logistic regression model. It was determined that the elements and their combinations with higher than 0.5 probability have the criticality not less than 0.6 in the analysed energy systems. 60 of such element combinations were found.
5. The analysis of the projects for the development of energy system infrastructure gas supply systems (the terminal of liquefied natural gas, the pipeline connections between Poland and Lithuania and the increase of the capacity of gas pipelines between Lithuania and Latvia) showed that the liquefied natural gas terminal had the greatest impact on reducing the criticality district heating systems. The criticality value of the analysed DH systems was reduced in average approximately 60% by LNG terminal. It also reduced the criticality of electricity systems in average by 7%. A greater impact on the criticality reduction of the electrical system had gas supply system connection with Poland, which reduces the criticality by about 21%.

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REZIUMĖ

Darbo aktualumas. Siekiant užtikrinti šalies ekonominį bei nacionalinį saugumą ir plėtrą yra svarbu užtikrinti energetikos infrastruktūrų darbo vientisumą ir funkcionalumą.

Kadangi šalies pramonės veiklos raida, esminių visuomenės funkcijų užtikrinimas, saugumas bei ekonominės ir socialinės gerovės palaikymas stipriai priklauso nuo energetikos sistemų patikimo (sklandaus) funkcionavimo, tai infrastruktūros elementų vertinimas ypač aktualus tokioms šalims kaip Lietuva, kurios didžiąją dalį energijos išteklių importuoja iš vienos šalies.

Daugelyje esamų energetikos ypatingos svarbos infrastruktūrų vertinimo modelių yra taikomi atskiri pažeidžiamumo ar rizikos analizės metodai. Pastarieji geriausiu atveju yra deterministiniai modeliai, nagrinėjantys vienos ar kelių infrastruktūrų poveikį tik fragmentiškai. Kiti vertinimo modeliai analizuoja tik infrastruktūrų tarpusavio sąryšius. Todėl, vertinant šalies energetikos infrastruktūrų kritiškumą, būtina įvertinti ne tik infrastruktūrų atskirų elementų techninius rodiklius, bet ir atsižvelgti į integralią energetikos sistemų visumą, bei jose esančius funkcinius priklausomumus ir įtaką vartotojams. Tai leistų įvertinti šalies energetikos infrastruktūrų kritiškumą daugeliu aspektų vienu metu (apjungiant energetikos sistemų rizikos vertinimo, optimizacinius modeliavimo ir funkcionalumo vertinimo metodus).

Darbo aktualumą pabrėžia ir tai, kad ES narės įpareigotos atlikti kritiškumo įvertinimą ir užtikrinti ypatingos svarbos infrastruktūrų objektų (YSIO) apsaugą pagal priimtą EK tarybos direktyvą 2008/114/EC dėl „*Europos ypatingos svarbos infrastruktūros objektų nustatymo ir priskyrimo jiems bei būtinybės gerinti jų apsaugą vertinimo*“. EK tarybos direktyva yra viena pirmaujančių pasaulio programų, apibrėžiančių svarbiausias sritis, kuriose turi būti sutelktos visos pastangos infrastruktūrų prevencijai ir apsaugai. Ypatingos svarbos infrastruktūrų vertinimo metodų kūrimas ir plėtojimas yra įtrauktas į Horizon2020 kryptis. Lietuvoje NATO „*Energetinio saugumo kompetencijos centras*“ taip pat vykdo veiklą energetikos ypatingos svarbos infrastruktūrų vertinimo ir apsaugos užtikrinimo srityje. Todėl disertacinio darbo tema yra aktuali tiek praktine, tiek moksline prasme.

Darbo tikslas. Sukurti energetikos sistemų infrastruktūros kritiškumo tyrimo metodiką ir ištirti Lietuvos energetikos sistemų infrastruktūros kritiškumą.

Darbo uždaviniai. Darbo tikslui pasiekti suformuluoti uždaviniai:

1. Sukurti metodiką energetikos sistemų infrastruktūros funkcionalumo ir kritiškumo matavimui.
2. Sudaryti energetikos sistemų infrastruktūros funkcionavimo ir kritiškumo įvertinimo matematinį modelį.
3. Pritaikyti sukurtą vertinimo metodiką Lietuvos energetikos sistemų infrastruktūros kritiškumui įvertinti.
4. Įvertinti energetikos sistemų naujų infrastruktūros projektų įtaką energetikos sistemų kritiškumui.

Mokslinis darbo naujumas. Disertaciniame darbe sukurta energetikos sistemų infrastruktūros kritiškumo vertinimo metodika, kurioje pirmą kartą atsižvelgiama į sistemų elementų tarpusavio sąryšius, patikimumą, riziką ir visų sistemų atsitiktinį darbą. Kritiškumo vertinimas atliekamas vartotojų atžvilgiu. Ši metodika leidžia išsamiau nustatyti mišrių energetikos sistemų kritinius elementus ir jų grupes, kurie energetikos sistemoms galutinių energijos vartotojų atžvilgiu turi didžiausią kritiškumą.

Naudojant logistinę regresiją sukurtas metodas leidžiantis identifikuoti energetikos sistemų infrastruktūros elementus ar jų grupes ir nustatyti tikimybes, su kuriomis šių elementų kritiškumas patenka į nustatytus intervalus.

Darbo rezultatai papildo ypatingos svarbos infrastruktūrų (energetikos sistemų) vertinimo bei modeliavimo teoriją naujais tikimybiniais kritiškumo vertinimo ir infrastruktūros elementų klasterizavimo metodais, pagal jų įtaką infrastruktūrų darbui.

Praktinė darbo vertė. Atliktų mokslinių tyrimų rezultatai leidžia įvertinti energetikos sistemų infrastruktūros kritiškumą ir palyginti įvairių energetikos plėtros scenarijų įtaką infrastruktūros kritiškumui. Tai leidžia nustatyti energetikos infrastruktūrų didžiausią kritiškumą turinčius elementus ar jų grupes bei jų sukeltus trikdžių procesus energetikos sistemose. Naudojantis gautais rezultatais įvertintas Lietuvos energetikos sistemų infrastruktūros kritiškumas, nustatytos kritiškiausių elementų grupės bei įvertinta dujų sistemos plėtros scenarijų įtaka energetikos sistemų kritiškumui. Gauti rezultatai prisidės prie Lietuvos įsipareigojimų įgyvendinant ES direktyvą 2008/114/EC.

Ginamieji disertacijos teiginiai:

- Sukurta energetikos sistemų ypatingos svarbos infrastruktūrų kritiškumo vertinimo metodika leidžia nustatyti kritiškiausius sistemų elementus pagal jų įtaką energijos vartotojų poreikiams tenkinti, atsižvelgiant į visų sistemų atsitiktinį darbą.

- Energetikos sistemų elementų patikimumas turi įtakos atskirų elementų ir jų grupių kritiškumui.
- Infrastruktūros elementų ar jų grupių kritiškumų tikimybiniam pasiskirstymui įvertinti tinka logistinės regresijos modelis.
- Papildomos gamtinių dujų tiekimo sistemos jungtys sumažina tiek elektros, tiek centralizuoto šilumos tiekimo sistemų kritiškumą.

Darbo aprobavimas. Disertacinio darbo tema paskelbta viena publikacija Thomson Reuters „Web of Knowledge" duomenų bazėje esančiuose mokslo žurnaluose, turinčiuose citavimo indeksą ir viena publikacija Thomson Reuters „Web of Knowledge" duomenų bazėje esančiuose mokslo žurnaluose, neturinčiuose citavimo indekso. Tyrimų rezultatai pristatyti 6 tarptautinėse konferencijose.

Darbo apimtis ir struktūra. Disertaciją sudaro įvadas, trys pagrindiniai skyriai, apimantys literatūros apžvalgą, metodologiją ir atliktų tyrimų rezultatus bei išvados. Disertacijos apimtis 113 puslapių (be priedų), juose 35 paveikslai, 12 lentelių, 115 cituojamų literatūros šaltinių ir mokslinių publikacijų disertacijos tema sąrašai.

IŠVADOS

Disertacijoje sukurta nauja energetikos sistemų ypatingos svarbos infrastruktūrų kritiškumo vertinimo metodika, skirta įvertinti tiek bendram sistemos, tiek atskirų elementų ar jų grupių kritiškumui galutinių vartotojų energijos poreikių užtikrinimo atžvilgiu bei palyginti naujų infrastruktūros elementų įtaką sistemų kritiškumui. Pagal šią metodiką atliktas agreguotų Lietuvos energetikos sistemų infrastruktūros (uždaros sistemos) tyrimas, vertinant esamų energetikos sistemų kritiškumą bei naujų energetikos infrastruktūrų įtaką kritiškumui sumažinti. Atsižvelgus į pasirinktus kritiškumo lygio priimtinumo parametrus, nustatyti nagrinėjamų sistemų elementai ir jų grupės, kurių kritiškumas viršija šiuos parametrus. Atliktų mokslinių tyrimų pagrindu galima daryti šias išvadas:

1. Pagal sukurtą integralią energetikos ypatingos svarbos infrastruktūrų vertinimo metodiką galima tiksliau nustatyti sistemos kritinius elementus, nei naudojant tik deterministinius metodus. Nagrinėtų energetikos sistemų atveju buvo nustatyta, kad taikant deterministinius metodus identifikuoti tik 3 kritiniai elementai, o tikimybinius metodus – 10 kritinių elementų.
2. Energetikos sistemų infrastruktūros elementų patikimumo rodiklių įtraukimas į kritiškumo vertinimo matematinį modelį leidžia nustatyti bendrą sistemos kritiškumo lygį, kas įmanoma tik įvertinant elementų patikimumą. Darbe parodyta, kad nagrinėtų energetikos sistemų atveju dėl elementų patikimumo bendras elektros sistemos kritiškumas padidėja apie

7 %, analizuotų CŠT sistemų bendras kritiškumas atitinkamai padidėja apie 2 %.

3. Atlikus nagrinėtos energetikos sistemų infrastruktūros kritiškumo vertinimą nustatyta, kad:
   - didžiausią kritiškumą elektros sistemai turi penki elementai, kurių kritiškumas yra nuo 0,16 iki 0,72. Taip pat nustatyta, kad yra viena elementų pora (iš 12246 kombinacijų), kurios kritiškumas yra didesnis nei 0,5. Identifikuoti keturi elementų trejetai (iš 632710 kombinacijų), kurių kritiškumas didesnis nei 0,6;
   - nagrinėtų miestų CŠT sistemų atžvilgiu rasti 7 atskiri elementai, kurių vidutinis kritiškumas yra nuo 0,1 iki 0,42; identifikuotos 0,3 % elementų poros, kurių kritiškumas didesnis nei 0,5 ir 2,8 % elementų trejetai, kurių kritiškumas didesnis už 0,6.
4. Naudojant logistinę regresiją galima nustatyti tikimybes, kad elementai ar jų grupės pateks į pasirinktus kritiškumo intervalus. Darbe nagrinėtose energetikos sistemose buvo nustatyti elementai ir jų kombinacijos, kurie su tikimybe didesne už 0,5 turi kritiškumą ne mažesnį nei 0,6. Rasta 60 tokių elementų kombinacijų.
5. Nagrinėjant energetikos sistemų infrastruktūros dujų tiekimo sistemos plėtros projektus (suskystintų gamtinių dujų terminalas; dujotiekių jungtis tarp Lenkijos ir Lietuvos; dujotiekių jungties tarp Lietuvos ir Latvijos pajėgumų padidinimas) nustatyta, kad didžiausią įtaką kritiškumui sumažinti CŠT sistemose turi suskystintų gamtinių dujų terminalas. Nagrinėtų miestų CŠT sistemose dėl jo įtakos kritiškumas sumažėja vidutiniškai 60 %. Elektros sistemos atžvilgiu kritiškumą suskystintų gamtinių dujų terminalas sumažina mažiau, apie 7 %, Tuo tarpu dujų jungtis su Lenkija – daugiau, apie 21 %.

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