The assessment technology of energy critical infrastructure

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HIGHLIGHTS

• We developed criticality assessment method for the critical energy infrastructures.
• This methodology is applicable for the mixed energy systems assessment.
• The systems component criticality assessment is performed.

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ABSTRACT

In order to keep state’s economical development and national security, it is necessary to secure integrity
and functionality of energy infrastructure.

Developed new criticality assessment method for the critical energy infrastructures is applicable to the
assessment of mixed energy system infrastructures, taking into account functional relations between
infrastructures and their elements. Component criticality assessment of critical energy infrastructures
is performed taking into account the entire energy sector operation. Such assessment enables better
quantitatively defining criticality of these components in terms of final energy consumers. The optimization
methods were used to simulate a real system (to implement allocation of demands of district heating
and electricity for generation technologies).

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1. Introduction

The country’s energy infrastructures are highly interconnected and mutually interdependent via transit gas pipelines or electricity transmission networks. Many systems are also interconnected inside the country and are dependent on each other. Critical infrastructure (CI) is defined as an asset, system or part thereof located in European Union Member States, which is essential for the maintenance of vital societal functions, health, safety, security, economy, etc., and the disruption or destruction of which would have a significant impact on a Member State as a result of the failure to maintain those functions [1]. We understand the criticality of the infrastructure element as impact of the defected/artificially removed infrastructure element on the secured needs of the final energy consumers.

Considerable efforts are currently put in order to develop models capable to analyze interdependent infrastructure systems. Some authors analyzed interdependences of infrastructures using a hybrid model. Huang et al. [2] used a combination of both the Decision-Making and the Analytic Network Process. The presented hybrid model was employed for infrastructures in Taiwan. These research results allowed identifying the infrastructure that contributes most to cascading failure. Holden et al. [3] used network model designed for interdependencies between infrastructure systems at different scales.

Some authors investigate separate systems of infrastructure such as gas and electricity systems or gas and oil systems [4], or heat supply system [5]. Chaudry et al. analyzed infrastructure expansion planning for ecological aspect [6]. The network planning approach allows making an assessment of the interactions between gas and electricity networks.

Another aspect of energy critical infrastructures assessment is the criticality evaluation of system infrastructures. Since the system infrastructures are closely dependent in terms of objects level,
thus it is essential to establish and quantitatively assess elements or groups of those systems infrastructures, the operation disturbance of which would affect functionality of the system or a number of systems [7,8]. For identifying critical elements authors very often employ various methods for system vulnerability analysis [9].

Shuang and Correa [10] in their works presented vulnerability assessment method based on graph theory; however, they analyzed only one type of infrastructures. Correa in his work analyzed vulnerability of tested electricity system “IEEE 118-bus” [11]. Shuang et al. analyzed water supply system operation presenting graph network node vulnerability index, which measures the number of each graph node in case of cascading process.

Some authors [12,13] assessing energy infrastructure vulnerability, which they have interpreted as network system clustering, presented clustering coefficients and components central. For assessment of vulnerability of two types of interconnected (electricity and water supply systems in a Chinese city) infrastructures and identification of systems critical elements, Wang et al. used the same principles defining them as vulnerability indicator [13]. With similar network clustering principle Dai et al. assessed electricity network vulnerability [12].

The drawback of the graph theory and network typology-based vulnerability assessments is that the assessment is carried out by modelling a discrete random activity of the system, when the elements of the system are in two states (exhausted or operable), and the evaluation depends only on the topology of the system. The results of the vulnerability assessment of the geographical area are highly dependent on network fragmentation density of the geographical area. A deterministic model of the criticality assessment of infrastructure elements, in case of a different type of infrastructure, was suggested by Johansson and Hassel [14]. The presented results demonstrate how interdependent the systems such as railway transport, electricity supply, and telecommunications systems are. The drawback of this method is that such an assessment is applied only to one type of infrastructures. Thus, such assessment criteria of critical elements are not relevant in mixed systems. In addition, this method does not take into account random operation of the system, and the performed assessment does not reflect the true level of criticality of elements of a real system. As well as systems consisting of a large number of elements, such a deterministic assessment of elements is complex for assessment of all possible cases of critical elements.

Johansson et al. presented global system vulnerability assessment method when analyzing IEEE RTS96 electricity system vulnerability without electricity generation sources [7]. The authors presented a method, which enables to simulate functional dependencies among system elements and evaluate the global system vulnerability by estimating unsupplied electricity to consumers, when exhausted system element combinations are selected according to element reliability indicators. The drawback of this method is that it assesses the general level of system vulnerability only for one type of system, and does not enable to identify the system elements or their groups, which are most critical.

In this article, a new assessment method of energy critical infrastructures criticality is presented, which was applied for the assessment of mixed energy system infrastructures, simulating functional connections between infrastructures and their elements. Estimating criticality of energy systems at component level, the random operation of all energy systems is taken into account. This enables more realistically identify critical elements and their groups and more quantitatively evaluate criticality of these elements from the point of view of the end user.

2. Criticality assessment model of energy 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 reversible connections exist, 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 for 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 decomposability particularity, the N-th element set may be possessed in the assessment model. Let us mark it as \( K : \{z_1, z_2, z_3, \ldots, z_N\} \).

Most often energy system connections are depicted as network systems (Fig. 1). The relations among the same infrastructure elements and different energy system infrastructure elements are expressed via element functionality with each other.

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 (CHP 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. 2.

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 graph:
$G = (V, E), \ V = V_{FN} \cup V_{CN}, \ \text{there} \ V_{FN} \cap V_{CN} = \emptyset,$

(1)

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

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. The 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 analyzed cities. This mathematical model allows distributing local heat demand to local generation technologies with the regard to the economic aspect. Preference is given to technologies using renewable energy sources (hydro power plants, wind power plants, etc.).

3. Method of critical assessment of the elements

The demands of any energy system end users may be estimated by unitary measure/standard, i.e., energy in MW h. It is complicated to form a mathematical criticality assessment model for infrastructure element, thus in order to assess infrastructure element criticality, a methodology based on energy system simulation is formed.

In general case, $k$-th infrastructure element criticality, per time unit, with moment $t$ with respect to end users [15] could be estimated according to expression:

$$c^k(t) = 1 - \sum_{i=1}^{M} \frac{s^i(t)}{V(t)}, \ \ 0 \leq c^k(t) \leq 1,$$

(2)

here $s^i(t)$ - $i$-th consumer supplied energy amount (MW h) per time unit in the system after turning off the $k$-th element at the moment $t$; $V(t)$ - $i$-th consumer energy demand (MW h) per time unit with moment $t$; $M$ - the number of consumers.

The $k$-th element of infrastructure is considered critical if $c^k(t) > 0$. For instance, when $c^k(t) = 1$, this means that at time moment $t$ after disruption of $k$-th element activity, the operation of all energy systems disrupts, and demands of end users are not fully satisfied; 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 analyzed system. The criticality range could be described as shown in Fig. 3.

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 regards to 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 regards to 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 $N-3$.

After estimating criticality of each infrastructure element, their criticality set $C^t_i$ (3 formula) is constructed. Since critical infrastructure element is selected, such element the criticality of which with regards to system end users is higher than the selected criticality level $\tau$ (when, $0 < \tau \leq 1$),

$$c^t_i(t) \geq \tau, \ \ k = 1, 2, \ldots, N, \ \ 0 < \tau \leq 1, \ \ c^t_i(t) \in C^t_i.$$

(3)

Such critical element is defined as $\tau$ level critical infrastructure element. $\tau$ level critical infrastructure element set $C^t_1$, which is formed from ranked in increasing order $\tau$ level critical infrastructure elements, is created.

$$C^t_1 := \{c^t_1(t); c^t_2(t); c^t_3(t); \ldots; c^t_m(t)\}, \ \ 1 \leq k \leq N.$$  

(4)

here $j$ - the position of an element in the ranked critical element set $C^t_1$, $j = 1, 2, \ldots, m$; $k$ – 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 (5). Thus the events of element pairs 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 $C^t_2$ is developed. From the latter $\tau$ level critical pair elements are selected and their set $C^t_3$ is created

$$c^k_i(t) \geq \tau, \ \ c^k_i(t) \geq \max_{1 \leq k \leq k_i N} \{c^k_{i_1}(t), c^k_{j_1}(t)\},$$

(5)

$$c^t(t) \cap c^k(t) \in C^t_1, \ c^k_i(t) \in C^t_2, \ 0 < \tau \leq 1, 1 \leq k_i \leq k_i N,$$

$$C^t_3 := \{c^k_i(t); c^k_j(t); \ldots; c^k_{m_i}(t)\}, \ \ 1 \leq k_i \leq k_i N.$$  

(6)
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 \( k = 1, 2, \ldots, N \).

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 the Monte Carlo simulation method. Criticality of energy systems is estimated by simulating random operation of systems by forced not eliminating infrastructure elements.

Our developed criticality assessment method consists of 5 steps (structural scheme is presented in Fig. 4):

step 1: analysis of statistical data and format inputs data for the model;
step 2: the Monte Carlo method is used to define the availability of system technologies that depend on statistical failure rate;
step 3: the Simplex optimization method is used for 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.

Two approaches for the assessment of element criticality with respect to system functionality are used:

**Approach 1**: calculations are performed with the assumption that only one element is out of order using the method presented in Fig. 4 (in this case step 2 is skipped). The obtained result is the estimate of the system criticality.

**Approach 2**: calculations are performed with the assumption that one element is out of order; operating statement of other elements is defined with respect to its failure probability. Calculations are performed according to the method presented in Fig. 4. In this case, element criticality \( X \) is a random value; its conditional probability distribution is obtained using the Monte Carlo method.

Approach 1 is hypothetic and does not represent realistic scenarios of the system operation: failure probabilities of other system elements do not equal zero.

Thus approach 2 can be used to obtain criticality results of a more realistic situation. With this method the \( k \)-th infrastructure element is forced turned off and random operation of energy systems using the Monte Carlo method is simulated, and average \( k \)-th infrastructure element criticality characteristics are obtained:

\[
c^{(\widetilde{\mathcal{U}})}(t) = 1 - \frac{\sum_{i=1}^{M} S_{\widetilde{\mathcal{U}}}(t)}{V_{i}(t)}, \quad k = 1, 2, \ldots, N, \tag{7}
\]
here $\tilde{\gamma}^k$ - indices of infrastructure elements damaged during $l$-th Monte Carlo iteration (vector of random variables) $l = 1, 2, \ldots, N_{MC}$; $c^{(k)}(t)$ – during $l$-th Monte Carlo iteration, criticality of $k$-th element, when system operation is random; $M$ – the number of consumers.

After establishing criticality polygons of relative frequency for each element of the infrastructure, elements of the infrastructure are classified by frequency of their criticality as those of high, medium and low criticality.

Critical elements of infrastructure evaluation (numerical experiment – aggregated Lithuanian energy model case).

For the developed aggregated Lithuanian energy system model real statistical data of country’s sector were used [16,17], information on country’s energy system infrastructure topology and expert assessment by accepting simulation presumptions. 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 analyzed. Reliability indicators are used to evaluate gas pipe system reliability characteristics, submitted in database of EGIS [18].

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

The objective of this criticality assessment method is to estimate and identify critical elements of state energy systems, in the developed aggregated energy system model, energy system is simulated without electricity import connections, presuming that country’s energy system available infrastructure should ensure energy demand of consumers. Fuel import is completely insured, i.e., possible political and economic supply disturbances are not analyzed.

Since the cold period of the year was chosen (the first term of the year) for criticality assessment of energy systems model infrastructure, as during this period the highest heat prevails, and electricity demand rise due to unfavourable air conditions, thus basic country cities’ thermal power plants, cities’ boiler houses as well as renewable energy sources technologies (hydro power plants, wind farms, bio-boiler houses and biofuel consuming thermal power plants) were chosen for energy production simulation.

Electricity, heat and natural gas supply systems were chosen for simulation. The criticality of systems and infrastructure elements was analyzed only with regards to electricity and district heating system end users.

The basic energy infrastructure system structure (the system composed of elements) is presented in Tables 1 and 2 below. Gas supply system is defined by the graph of 89 main pipelines. The natural gas is supplied to the system from two sources: the debit of import from neighbour 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 [17].

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 analyzed (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. Evaluating criticality of infrastructure elements of power systems, infrastructure of power systems consists of 157 elements. The elements of different systems are marked by number of intervals. The elements of gas supply systems are from $z_1$ to $z_90$, the elements of the heat generation technologies in the cities (which used the natural gas as main fuel) are from $z_91$ to $z_{126}$. The elements of the 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 model of these power systems is shown in Fig. 5.

### 4. Results

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 to the power system, the number of critical elements is small (when the criticality of elements is higher than 0.1). During the evaluation, only two critical elements $z_3$ and $z_{98}$ were identified, criticality estimates of which are respectively $c^3 = 0.6$ and $c^{98} = 0.544$. These elements ($z_3$ and $z_{98}$) are the elements of gas supply system (the pipe section of main import pipeline and the pipe connected the highest capacity electricity generation technology with 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 to 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. 6.

Examining the criticality of infrastructure elements of two elements, 344 critical combinations have been identified (that is, 2.81% of all the examined combinations). The highest criticality 0.72 is reached upon simultaneous failure of the pair of elements \( z_1 \) 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 \( z_{22}, z_{23}, z_{24}, z_{37}, z_{38}, z_{39} \). 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 system). Examining the criticality of infrastructure elements (of three elements), with the regard to 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. 7 and 12,498 critical combinations have been identified (i.e., 1.98% 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 \( z_1, z_{131}, z_{135} \) (\( c_{1,131,135} = 0.763 \)). The elements of these combinations 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 to 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 to 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

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**Fig. 5.** Topology scheme of the infrastructure of energy systems.

**Fig. 6.** Combinations (of two elements) of elements with the highest criticality to power system users.

**Fig. 7.** Combinations (of three elements) of elements with the highest criticality to power system users.
criticality for the City A district heating system is caused by gas supply system elements $c^1 = 0.778$, $c^{37} = c^{38} = c^{39} = 0.677$, $c^{73} = 0.369$. 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 system). Combinations with the highest criticality of elements of two elements to the City A district heating system users are presented in Fig. 8, and to the City E district heating system are presented in Fig. 9.

Examining the criticality of infrastructure elements of two elements, 574 critical combinations have been identified (that is, 4.69% of all the examined combinations). Examining the criticality of infrastructure elements of three elements, 110 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 $z^1$, $z^{37}$, $z^{38}$, $z^{39}$ (these elements are the elements of gas supply system).

During assessment of the criticality of elements with the regard of the district heating system of City E, only two critical elements $z^1$ and $z^{26}$ have been determined, the criticality estimates of which are respectively $c^1 = 0.6$ and $c^{26} = 0.392$.

During criticality assessment of pairs of infrastructure elements with the regard to City E district heating system, 328 combinations with criticality have been identified, and only four combinations of critical element pairs, the criticality of which is higher than 0.5 (Fig. 9) ($c^{1,113} = c^{56,148} = 0.735$ and $c^{1,113} = c^{56,113} = 0.647$). The elements of these combinations are the elements of gas supply system and the heat generation technologies with the 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, 6397 critical combinations have been identified (that is, 1.01% of all the examined combinations). When assessing the criticality of infrastructure elements with the regard to consumers of district heating system of City E, combinations of critical elements of three have been determined, which completely disrupt district heating system activity, these are $\{z^1, z^{113}, z^{148}\}$ and $\{z^{26}, z^{113}, z^{148}\}$. The criticality of these elements reaches the maximum value $c^{1,113,148} = c^{56,113,148} = 1$. The elements of these combinations are the elements of gas supply system and the heat generation technologies with the highest power capacity. Such a difference in the amount of the determined critical elements and their combinations of district heating systems of the analyzed 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.

The highest criticality values of infrastructure elements and their combinations are presented in Table 3.

### 4.1. Probabilistic assessment of the criticality of infrastructure elements

In order to demonstrate probabilistic methodology of assessment of criticality of infrastructure elements of power systems (formulas (7), (8)), determining critical elements of such a system, modification of the infrastructure of power systems supplemented by a liquefied natural gas terminal was chosen (debit of LNG is 3000 Mm$^3$ per year). The operation of these systems was simulated by generating random failure of elements of the infrastructure by means of Monte Carlo simulated calculations (iterations per 100,000), when random failures of elements of infrastructure are generated, depending on reliability characteristics of each element.

It was also assumed that the Lithuanian power infrastructure in the model is analyzed as one element of the infrastructure without breaking it into separate blocks. This assumption has been adopted in order to reduce the number of elements in the system, due to the long-lasting simulation calculations. After assessing the criticality of each element of the infrastructure of power systems, the obtained results are presented in respect of the systems in question (with the regard to the power system, district heating system of City A, and district heating system of City E).

The polygon of relative frequencies of the criticality of infrastructure elements for power systems (the empirical density function) is presented in Fig. 10.

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 modelling systems activity, various combinations of exhausted infrastructure elements formed together with a forcedly removed element.

When analyzing modelling 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. 10). Elements and their combinations, according to their criticality, get into these clusters with different probabilities. The results are presented in Table 4.

The obtained results show that taking into consideration random operation of the systems, element $z^{127}$ ($c = 0.375$) obtains average criticality with the probability $p = 0.64$. Element $z^{39}$ 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 $c^{39} = 0.775$ with the respect to power system consumers.
The obtained modelling 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.

$\{89, 127, 38, 37, 39, 1, 26, 25, 24, 27, 86, 86, 83, 148, 150, 87, 99, 36, 35\}$. Infrastructure elements with the highest average criticality are presented in Fig. 11. It should be emphasized that frequent and high criticality of the elements also occurs due to random operation of the systems.

Similarly, when assessing the criticality of individual infrastructure elements of power systems, the criticality of these elements was also analyzed in respect of district heating systems. The polygon of relative frequencies of the criticality of infrastructure elements for power systems of district heating system of City A (the empirical density function) is presented in Fig. 12.

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 5.

<table>
<thead>
<tr>
<th>Highest criticality value</th>
<th>Power system</th>
<th>Number of element</th>
<th>DHS of City A</th>
<th>Number of element</th>
<th>DHS of City E</th>
<th>Number of element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination by one element</td>
<td>0.6</td>
<td>1</td>
<td>0.778</td>
<td>1</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>Combination by two elements</td>
<td>0.72</td>
<td>1, 131</td>
<td>0.883</td>
<td>1, 91, 37, 91</td>
<td>0.735</td>
<td>1, 148</td>
</tr>
<tr>
<td>Combination by three elements</td>
<td>0.763</td>
<td>1, 131, 135</td>
<td>0.952</td>
<td>1, 91, 138, 37, 91, 138, 38, 91, 39, 138</td>
<td>1</td>
<td>1, 113, 148</td>
</tr>
</tbody>
</table>

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Table 3
The highest criticality value of infrastructure elements and their combinations for country energy systems.

<table>
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<tr>
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<th>Power system</th>
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<th>DHS of City A</th>
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</tr>
<tr>
<td>Combination by two elements</td>
<td>0.72</td>
<td>1, 131</td>
<td>0.883</td>
<td>1, 91, 37, 91</td>
<td>0.735</td>
<td>1, 148</td>
</tr>
<tr>
<td>Combination by three elements</td>
<td>0.763</td>
<td>1, 131, 135</td>
<td>0.952</td>
<td>1, 91, 138, 37, 91, 138, 38, 91, 39, 138</td>
<td>1</td>
<td>1, 113, 148</td>
</tr>
</tbody>
</table>

Table 4
The results of criticality assessment by probabilistic assessment method.

<table>
<thead>
<tr>
<th>Power system</th>
<th>The number of cluster</th>
<th>The range of criticality value</th>
<th>The range of probability value</th>
<th>Top 10 number of elements with highest probability to get in the criticality range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cluster</td>
<td>[0.0; 0.05]</td>
<td>[0.65; 0.91]</td>
<td>All elements except 89 and 127</td>
<td></td>
</tr>
<tr>
<td>2 Cluster</td>
<td>[0.06; 0.225]</td>
<td>[0.0002; 0.09]</td>
<td>83, 86, 40, 39, 37, 38, 1, 30, 32, 87</td>
<td></td>
</tr>
<tr>
<td>3 Cluster</td>
<td>[0.625; 0.925]</td>
<td>[0.08; 0.28]</td>
<td>89, 39, 37, 38, 1, 27, 25, 26, 24, 28</td>
<td></td>
</tr>
</tbody>
</table>

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 $c^{73} = 0.42$ with probability of $p = 0.94$.

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

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In this case, only two clusters of elements on the basis of the criticality are formed (Table 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 \( c^{56} = 0.38 \) 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 \( c^1 = 0.38 \) \( p = 0.2 \)). \( z^9 \) is the element of gas supply system, which are one-pipe natural gas supply section (where the two-pipe system moves into a one-pipe system), and \( z^1 \) is the pipe section of main import pipeline.

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

### 4.2. Clustering results of critical infrastructure elements and their combinations

Defining infrastructure elements, cluster composition based on analyzed criticality range, selected electricity network system criticality and incidental systems operation results obtained by infrastructure of analyzing energy systems. In particular, one cluster was selected, which was obtained from elements with the criticality higher than \( c^k > 0.6 \) (Fig. 10).

Such cluster was selected in order to determine which of combinations in incidental cases have high criticality, and in such way, obtaining key critical elements in terms of electricity system.

![Fig. 12. The relative frequency distribution of \( k \)-th element criticality of the district heating system of City A \( k = 1, \ldots, 157 \).](image-url)

<table>
<thead>
<tr>
<th>DHS of City A</th>
<th>The number of cluster</th>
<th>The range of criticality value</th>
<th>The range of probability value</th>
<th>Top 10 number of elements with highest probability to get in the criticality range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cluster</td>
<td>[0;0.04]</td>
<td>[0.75;0.96]</td>
<td>All elements except 73</td>
<td></td>
</tr>
<tr>
<td>2 Cluster</td>
<td>[0.38;0.5]</td>
<td>[0.0001;0.12]</td>
<td>73, 38, 37, 39, 1, 28, 29, 30, 32</td>
<td></td>
</tr>
<tr>
<td>3 Cluster</td>
<td>[0.5;0.7]</td>
<td>[0.0004;0.06]</td>
<td>1, 93, 94, 39, 37, 38, 64, 73, 88, 34</td>
<td></td>
</tr>
<tr>
<td>4 Cluster</td>
<td>[0.78;0.86]</td>
<td>[0.610^{-4};0.117]</td>
<td>37, 38, 39, 1, 26, 27, 24, 25, 71, 73</td>
<td></td>
</tr>
</tbody>
</table>

Table 5

The results of criticality assessment by probabilistic assessment method.

<table>
<thead>
<tr>
<th>DHS of City E</th>
<th>The number of cluster</th>
<th>The range of criticality value</th>
<th>The range of probability value</th>
<th>Top 10 number of elements with highest probability to get in the criticality range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Cluster</td>
<td>[0.06;0.14]</td>
<td>[0.799;0.99]</td>
<td>All elements except 56</td>
<td></td>
</tr>
<tr>
<td>2 Cluster</td>
<td>[0.34;0.42]</td>
<td>[0.03;0.2]</td>
<td>56, 1, 9, 51, 53, 22, 23, 4, 5, 6</td>
<td></td>
</tr>
</tbody>
</table>

According to the criticality assessment results, the following pseudo variables were developed:

\[
Y = \begin{cases} 
1, & c^{(k)}(i) \in [0.6; 1], \\
0, & c^{(k)}(i) \notin [0.6; 1].
\end{cases}
\] (9)

For clustering of such elements, logistic regression model is applicable \[19,20\]. Developed logistic regression element classification model based on their criticality, enables to statistically significantly (level of significance \( \alpha = 0.05; 0.95 \)) divide elements of the infrastructure into groups (clusters) in each measure range \( C_j \).

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 \[19,20\], the cluster elements of the infrastructure and significant coefficients of logistic regression model were obtained. Element \( z^{59} \) 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 \( z^{59} \), the criticality value falls into the range \([0.6; 1]\) with probability \( \hat{P}(Y = 1|z^{59})/c, = 1 \). The element is put into the set of critical elements.

Using the developed logistic regression model and selecting combinations of variables \( z^k (z^k = 0, \text{ when kth element is functioning } z^k = 1, \text{ when kth element fails}) \), the forecasted probability...
estimate $\tilde{P}(Y = 1 | z_{89})_{C_s} = 1$ that those element 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 7.

The generalization of the obtained results (Table 7) from the forecasted number of element combinations, when those combinations consists of one, two, etc. elements, show how the number of critical element combinations increases when the sum of element combination numbers increases.

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

Results of infrastructure elements in combination of three elements with the largest forecasted probability is presented in Fig. 13.

Since the developed model of infrastructure elements is probabilistic, the classical sensitivity and uncertainty analysis cannot be applied. Thus for the developed model, the assessment of element importance is performed. These assessments are applied as interpretation of sensitivity analysis. Measures of element importance assessing element impact on the system reliability most frequently are applied in probabilistic safety analysis [21–23].

Most frequently, for the sensitivity analysis using measures for the elements importance it is usual to apply Birnbaum and Fussell-Vesely indices [23–25].

Summarized results of element measures of electricity system infrastructure and city A as well as City E district heating system results are presented in Figs. 14–16.

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, except $z_{127}$ that 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 element criticality (in case of incidental operation of systems) identified by the results of critical elements.

5. Conclusion

The new assessment method of energy system critical infrastructures is presented in the article. The method is devoted both to the general and separate elements or groups of the system criticality assessment in terms of final energy consumers’
requirements. Based on this method, aggregated criticality assessment of the Lithuanian energy system infrastructure was performed.

Energy systems infrastructure functioning and criticality assessment mathematical model was developed. The model enables to more impartially assess criticality than traditional methods without reliability assessment.

After the assessment of the analyzed energy system infrastructure criticality, it was observed that the largest average criticality has five elements with average criticality from 0.16 till 0.72 in analyzed district heating systems, 7 elements were found with the criticality from 0.1 till 0.77.

Assessing reliability of analyzed energy system elements using logistic regression, elements and their combinations were obtained that with the probability more than 1/2 have the criticality 0.6 and more than 60 combinations of such elements were found.

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References