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The aggregate energy sector criticality risk assessment

Keywords

energy infrastructure, risk, criticality, assessment

Abstract

One of the aims of this work is to create a method of identification of critical elements (elements or groups of elements) in the energy infrastructure, and this method should allow ranking these critical elements by relevance to consumers (the consumer could be from the systems of different energy sector).The risk estimate of an element is one of the proposed sorting criteria for critical elements or their groups. It allows assessing the importance of the combination of critical elements and takes into account the probabilities of faults of these combinations. The key result of the research is the identification of the weakest links in the system, namely those elements, the failure of which (together with other elements) would lead to the worst consequences for the consumers and response to the availability of the infrastructure element.

1. Introduction

1.1. The risk assessments of energy critical infrastructure

One of the significant aspects of the assessment of critical energy infrastructure is risk assessment of interdependent energy infrastructure systems. The energy systems are fairly large, complex and adaptive (for example: electricity, gas, oil, etc.); for those reasons, it is difficult to use classical risk assessment methods based on probabilistic calculations. Research in this aspect has not yet made significant progress comparing to risk assessment of nuclear power plants. The reason is the complex relationship between different systems; moreover, there are many potential initiating events in respect of each system.

However, the importance of ideology of critical infrastructure risk assessment is emphasized by the EC Directive 114/08 / EC [10] and the US NIPP. The six-step risk management system is offered by NIPP [6]. Risk analysis of critical energy infrastructures can vary depending on: the type of risk; the objectives of analysis; the required relevant level of information about protection; the data and their sources. The analysis can be: qualitative, semi-quantitative, quantitative or a combination thereof. Generally, empirically based risk analysis is used for the risk assessment of critical energy infrastructures, due to the complexity of the system infrastructure. The data of historical failure of the system infrastructure and the expertise of experts are usually taken into account. The purpose of risk analysis is to identify the vulnerable elements of energy system infrastructure, taking into account the potential initiating events (threats), and to give suggestions on how to reduce the risk level of these elements. In this work, the aggregate energy sector model was analysed based on risk of infrastructure elements. The deterministic vulnerability and criticality assessment methods were applied to the risk analysis of the aggregate energy sector.

1.2. The case studies of risk assessment of critical infrastructure

The risk analysis of system infrastructure of Oslo City power and trains was presented by I. B. Utne with co-authors [8], [12]. Researchers analysed the occurrence of a disaster at the Oslo central station, where the initiating event was a disrupted electrical cable that caused the fire in the station and disrupted railway infrastructure for 20 hours, and Internet systems for 10 hours. Risk analysis of infrastructure of these systems was performed using semi-quantitative assessment methods and cascading failures process across infrastructures. The risk of initiating event was assessed by economic indicators, and the optimal strategy to reduce the risk level was proposed.

The semi-quantitative methods of risk analysis and risk assessment matrix were used for Colombian power system infrastructure risk assessment by G. J. Correa-Henao with colleagues [3]. E. Cagno and colleagues performed risk and interoperability analysis of underground infrastructures of a northern Italian city center [2]. The authors analysed the underground electricity, district heating, gas, water supply and telecommunication systems, using input-output analysis and modeling approach to assess the impact on the relationships between the different infrastructures.

The societal risk level of each geographic area of urban public was estimated, taking into account the risks to people, buildings and businesses [7]. The blind side of empirically based risk analysis methods is that the analysis is highly dependent on expert judgment and available empirical data. The risk analysis may be inaccurate considering small amount of data.

The probabilistic risk assessment methods are often used for the assessment of the infrastructure of one type. For example, P. Henneaux together with colleagues performed the main power system blackout risk assessment [5]. This assessment is one of the examples of probabilistic risk assessment approach. In summary, it may be argued that the risk assessment of energy critical infrastructure is generally performed for specific and small infrastructures (one type). In other cases, the assessment of energy systems is composed of several systems of different types (complex systems); the risk assessment is very complex and requires additional assumptions. Besides, this risk assessment method is used for the assessment of specified and predefined initiating events and scenarios. In general, the assessment is restricted by the analysis of several specific initiating events.

2. Method

The risk assessment of complex energy infrastructures (power, district heat and natural gas supply systems) in regard to dissatisfied consumer energy demand is presented in this work, which is a continuation of previous research for critical energy infrastructure assessment [1]. The criticality assessment technology is presented in the former work. This assessment is based on deterministic and probabilistic methods. The criticality value presents the influence of failure of infrastructure elements on energy system consumers. For example, if criticality value of infrastructure element is 0.45, it means that the consumer demand is not satisfied by 45% (the criticality value ranges from 0 to 1). This type of threat is the internal system initiating event, and only these threats were analysed in this work. The consequences of the initiating event are estimated by criticality value.

The deterministic (empirically-based) assessment approach was applied for complex energy system to estimate the risk of dissatisfied consumer energy demand. The risk assessment is performed using the artificial elimination the infrastructure elements of the mixed systems (N-1, N-2, N-3 principle). This type of assessment allows identifying most critical (and high risk) elements and their combination, and it enables relatively quickly assessing the infrastructure. For calculations, the assumption was used: assessed infrastructure element (groups of elements) is/are out of order, the remaining elements of infrastructure are working reliably.

The risk of infrastructure elements (or groups of elements) could be estimated as a product of probability of failure and case criticality

$$rc^k(t) = q^k(t) \cdot c^k(t),\ 1 \le k \le N, \qquad (1)$$

here $q^k(t)$ – the probability of k-th element failure; $c^k(t)$ – criticality of the k-th element of infrastructure,

$$rc^{k_i,k_l,\dots,k_r}(t) = q^{k_i,k_l,\dots,k_r}(t) \cdot c^{k_i,k_l,\dots,k_r}(t), \qquad (2)$$
$$1 \le k_i \le k_l \le k_r \le N;$$

here $q^{k_i,k_l,\dots,k_r}(t)$ – the probability of failure of group of elements; $c^{k_i,k_l,\dots,k_r}(t)$ – the criticality value of group of elements.

This assessment technique allows rating the elements (or their group) more objectively according to their criticality and reliability characteristics.

2.1 Aggregate energy system description

The risk assessment approach of critical energy infrastructure was performed for aggregated energy system of Lithuania. These numerical calculations demonstrate the applicability of assessment method technique. A one-month period (2014 January) with the greatest need of thermal and electrical energy was chosen for simulation. Infrastructure elements are assessed through the exigencies of the final energy consumer satisfaction.

Consumer energy demands are based on 2014 January data for the modeling. The aggregated energy system model is composed of the six largets cities in Lithuania. Basic thermal power plants of the country's cities, cities boiler houses as well as renewable energy sources technologies such as 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 system was composed of 157 elements. Gas supply system is defined by graph of 89 main pipelines. The heat generation technologies are composed of 30 boiler houses, seven combined heat and power plants and 19 biofuel boiler houses. Power generation technologies are composed of two hydro power plants, two wind farm units and one power plant (thermal power plant is composed of seven units). The description of the aggregated energy system model is presented in the paper [1]. The data on failure rate of CHP and PP are estimated by statistical data [9], [11], and the data on failure rate of gas supply system (in the period from 1971 to 2010, the average failure frequency of gas transmission pipeline was 3.5 × 10-5 per kilometer-year.) are taken from EGIG report [4]. The scheme of aggregated energy system model (the topological structure) is presented in *Figure 1*.

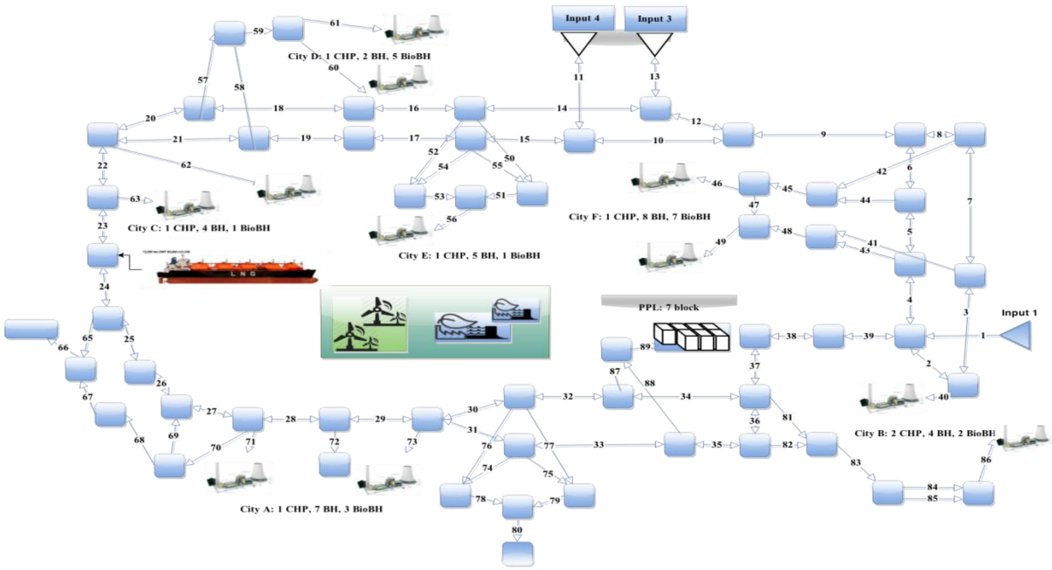

Figure 1. Aggregated energy sector scheme

The assumptions: closed energy system, the demands of heat and power were selected from statistical sources [11]. The main results of risk assessment are obtained for the power system and the heat systems of analysed cities.

3. Results and discussion

The simulation was performed based on N-1 principle: in each scenario, one (different) element of the energy system infrastructure is out of order. Later, the analysis is performed based on N-2 and N-3 principles. The risk assessment results (the risk 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 system risk of the analysed energy systems. The risk assessment results are presented in *Figure 2*.

As showed in *Figure 2*, the risk level of not satisfied consumer energy demands in each DHS of the analysed city is different. The highest risk level defeated in the DHS of city F, the value is $3.1 \cdot 10^{-6}$ (the criticality and risk of the energy sectors was analysed based on N-2 principle). The risk level when energy sectors analysed based on N-3 principle also had the highest value for DHS of city E (risk level value is $1.3 \cdot 10^{-6}$). The highest risk level for consumers when the energy sector is analysed based on N-1 principle had consumers of power system (the risk level is $3.8 \cdot 10^{-6}$). The risk level is less than 10^{-7}. The criticality value of infrastructure elements (their combination) and the probabilities of failure of these elements are presented in *Figure 3*.

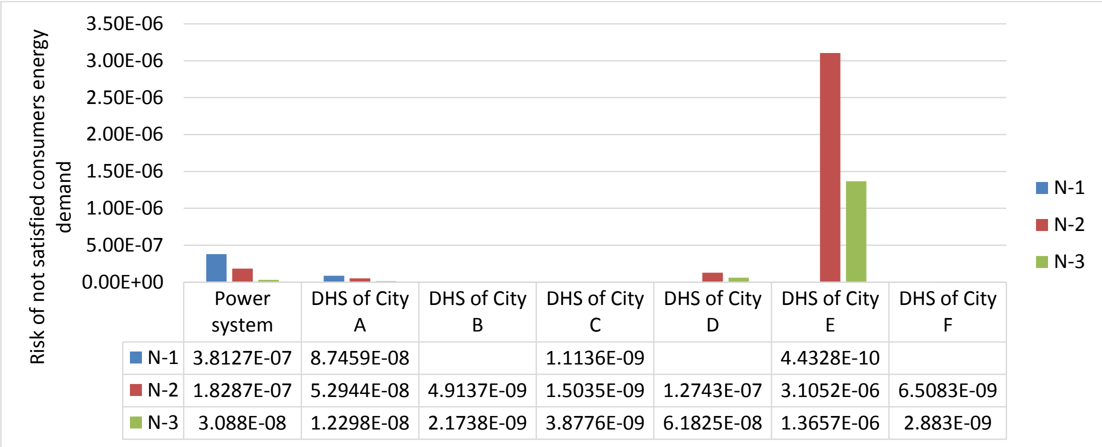

Figure 2. The risk results for consumers of analysed energy system

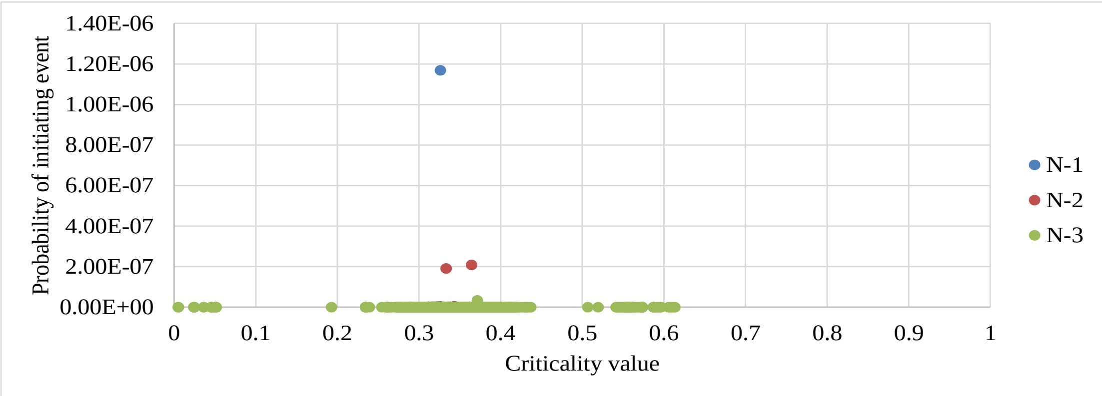

Figure 3. Criticality results of combination of elements for power system consumers

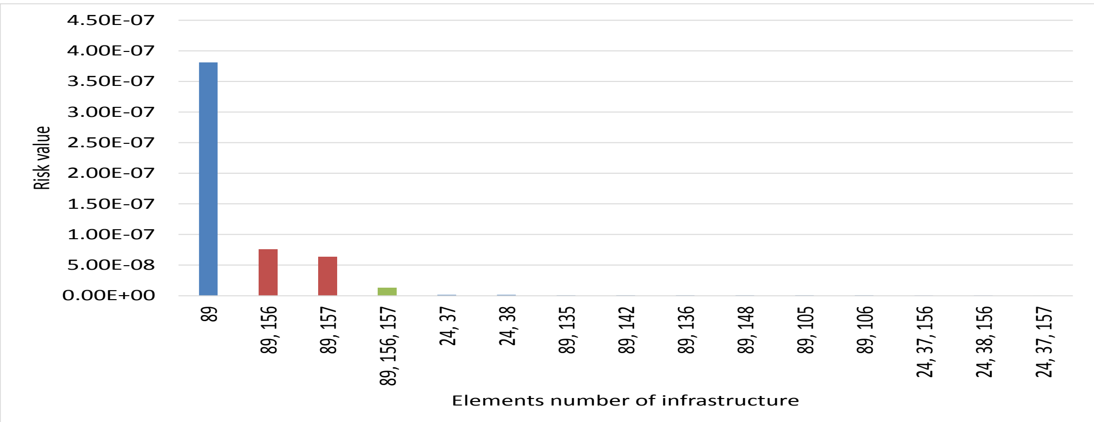

Figure 4. Risk results of combination of elements for power system consumers

The results of risk assessment of each element (their combinations) of energy sector infrastructure (for power system consumer) are presented in *Figure 4*.
The results (*Figure 3* and *Figure 4*) showed that there were just a few critical elements of energy systems, which influenced the power energy demands of consumer. One gas supply system element z^{89} had a relatively large impact on the satisfaction of consumer power energy demand. The risk arising from this element is the highest comparing with other elements (or combination of elements) of infrastructure. The risk value of this element is $3.81 \cdot 10^{-7}$. The risk assessment (N-2 principle) of infrastructure combination showed that only two combinations (z^{89}, z^{156} and z^{89}, z^{157}) had a lower risk in comparison with system element z^{89}. The risk values of these combinations are $7.58 \cdot 10^{-8}$ and $6.37 \cdot 10^{-8}$, respectively. However, the criticality value of these combinations is not significantly higher comparing with the criticality value of separate element z^{89} (*Figure 3*).

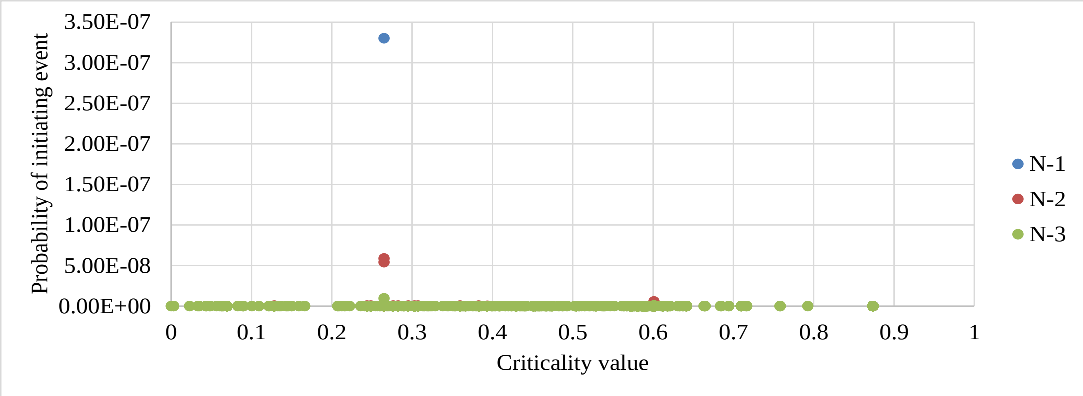

Figure 5. Criticality results of combination of elements for the city A consumer

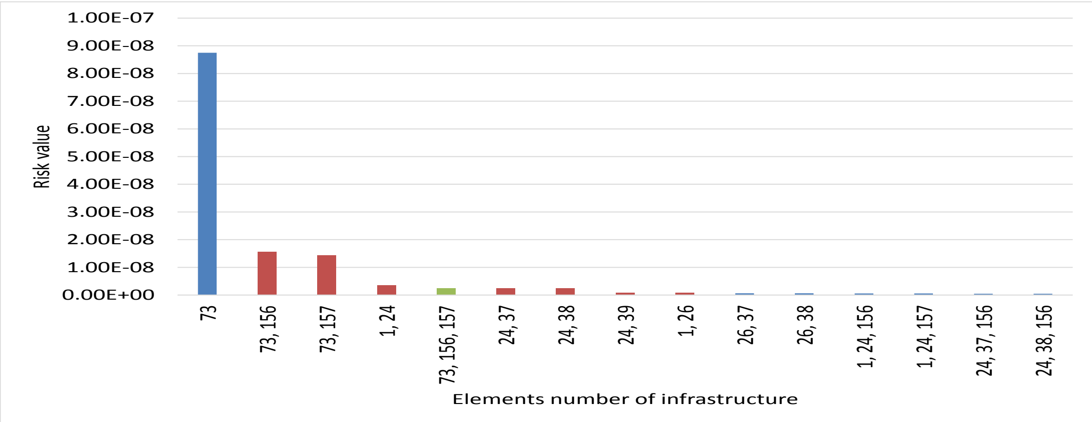

Figure 6. Risk assessment results of combination of elements for DHS of the city A consumers

The risk assessment (N-3 principle) of infrastructure combination showed that there were no combinations with significant risk influence (concerning the probability of rare events). The risk of these combinations is lower than $1.26 \cdot 10^{-8}$, but the criticality value of these combinations is from 0.38 to 0.61.

Similar situations are in risk assessment for the DHS of the analysed cities. The results are presented in *Figure 5* and *Figure 6*.

There is one gas supply system element z^{73}, which has a relatively large impact for the satisfaction of consumers heat energy demand of the city A (*Figure 5* and *Figure 6*). The risk (and criticality) arising from this element is the highest comparing with other elements (or combination of elements) of infrastructure. The risk value of this element is $8.74 \cdot 10^{-8}$. The risk of the combination of infrastructure elements (N-2 and N-3 principle) is lower than $1.55 \cdot 10^{-8}$.

The results of criticality assessment and risk assessment for city B consumers are presented below.

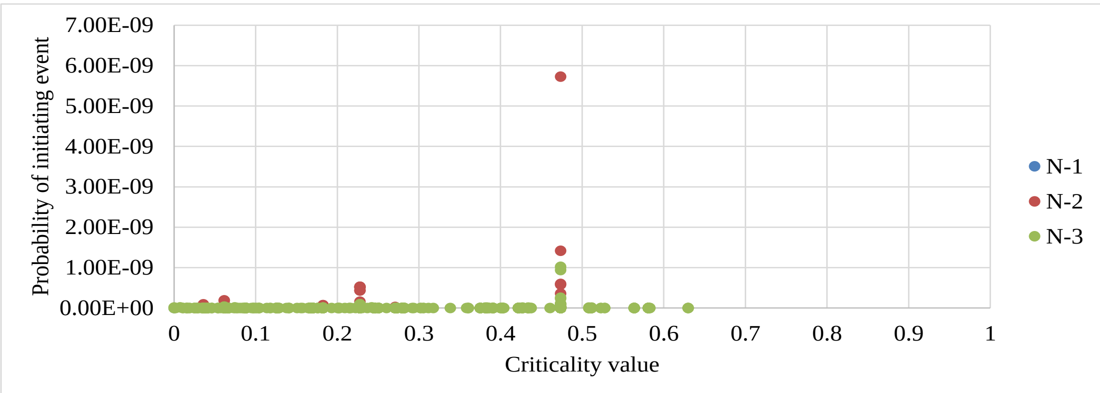

Figure 7. Criticality results of combination of elements for the city B consumer

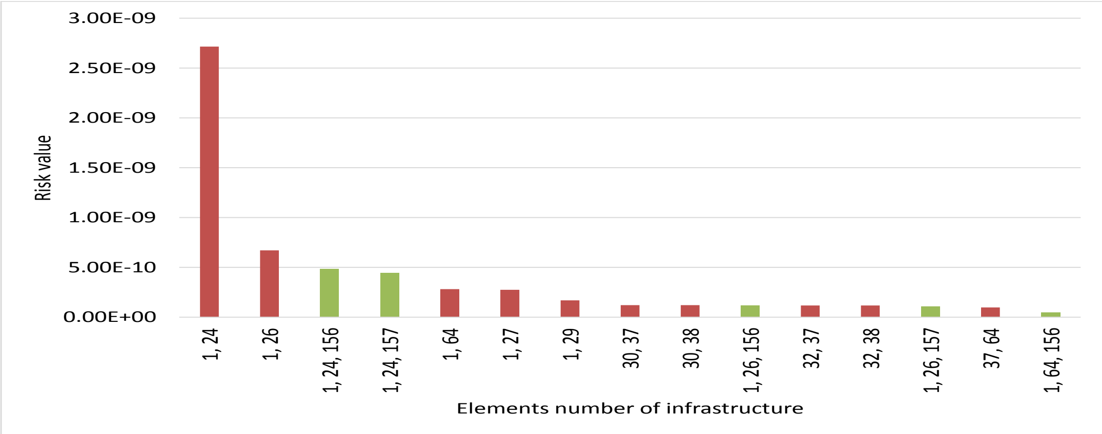

Figure 8. Risk assessment results of combination of elements for DHS of the city B consumers

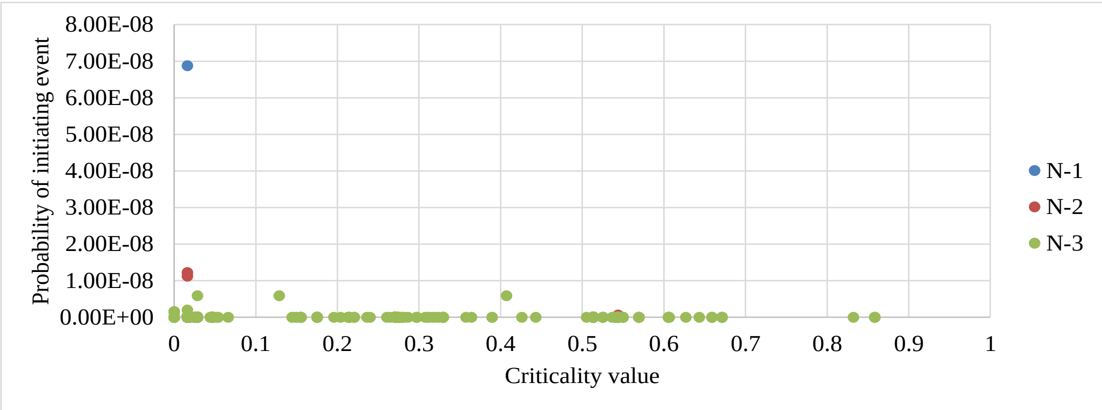

Figure 9. Criticality results of combination of elements for the city C consumer

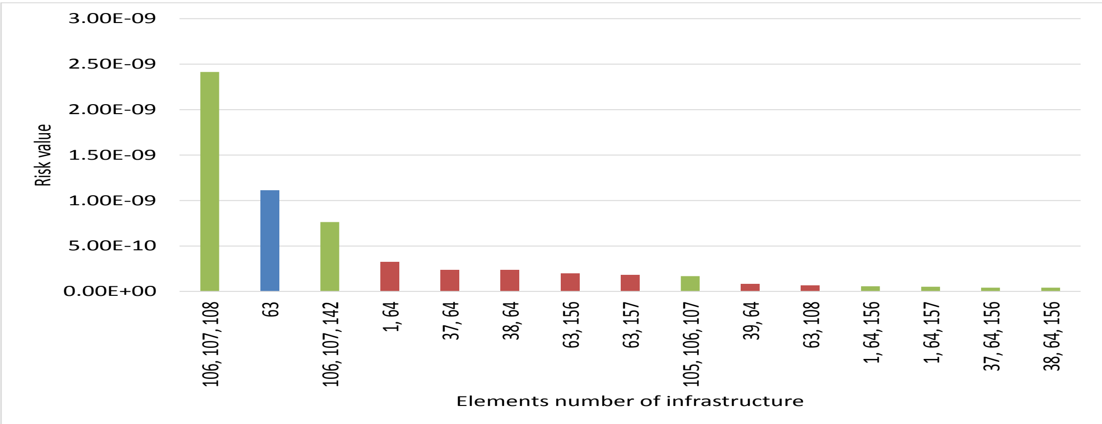

Figure 10. Risk assessment results of combination elements for DHS of the city C consumers

The assessment showed that DHS of city B is sufficiently reliable, there is no critical element (N-1 principle), and the risk value of infrastructure element combinations is lower than $2.71 \cdot 10^{-9}$ (*Figure 7* and *Figure 8*). The similar situations are in the risk assessment for the DHS of the city C.

The risk value of infrastructure element combinations is lower than $2.41 \cdot 10^{-9}$ (*Figure 9* and *Figure 10*). The results of criticality assessment and risk assessment for city D consumers are presented below.

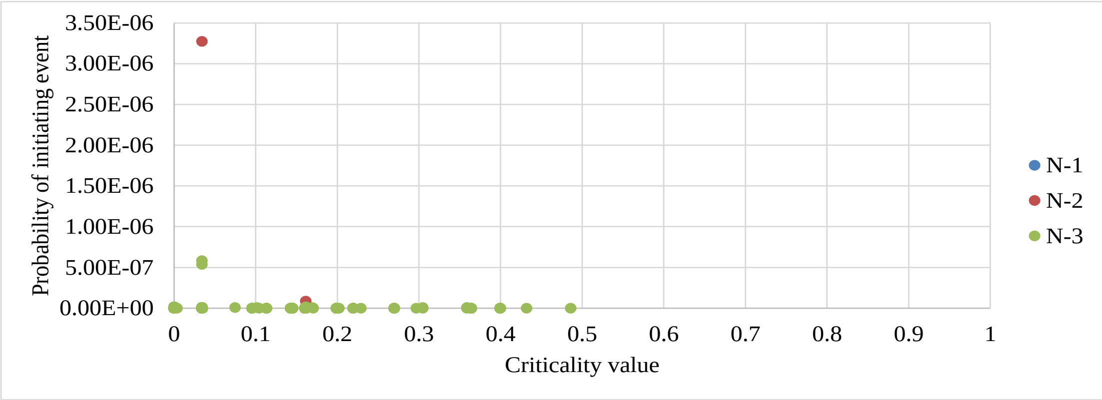

Figure 11. Criticality results of combination of elements for the city D consumer

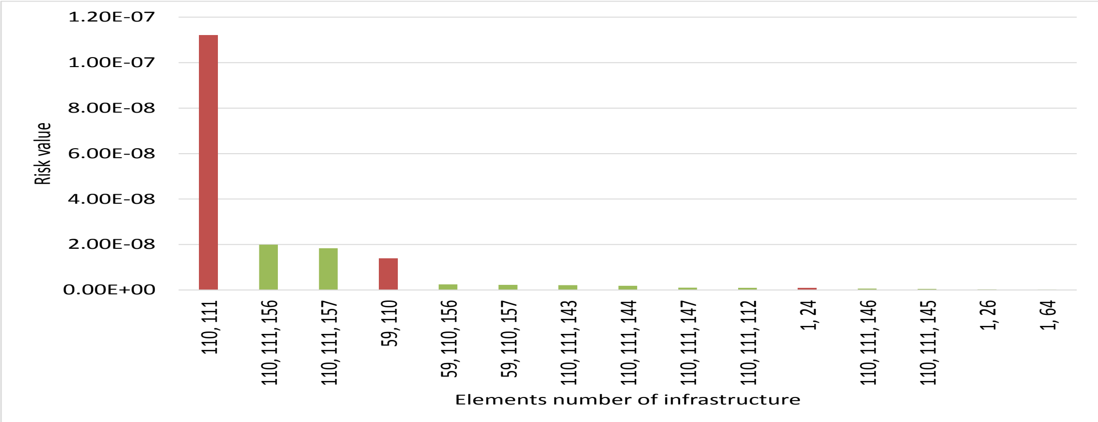

Figure 12. Risk assessment results of combination of elements for DHS of the city D consumers

The assessment shows that DHS of city D is sufficiently reliable (*Figure 11* and *Figure 12*), there is no critical element (N-1 principle), and the risk value of infrastructure elements combinations is lower than $1.12 \cdot 10^{-7}$.

The similar situations are in the risk assessment for the DHS of city E and city F, there is no critical element (N-1 principle). The results of criticality assessment and risk assessment for city E and city F consumers are presented below (*Figure 13, Figure 14, Figure 15, Figure 16*).

The risk value of infrastructure combinations of elements for DHS of city E is lower than $3.96 \cdot 10^{-9}$, and the risk value of infrastructure combinations of elements for DHS of city E is lower than $1.2 \cdot 10^{-6}$.

In summary, the greatest risk (for the infrastructure elements for power system and DHS of analysed cities consumers) caused by the most common combinations of infrastructure elements { z^1, z^{73}, z^{64}, z^{24}, z^{26}, z^{37}, z^{38}, z^{27}, z^{114}, z^{29}, z^{30}, z^{39}, z^{110}, z^{123}, z^{156}, z^{157}}. The elements of these combinations are the elements of gas supply system (which is one-pipe natural gas supply section (where the two-pipe system moves into the one-pipe system)) and the power and heat generation technologies with the highest power capacity.

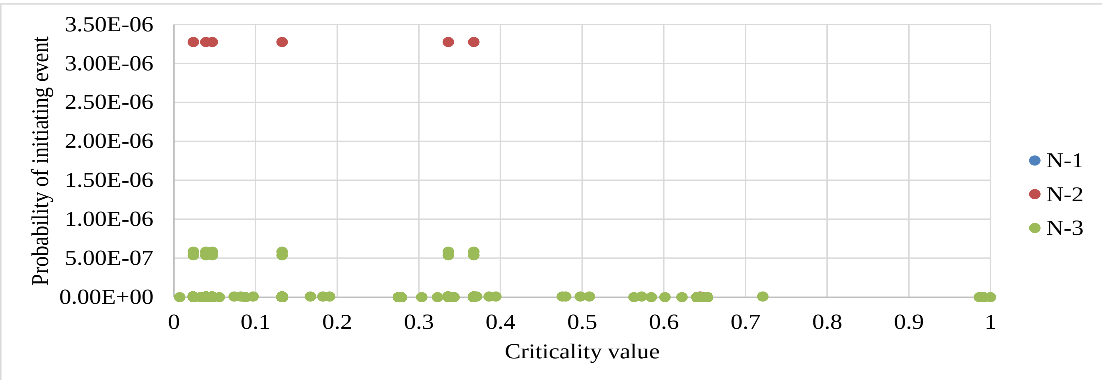

Figure 13. Criticality results of combination of elements for the city E consumer

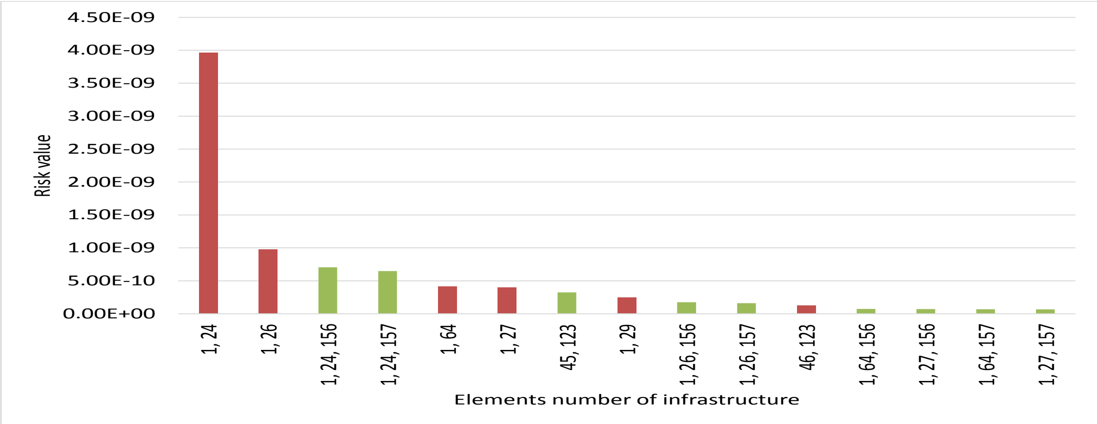

Figure 14. Risk assessment results of combination of elements for DHS of the city E consumers

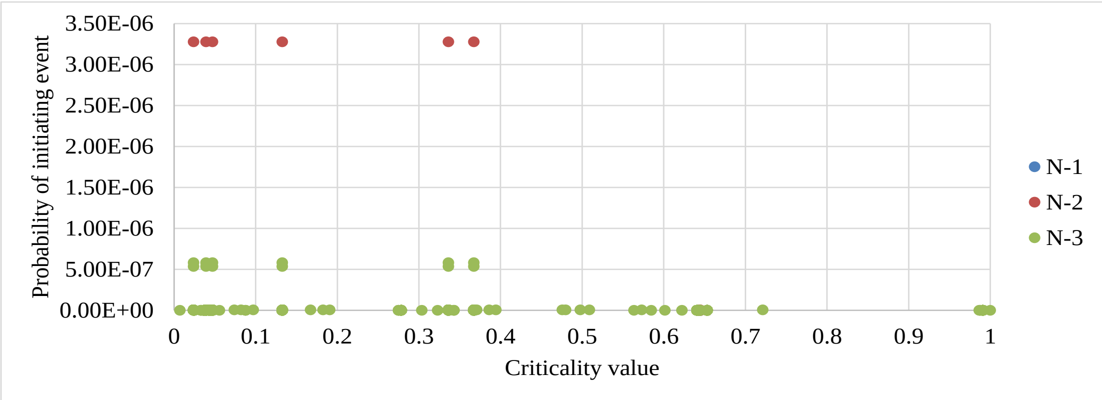

Figure 15. Criticality results of combination of elements for the city F consumer

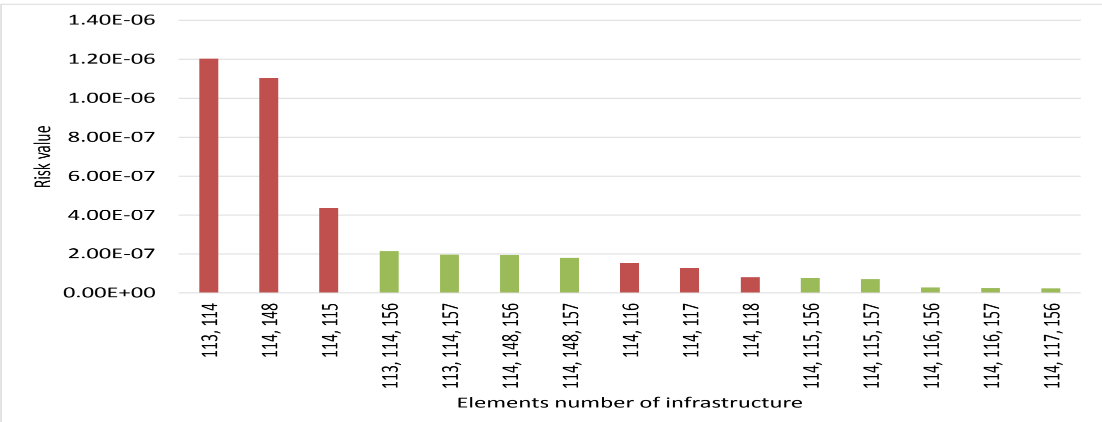

Figure 16. Risk assessment results of combination of elements for DHS of the city F consumers

4. Conclusions

The paper describes the approach of risk assessment methodology of energy infrastructure for the aggregate energy sector model. This approach for risk assessment of energy infrastructure allowed easily identifying mostly critical and high risk elements and their combinations, but this approach assessed the risk considering only the reliability of the infrastructure availability. The probabilistic risk assessment should be adjusted in future works, and the uncertainty analysis as well. The model is useful for comparison and assessment of the influence of different energy infrastructure elements for final energy consumers, new development plans of energy system infrastructure.

In order to reduce the criticality of these elements (and combinations) and their impact on the risk of segments of the pipeline system, taking advantage of the risk-based decision, it is recommended to duplicate pipeline segments or otherwise ensure their greater reliability for the independence of various energy systems.

References

[1] Augutis, J. *et al*. (2015). The assessment technology of energy critical infrastructure. *Applied Energy*. (In press).

[2] Cagno, E. *et al*. (2011). Risk analysis of underground infrastructures in urban areas. *Reliability Engineering & System Safety*, 96, Issue 1, Pages 139-148, ISSN 0951-8320.

[3] Correa, G.J. Ir J.M. Yusta, (2013). Grid vulnerability analysis based on scale-free graphs versus power flow models. *Electric Power Systems Research.* 101, 71-79. ISSN 0378-7796.

[4] EGIG. 8th Report of the European Gas Pipeline Incident Data Group, 1970-2011, Doc. Number EGIG 11.R.04022011. <http://www.egig.eu/>

[5] Henneaux, P., *et al*. (2013). Blackout Probabilistic Risk Assessment and Thermal Effects: Impacts of Changes in Generation. *IEEE Transactions on Power Systems*, 28, 4722-4731. ISSN 0885-8950

[6] Homeland Security. (2009). *National Infrastructure Protection Plan*. <http://www.dhs.gov/files/programs/editorial_0827.shtm>

[7] Johansson, A., *et al*. (2009). The typology for allocations of societal risk and safety management tasks at the local governmental level – Framing the current directions in Sweden. *Safety Science*. 47, 680-685. ISSN 0925-7535.

[8] Kjølle, G.H., *et al*. (2012). Risk analysis of critical infrastructures emphasizing electricity supply and interdependencies. *Reliability Engineering & System Safety*. 105, 80-89. ISSN 0951-8320.

[9] Ministry of Energy of the Republic of Lithuania. (2011) Monitoring report on security of supply in the Lithuanian power market. <http://www.enmin.lt/lt/>

[10] The Council of the European Union, Council Directive 2008/114/EC of 8 December 2008. Official Journal of the European Union, 2008.

[11] The Lithuanian District Heating Association. (2012). Review of the economic performance of heat supply associations in 2011. <http://www.lsta.lt/>

[12] UTNE, I.B., *et al*. (2011). A method for risk modeling of interdependencies in critical infrastructures. *Reliability Engineering & System Safety*. 96, 671-678. ISSN 0951-8320.