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Article

Resilience of socio-ecological and energy systems: Intelligent information technologies for risk assessment of natural and technogenic threats

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Abstract: A method for studying the resilience of energy and socio-ecological systems is considered; it integrates approaches developed at the International Institute of Applied Systems Analysis and the Melentyev Institute of Energy Systems (MESI) of the Siberian Branch of the Russian Academy of Sciences. The article discusses in detail the methods of using intelligent information technologies, in particular semantic technologies and knowledge engineering (cognitive probabilistic modeling), which the authors propose to use in assessing the risks of natural and man-made threats to the resilience of the energy sector and social and ecological systems. More attention is paid to the study and adaptation of the integral indicator of quality of life, which makes it possible to combine these interdisciplinary studies.

Keywords: risk assessment; the quality of life; energy and environmental safety; ontology; cognitive and probabilistic modeling; Bayesian Belief Network; machine learning

1. Introduction

Recently, there has been great interest in the direction defined by the term “resilience”, as opposed to “sustainability”. Until recently, Russian research was more focused on studying issues related to technical sustainability. In Western European countries, the focus on sustainable development has been more interdisciplinary, including studies of psychological, environmental, economic and social systems. The factors that foreign authors consider as criteria when assessing social resilience correspond in their importance and degree of importance to the factors that Russian scientists highlight in their works.

Many scientists believed that man-made and natural hazards were primarily inherent in the energy security of countries. But we believe that these risks are extremely important and should also be taken into account when assessing the resilience of technical systems.

We consider the growing number of natural hazards in the world and the associated increase in the number of negative consequences and economic losses for many countries and regions, in particular, to be another challenge that requires more rigorous risk assessment and the development of appropriate risk reduction measures. The significant danger of such threats lies in their very real potential to trigger emergencies that could cause multiple accidents in the energy sector, including cascading accidents. And, of course, it is an indisputable fact that the energy sector more than any other infrastructure affects the quality of life of residents in any region.

In the resilience studies scientists should analyze the goals of the energy transition, one of which is maximizing the use of renewable energy sources. It is also necessary to take into account the fact that there is increasingly a metamorphosis of energy consumers into energy producers, i.e. the energy system is gradually becoming decentralized (Antonov, 1990; Voropay, 1991). Thus, the consumer not only receives electricity from the manufacturer, but also supplies it back to the electrical network, and this can significantly affect the reliability of the power system. This entails a change in the requirements for the energy transmission system (Afanaseva et al., 2023; Makarov and Voropay, 2018).

One of the problems considered in the resilience studies of energy systems is the difficulty of constructing adequate mathematical models of weakly structured systems for these studies. As the consideration of social-ecological systems aggravates this problem, in this work we propose the use of intelligent information technologies based on semantic models, namely cognitive and probabilistic (with the participation of Bayesian Belief Networks). All proposed technologies relate to knowledge engineering, which in turn allows using of formalized expert knowledge when modeling various situations, which is especially important in interdisciplinary research. This approach allows us to partially offset the lack and possibility of using traditional mathematical models.

The main goal of this study is to identify indicators of resilience of energy and socio-ecological systems, adapt methods for assessing the risks of man-made phenomena and natural disasters for the resilience of energy and socio-ecological systems using intelligent information technologies.

2. Overview of current research and methods used to determine resilience

The definition of resilience has many interpretations depending on the subject area. For example, Arefiev et al. (2022) defines resilience as the ability to recover from shocks and continue to function, and Nevskaya et al. (2023) describes it as the ability to adapt to change and overcome difficulties. Cimellaro et al. (2010); Ilyushin and Kapostey (2023); Ilyushin (2022); Nan et al. (2014) define resilience as the ability to maintain stability and functioning despite external influences. Davoudi (2012); Wang et al. (2016); Z. Wang et al. (2017) highlight the importance of resilience as a coping mechanism for people facing adversity. Holling (1996); Ilyushin (2022); Pashkevich and Danilov (2023) pay special attention to the role of resilience of ecological systems. Golovina and Karennik (2021) highlight the positive aspects of resilience, describing it as a strength that allows people to overcome challenges and move forward. In general, resilience can be understood as the ability to adapt, recover, and grow in the face of adversity, injury, or other challenges. This is a complex and multifaceted concept that can take different forms depending on the context and specific needs of the individual or system (Arefiev and Afanaseva, 2022; Ilyushin and Kapostey, 2023; Nevskaya et al., 2023). Cimellaro et al. (2010); Nan et al. (2014) view “resilience” as an individual's ability to successfully cope with personal experiences and avoid traumatic mental health consequences. The authors use Davoudi's definition of resilience (Davoudi, 2012).

Ecosystem resilience refers to the ability of a system to absorb disturbances and reorganize as it experiences change. This concept was first proposed by Wang (1952) in 1952 and developed by Z. Wang and his colleagues (2017) in 2017.

Many scientists see a significant correlation between disaster risk reduction and social resilience (Semenova et al., 2022; Semenova and Martínez Santoyo, 2024). Also, many researchers highlight corporate resilience separately. This applies not only to the financial strength of a company, but also to the area of thought and practice in which companies work to increase the longevity of ecosystems (and the natural resources they provide); society (and the cultures and communities underlying business activities); and economics (which provide the managerial, financial, and other market context for corporate competition and survival) (Cherepovitsyn et al., 2021; Luebeck, 2019; Ponomarenko et al., 2022).

When talking about the resilience of energy systems, we apply the so-called 4 Rs concept of resilience developed by Cimellaro (2010): Robustness, Redundancy, Rapidity, and Resourcefulness.

The main methods for studying resilience come down to studying the resilience of technical systems that have clear evaluation criteria. At the same time, to study weakly structured systems, it is logical to use artificial intelligence methods that are aimed at working with expert knowledge.

In the article, the authors consider resilience of socio-ecological systems through the concepts of energy security and quality of life. These concepts will be discussed in more detail below.

3. Energy and environmental safety

Energy security (ES) is understood as the state of protection of citizens, society, the state, and the economy from threats of energy resource shortages caused by internal and external factors, while providing their reasonable energy needs with economically available fuel and energy resources of acceptable quality under normal conditions and under emergency circumstances, as well as from violations of stability, uninterrupted fuel and energy supply (Bykowa et al., 2023; Kirsanova et al., 2021; Lebedev and Cherepovitsyn, 2024; Nevskaya et al., 2021). Many scientists have formulated and analyzed factors that can become strategic threats to energy security, for example, natural disasters (Radoushinsky et al., 2023; Tsyglianu et al., 2023; Tsyglianu et al., 2023). Previously, the focus of scientists was on managerial, economic and foreign policy threats (Golovina and Grebneva, 2022; Pyatkova, 2011; Senderov et al., 2017; Voropay et al., 2013).

To ensure the country's energy security, it is necessary to at least significantly reduce, if not minimize, the impact of natural disasters on the electric power system (EPS). This helps to reduce the risk of serious system failures, since they have a significant impact on people's quality of life. Risks that are emphasized include tornadoes, flood waters, earthquakes, and drought seasons. These events can cause additional load on the system, leading to system failures. Climate change is also a major contributing factor to the increasing frequency and severity of these natural events. This can put even more stress on the EPS, potentially leading to even more system failures.

The Energy Security Doctrine of the Russian Federation, approved by Decree of the President No. 216 dated 13 May 2019 defines the potential harm to the life and health of citizens, which must be taken into account when studying resilience of technical, socio-ecological and other systems.

Ignatenko and Afanaseva (2023) emphasize that, given the significance of natural risks for energy security, it is extremely important to take into account resilience of ecological systems. Natural disasters need to be assessed for their likelihood of becoming more frequent; and strategies to prevent them must be developed.

Numerous publications discuss natural disasters in Russia: Lake Baikal (Ivanova et al., 2016; Saneev et al., 2016), the Arctic region, which are examples of natural objects that should be given special attention in these circumstances (Babyr et. al., 2024; Dmitrieva et al., 2023; Fadeev et al., 2021; Golovina et al., 2023). Also, the introduction of renewable energy sources is very important for these territories.

Several natural disasters are known to cause cascading failures in power systems, including earthquakes, hurricanes, floods, and heat waves (Lvov and Chitalov, 2020; Lvov et al., 2022; Martirosyan et al., 2021). According to recent data, climate change is causing natural disasters that can cause system failures. Over the past ten years, the number of system accidents has steadily increased, affecting an increasing number of people in many countries.

The concept of intelligent energy systems (IES) or “Smart Grid” has increased the relevance of this issue (Nan et al., 2014). In particular, decentralization of management greatly affects the reliability of energy systems, which in turn carries risks of causing damage to environmental systems in the event of accidents.

We will also integrate these models and evaluate the impact of these disruptions on other systems. This will be done by applying knowledge engineering techniques. By these methods we will be able to justify directions and measures to improve resilience of these systems.

4. Integral indicator of quality of life

Standard of living is not the same as quality of life. The quality of a person’s life is determined both by what he has and how he perceives it.

Health, safety, living conditions, social interactions, environmental conditions, financial well-being, emotional well-being, self-realization (work, education) are the most important indicators of quality of life (**Figure 1**).

Previously, Massel (2017) presented the methodology for assessing quality of life, based on the SF-36 methodology, which included indicators of the impact of energy supply directly on the integral indicator of quality of life.

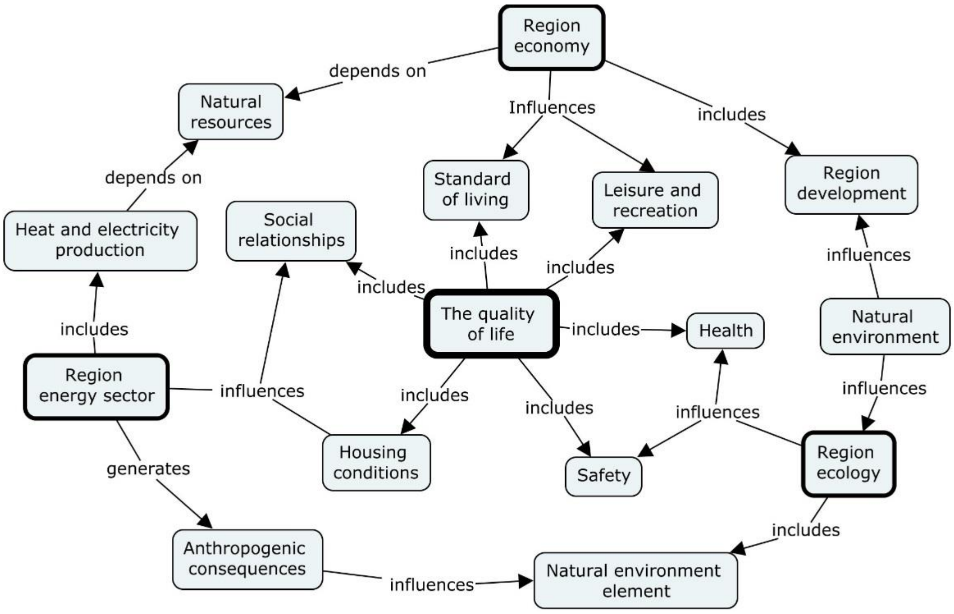

Figure 1. Ontology of quality of life (Source: compiled by the authors).

It is widely accepted that the population is well protected from hazards that could threaten the energy security of a country or a region, and that the standard of living of people cannot be influenced by environmental factors and the availability of energy resources. Russian scientists have never before investigated the risks of natural phenomena that could affect the energy security of a country or a region. Their academic research mainly concerned investment, economics, supply security and logistics (Buyanov et al., 2002; Knight, 2003; Korolev et al., 2011; Orlov, 2008; Savelev and Bataeva, 2015).

To measure the quality of life, subjective and objective indicators are used (Finogenko et al., 2016); therefore, to fully resolve the issue, a qualitative approach to system analysis is required, namely semantic modeling. Silich and Silich (2011) fuzzy calculations attempted. The concept of using cognitive and mathematical models for this purpose was developed (Massel and Komendantova, 2019; Massel et al., 2020). Since the method of joint use of cognitive and mathematical models has proven itself well in quality of life studies, it was proposed to expand the number of technologies through the use of probabilistic models to move on to risk assessment.

5. Approaches and methods proposed to achieve the goals and objectives of the study

During the study the author’s methods for constructing semantic (Bayesian Belief Network, ontological and cognitive) knowledge models were adapted. Intelligent decision support tools developed by the authors are also used.

During the research process, it was proposed to use the following criteria for assessing resilience of energy and socio-ecological systems:

(1) Indicators of energy security of energy systems;

(2) Social and environmental indicators of the environment and society;

(3) Economic indicators of economic growth and development;

(4) Environmental indicators for the conservation of natural resources and biodiversity;

(5) Social indicators for ensuring social justice and equality;

(6) Technological indicators of innovation and adaptation to change. These criteria will help to assess the performance of energy and environmental systems in terms of their resilience;

(7) For ecological systems, quantitative values of maximum permissible concentrations, qualitative values such as CO 2 emissions are taken into account.

The use of the proposed intelligent technologies makes it possible to combine completely disparate criteria for joint assessment of resilience of energy and socio-ecological systems.

The proposed approach will be discussed in more detail in the next section.

5.1. Adaptation of methods for assessing the risk of man-made and natural hazards for resilience of energy and socio-ecological systems

To study resilience, it is proposed to use situational management, which the authors used to create intelligent decision support systems for the energy industry (**Figure 2**).

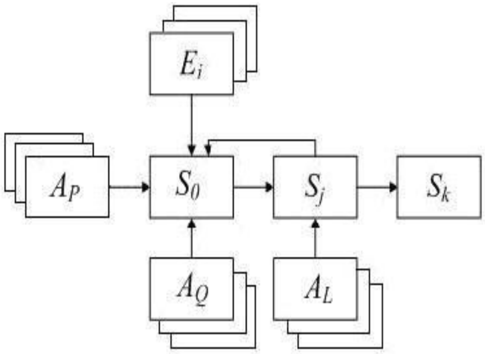

Figure 2. The concept of situational management for resilience research. Source: compiled by the authors.

Comments on figure: A_P, A_Q, A_L—a set of preventive, operational and liquidation measures; E_i,, S_j—state of the system after preventive and/or operational measures; S_k—state of the system after liquidation measures.

The essence of the idea is that in order to transition from the current situation C to the desired state Gg, it is necessary to select a control action U from the class of admissible “A”.

Figure 1 illustrates the return of the system to a stable state after disturbances E_i caused by control actions A, or the transition to another stable state.

The use of situational management methodology allows formalizing the scenario approach and systematizing the creation of a common knowledge base for the subsequent use of simulated situations. That is, based on models of situational management, using semantic technologies, we ultimately obtain formalized models of sets of emergency situations and control actions, which together lead to a stable state of the system. In the future, decision makers can use these models from the knowledge base without additional involvement of experts. This, in turn, significantly speeds up the decision-making process in extreme situations.

The authors use ontological, cognitive and probabilistic modeling (based on Bayesian Networks) to implement the concept of situational management of resilience research from an energy security perspective. Ontologies are used to define the basic concepts in different systems and their relationships with each other, which is very important when experts from different subject areas work. Cognitive models are used to construct scenarios for the development of situations and determine the main factors influencing the situation. Bayesian Networks are used to identify and calculate probabilistic risk estimates. Later in the article, cognitive and probabilistic modeling is discussed in more detail.

5.2. Cognitive and probabilistic modeling for risk assessment

To assess risks, it is proposed to modify and use the strategy previously developed by the project participants and discussed in more detail using the example of assessing cyber security risks in the energy sector (Gaskova and Massel, 2018). This approach combines quantitative and qualitative (based on expert opinions) assessment of the probabilities of damage or destruction of an object, as well as the possibility of cascading accidents.

This approach allows us to build a chain of events that are mutually influenced by different systems, and to link the risks and damage possible in the systems under consideration. The set of risks can be described by three main types: hazards (in this case, natural hazards), vulnerabilities (which are parameters that describe the possibility of damage to the system due to certain external factors) and damage resulting from the threat (the total set of risks; an indicator including social damage caused, for example, by a decrease in quality of life).

A Bayesian Belief Network is used, which displays the dependence of threats (accidents), the consequences of their impact on threats and scenarios for determining the level of risk. The risk level is determined as the product of probability and an integral indicator expressed in monetary terms. Moreover, this approach allows automating the calculation of conditional probabilities depending on the situation and evaluating the effectiveness of the impact of various measures within the framework of changing the level of risk.

Subsequently, all scenarios are divided depending on the level of risk into high, medium and low. Considering the interdisciplinarity of research, taking into account expert qualitative assessments that neutralize the state of uncertainty in the relationships between systems plays a special role. Creating cognitive models or, alternatively, cognitive maps (directed graphs) is called cognitive modeling. Wang (1952), Axelrod (1976) and Pospelov (1981) eventually laid the foundation for cognitive modeling. This approach, first created in the works of Trakhtengerts (1998), is currently being actively researched to study the factors influencing the management of weakly structured situations.

The cognitive map “Accidents, explosions and fires”, created using the author’s CogMap tool, is presented in **Figure 3**.

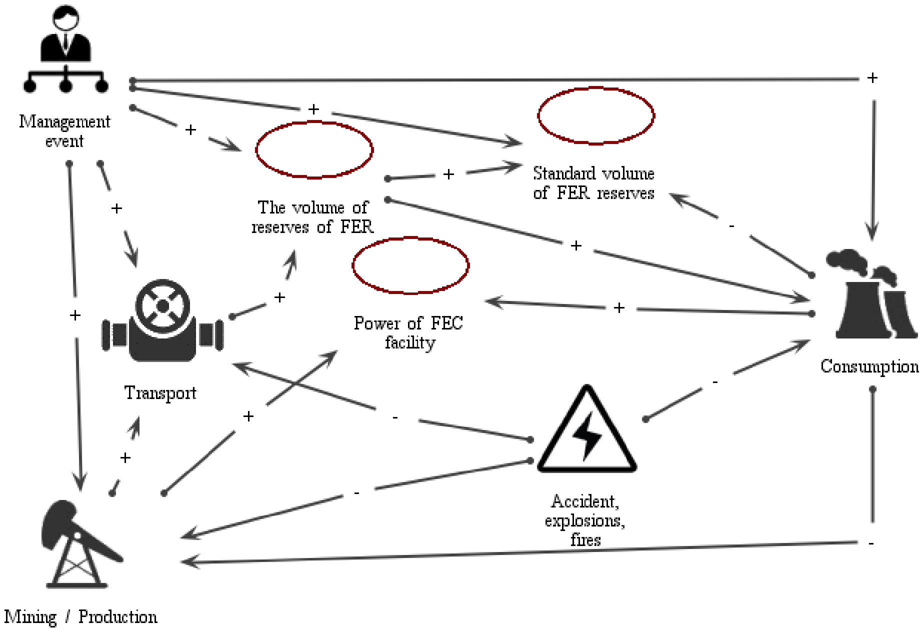

Figure 3. An example of a cognitive map “Accidents, explosions, fires” in the CogMap tool.

Source: compiled by the authors.

Testing the risk assessment of emergency situations in the energy industry and the danger of cyber threats using probabilistic modeling based on the use of Bayesian Belief Networks is discussed in more detail by Gaskova and Massel (2019). By applying this approach, it became possible to link qualitative parameters and quantitative assessment of risks and damages when assessing cyber-attacks on energy infrastructure.

An example related to the natural threat of changes in average temperature on the supply of energy resources to consumers and the probabilistic model based on it are shown in the cognitive model of environmental hazard “Coldness” (**Figures 4** and **5**).

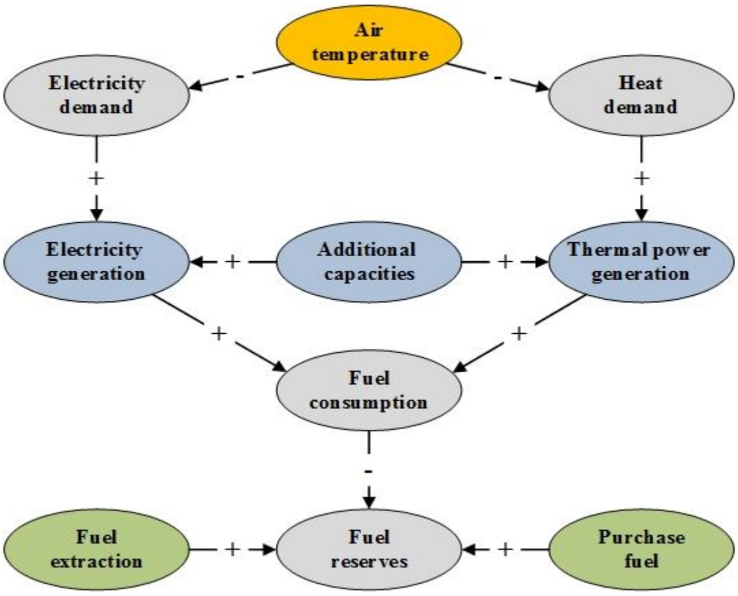

Figure 4. Cognitive map of the threat “Coldness”.

Source: compiled by the authors.

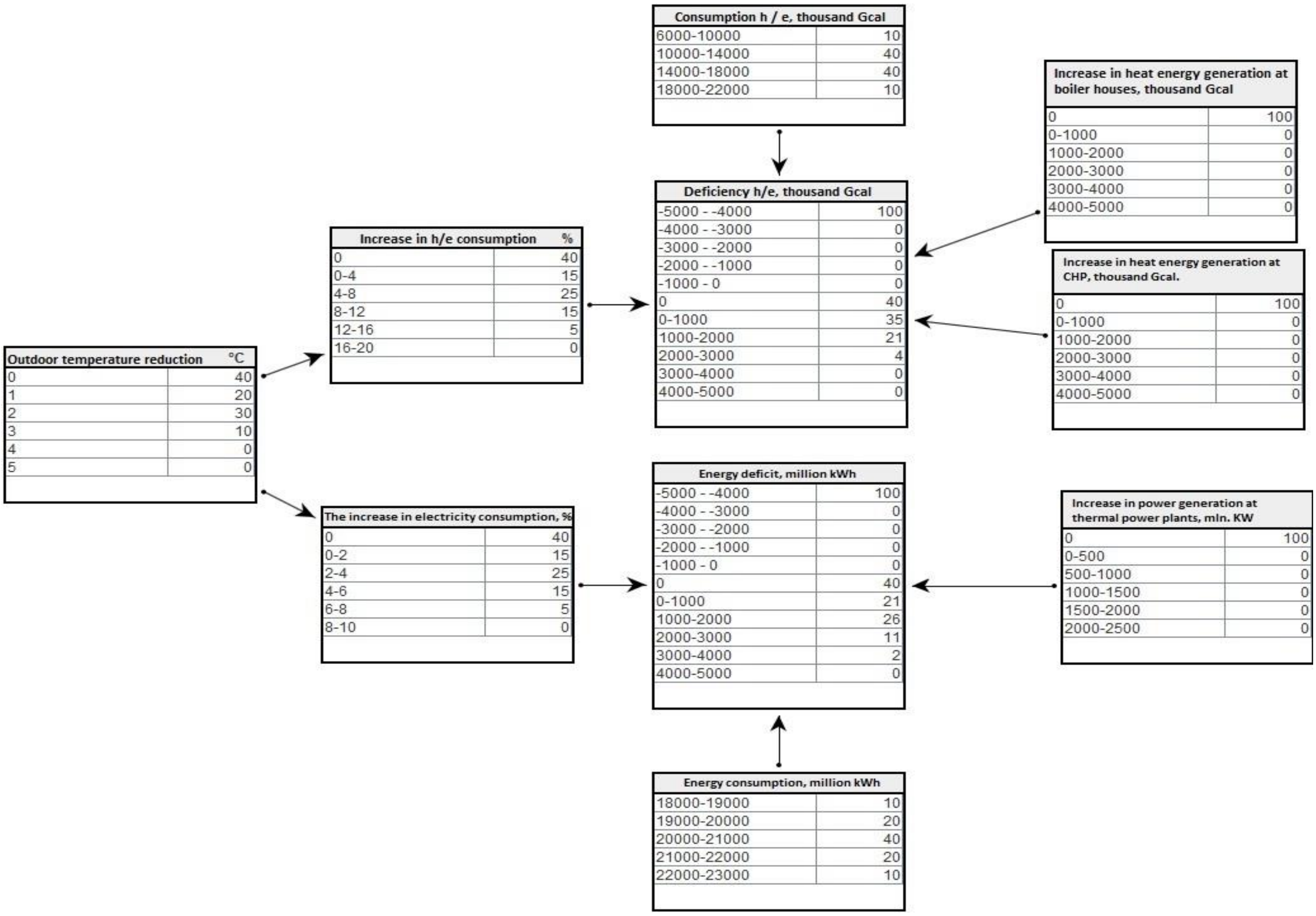

Figure 5. Bayesian Belief Network “Coldness Threat”.

Source: compiled by the authors.

The works (Massel et al., 2020; Komendantova et al., 2021) consider the cognitive map of the integral indicator of quality of life, on the basis of which we can integrate semantic models of energy, social and environmental systems.

The use of cognitive and probabilistic models taking into account an expanded methodology for assessing the quality of life, including an indicator of energy resource availability, allows combining studies of resilience of energy and socio-ecological systems. Moreover, this approach allows us to simulate various natural and anthropogenic factors that have both explicit and implicit influence on energy and socio-ecological systems. Due to the absence or small amount of data on the influence of natural factors on energy and socio-ecological systems, or their slight correlation, the use of expert knowledge in modeling, its formalization and the possibility of use in the future comes first.

6. Conclusion

The article discusses a method for incorporating research into resilience of energy and socio-ecological systems. Such integration is achieved by calculating the integral parameter “quality of life”, which takes into account the influence of energy and socio-ecological systems on human well-being. In addition, the use of intelligent information technologies to assess the risk of natural and man-made hazards to resilience allows the joint application of both quantitative and qualitative assessment methods. This approach initially relies on cognitive and probabilistic modeling methods. The research discussed in this article builds on and extends the authors' previous work, which is described in detail by Massel and Komendantova (2019) and Massel et al. (2020).

The novelty of the proposed approach will be assessed. To evaluate the risks associated with natural and man-made hazards to resilience, it will first be necessary to integrate qualitative (smart) methods (based on semantic and probabilistic modeling) and quantitative methods (mathematical modeling and indicative analysis). Massel and Komendantova (2019) suggest this. Machine learning techniques and genetic algorithms will be used to restore systems to a stable state after shock events, as well as the concept of situational management from resilience studies. Third, integrating research into resilience of energy and socio-ecological systems, taking into account the concept of "quality of life", will be important.

Systemic risk assessments often consider only a few components. The requirement for experts from many fields of knowledge to collaborate makes comprehensive risk assessment difficult, and the use of mathematical models is often impractical due to significant uncertainty (Massel et al., 2020). We can formalize and leverage expert knowledge using semantic models in risk assessment, and we can incorporate data from cross-disciplinary research methods to create cognitive and Bayesian models.

On the other hand, the authors proposed an adaptation of the idea of situational management based on machine learning within the framework of risk assessment. The main difference of this method is the use of qualitative risk assessment results in addition to actual data sets (Massel and Komendantova, 2019). By applying and formalizing expert judgment in creating control actions, this can help identify data at an aggregate level and eliminate problems of uncertainty.

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