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Energy mix optimization from an energy security perspective

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ABSTRACT

In this article, an integrated methodology is presented to assess an optimal mix and perspective development of energy generation technologies not only by technical, economic or other criteria, but also from an energy security perspective. The energy security is evaluated in terms of energy system resistance to disturbances. The methodology comprises several models, such as a stochastic model of energy systems disturbance parameters, economic-optimization model of energy systems functioning, metric and analysis techniques of energy security. The perspective development and functioning of the energy systems with stochastic disturbances is modelled using economic-optimization model with the development of different energy generation technologies. An open source energy modelling system is used as a tool for this model. The concept of energy security coefficient, which is calculated to assess energy security in terms of energy price increase and the amounts of unsupplied energy due to the disturbance consequences, is presented in the article as well.

The developed methodology is applied to the case study of the reference energy system. Its various development scenarios with different energy generation technologies are analysed according to the share of technologies in the energy production. Scenarios are simulated in the stochastic environment of various disturbances and results are obtained in terms of variation of energy security coefficient over time by comparing scenarios from the energy security point of view. Finally, the results of the development scenarios are discussed, threshold shares in the energy production and optimal mix of energy generation technologies in terms of energy security are proposed, limitations of the case study are identified and some general conclusions are given.

1. Introduction

The energy security of a country depends on a number of factors, which have different impact in due time and are often inter-dependent. An adequate level of energy security is vital to the functioning of a modern economy and is one of the main guarantees of national security since reliable energy supply is needed for the assurance of industry activity and to meet the needs of people. Planning prospective long-term development potential of the energy systems and supporting energy development projects, it is not enough to evaluate only the economic side of projects. Energy security aspect should be taken into account as well in decision-making for supplying projects, which could enhance energy security [1]. It is necessary to take into account the energy system resistance to potential disturbances arising due to various reasons, and leading not only to the increase in the cost of energy, but also to energy supply restrictions or even interruptions.

Optimal mix of energy generation technologies in planning prospective development of energy systems should be determined not only by technical, economic or other criteria, but according to multiple criteria approach. Energy security as a multiple characteristic must also be included in the decision-making. Technically challenging in the study presented in the article is to develop such methodology that could provide optimal mix of energy generation technologies not by single criteria, such as technical, and economic, but from an energy security perspective as a multi criteria approach. The methodology has to comprise several different methods (e.g. deterministic, stochastic) in order to solve this issue. Currently in the scientific literature, there are no methods that optimize mix of energy generation technologies in the energy system according to energy security criteria, and most of the studies take into account only one of the criteria solving this issue, for example, economic criteria, reliability of energy supply, etc., but the energy security characteristic is not included in the analysis. The authors' contribution to this specific issue is the development

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of new methodology that can carry out the optimization of energy technologies mix from an energy security perspective as multiple criteria, which enable to obtain more reliable and accurate results. Therefore, a new technique, which combines separate methods into a single model, takes into account the internal and external risks and is more versatile than other used methods. Since methodology presented in the article is based on the assessment of energy security, the article continues with a review of the energy security concept and methods of assessment.

Energy security is usually understood as the assurance of the individual consumer's energy needs, securing economic interests of the society and the state from both internal and external threats. It is agreed that to ensure energy security, sufficient different energy supply options are necessary, i.e. diversification of energy sources and their supply should be ensured. In the scientific literature, it is accepted that the concept of energy security is still not clearly defined, but is emphasized rather "blurred" [2], "weak" [3,4], "slippery" or "difficult to define" [5], quite complicated and involves a lot of aspects. A considerable amount of energy security definitions can be found in literature, but it is difficult to identify one that would include all the relevant factors, which are important evaluating energy security and would fully describe energy security and be acceptable to all.

The definition and concept of energy security are analysed and pointed out by International Energy Agency [6], World Energy Council [7] as well as by Winzer [8], Chester [5], Sovacool and Mukherjee [9] and other authors that analyse and clarify the energy security concept by summarizing different literature and provide a list of energy security definitions used worldwide. However, most of the definitions of energy security are characterized by the fact that they require to perform a qualitative energy security analysis and are based on qualitative criteria, which not in all, but in some cases can be rather subjective. It should be noted that energy security is not only related to a reliable energy supply under acceptable prices, but it must include such criteria, which can be measured quantitatively. The detailed analysis of worldwide energy security research, scientific publications, studies, regulatory documents, and the acquired know-how enables to propose a new energy security definition in this article as follows: "Energy security is not only the ability of the energy systems to supply energy to consumers under reasonable conditions and acceptable prices, but also a system ability to resist potential disturbances arising due to technological, natural, economic, sociopolitical and geopolitical reasons." This proposed new definition of energy security enables the transition from a qualitative to a quantitative assessment of energy security.

Both in Europe and worldwide there are currently no universally accepted criteria and methods to quantitatively evaluate allowable energy supply strategic dependence on supply from a country, which due to different reasons may be treated as an unreliable supplier or uses energy and other raw material supply for political purposes. Performed investigations in this field are often confidential and not available in public scientific studies. In most of the studies, energy security is assessed with the individual factors or parameters, for example, according to the diversification of energy sources [10], share of the energy import in total balance [11], available reserves of energy systems [12], energy vulnerability [13], modelling methods of energy system functioning [14], or concentrating only on power system security [15–17], etc. However, in order to increase energy security, risks that derive from energy use, production and imports should be reduced or hedged [18]. In summary, energy security is a complex area of research based on studies of the development patterns of energy systems, analysis of geopolitical situation, modelling of economic processes, analysis of energy system reliability and resistance to energy supply disturbances, statistical and expert research of emergency situations and disruptions in energy systems, risk analysis, assessment of technical, social, political and other consequences.

A variety of methods and models are used for energy security assessment: simple indicators and indicator systems, probabilistic, economic, simulation, geopolitical evaluation, etc. However, in order to quantitatively assess energy security and energy system resistance to disturbances, it is necessary to create a model of energy system functioning, which would characterize all the features as well as the real energy systems with stochastic disturbances. This model should be a simulation or optimization model, which would simulate activity of the energy systems and enable to assess the risk of stochastic disturbances, system resistance to disturbances and consequences.

The most widely used approach is the methods based on the analysis of indicators or indexes. The analysis is mostly restricted by a list of indicators with its metrics, which describes the energy system situation in a particular country or region. Sovacool and Mukherjee [9] have listed 320 simple indicators and 52 complex indicators. After research interviews, survey results, a focused workshop, and an extensive literature review, the authors distinguished five dimensions: availability, affordability, technology development and efficiency, environmental and social sustainability, regulation and governance. For every dimension the authors indicated a set of components and for every component attributed some simple and complex indicators. Moreover, Vivoda [19] points out 7 dimensions and 44 attributes of energy security indicators and Kruyt et al. [4] define 24 simple and complex indicators for energy security.

Geopolitical and socio-political factors are vital for making decisions about energy development plans and assessing energy security. The main task in energy security analysis is to assess the resistance of the existing or planned energy system to different threats, which do not only include technological, natural and economic, but geopolitical and socio-political threats as well. If such threats come into effect, the resulting disturbances could terminate or limit energy and fuel supply to consumers or significantly increase prices.

Another group of methods, which can be used in energy security assessment, is economic analysis, where economic or optimization tools of energy systems can be used in the analysis of development scenarios of energy system with different energy generation technologies. Energy systems simulation or optimization models have some disadvantages as stand-alone models. Bottom–up models are traditionally technology-oriented and treat energy demand as either given, for example, expressed as useful energy demand, or as a function of, for example, energy prices and national income. In the latter case, bottom–up models may be regarded as partial-equilibrium models in the sense that economic equilibrium is achieved between supply and demand for energy [20]. Economic-optimization models can function as a part of bottom–up model group, which also includes optimization, simulation and multi-agent based models (BALMOREL [21], POLES [22], MARKAL [23], MESSAGE [24], LEAP [25], etc.). Optimization models of optimal energy allocation of the conventional energy sources as well as renewable energy sources in the energy systems were developed [26,27]. However, most of the economic-optimization models are designed for separate scenario analysis. The increasing number of such scenarios makes simulation complicated and time-consuming. The mentioned tools are purely deterministic, but energy disturbances have stochastic nature, and there is a need to use the probabilistic methods as well. For this goal, open source tools come useful as the user can change them according to the needs by creating new modules or additional codes. Connolly et al. [28] review 37 energy system modelling tools, but only BALMOREL is indicated as an open source code. Another open source tool known for the authors OSeMOSYS (Open Source Energy