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Dynamic model based on Bayesian method for energy security assessment

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ABSTRACT

The methodology for the dynamic indicator model construction and forecasting of indicators for the assessment of energy security level is presented in this article. An indicator is a special index, which provides numerical values to important factors for the investigated area. In real life, models of different processes take into account various factors that are time-dependent and dependent on each other. Thus, it is advisable to construct a dynamic model in order to describe these dependences. The energy security indicators are used as factors in the dynamic model. Usually, the values of indicators are obtained from statistical data. The developed dynamic model enables to forecast indicators' variation taking into account changes in system configuration. The energy system development is usually based on a new object construction. Since the parameters of changes of the new system are not exactly known, information about their influences on indicators could not be involved in the model by deterministic methods. Thus, dynamic indicators' model based on historical data is adjusted by probabilistic model with the influence of new factors on indicators using the Bayesian method.

1. Introduction

Energy security was first defined in 1913 by Winston Churchill, Minister of the United Kingdom's naval warfare force, who claimed that "assurance of oil supply security lied only in diversity of the supply". First attempts to assess the security of energy supply sources can be quantitatively associated with D.F. Hewet, who in 1926 visited and collected data from 28 European fuel production regions. In 1929, Hewet performed a statistical analysis of the collected data and announced the results of the analysis. In his publication, he correctly predicted when the US oil production would reach its largest volumes. This statistical analysis and the oil production estimate obtained during it can be considered the first statistical model of energy system.

Recent literature on the issue of energy security focuses on broad definition and conceptualization of energy security. Ang et al. [1] surveyed 104 energy security studies and found 83 energy security definitions. They identified seven major energy security themes: energy availability, infrastructure, energy prices, societal effects, environment, governance, and energy efficiency. The most common component in all energy security definitions is "energy availability" (in 82 studies); "infrastructure" (60 studies) and "energy prices" (59 studies) are also among the most important factors defining energy security. The authors finally concluded that the definition of energy security should be revised periodically to reflect changes in priorities or newly emerged threats. In this article, energy security analysis follows such energy security definition: "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's ability to resist potential disturbances arising due to technological, natural, economic, socio-political and geopolitical reasons". This definition of energy security enables to combine both qualitative and quantitative assessment of energy security [2].

In literature, a lot of methods for assessing energy security are proposed. They could be divided into deterministic and probabilistic. As an example of deterministic methods, methods based on energy security assessment with aggregated index could be pointed out. Usually, it combines a set of indicators and presents energy security as one number. First of all, the US Chamber of Commerce could be mentioned. They calculate the index of the US energy security risk [3]. The index combines 37 metrics into four sub-indices that identify the major areas of risk to energy security: geopolitical, economic, reliability and environmental.

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Nomenclature

AM	algebraic method	MAPE	mean absolute percentage error
BM	Bayesian method	PCM	pairwise correlation method
CI	credible interval	pdf	probability density function
LNG	liquefied natural gas	PL	power link
NP	non-stationary process	OLS	ordinary least square method

Wu et al. [4] evaluated the index of energy security, which consists of 14 indicators. Martchamadol and Kumar presented an aggregated indicator of energy security performance [5], which was developed by considering 25 individual indicators representing social, economic and environmental dimensions. Moreover, indicators are used for the assessment of the level of energy security [16]. However, in this research, the methodology has not been developed; it was introduced only as an idea. Furthermore, in [16], first attempts were made to describe dependences of indicators on each other and on time by applying system of differential equations. However, the research practically did not address the issue of calculating coefficients of such system of differential equations. In [17], differential equations have already been used to describe country's economic processes such as GDP, population, energy consumption in the country and other changes that affect energy security.

Probabilistic models are not widely used in the evaluation of energy security. Some theoretical considerations of probabilistic risk analysis in energy security were introduced by EC JRC [6]. Colli [7] developed a probabilistic method of event and fault tree, which allows to assess different forms of energy risks and to compare them. Stochastic programming models are used as probabilistic ones, but they concentrate on the analysis of economic energy system; the review of the methods used in it is provided in the next paragraph. A two-stage stochastic programming model was presented by Zhou et al. [8], where distributed energy systems were analyzed. A similar model was developed by Mirkhani and Saboohi [9], which was realized to assess power generation with uncertain fuel price. However, these stochastic models of energy system are not directly designed for energy security assessment.

Finally, Mansson et al. provided an overview of methodologies used for quantitative evaluations of security of supply [10]. They classified the methodologies according to the flow of energy in the supply chain. One of the main observations was the lack of research on forecasting the quantitative characteristics of energy security.

In addition to the above-mentioned methods, tools combining quantitative and qualitative methods can be found in literature. Ren and Sovacool [11] proposed a decision-making tool based on Fuzzy Analytic Hierarchy Process technique. They investigated the most influential factors affecting China's energy security. Stegen and Palovic [12] proposed another decision-making tool based on four-dimensional model to help policymakers and managers identify suitable suppliers and prioritize the best courses of action for overcoming obstacles. The proposed model is based on timeframe, supply availability, infrastructure constraints and assessment of the political, geopolitical and commercial stability of the remaining candidates.

As a matter of fact, some works on forecasting certain indicators characterizing energy security can be found. For example, Ardakan and Ardehali investigated accuracy of electrical energy consumption modeling and long-term forecasting of electrical energy consumption [13]. For that they used a forecasting method based on artificial neural networks. In paper [14], the authors reviewed various energy demand forecasting models. They distinguished time series, regression, econometric, decomposition, gray prediction, input–output and other models.

In paper [15], the methodology for estimation of energy security level was proposed. The main idea was to collect historical data and present energy security level as an integral characteristic of different energy security indicators. The suggested indicators' method allows evaluating the state of energy security only at certain fixed points of time, i.e. it is a discrete model. However, indicators are usually dependent both on time and on each other, so it is appropriate to establish a dynamic indicator model, by realizing which, all indicator expressions can be obtained as functions dependent on time variable. Also, the proposed methodology is difficult to apply when new development scenarios of the energy system need to be taken into account, where future values of indicators should to be forecasted. Using the expert opinion is the easiest way to do that. However, in order to perform forecasts of a better quality, the fact that there is a correlation between the majority of energy security indicators has to be taken into consideration. These correlations need to be assessed for forecasting the corresponding indicators. Therefore, it is appropriate to establish a dynamic indicator model for the assessment of the level of security of energy supply.

The main objective of this study is to present the methodology for the assessment of the level of energy security using the dynamic indicator model and the Bayesian method for including the expert judgment on new future objects in the model. The developed dynamic indicator model as a tool is effective for estimating the level of energy security in the future both in case of lack of information and when having sufficiently long time series. In this way, it is a tool for decision-makers in planning various scenarios for development of energy systems when it is necessary to evaluate technical, economic and environmental aspects individually, but also to analyze these aspects as a complex through the prism of energy security. In this way, the originality of this work is merging the well-known probabilistic, statistical and differential equation methods into a single dynamic model and their application in the analysis of energy security. The paper proposes four methods for calculating coefficients of the differential equations system of indicators; also, by applying the Bayesian method to the dynamic model, the expert opinion is included. It enables the analysis of various energy system development scenarios, which is important for decision-makers (ministries, politicians, etc.) in planning the further development of energy system.

2. Dynamic model for assessment of energy security

Each indicator is given a variation, and a system of algebraic equations is constructed:

$$\begin{aligned} &I_i(t+\Delta t) - I_i(t) = \sum_{j=1}^{N} a_{ij} I_j(t)\Delta t, \quad i = 1,\dots,N, \\ &\Delta I_i(t) = \tfrac{I_i(t+\Delta t)-I_i(t)}{\Delta t} = \sum_{j=1}^{N} a_{ij} I_j(t), \quad i = 1,\dots,N, \end{aligned} \tag{1}$$

Here I_i, $i = 1, \dots, N$ is the indicator of energy security assessment, a_{ij} – coefficients that can be calculated employing both statistical and algebraic methods.