MODELING OF ENERGY SYSTEM SUSTAINABILITY INDEX

by

Naim H. AFGAN, Maria G. CARVALHO,
and Nikolai V. HOVANOV

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Sustainability comprise complex system approach in the evaluation of energy system state. By its definition sustainability include definition of quality merits without compromising among different aspect of system complexity. It is of paramount importance for any energy system as the complex system to quantify elements of complexity taking into a consideration various degree of complexity.

Energy conversion process is characterized by the entropy production as the measure of the irreversibility of the processes within the energy system. So, the complexity element of the energy system reflecting internal parameter interaction can be defined by the entropy production in the system.

Complexity elements of the economic indicators are structured in different levels are intrinsic to the specific levels and are measured in different scale. The economic quality is reflecting the finale energy cost. There are a number of parameters which are of interest to be taken into a consideration in the mathematical model for the determination of the optimized values of required for its evaluation .

Mutual interaction between the energy system and its surrounding is immanent for any life support system. As it is known every energy system is taking energy sources from the surrounding and disposing residual to the environment.

In the social aspect of the energy system are included risk of environmental changes, health and nuclear hazards and may have to deal with a compounding of complexity at different level.

Key words: *sustainability, complex system, energy system, resource indicator, economic indicator, technological indicator, environment indicator, social indicator, normalization, agglomeration, aritmetization*

Introduction

Energy system as complex system requires special methodology for the evaluation. Since the complexity of the system is closely related to the multi-dimensional space with different scale, the methodology has to bear multi-criteria procedure in evaluation of the energy system.

The method for multi-criteria evaluation and assessment of energy system have proved to be promising tool for the determination of quality of the energy system. Even it was shown that there are some deficiencies in the presented method, it a new rout in the tracing future analysis of complex system. The energy system is a good example for the identification of the potential sustainability development of energy system. It open new field of research for those willing to dwell for further understanding of the methods for evaluation of complex systems.

Demonstration of the examples of application of the multi-criteria in evaluation potential options of energy system prove that the evaluation of energy system as complex system is the sustainable development research. Associate uncertainty is suggesting that that the research should move toward the search for general principle and guiding questions for new investigation.

The definition sustainability includs definition of quality merits without compromising among different aspect of system complexity [1, 2]. It is of paramount importance for any energy system as the complex system to quantify elements of complexity. As regards complexity elements of energy system it can be codified as the specific structure reflecting different characteristics of the system [3, 4]. The adoption of energy system to its surrounding leads to the physical, social and environmental interaction between the system and its surrounding. If there are number of energy systems to be compared taking into a consideration potential behavior of individual system in the same surrounding there must be potential option which will give quantified quality priority among the system under consideration. In order to define quantity which will be used as measuring parameter in evaluation of the energy systems a following definition of the quantities is adapted [5].

The technology quality of the energy system may be defined and qualified as the potential of the individual part of the energy system. In the language of complex system this property can be understood as the inherent creativity of spontaneous appearance of novel structure. Thermodynamically, information introduced in the system is the negentropy as the result of the change in the structure of system leading to the better performance [13]. In evaluation of the energy system a following quality elements are taken into a consideration.

Resource quality

Energy system is composed of number of elements which are connected with the aim to perform specific function, meaning to convert any form of primary energy into finale form of energy to be used for the improvement of quality of life. Organization of the energy system elements is optimized structure of specific pattern. The energy conversion characterization is thermodynamically justified with optimal internal parameters of the system. In this respect any quantification of thermodynamic quality of the energy system is reflecting number of parameters which are defining the design of energy system. Otherwise, it can be stated the complexity element of the internal parameters of energy system can be defined as the quality of energy conversion measured by the thermodynamic efficiency of the system or any other parameter including integral parameters of thermodynamic system [6]. Energy conversion process is characterized by the entropy production as the measure of the irreversibility of the processes within the energy system. So, the complexity element of the energy system is internal parameter which can be defined by the entropy production in the system. Lately it is becoming popular to make exergy analysis of energy system as the tool for the quality assessment of the system as whole and also determine exergy losses in individual elements of the system [7]. In the complexity definition of energy system one of the element is entropy generation on the system or exergy losses in conversion process [8]. If considering a number of energy systems the entropy generation comparison among systems due its non-linearity will lead to the fuzzy set and will require corresponding procedure for the appropriate evaluation. Indicators for each energy system are property of complex system and their fuzzy set reflects wholeness of the energy system.

Economic quality

Any energy system evaluation has to include economic validation and it has to be basic building block of the assessment procedure [9]. Also, it is indispensable element of the complex system. Quality of energy system for economic validation of the system. as the element of complexity. The main characteristic of the economic quality of the system is defined by the parameters comprising individual elements of complexity. It is usually accepted to determine economic indicator as elements of complexity. For this reason formation of fuzzy set of those indicators for the options under consideration is not trivial and has to reflect different conception of the energy system. The complexity elements of the economic indicator are structured in different levels are intrinsic to the specific levels and are measured in different scale. In the classical evaluation of energy system economic merits are of primary interest. Since, the economic quality is optimization function imposing minimum finale energy cost, there is a number of parameters which are of interest to be taken into a consideration in the mathematical model for the determination of the optimized values of required for its evaluation [10].

Environment quality

Mutual interaction between the energy system and its surrounding is immanent for any life support system [11]. For the energy system there are several interaction which are defined by the respective parameters. On the first places of these interaction is the effect of energy system on the environment. It is known that every energy system is taking energy resources from the surrounding and disposing residual to the environment. Also, most of the energy system is disposing low entropy heat to the environment. It is known that only one tried of the energy is converted to the useful energy, there is two tried of the energy to be disposed to the environment. So the interaction between the energy system and environment defined by the amount of material and energy. The assessment of these interactions between the energy system and environment leads to recognition of the new element of complexity of the energy system. There are ontological changes *i. e.* human-induced changes in the nature proceeding at unprecedented rate and scale and resulting in grooving connectedness and inter dependency. Molecules of carbon dioxide produced in the energy system leads to the global climate changes and adding new element to the complexity of energy system.

Technological quality

Energy system structure organization is subject to the constant development in order to improve its functionality and performance quality [12]. The adoption of the system to new requirements is complementary to the organization changes the property of the complex system. There are numerous studies with mathematical model of energy system through computer simulation which are aimed to predict potential structure of the system and its quality. The process of the energy system development is an attempt to understand how network of mutually acting elements is contributing to the change in the quality of the energy system. The assessment of technological development implies adaptability of complex system to its evaluation. Information technology has demonstrated that its application in the energy system can lead to the intelligent system with self controlling ability. The technological development is one of the properties of complex system. The potentiality for further improvement can be seen as the potentiality for self-organization of the system. The technology quality of the energy system is the element of the complexity of the system. It may be defined and qualified as the potential of the individual part of the energy system and also as the interrelation among the elements. In the language of complex system this property can be understood as the inherent creativity of spontaneous appearance of novel structure. Thermodynamically, the information introduced in the system is the negentropy as the result of the change in the structure of system leading to the better performance [13].

Social quality

Social aspect of the energy system is important factor to define the quality of the system. Beside the adverse effect of the energy system on the environment, it can be also be driving force for the social changes in the region [14]. It can bring new jobs, new investment, new infrastructure and many other advantages in the region. This quality of the system must be defined as the elements of the complexity of the system. The interactions of the energy system with society are properties of the whole, arising from the interactions relationship among the system and surrounding. With a number of energy system options under consideration the social element of complexity of energy system will comprise integral parameters and their evaluation. In the social element of the energy complex system is included risk of environmental changes, health and nuclear hazards and may have to deal with a compounding of complexity at different level. Also, under social constrain reflecting social aspect of complexity of energy system are added values which improve the quality of the human life.

Indicators

In order to develop appropriate tool for the quantitave presentation of the energy system properties it is of interest to introduce notion of the indicators which are measuring parameters of the respective quality [15]. Before, we will introduce individual indicators. The agglomeration procedure is described.

Hierarchical concept of indicators

As it was shown different complexity elements are expressed as the integral property of energy system. For the determination of these elements respective model are used based on the mathematical description of the processes within the system. Once the integral parameters are formed and appropriate scale is defined , the next step in deriving quantitative values complexity elements is the agglomeration of the indicators. There may be number of the indicators levels. Each level will represent platform for the agglomeration in order for the integral property of the energy system. Order to measure these integral properties it necessary to master the respective scale of each component of the complex indicator.

Recently it has become necessary to make assessment of any system taking into a consideration the multiple attributes decision making method. It has been exercised in the number of cases the evolution of systems with criteria reflecting resource, economic, environment, technology, and social aspect [16-18]. A complex (multi-attribute, many-dimensional, multivariate, *etc.*) energy system is a system, whose *quality* (resources, economics, environment, technology, and social) under investigation is determined by many *initial indices* (indicators, parameters, variables, features, characteristics, attributes, *etc.*). Any initial indicator is treated as the quality's , which are made from the point of view of the corresponding *criterion*. It is supposed that these indices are necessary and sufficient for the systems' quality estimation [19].

Let initial ("zero-level", "0-level") indices of fixed energy systems under investigation are:

$$Q(1;0), \ldots, Q(i[0];0), \ldots, Q(m(0);0) \tag{1}$$

where number $m(0)$ of all initial indices is sufficiently large ($m(0) \gg 0$) and include indices of the "zero/level".

Without loss in generality it may be assumed that initial indices meet the *condition of normalization*:

$$0 \quad Q(i[0];0 \quad 1,\ i[0] = 1, \ldots, m(0) \tag{2}$$

As this normalization takes place, the minimal value $Q(i[0];0) = 0$ of $i[0]$-th criterion is correlated with a system, which manifests the minimal degree of the quality under consideration, and the maximal value $Q(i[0];0) = 1$ is associated with a system, which manifests the maximal degree of this quality. So, the complex energy systems are described by values of the $m(0)$-dimensional variable vector:

$$Q(0) = (Q(1;0), \ldots, Q(i[0];0), \ldots, Q(m(0);0)) \tag{3}$$

of the initial indices (the indices of 0-level).

Suppose that these initial indices are aggregated into new *general indices*, which are formed in a $m(1)$-dimensional vector:

$$Q(1) = (Q(1;1), \ldots, Q(i[1];1), \ldots, Q(m(1))) \tag{4}$$

of the first-level (1-level) indices, where $i[1]$-th component $Q(i[1];1)$ of the vector $Q(1)$ is a *synthesizing function (convolution)*:

$$Q(i[1];1) \quad Q(Q(0); i[1];1) \quad Q(Q(1;0), \ldots, Q(i[0];0), \ldots, Q(m(0);0); i[1];1) \tag{5}$$

of the vector $Q(0)$ of initial (0-level) indices.

Then we can form a $m(2)$-dimensional variable vector:

$$Q(2) \quad (Q(1;2), \ldots, Q(i[2];2), \ldots, Q(m(2);2)) \tag{6}$$

of second-level (2-level) indices $Q(i[2];2)$, $i[2] = 1, \ldots, m(2)$, $i[2]$-th second-level index being a function:

$$Q(i[2];2) \quad Q(Q(1); i[2];2) \quad Q(q(1;1), \ldots, Q(i[1];1), \ldots, Q(m(1);1); i[2];2) \tag{7}$$

of the vector $Q(1)$ of 1-level indices.

An example of graph-representation of a 2-height pyramidal hierarchy of indices is pictured on the fig. 1.

The final goal of k-height pyramidal hierarchy of indices consists in estimating of complex energy systems' quality by the unique k-level super-index $Q(1;k)$. So, a pyramidal hierarchy $PH(k)$ produces a *one-criterion determination* $Q(1;k)$ of a fixed quality of complex systems under investigation.

Energy system indicators

In the further analysis we will use indicators instead indices. If it assumed that the Energy System Hierarchy (ESH) of indicators will meet condition:

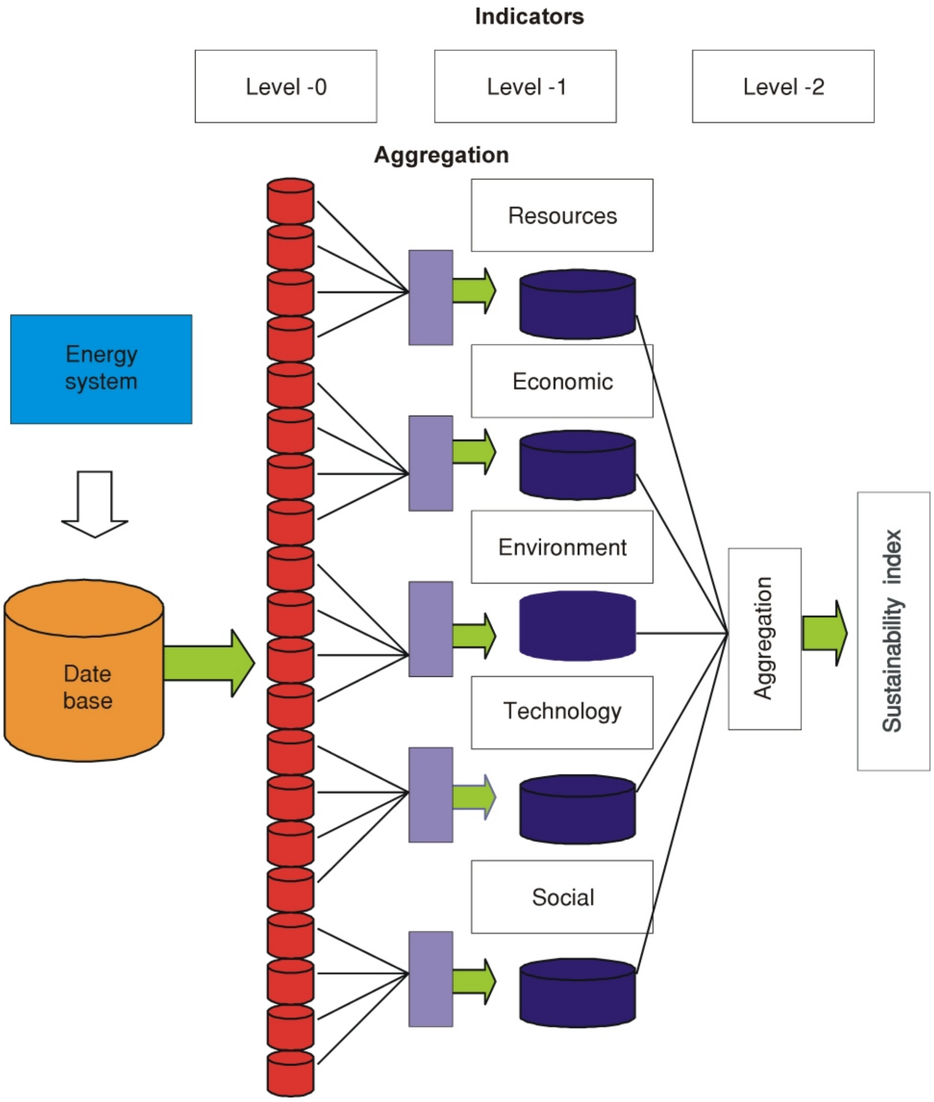

Figure 1. Graphical presentation of the algorithm for the evaluation of energy systems

$$m(0) > m(1) > \ldots > m(t) > \ldots > m(k) = 1, \quad \text{and} \quad m(0) = \mathrm{N}_0, \\ \text{and} \quad m(1) = \mathrm{N}_1 \quad \text{and} \quad m(2) = \mathrm{N}_2 \tag{8}$$

the pyramidal hierarchy of energy system will be reduced to a multi-criteria value of the fixed quality of complex energy systems.

The general index of energy system quality can be used in the evaluation of energy systems in order to obtain hierarchy among the systems under consideration. Figure 1 shows graphical presentation of the algorithm to be used in the in the evaluation of energy systems. Beside universal name for all indices to be indicators of different level and described with respective sub-addition.

Data base is collection of data comprising physical and chemical properties of the material and fuel, geometrical characteristics of element, intensity of the processes, temperature and pressure field within the element of the system, and other characteristics of energy system which are of importance for the determination of indices of "zero level". The date base is used for the calculation of the indices of "zero level". These calculations are based on the respective models which are obtained by the description of the integral characteristics of the energy system.

Once indicators of "zero level" are determined, the next step in this evaluation is the agglomeration of "zero level" indicators into a indicators " level-1". The indicators "level-1" are Resource Indicator, Economic Indicator, Environment Indicator, Technology Indicator, and Social Indicator which are formed as an $m(1)$-dimensional vector.

Mathematical operation for the formation of the indicators of 1-level and 2-level is called aggregation and is defined by the linear additive function of the components of the vector of 0-level and 1-level, respectively.

Suppose that all synthesizing functions from a k-height hierarchy of indices are additive functions:

$$Q(i[t];t) = Q(Q(t-1);i[t];t) = \sum_{i[t-1]=1}^{m(t-1)} w(i[t-1];i[t];t-1)Q(i[t-1];t-1) \tag{9}$$

of $(t-1)$-level indices $Q(i[t-1];t-1)$, $i[t-1] = 1, ..., m(t-1)$.

Non-negative coefficients $w(i[t-1];i[t];t-1)$, $i[t-1] = 1, ..., m(t-1)$, are called "*weight-coefficients*", "*weights*" meet the *normalization condition*:

$$\sum_{i[t-1]=1}^{m(t-1)} w(i[t-1];i[t];t-1) = 1 \tag{10}$$

what permits to interpret $i[t-1]$-weight coefficient $w(i[t-1];i[t];t-1)$ as a *measure of significance* (importance) of the index $Q(i[t-1];t-1)$ for the general estimation $Q(i[t];t) = Q(Q(t-1);i[t];t)$, [20].

The "level-1" hierarchy of indices are being given with the use the recurrent formula to construct indices of different levels in explicit form:

$$Q(i[1];1) = \sum_{i[0]=1}^{m(0)} w(i[0];i[1];0)Q(i[0];0) \tag{11}$$

$$Q(i[2];2)\quad \mathop{}\limits_{i[1]\;\;1}^{m(1)} w(i[1];i[2];1)Q(i[1];1)$$

$$\mathop{}\limits_{i[1]\;\;1}^{m(1)} w(i[1];i[2];1)\quad \mathop{}\limits_{i[0]\;\;1}^{m(0)} w(i[0];i[1];0)Q(i[0];0)$$

$$\mathop{}\limits_{i[0],\,i[1]\;\;1}^{m(0),\,m(1)} [w(i[0];i[1];0)w(i[1];i[2];1)]Q(i[0];0) \qquad (12)$$

If this definition of indices will be applied to the indicators presented in the previous chapter we will be in position to use this methodology and introduce following definition for agglomerated indicators.

Resource indicator

$$RI\quad Q(i[1];1)\quad w^{1}_{i[1]}(0),Q_{1}(0)\quad w^{2}_{i[1]}(0),Q_{2}(0)\quad w^{3}_{i[1]}(0),Q_{3}(0) \qquad (13)$$

Economic indicator

$$EcI\quad Q(i[2];1)\quad w^{4}_{i[2]}(0),Q_{4}(0)\quad w^{5}_{i[2]}(0),Q_{5}(0)\quad w^{6}_{i[2]}(0),Q_{6}(0) \qquad (14)$$

Environment indicator

$$EI\quad Q(i[3];1)\quad w^{7}_{i[2]}(0),Q_{7}(0)\quad w^{8}_{i[3]}(0),Q_{8}(0)\quad w^{9}_{i[3]}(0),Q_{9}(0)\quad w^{10}_{i[3]}(0),Q_{10}(0) \qquad (15)$$

Technology indicator

$$TI\quad Q(i[4];1)\quad w^{11}_{i[4]}(0),Q_{11}(0)\quad w^{12}_{i[4]}(0),Q_{12}(0)\quad w^{13}_{i[4]}(0),Q_{13} \qquad (16)$$

Social indicators

$$SI\quad Q(i[5];1)\quad w^{14}_{i[5]}(0),Q_{14}(0)\quad w^{15}_{i[5]}(0),Q_{15}(0)\quad w^{16}_{i[5]}(0),Q_{16}(0) \qquad (17)$$

It is well known that the most subtle and delicate stage in the general index construction is the stage of determination of "weights" $w(1), ..., w(m)$ because of usual shortage of an information about exact numerical values of the weight-coefficients.

As a rule, we have only *non-numerical (ordinal) information*, which can be represented by a system:

$$OI = \{w(i) > w(j);\ w(r) = w(s), \ldots;\ i,j,r,s, \ldots \quad \{1, \ldots, m\}\} \tag{18}$$

of equalities and inequalities. These relations are interpreted as follows: $w(i) > w(j)$ – i-th indicator $q(i)$ is more significant for objects quality determination by the index $Q = Q(q;w)$ than j-th indicator $q(j)$; $w(r) = w(s)$ – r-th and s-th indices are equal in their significance for objects quality estimation by the index $Q = Q(q;w)$.

The availability of a non-trivial nnn-information I about weight-coefficients permits to reduce the set:

$$W = \{w = (w(1), \ldots, w(m)) : w(i) \quad 0,\ w(1) + \ldots + w(m) = 1\} \tag{19}$$

of *all possible* weight-vectors w to the set $W(I)$ $\quad W$ *all conditionally admissible* (from the point of view of the nnn-information I) weight-vectors.

If it is supposed that a set of all conditionally selected weight-vectors are formed, than these weight-vectors are known "with the precision of the set $W(I)$". So, we have not a unique weight-vector, but a whole set of the vectors. To model such type of uncertainty when a mathematical object x is determined with an accuracy to within an appropriate set $X = \{x\}$ of all admissible variants we shall address ourselves to the *concept of randomization*. So, we'll use the random weight-vector $\tilde{w}(I)$ $\quad (\tilde{w}(1;I), \ldots \tilde{w}(m;I))$ uniformly distributed on the set $W(I)$, as a model of the nnn-information I deficiency. The randomization $\tilde{w}(I)$ $\quad (\tilde{w}(1;I), \ldots, \tilde{w}(m;I))$ of the weight-vector w $\quad (w(1), \ldots, w(m))$ implies the randomization $\tilde{Q}(q;I)$ $\quad Q(q;\tilde{w}(I))$ of a corresponding general index $Q(q;w)$.

It is quite natural to use the average of weight-coefficients, *i. e.* mathematical expectations $\overline{w}(i;I)$ $\quad M\tilde{w}(i;I)$, $i = 1, \ldots, m$. To measure the exactness of weigh-vector $\overline{w}(i;I)$ $\quad M\tilde{w}(i;I)$ we may use the standard deviation $Sw(i;I)$ $\quad [D\tilde{w}(i;I)]^{1/2}$ where $D\tilde{w}(i;I)$ is the variance of the random weight-coefficient $\tilde{w}(i;I)$. The vector $\overline{w}(I)$ $\quad \overline{w}(1;I), \ldots, \overline{w}(m;I))$ may be treated as *a numerical image of the nnn-information I.*

An example of the definition of the sub-indicators for the two level indicators describing the General Index of Sustainability is given on tab. 1.

In the procedure for the sustainability evaluation there are several steps which are importance to be obeyed.

The first step in this procedure is data collection in data base, which imply gathering all relevant parameters to be used in the definition and calculation of the, "zero level" indices. Each sub-indicator is presented in the appropriate dimensions which are not necessary in the same scale. Dimension selection is important for the definition of the accuracy of sub-indicators.

Second step is arimetization. This is mathematical procedure to convert all "zero level" indices in the non-dimensional values. By loosing dimension of the "zero level" indices it will give us possibility to form fuzzy sets representing group of " zero level" indices for respective option under consideration.

Table 1.

"level-1" indecis	"zero level" indices	Parameters
Resource	Fuel – coal – oil – gas – biomass – solar – wind – nuclear Material – steel – cooper – aluminum – silicon	Power Maximum temperature Minimum temperature Reheating temperature Insulation Wind velocity Fuel quality Heating values
Economic	Electricity cost Investment cost Operation cost Maintenances cost Trade balance	Fuel cost Material cost Energy system structure Men-power cost Men-power qualification Life time
Environment	CO_2 production SO_2 production NO_x production Ash production Heat disposal Climate change	Chemical composition of fuel Air quality standard Waste composition Soil degradation Water degradation
Technology	R & D expenditure Hitech funding New market New companies	Man-power in development Potential for hi-tech Energy strategy Energy forecast Labor market
Social	Health effect Living condition New job opportunity Footprint of power plant	Mortality Physical illness Psychological health Education Age equity

The tried step comprise agglomeration procedure. In this step we will form next level of indices. Procedure adapted is based on the nnn information with weighting coefficients determined by randomisation of all conditionally admissible weight coefficient vectors. The formation of "level -1" indices is result of the next step of procedure.

Fourth step is aimed to repeat procedure of agglomeration of indices in order to obtain the second level indices called Sustainability Index of Energy System.

Demonstration of the method have been shown in the assessment of several energy systems. Namely:

(1) Sustainability Assessment of New and Renewable Energy Sources [21],
(2) Sustainability Assessment of Clean Air Technologies [22],
(3) Sustainability Assessment of Hydrogen Energy Systems [23],
(4) Sustainability Assessment of Solar Energy Systems [24], and
(5) Sustainability Assessment of Biomass Energy Systems [25].

Conclusions

Sustainability evaluation of complex system is an approach to assess quality of energy system In this approach the energy system is considered as complex system with respective elements of quality. By the sustainability which included definition of quality merits without compromising among different aspect of system complexity. It is of paramount importance for any energy system as the complex system to quantify elements of complexity taking into a consideration various degree of complexity.

The sustainability Index was used as the measuring parameter in evaluation of the energy systems quality. In this procedure, it was adapted several indicator and respective number of sub-indicators derived from the data base.

The model of sustainability is demonstrated in generic form and graphical presentation. Several examples introduced in the reference list are numerical examples of energy system evaluation.

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Authors' addresses:

N. H. Afgan, M. G. Carvalho
Instituto Superior Tecnico
Lisbon, Portugal

N. V. Hovanov
St. Petersburg University
St. Petersburg, Russia

Corresponding author (N. H. Afgan):
E-mail: nafgan@navier.ist.utl.pt

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