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Article

Sustainability Paradigm: Intelligent Energy System

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Abstract: The promotion of sustainable development is the European affirmation in the international arena and is European policy for the Union. However, the current situation—where the Sustainability is more intention than a practice—risks such European affirmation. In our analysis, we have assumed that the energy system is a complex system, which may interact with its surrounding by utilizing resources, exchange conversion system products, utilizing economic benefits from conversion processes and absorbing the social consequences of conversion processes. Information and communication technologies are recognized as one of the pillars in the development of sustainable global life support systems. Information and communication technologies improve the capability to monitor and manage energy systems and to help to reduce the impact of natural and human-induced disasters through prediction, early warning and registration of potential changes which may lead to the unexpected disasters. With the respective methodology and monitoring system, the resilience of an energy system can be evaluated as the safety parameter of the energy system. In this respect, it is of the paramount importance to introduce the ICT (Information and Communication Technology) in the online evaluation of an energy system. The main attention of this paper is devoted to: (1) Energy efficiency as a complex problem, which has to be defined with an additive function of agglomerated economic efficiency, environment efficiency and social efficiency; (2) Information and communication technologies recognized as the tool for the development of sustainable and safe global life support systems. This comprises monitoring tools for the assessment and evaluation of potential degradation and resilience of the energy system; (3) Multi-criteria evaluation method is verified as an appropriate procedure for the Sustainability Index determination.

Keywords: sustainability; energy efficiency; information system; communication system; energy system

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1. Introduction

A knowledge society is based on the need for knowledge distribution, access to information and the capability to convert information into knowledge. Knowledge distribution is one of the essential requirements of a knowledge society [1].

Knowledge is more than information. It requires information processing with the specific aim to obtain the conceptual understanding of life support systems within a specific cultural system. The global validation of information is immanent to the knowledge society. Thus, the access to the global information pool is the main driving force for the progress of development of sustainability platform [2].

Assessing the progress towards sustainability requires consideration of a plethora of economic, environmental and social issues and equity. At the moment, none of the current popular methodological proposals, which fall within the reductionist paradigm, seem to be able to encompass all these considerations simultaneously [3] Methodological limitations, different concepts of value and new insights from complexity theory and post-normal science leave little room for believing the contrary. The existence of a value system is a prerequisite of any approach for measuring the progress toward sustainability. However, difficulties in either finding an absolute measure of value or obtaining consensus about which value system to use, creates a controversy which so far has eluded resolution [4,5].

Not surprisingly, measuring sustainable development performance and quantifying the progress towards sustainability is currently at the center of an ongoing debate that has strong policy implications and is, thus, progressively moving beyond academia. Over the past years, tools and methodologies based on the reductionist paradigm have been used to measure the progress towards sustainability, but very few of them seem to be able to assess sustainability in a holistic manner at the moment [6,7].

Information and communication technologies are recognized as one of the pillars in the development of sustainable and safe global life support systems. Such technologies improve the capability to monitor and manage systems under consideration and help to reduce the impact of natural and human-induced disasters through prediction, early warning and registration of potential changes which may lead to the unexpected [8].

Sustainability ranges from policy making, at the top, to engineering practices at the bottom [8]. No policy, in a top-down approach, may be successful if not served by the tools, methods and skills that may make it real in practice. The present method intends to contribute to develop a bottom-up approach, skills, methods and tools able to make the implementation of a sustainability policy a reality: by applying methods in demonstrative cases. By providing tools that make it possible to treat sustainability index as the macro-policy parameter to evaluate sustainability as the development assessment, by disseminating best practices.

Several studies devoted to the forecast of energy consumption in the future have emphasized the need for analyzing future strategies. In this respect, particular attention has been devoted to world energy, and American and European strategies [9,10]. The current power production capacity installed in Europe is based on several sources: natural gas (18%), oil (6%), coal (26%), nuclear (33%), hydro (12%) and other renewable (3%). The current trend in power production point to an increased use of natural gas and renewable resources, a slight increase in nuclear and a decrease in coal and oil

consumption; however, two factors are expected to influence future trends in the European energy sector: the need to meet Kyoto commitments and the issue of the security of energy supply, reflected in the Green Paper Towards a European Strategy for the Security of Energy Supply [11].

In view of this, the sustainability of energy system cannot be viewed simply on the basis of its environmental impact, but must also take into consideration the need to assure that the system has the capacity to meet requirements set by the consumers, not only in terms of installed power and availability, but most importantly in the capacity to use different primary sources: indigenous and imported.

2. Sustainability Paradigm and Information and Communication Systems

The sustainability paradigm [12] is based on the modern information and communication systems. For this reason, it is of special interest to verify the need for the deep understanding of sustainability as the pattern with the agglomerated set of indicators defined by the respective criteria. It is of interest to define indicators as the parameters devoted to the description of the energy system.

In this respect, the ICT system is designed within the frame to be able to recognize and quantify indicators as the quality measurements of the specific properties of the energy system. This implies the monitoring of agglomerated indicators comprising specific qualities of the energy system. The global parameters of the energy system are those which are devoted to the verification of specific properties of energy system [13-15]. In this respect, the efficiency of individual processes is the main quality parameter for the assessment of the energy system. Among the processes of special interest are: energy efficiency, environmental efficiency and social efficiency of the energy system.

2.1. Energy Efficiency

Efficient utilization of energy resources has become an ultimate goal for the future energy strategy. As the global scarcity of energy resources is imminent on our planet, it is of paramount interest for our society to devote special attention to the sustainable development of the energy system. In this respect, our attention has to be devoted to those actions which aim to the sustainable development. The energy system, as a complex system, requires special methodology for its evaluation. Since the complexity of the energy system is closely related to multi-dimensional space with different scales, the methodology has to bear a multi-criteria procedure in the evaluation of the energy system [16-18].

The effective use of energy resources implies that the energy resources will be used to produce a respective amount of energy corresponding to their caloric value. If the energy resources are used as the fuel to produce heat, electricity and hydrogen, we talk about the efficiency of conversion. It is necessary to introduce the specific parameters which are to be used to define sustainability indicators comprising the efficiency model of energy conversion.

ICT, through advanced control, metering and information, can automatically control equipment and processes such that their uses are optimized, and also to take advantages of optimal energy supply (low prices, grid availability, e.g., night time, and lastly, production by sustainable sources). Metering and feedback, together with the right price incentives (e.g., real time tariff communicated to user or equipment), can results in short- or long-term power and energy savings.

The impact of security on the interaction between ICT and the power grid can improve power system control and performance but can also increase its vulnerability, especially with regards to malicious and cyber attacks [19].

New energy technologies for co-generated heat and power, and increased renewable sources such as biomass, solar energy, and wind, will need to be integrated in the intelligent information based on the global energy infrastructure. This will reshape the energy map and associated business domains: an Internet of Energy in which ICT is an enabler of self-managing, self-sustaining, robust distributed energy systems.

ICT-based monitoring system [20] methods and tools are needed to improve the energy efficiency of energy-intensive systems. Priority areas where ICT can contribute significantly have been identified. They are:

- Design and simulation of energy use profiles covering the entire life-cycle of energy intensive products, processes, services and environment control.
- Intelligent and interactive monitoring of energy production, distribution and use with environmental control.
- Innovative tools, business models and platforms for energy efficiency service provision.
- Establishment of resilience monitoring as the tool for safety evaluation.

2.2. Environmental Efficiency

The energy system operation comprises different aspects of energy production. Beside the economic quality of the system, it includes constant monitoring of the environmental and social parameters of the system. For this reason, every energy system has to be monitored as a complex system with economic, environmental and social parameters in order to verify the integral state of the system [21].

It is immanent to any energy system to have adverse effects on the environment. This demonstrates the need for an appropriate monitoring system with potential control of effect on the environment and justification of its effect on the environment. In this respect, the ICT based monitoring system contributes to the improvement of the quality of the whole energy system.

The environmental efficiency of the energy system comprises the verification of the interaction of the energy production system with its surrounding. The environment quality monitoring is an essential indicator for the justification of the energy system as the whole.

2.3. Social Efficiency

Every energy system is subject to the validation by its users. Thus, the monitoring of the energy system has to include a social aspect of the system. In this respect, the public acceptance is of major importance for any energy system. In particular, the monitoring of the public satisfaction of the service is a measurement of the quality of life in the community.

Besides the adverse effects of the energy system on the public life, the energy system has some positive contributions to the quality of life. An energy system is usually a large investment capital introduced in the economy of the community. It opens a new opportunity for the local businesses and

community development. Local tax for the energy system operation is a milestone for the development of any community. Lack of support of the local community may be a drawback for the development [22].

Monitoring of the social aspect of the energy system is a common political and economic interest for both the local community and community in large.

3. Sustainability Index

The evaluation of an energy system as a complex system is the prestigious goal of the modern approach to the validation of an energy system. In this context, the Sustainability Index is introduced as a notion of the agglomerated indicator for the measurement of an energy system's quality. Sustainability Index is the property of an energy system based on the assumption that the energy system is a complex system.

It has become necessary to make the assessment of any system by taking the multiple attributes decision-making method into consideration. In a number of cases, the evolution of the system with criteria reflecting resource, economic, environment, technology and social aspects, has been exercised The complex (multi-attribute, multi-dimensional, multivariate, *etc.*) system is a system [23] whose qualities (resources, economics, environment, technology and social) under investigation are determined by many initial indices (indicators, parameters, variables, features, characteristics, attributes, *etc.*). Every initial indicator is treated as a quality, corresponding to respective criteria. It is supposed that these indices are necessary and sufficient for the system's quality estimation.

Definition of Sustainability Index

With the monitoring of the Sustainability Index as the time dependent variable, with appropriate selection of the time scale it is possible to verify respective changes within the specific potential hazard [24]. In particular, the resilience assessment is used as the safety parameter for the evaluation of an energy system.

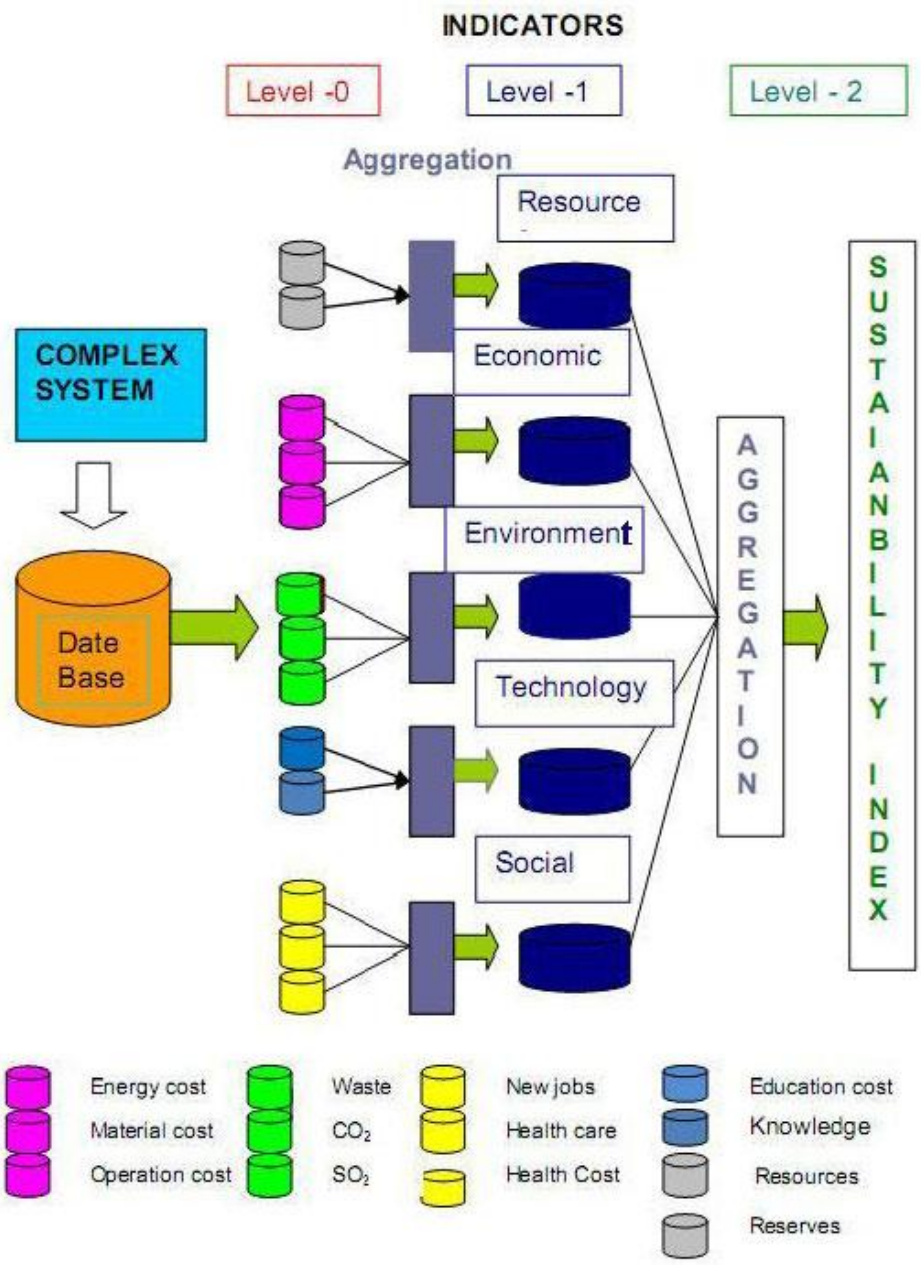
A graphical-representation example of a 2-level pyramidal hierarchy of indices is shown in Figure 1.

4. Sustainability Assessment of Energy Systems

The development of tools for the sustainability assessment of energy systems is one of the objectives for quality energy systems. It is anticipated that such a tool has to be designed to offer the numerical measurement of sustainability.

The method for evaluation and assessment of an energy system has proved to be a promising tool for the determination of the quality of the energy system. As the energy system is a good example for the identification of potential for sustainability development, it open new fields of research for those willing to dwell into the further understanding of the methods for evaluation of complex systems [25].

Figure 1. Graphical presentation of the algorithm for sustainability evaluation of a complex system.



In general, the energy system is characterized by organizational, operational, financial, resourceful, social and capacity building properties. The assessment and evaluation of the energy system requires all properties of the system to be taken into consideration. The contribution of each property to the General Index is defined with appropriately selected weighting coefficients.

Recently, it has become necessary to make the assessment of an energy system by taking into consideration the multiple attributes. The evolution of energy systems with criteria reflecting resource, economic, environment, technology and social aspects, has been exercised in a number of cases. With the adaptation of multi-criteria methods for the assessment and evaluation of an energy system, the potential possibility of sustainability index as the indicator for the quality of an energy system is demonstrated [26-29].

A complex (multi-attribute, many-dimensional, multivariate, *etc*.) energy system is a system whose qualities under investigation are determined by many initial indices. Initial indices are treated as the qualities, which are related to the corresponding criterion. It is supposed that these indices are necessary and sufficient measuring parameters for the quality determination of the system.

5. Sustainability Index Definition

If an alternative of the energy system technology is assigned as the object, then all alternatives that are taken into consideration are making the finite set of objects [24].

$$X = X(x(j)),\ j = 1, ..., k \tag{1}$$

where X represents the finite set of all objects; k represents the total number of objects.

(a) Vectors $X = (x_1, x_2, x_m)$ of the total initial quality is needed for the full assessment of the investigated object's quality

It is assumed that energy technology objects are identified with vectors:

$$X(j) = (x_1(j), ..., x_m(j)), \tag{2}$$

$i = 1, \ldots, m;\ j = (1, ..., k)$, k represents the number of objects under investigation.

where $x_i(j)$ is a value of the 'I'-th initial parameter; x_i for 'j'-th energy technology object. Component $x_i(j)$ of vector X(j) refers to the value of the initial quality (indicator) x_i of object x(j). The finite set of objects shows the base for the fuzzy sets.

The initial quality of the energy technology object can be defined by the vector:

$$X(j) = (x_1(j), ..., x_m(j)) \tag{3}$$

It is supposed that each value of the vector x_i is necessary and that the total value of the quality vector is sufficient for the fixed quality of the energy object, respectively for the sustainability assessment of configured energy object.

(b) Forming vectors of specific energy object quality $q = (q_1, ..., q_m)$

Quality of the energy technology objects x(j), j = 1, ..., k, is defined by a number of specific quality $q_1, ..., q_m$, where each is a function of a corresponding attribute (or initial parameters of vector):

$$q_i = q_i(x(i)),\ i = 1,..., m \tag{4}$$

where m is the number of the specific energy technology object quality.

The function $q_i = q_i(xi)$ may be treated as a particular membership function of a fuzzy set of objects which are preferable from the point of the 'i'-th criterion's view. The quality level (degree of preferability) of the 'j'-th object is estimated by the value $q_i(j) = q_i(x_i(j))$ of function $q_i(x_i)$ from the point of the 'I'-th criterion's view. The quality vector is an indicator defined with a number of attributes reflecting its properties.

(c) The process of normalization of a specific quality

Normalization of specific criteria is done on the basis of initial values of indices. Sustainability indices are not suitable for use because they have different dimensions and interval of range ($/kWh, kg/kWh, kWh/$, ...), and can thus not be compared. With the normalization of sustainability indices, comparison among indices is achieved.

(d) Introducing the weight coefficient and choosing the vectors of weight coefficients

The weight-coefficient w_i (i = 1, ..., m) shows which importance is given to particular criterion q_i when the General Index Q(q;w) is formed. The weight-coefficient $0 < w_i < 1$, for each I = 1, ..., m, is called the relative "weight" of the specific criterion q_i. Specific quality q_i has more influence on the value of General Index Q(q) with increasing values of w_i. Varying coefficient w_i, ($w_i = 1$; $w_i = 0$), the influence of $q_i = q_i(x_i)$ on the General Index Q(q;w) is changed, and respective importance is given to the specific quality q_i at General Index forming.

The General Index method comprises formation of an aggregative function with the weighted arithmetic mean as the synthesizing function defined as:

$$Q = \sum_{i=1}^{i=k} w_i q_i \tag{5}$$

where w_i is the weight-coefficient elements of vector w; q_i are indicators of specific criteria.

Based on the presented procedure, the Sustainability Index is defined as the General Index in form of an aggregative function with weighted arithmetic means as the synthesizing function.

It is assumed that the Sustainability index is a linear agglomeration function of the products between indicators and corresponding weighting coefficients, which is presented in the form of additive convolution. If it will be adapted that each of the criteria is weighted by the respective factor, the sum of criteria multiplied by the corresponding factor will lead to the Sustainability Index.

The presented multi-criteria method is essentially based on the evolution of fuzzy sets comprising the quality of energy technology objects defined with respective attributes corresponding to the specific criteria of the energy technology system. This proves that the multi-criteria method for the assessment of energy technology objects is a procedure that implies a new approach for the validation of objects defined with multi-attributes of the system.

6. Selection of Energy Indicators

The selected energy indicators must reflect the sustainability concept while describing real situations. Data availability and accuracy is one important constraint that decision-makers will have to deal with.

Indicators for the energy technology objects have to be chosen taking into account the sustainability of the whole system. The indicators should describe the interaction of the energy technology objects with the environment, resources, social and economic (sub) systems.

6.1. Economic Indicators

Commonly, economic and financial parameters are very important in the decision-making of the energy technology to be chosen for a given application [25].

For each plant, three Sustainability Indicators will be used to describe the interaction between energy technology and economic (sub) systems:

II_i: Investment Cost Indicator
OMI_i: Maintenance and Operation Cost
ECI_i: Cost of Electricity Generation

6.2. Environment Indicators

Energy production, transport and use are the most important causes of environmental injuries.

The impact of an energy plant construction, operation, maintenance and demolition on the environment affects the atmosphere, water and land. Some impact can be local (such as acidification) and others global (such as climate change). For the decision-making purpose, this classification is important. Risk perception depends heavily on the available information and the visibility of each impact. Actually, people are more aware of issues related to climate change and air pollution.

For each energy technology object, three Sustainability Indicators will be used to describe the interaction between the energy technology and the environment system [26]:

CO_2 E—CO_2 Emission
AP—Air pollution
PE—Particulates Emission

6.3. Social Indicators

The acceptability and job creation are the two main social indicators that can be used in the selection of appropriate technologies. The acceptability is a qualitative indicator that depends on the level of selected region development and the technology. New technologies will have more difficulties to penetrate into a market characterized by a high level of inertia. For example, if specialized skills are needed to run new technologies, they can be rejected in less developed regions. Cultural practice and values can also affect the way a new technology is adopted or refused.

The construction, operation, maintenance and demolition of a plant contribute to the creation of new jobs. However, the plant construction can be done in a different country than the one where it will operate. Thus, when counting new jobs, a clear distinction between each phase of each technology should be done [27].

For each technology, two Sustainability Indicators will be used to describe the interaction between energy technology and the social (sub) system:

AI_i: Acceptability Indicator
JI_i: New Job Creation Indicator

6.4. Resources Indicators

The life cycle of material and energy flows analyses are necessary to fully describe the impact of each Energy Production Technology (EPT) on the resource subsystems. The resource indicators will describe the total material and energy needed for the construction, maintenance, operation and demolition of each energy plant. All steps from mining to the finished product and posterior demolition and treatment of each material used in the construction, maintenance and operation of the energy plant will be accounted.

From the energy technology point of view (considered as a whole), the finished material product used in the construction of an energy plant will have a social, economic, environmental and institutional impact, which forms the overall impact during the whole life cycle from mining to plant demolition. Thus, the global Sustainability Indicators for a particular energy technology take into account (and is a combination of) each of the Sustainability Indicators of its parts. [28]

To stress the concern about resources depletion, a corresponding resources indicator can be used. The amount of material used itself is often used as the indicator. However, this does not point out whether a related activity contributes to the depletion of a particular resource or not. A measure of weight of material used over time for a specific activity (in our case the construction of an energy plant) can be more useful. "Lower materials intensity of the economy could reduce the amount of garbage produced, limit human exposures to hazardous materials, and conserve landscapes" [29].

Dematerialization, *i.e.*, the absolute or relative reduction in the quantity of materials required to serve economic functions, is a better and dynamic indicator rather than the amount of material used; however, it does not secure from resources depletion.

Sustainability implies a slow reduction of resources (and in this case dematerialization can be a good measure of trend towards sustainability) or even the preservation of current stocks. For non renewable resources (finite), only the possibility of re-using the existing materials can guarantee that currents stocks will be available for future generations. That is, a Sustainability Indicator for resources can be the potential for recycling.

To conclude, the Sustainability Indicators will be used to describe the interaction between energy technology and resources (sub) systems. For each material used in the construction of the selected technology, these terms will be defined:

RI_i: amount of material *reserves*
Resource Cost.

7. Energy System Assessment

The sustainability assessment of energy system is based on the number of selected indicators defined as the quality criterions for the specific quality indices. In order to demonstrate the sustainability assessment of energy system it was selected a number of objects representing individual energy technologies for the electric energy production. The verification of options to be analyzed is focused on the power plant systems with different energy sources. Among the technologies to be taken into consideration are:

7.1. Pulverized Coal Fired Power Plant (PCPP)

For the energy system assessment of a pulverized-coal fired power plant, we will take into consideration a 300 MW plant with the lignite fuel combustion at the maximum gas temperature of 1,200 °C and steam pressure p = 165 bars, steam temperature T_{steam} = 570 °C. The thermal efficiency of the plant is η_{el} = 0.43. The emission of CO_2 of the plant is assumed to be 0.82 g CO_2/kWh. The installation cost is estimated at 1,100–1,300 Euro/k [30]. The modern pulverized coal fired power plant incorporates several clean air technologies. Among those technologies are: pulverized coal combustion with a new design of burners, a new scheme of organization of combustion in the boiler furnace, and a new design of steam superheater and gas cleaning system.

7.2. Natural Gas Combined Cycle (NGCC)

Due to the favorable conditions with gas resources, it has become interesting to investigate the natural gas cycle power plant as a potential option for power generation. With the present design of gas turbines, the efficiency of the NGCC has become very attractive in many respects. The investment cost is 400–600 Euro/kW. Other advantages include the ease of control, NO_x control and limited air pollution with CO_2 emission of about 0.3–0.4 g/kWh .NGCC has become one of the most promising options in the future strategy of energy system development [31].

7.3. Nuclear Power Plant

The nuclear power industry is a mature business. Since 1980, the nuclear industry has made significant changes in the way it operates nuclear power plants. These changes, which required increased staffing and safety improvement work, boosted plant performance, reliability and output.

At the same time, they pushed up the operating and maintenance (O&M) costs. As these changes became institutionalized in the utility programs, the O&M costs have stabilized. The average O&M costs for a nuclear plant—measured in 1996 in Eurocents—were 1.48 Eurocents in 1994, 1.39 Eurocents in 1995 and 1.36 Eurocents in 1996, based on figures from the Utility Data Institute, an independent research organization. Moreover, nuclear energy is competitive with other sources of electricity production. The average electric energy production cost, including fuel, was 1.91 Eurocents per kWh in 1996. For good performing plants (with capacity factors greater than 90%), nominally the fuel costs are 0.45 to 0.56 Eurocents/kWh; O&M costs are 1.2 to 1.8 Eurocents/kWh, capital costs are 1.4 to 2.0 Eurocents/kWh [32].

7.4. PV Solar Power Plant

The solar cell costs are important elements of the PV economic viability [33]. The modules account for about 50% of the cost of a PV power plant. The solar cells themselves account for only about half of the module cost, or 20% of total system cost. Thin film polycrystalline technology may make it possible to have the module cost about 40 Euro/m^2 and electricity price of 6 Eurocents/kWh. This is only a planning target for 10% efficiency. With the increase of efficiency to 20%, the target will be 4 Eurocents/kWh.

The production of solar cells themselves leads to the emission of greenhouse gases. Taking a life cycle perspective of a PV plant, it will produce more electric energy during its life than it takes to build.

7.5. Wind Power Plant

The present technology, including a new material for wind turbine blades, has reached the size of 1.5 MW for off-shore use. Its three blade rotor diameter is 63 m, while the swept area is 3,117 m^2. It rotates at a constant speed of 21 rpm, and has a noise level of 104 dBA. The tower height is 57.8 m. It start delivering energy at wind speed above 4 m/sec, reaches full power at a wind speed of 15 m/sec and stops at speeds above 25 m/sec. For the annual average wind speed between 6 and 10 m/sec, its production varies between 2.4 GWh and 6.5 GWh. Since 1981, the installation cost of a typical wind turbine has been decreasing and has reached 780 Euro/kW. The electricity price is 7–9 Eurocent/kWh, with further cost reduction expected through the economics of scale of the low-cost manufacturing and improved design. Wind farms require a lot of space. Most wind farms fall into a range of 0.1–1 km^2 per installed MW [34].

8. Multi-Criteria Sustainability Assessment

The multi-criteria assessment is based on the decision-making procedure [35-38] reflecting combined effects of all criteria under consideration and is expressed in the form of the General Index, comprising specific information about the options under consideration. A selected number of indicators are taken as the measure of the Sustainability. The procedure is aimed at expressing the options' properties by a respective set of indicators [39,40].

8.1. Indicators Numerical Value

The decision-making procedure comprises several steps in order to obtain the mathematical tool for the assessment of rating among the options under consideration [41,42] In order to prepare respective data for the energy technology assessment, Table 1 presents the data to be used in this analysis.

Table 1. Sustainability indicators.

Options	**Indicators**				
	Efficiency %	Investment Euro/kW	Electricity cost Eurocents/kWh	CO_2emission $kgCO_2$/kWh	Area km^2/kW
Coal fired power plant	43	1,070	3.8	0.82	0.4
Oil fired power plant	46	1,000	4.6	0.45	0.1
Gas fired power plant	64	460	2.85	0.38	0.04
PV solar power plant	10	3,100	53.5	0.1	0.12
Wind power plant	18	780	5.0	0.02	0.79
Nuclear power plant	33	1,650	4.0	0.03	0.01

The multi-criteria sustainability assessment is based on the Sustainability Index defined as the additive aggregative function, which meets the condition of monotonicity.

The weighted arithmetic mean is the most popular type of synthesis function. This function is a most simple and easily interpreted synthesis function. Sustainability Index is an additive aggregative function defined as follows

$$Q(q,w)=\sum_{i=1}^{m} w_i q_i \tag{6}$$

where w_i represents weight-coefficients; q_i represents normalized specific indicators.

The normalization of indicators is achieved by the use of respective membership function in presenting the actual values of indicators. Assuming maximum and minimum values of an indicator will correspond to 0 and 1, respectively, and using the linear membership function, the set of indicators for all option under consideration will be converted to the fuzzy set of the respective indicators.

The membership functions are defined as follows

$$q_i(x_i)=\begin{cases} 1, & if \quad x_i \le MIN(i), \\ \left(\dfrac{MAX(i)-x_i}{MAX(i)-MIN(i)}\right), & if \quad MIN(i) < x_i \le MAX(i), \\ 0, & if \quad x_i > MAX(i) \end{cases} \tag{7}$$

Membership function value corresponding to each actual value will lead us to the normalized specific indicators, as given in Table 2.

Table 2. Normalized specific indicators.

Alternative	Efficiency	Investment Cost	Electricity Cost	CO_2 Emission	Footprint
Coal Power Plant	0.4815	0.2340	0.3800	1.0000	0.5000
Oil Power Plant	0.7037	0.2075	0.7000	0.5309	0.1154
Gas Power Plant	1.0000	0.0000	0.0000	0.4444	0.0385
PV Power Plant	0.0000	1.0000	1.0000	0.0988	0.1410
Wind Power Plant	0.1481	0.1245	0.8600	0.0000	1.0000
Nuclear Power Plant	0.4259	0.4528	0.4600	0.0123	0.0000

The analysis is based on the results obtained by the "Analysis and Synthesis of Parameters under Information Deficiency" ASPID-3W Program. In this analysis, we will take into consideration different alternatives as regard to weighting factors. For the General Index for the sustainability assessment of the contribution of the individual criteria to the sustainability assessment, it is considered appropriate to use the following expression

$$Q(q,w)=\sum_{i=1}^{4} q_i w_i$$

which will allow linear comparison of all options under consideration by the degree of generality of Q (q,w), taking into consideration the individual normalized indicators and respective factors defined by the probability coefficients w_1, w_2, w_4. With the assumption that all weighting factors are equal and additional information I = 0, then there is no non-numerical information which might take into consideration cases with mutual relation among the weighting factors.

If it is assumed that there is the non-numerical information, then $I \neq 0$, related to the weighting of contribution of individual indicators. In other words, the non-numerical information with regard to the relation among the individual weighting factors in the form of no equity system is

$$I_1 = \{ w_1 \neq w_2 \neq w_3 \neq w_4 \}$$

for weighting factors w_1, w_2, w_3, w_4.

In our analysis, the effect of individual criteria on the General Index of Sustainability in a number of cases will be designed to reflect changes in the mutual relation of the weighting factors on the decision making process

With the use of the Sustainability Index as the quality parameter for the options under consideration, a number of cases could be defined with the specified conditions reflecting non-numerical constrains. Each of the cases will result in the rating list of options. With the design of a sufficient number of cases, a platform can be defined for the decision process.

9. Demonstration of the Energy System Evaluation

For the demonstration of cases, in this analysis, the following cases are evaluated:

1. Efficiency > Investment Cost = Electricity Cost = CO_2 Emission = Footprint
2. CO_2 Emission > Investment Cost > Electricity Cost > Efficiency > Footprint

CASE 1—Efficiency > Investment Cost = Electricity Cost = CO_2 Emission = Footprint

Case 1 is designed with the priority given to the efficiency indicator with assumption that the other indicators have the same weighting coefficients. Under this constraint, the result shown in Figure 2 is obtained.

The result obtained shows that under this constraint, priority is given to the gas fired power plant, with the other options having the following decreasing priority rating: oil power plant, nuclear power plant, coal power plant, wind power plant, PV power plant. It can be noticed that the main contribution to the Sustainability Index is obtained from the efficiency criteria. It is of interest to recognize that the normalization of indicators has not substantially contributed to the difference in rating due to linear function.

Figure 2. Weight Coefficient and General Sustainable index for CASE 1.

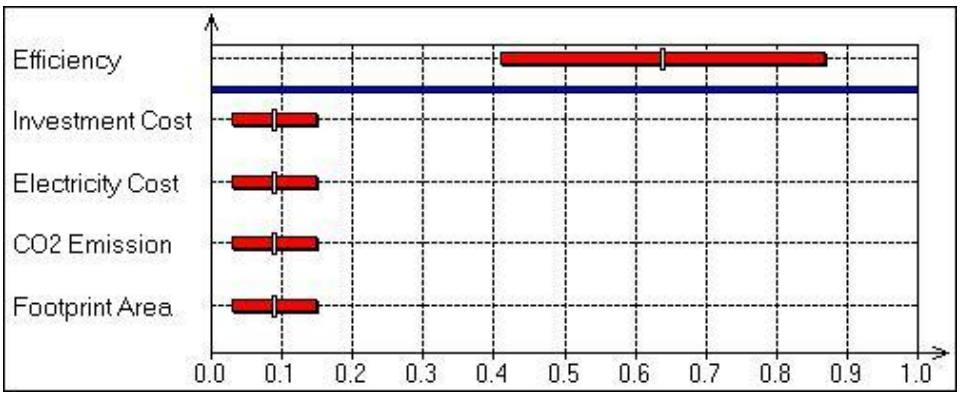
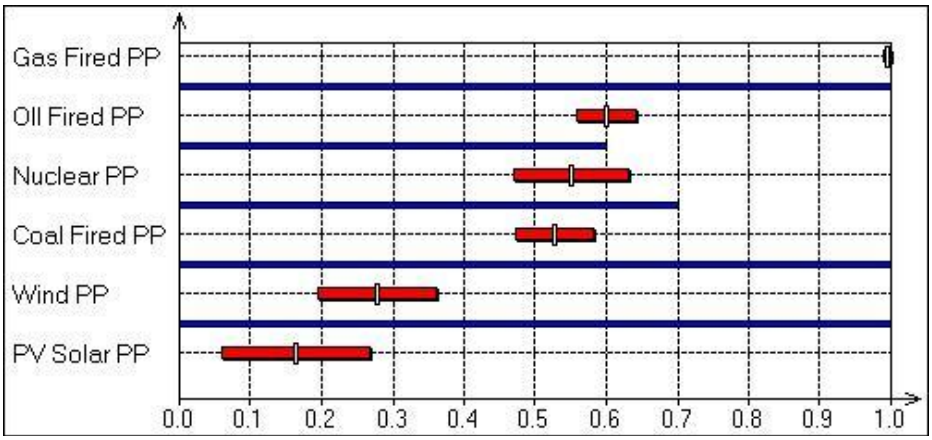


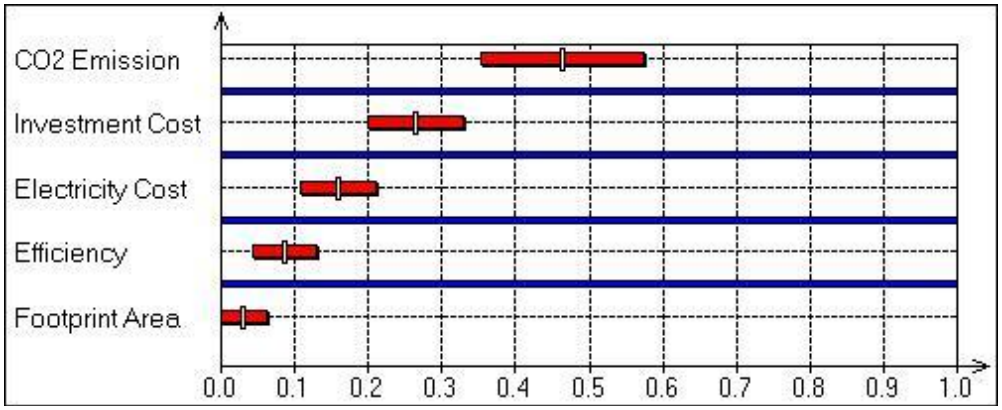
Figure 2. *Cont.*

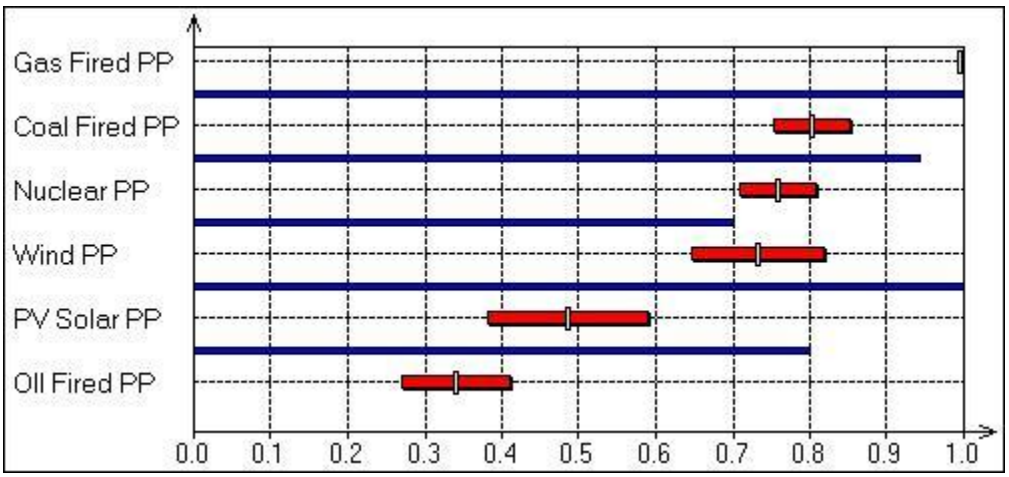


CASE 2—CO_2 Emission > Investment Cost > Electricity Cost > Efficiency > Footprint.

CASE 2 is designed with priority given to the criteria CO_2 emission followed by investment cost, electricity cost, efficiency, and footprint area. The gas fired power plant option gained first place in the rating list. The group coal fired power plant, nuclear power plant and wind power plant have marginal difference in the priority list of the options under consideration.

Figure 3. Weight Coefficients and General Sustainability Index for CASE 2.





10. Discussion

It is of interest to notice that the multi-criteria approach with non-numerical constrains now offers quality in the assessment and evaluation of potential options to be selected by the decision-makers. The use of this tool attempts to understand a system quality and can offer information in the format that can assist the decision-making process. As it was shown by qualifying certain aspects of the economic, environmental, and social indicators, it is possible to verify ratings among the options to be used in the decision-making process.

In the evaluation of life support systems, it is of primary interest to introduce normalized values as the average quality of the system. In this respect, the normalization under constraint leads to the non-monetary qualification of the obtained result.

With regard to the energy technology system, it is of primary interest to introduce those indicators which are relevant to the economic, environmental, technological and social impact.

MCA (Multi Criteria Assessment) imply the potential to utilize composite indicators obtained by the agglomeration of the individual indicators. This leads to the concept of strong sustainability discussed by some authors.

11. Conclusions

The sustainability paradigm is a model designed to introduce the potential of quality assessment of the system. There are a number of methods used in the sustainability assessment of different systems.

The energy technology system is one of the life support systems which are immanently related to the information and communication system in order to monitor the quality of the system. There are several methods used for the sustainability assessment of the energy system.

In this paper, it is demonstrated that the sustainability paradigm based on the modern information and communication systems proves to be an essential tool for the assessment and evaluation of the energy technology system. The need for deep understanding of sustainability as the pattern of the agglomerated set of indicators defined by the respective criteria was verified. It is of interest to define indicators as the parameters devoted to the description of the energy system.

By demonstration of the energy technology system assessment, it was shown that the multi-criteria assessment method, with economic, environmental, and social indicators, can be used as a tool for the quality assessment of an energy system. In this respect, the multi-criteria method proves to be an appropriate tool for the quality assessment of the energy system.

References

1. Afgan, N.H. Sustainable Knowledge Management. In *Proceedings of the PICMET 2006 Conference on "Technology for the Global Future"*, Istanbul, Turkey, 9–13 July 2006.
2. *Chapter of Civil Right for a Sustainable Knowledge Society*; Heinrih-Boll-Foundation: Berlin, Germany, May 2003.

3. Kates, R.W.; Clark, W.C.; Corell, R.; Hall, J.M.; Jaeger, C.C.; Lowe, I.; McCarthy, J.J.; Schellnhuber, H.J.; Bolin, B.; Dickson, N.M.; Faucheux, S.; Gallopin, G.C.; Grübler, A.; Huntley, B.; Jäger, J.; Jodha, N.S.; Kasperson, R.E.; Mabogunje, A.; Matson, P.; Mooney, H.; Moore III, B.; O'Riordan, T.; Svedin, U. Sustainability science. *Science* **2001**, *292*, 641-642.
4. Gallagher, R.; Appenzeller, T. Beyond reductionism. *Science* **1999**, *284*, 79.
5. Gasparatos, A.; El-Haram, M.; Horner, M. A critical review of reductionist approaches for assessing the progress towards sustainability. *Environ. Impact Assess. Rev.* **2008**, *28*, 286-311.
6. Munda, G. Multiple criteria decision analysis and sustainable development. In *Multiple Criteria Decision Analysis: State of the Art Surveys*; Figueira, J., Greco S., Ehrogott, M., Eds.; Springer: New York, NY, USA, 2005; pp. 953-986.
7. Afgan, N.H; Gobaisi, D.A; Carvalho, M.G; Cumo, M. Sustainable energy development. *Renew. Sustain. Energy Rev.* **1998**, *2*, 235-286.
8. Afgan, N.H.; Carvalho, M. Modeling of energy systems sustainability indicators. *Therm. Sci.* **2005**, *9*, 3-16.
9. Sciubba, E. Cost analysis of energy conversion systems via a novel resource-based quantifier. *Energy* **2003**, *28*, 457-477.
10. Sciubba, E.; Ulgiati, S. Emergy and exergy analyses: Complementary methods or irreducible ideological options? *Energy* **2005**, *30*, 1953-1988.
11. Afgan, N.H.; Carvalho, M.G.; Hovanov, N.V. Energy system assessment with sustainability indicators. *Energy Policy* **2000**, *28*, 603-612.
12. Afgan, N.H.; Carvalho, M.G. Multi-criteria assessment of new and renewable energy power plants. *Energy* **2002**, *27*, 739-755.
13. Afgan, N.H.; Carvalho, M.G. Sustainability assessment of a hybrid energy system. *Energy Policy* **2008**, *36*, 2893-2900.
14. Afgan, N.H.; Carvalho, M.G. *Sustainability Assessment of Energy System*; Kluwer Academic Publisher: New York, NY, USA, 2000.
15. Afgan, N.H.; Carvalho, M.G. *Quality, Sustainability and Indicators for Energy System Assessment*; Begell House Publisher: New York, NY, USA, 2009.
16. Hovanov, A.N.; Hovanov, N.V. DSSS "ASPID-3W" Decision Support System Shell. Registered by Federal Agency for Computer Programs Copyright Protection Russia Federation, Number 960087, 22 September 1996.
17. Mazzuracchio, P.; Raggi, A.; Barbiri, G. New method for assessing the global quality of energy system. *Appl. Energ.* **1996**, *53*, 315-324.
18. Afgan, N.; Carvalho, M.G. Multi-criteria assessment of new and renewable energy power plants. *Energy* **2002**, *27*, 739-755.
19. D'Angelo, E.; Perrella, G.; Bianco, R. *Indicators of Sustainable Engineering*; Physical Sciences Research Council: Roma, Italy, December 1996.
20. Afgan, N.H.; Carvalho, M.G. Sustainability assessment of hydrogen energy systems. *Int. J. Hydrogen Energ.* **2004**, *29*, 1327-1342.
21. Afgan, N.; Darwish, M.; Carvalho, M.G. Sustainability assessment of desalination plants for water production. *Desalination* **1999**, *124*, 19-31.

22. Afgan, N.H.; Al Gobaisi, D.; Carvalho, M.G.; Cumo, M. Sustainable energy development. *Renew. Sustain. Energy Rev.* **1998**, *2*, 235-286.
23. Munde, G.; Nardo, M. *Constructing Consistent Composite Indicators: The Issue of Weights*; The Institute for the Protection and Security of Citizens: Ispra, Italy, 2005.
24. Schwartz, J.; Beloff, B.; Beaver, E. Use sustainability metrics to guide decision-making. *Chem. Eng. Prog. Mag.* **2002**, *37*, 58-63.
25. *Energy to 2050, Scenarios for a Sustainable Future*; OECD (Organization for Economic Co-Operation and Development)/IEA (International Energy Agency): Paris, France, 2003.
26. *The National Academy Summit on American Energy Future*; The National Academies Press: Washington, DC, USA, 2008.
27. Mohammed, A.R.; Lee, K.T. Energy for sustainable development in Malaysia: Energy policy and alternative energy. *Energy Policy* **2006**, *34*, 2388-2397.
28. Mochner, A. *Toward a Sustainable Energy Future*. Ph.D. Theses, Ernst Moitz Arndt University, Greitswald, Germany, 2003.
29. *Commission Green Paper of 8 March 2006: A European Strategy for Sustainable Competitive and Secure Energy*; Com (2006) 105 Final; European Commission: Brussels, Belgium, 2006.
30. Afgan, N.H.; Andre, P.; Sustainability: The Management System Property, Technology Management for the Global Future. In *Proceedings of the PICMET 2006 Conference on "Technology for the Global Future"*, Istanbul, Turkey, 9–13 July 2006.
31. Wang, J.J.; Jing, Y.Y.; Zhang, C.F.; Zhao, J.H. Review on multi-criteria decision analysis on sustainable energy decision-making. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2263-2278.
32. Wang, J.J.; Zhang, C.F.; Jing, Y.Y. Multi-criteria analysis of combined cooling, heating and power in different climate zones in China. *Appl. Energ.* **2010**, *87*, 1247-1259.
33. Begić, F.; Afgan, N.H. Sustainability assessment tool for the decision making in selection of energy system—Bosnian case. *Energy* **2007**, *32*, 1979-1985.
34. Jovanović, M.; Afgan, N.; Radovanovic, P.; Stevanovic, S. Sustainable development of Belgrade energy system. *Energy* **2009**, *34*, 532-5399.
35. David, P.A.; Foray, D. Economic fundamentals of the knowledge society. *Policy Futures Educ.* **2003**, *1*, 20-49.
36. *Vision in Progress*, *Proceedings of the World Summit on the Information Society*, Geneva, Switzerland, 10–12 December 2003.
37. Burch, S. The Information Society/The Knowledge Societies. In *World Matters*; C & F Éditions: New York, NY, USA, 2005.
38. *UNESCOs Basic Texts on the Information Society*; UNESCO (United Nations Educational, Scientific and Cultural Organization): Paris, France, 2003.
39. da Paz, L.R.L.; de Silba, N.F.; Roza, L.P. The paradigm of Sustainability in the Brazilian energy sector. *Renew. Sustain. Energy Resour.* **2007**, *11*, 1558-1670.
40. Becker, H.A. Social impact assessment. *Eur. J. Oper. Res.* **2001**, *128*, 311-321.

41. Slater, D.; Jones, H. Environmental risk assessment and the environment agency. *J. Hazard. Mater.* **1999**, *65*, 77-84.
42. Aseffa, G.; Froskel, B. Social sustainability and social acceptance in technology assessment: A case study of energy technologies. *Technol. Soc.* **2007**, *29*, 63-70.