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Sustainability assessment of hydrogen energy systems

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Abstract

This paper gives an overview of the potential on multi-criteria assessment of hydrogen systems. With respective selection of the criteria comprising performance, environment, market and social indicators the assessment procedure is adapted for the assessment of the selected options of the hydrogen energy systems and their comparison with new and renewable energy systems.

The single parameter assessment for each indicator is demonstrated as the traditional approach in the evaluation of the option under consideration which reflects a biased result depending on the selected indicator. In order to apply the multi-criteria approach to the hydrogen systems, it was necessary to use the multi-criteria procedure based on the sustainability index rating composed of linear aggregative functions of all indicators with respective weighting function.

The example under consideration are hydrogen fuel cell systems with three options including natural gas turbine, photovoltaic and wind energy systems representing different renewable power plant option. These options are evaluated with the multi-criteria method comprising the following indicators: performance indicator, market indicator, environment indicator and social indicator. The indicators are composed of a number of sub-indicators agglomerated in respective indicators. The evaluation of options under consideration was performed under constraint expressing non-numeric relation among the indicators. The group comprises cases when priority is given to a single indicator and other indicators have the same value.

Keywords: Sustainability index; Multi-criteria assessment; Hydrogen energy systems; Indicators; Natural gas turbine; Photovoltaic system; Wind energy system

1. Introduction

It has become of great interest to evaluate power plants using different criteria. In this respect there are a number of methods, which are used in presenting quantitative merits for the rating of different power plant designs [1,2]. Among popular methods applied in the evaluation of power plants are: thermodynamic method, energy cost evaluation method and life-cycle method. Each of the methods is based on an optimization function reflecting a single indicator in the evaluation of individual options of power plant design. It has been noted that the energy system complexity requires multivariable assessment taking into consideration different aspects of the power plant. It is obvious that besides the economic valorization of the power plant, the modern approach has to take into consideration the other aspect of the individual design of the power plant. Since energy production in the power plant is based on different physical principles, each power plant option will reflect the importance of different optimization parameters. Also, each power plant option will use a different energy sources, and conversion in to final energy will impose different interactions with its environment [3].

The decision-making method based on the probabilistic assessment of a fuzzy set of indicators with information deficiency has proved to be a powerful tool for the evaluation of complex systems defined by multi-parameters [4–6]. It has become obvious that comparing the desirability of different means of action leads to the sustainability of products. This area, multi-criteria decision-making, has lead to numerous

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schemes and to the formation of vector-maximum problem in mathematical programing.

2. Sustainability assessment

Measuring sustainability is a major issue as well as a driving force of the discussion on sustainability development. Developing tools that reliably measure sustainability is a prerequisite for identifying nonsustainable processes, informing design-makers of the quality of products and monitoring impacts on the social environment. The multiplicity of indicators and measuring tools being developed in this fast-growing field shows the importance of the conceptual and methodological work in this area. The development and selection of indicators require parameters related to the reliability, appropriateness, practicality and limitations of measurement.

The effective indicator has to meet characteristics reflecting a problem and criteria to be considered [6]. Its purpose is to show how well the system is working. In case there is a problem, an indicator has to indicate its origin and the direction to be taken in order to solve the problem. Indicators are strongly dependent on the type of system they monitor.

Collecting information and its processing will convert them into data. So, data represent agglomerated information, which are partially or finally processed. Examples of data can be found as a parameter, which describes evaluated information to be used for the specific purpose. In this respect, the average inlet temperature of cooling water in the condenser is obtained by the averaging procedure adapted for this purpose. Also, the heat transfer coefficient used in the design of condenser is the data obtained by the experimental procedure for the heat transfer evaluation.

In order to use the data for the assessment of the respective system, it is necessary to convert them into indicators. So, an indicator represents the measuring parameter for the comparison between the different states or structure of the system. For example, the efficiency of the system is an indicator for the quality of energy used in the respective system.

3. Hydrogen system sustainability criteria

There have been a number of attempts to define the criteria for the assessment of the sustainability of the market products [7]. In this respect the Working Group of UNEP on Sustainable Development has come out with the qualitative assessment criteria for the assessment of product design.

Having those criteria as a base, we would like to introduce them in the specific application to a hydrogen system design. In this consideration hydrogen system design is taken as an entity which should comply with the sustainability criteria.

Energy system design is defined as:

3.1. Strategic design

The strategic design of an energy system will require holistic planning that meets energy demand and considers all interrelated impacts, e.g. logistic, space planning and resource planning. Regarding the hydrogen energy system, it may be interpreted as an energy concept with optimization of local resources, urban and industrial planning with transport optimization and use of the renewable energy sources.

3.2. Optimized design

The design optimization of a hydrogen energy system means the selection of structure and design parameters of the system to minimize energy cost under conditions associated with available material, financial resources, protection of the environment and government regulations, together with the safety, reliability, availability and maintainability of the system.

3.3. Dematerialization of design

This will imply that the hydrogen system, plant and equipment are designed with optimal use of information technology in order to prevent duplication, prevent operational malfunction, and assure rational maintenance scheduling. Dematerialization in the design may be seen as an introduction of knowledge-based systems, use of virtual library, digitized video, use of on-line diagnostic systems, development of new sensor elements and development of new combustion technologies.

3.4. Longevity of design

Hydrogen system is commonly composed of different subsystems and individual equipment elements. In this respect, optimal selection of the life cycle for elements and subsystems may lead to the retrofitting procedure which will reflect the need for the sustainable criterion's application. Examples for this criterion can be seen as: modular design of the subsystems, standardization of the elements, lifetime monitoring and assessment, co-ordination of suppliers and buyers.

3.5. Life cycle design

This will mean that the hydrogen system and its subsystems have to be designed to meet sustainability through every stage of the life cycle. It is known that the hydrogen system is designed to work under different conditions in order to meet load change, environment change, social change, etc. It is obvious that there will be different cycles for each of the mentioned time scale processes. In this respect, the system has to fulfill its function without failing to meet sustainability requirements.

4. Selection of options and indicators for hydrogen systems

In this exercise we will focus our attention on the hydrogen systems [8]. In order to have comparison between hydrogen and other new and renewable energy systems, options are included in this analysis representing those systems. In this respect we will select a number of options to be taken into consideration, corresponding to a number of indicators which are of importance for the assessment of the system. In selecting appropriate options for consideration the following systems will be used.

The selection of criteria and indicators depends on the system. Usually, it is anticipated that the system is an entity defined with the respective number of parameters describing the state of the system.

4.1. Selection of options

In this exercise, we will focus attention on the hydrogen energy systems. In selecting appropriate options for consideration, the following systems will be used:

1. Phosphoric acid fuel cells—PAFC
2. Solid oxide fuel cells—SOFC
3. Natural gas turbine system—gas turbine
4. Photovoltaic system—photovoltaic
5. Wind energy system—wind

4.1.1. Phosphoric acid fuel cells—PAFC

PAFCs have been in 'commercial' production for more than 5 years, with about two hundred 200 kW units installed or in production [9]. These have historically been expensive at \$3000/kW, though assistance for purchasers has come through the US Government programs. The price, even at that stage, was subsdized internally, and the current market price is \$3750/kW. This may seem like an increase but for the first time actually covers all of the costs of production.

The PAFC represents the first generation of 'commercial' fuel cells. Although successful in terms of technical performance, questions are raised with regard to its cost reduction potential and whether there may be a more competitive option in the future.

4.1.2. Solid oxide fuel cells—SOFC

The *Solid Polymer fuel cell* is receiving much more public attention than any other types [10]. These units will most likely run on hydrogen gas and will produce power in the 5–250 kW range. This allows for flexibility in providing for small commercial users and also even the ultimate in decentralized generation—a fuel cell in every home. The systems also provide just about enough heat for space heating and hot water for an average domestic or commercial facility. It is unclear exactly how much SOFCs cost at this point, though figures of US\$3–4000/kW seem to be close to the mark.

4.1.3. Natural gas turbine system—gas turbine

For comparison with hydrogen fuel cell plant in this analysis is the simple natural gas turbine energy system. Gas turbine energy system fueled with natural gas is one of the options to be taken into consideration in this evaluation [11]. In order to be compared with other systems, the simple gas turbine system is used in order to prevent advantages obtained by additional complexity of the energy system. Under this constraint the total efficiency of the system is $\eta = 0.46$ with an inlet temperature of 850°C.

4.1.4. Photovoltaic system—photovoltaic

Since the photoelectric solar system is one of the potential options in the selection of energy system, it is selected as one of the potential configurations. In the local resources evaluation, photovoltaic solar systems could take into consideration its minimum and maximum capacity to be installed [12]. From the present status of the development, the following capacity can be taken into consideration for the decentralized electric solar plant: Min > 30 kW and Max > 5000 kW.

The mean insulation for the specific location taken into consideration is $q_R = 5.4\ \text{kWh/m}^2/\text{day}$ so that the following land is required for the specific use of solar energy.

4.1.5. Wind energy system—wind

In this evaluation the wind energy system is based on the horizontal-axis wind turbine in which the direction of the wind is parallel to the axis which has been demonstrated and technologically developed. At present the horizontal-axis wind turbine generators represent approximately 95% of the capacity installed in the wind plants.

Small sized wind turbine generators are used in a large number of applications. Most of these applications are limited to the supply of isolated dwellings: pumping, desalination, integration with diesel, storage, integration with other renewable energy sources. In all these applications storage capacity is an essential factor [13].

4.2. Indicators selection

For the sustainability assessment of HE system the following indicators are used:

1. Performance indicator—P
2. Market indicator—MI
3. Environment indicator—EI
4. Social indicator—SI

4.2.1. Performance indicator (PI)

Since every system under consideration is subject to different efficiency, it is of interest to have efficiency as the integral indicator for the internal parameter of the system which comprises different design characteristics of the system. The performance indicator in this assessment procedure is composed of a number of sub-indicators, namely, efficiency, total energy cost, capital cost and lifetime.

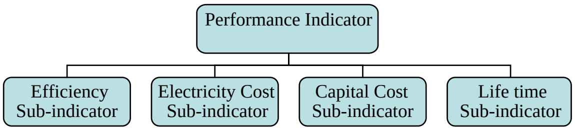

Fig. 1. Performance indicator chart.

Table 1

	Name	Definition	Unit
EfI_{fuel}	Efficiency indicator	Carnot efficiency	%
ECI_{CS}	Electricity cost indicator	Electric energy cost per unit kWh	Euro/kWh
CCI_{Coop}	Capital cost indicator	Capital cost per unit kWh	Euro/kWh
LTI_{Al}	Lifetime indicator	Lifetime of the plant	Years

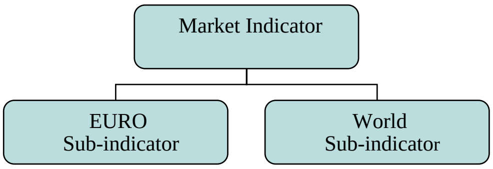

Fig. 2. Market indicator chart.

Table 2

	Name	Definition	Unit
MI_{Euro}	European market indicator	Number of GW per next 10 years	GW/10 years
MI_{world}	World market indicator	Number of GW per next 10 years	GW/10 years

The efficiency of the system is considered as the integral parameter for the performance validation. The total energy cost is a result of the system optimization with minimum energy cost constraint. The capital cost is a measure of the investment per unit energy produced in the lifetime of the system. Also, the important parameter in the assessment of performance of the energy system is the lifetime of the system (Fig. 1, Table 1).

4.2.2. Market indicator (MI)

In general terms, the market indicator is a measure of the market penetration of the respective product. In this case the market indicator will comprise two sub-indicators, namely: Euro market for the respective system under consideration and world market for the same systems. They will be expressed as the participation of the respective system in the total market for the specific time period (Fig. 2, Table 2).

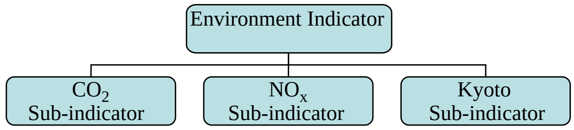

Fig. 3. Environment indicator chart.

Table 3

	Name	Definition	Unit
EI_{CO_2}	Carbon dioxide environment indicator	CO_2 concentration in ppm	ppm
EI_{NO_x}	Nitrogen oxide environment indicator	NO_x concentration in ppm	ppm
KyI	Kyoto indicator	Contribution to Kyoto limits	%

4.2.3. Environment indicator (EI)

The present strategy in power plant design is strongly related to the modern approach in flue gas emission control. Due to the global effect of CO_2, its monitoring has become of paramount interest in the design of new power plants. For this reason, any design of power plant has to incorporate those features which are related to the low emission of CO_2 and NO_x per unit energy produced (Fig. 3).

The environment indicators are composed of three elements namely, CO_2, NO_x and Kyoto indicator. CO_2, NO_x Indicators are represented by the respective concentration of gases. Kyoto indicator is designed to reflect the contribution of the respective systems to the Kyoto Protocol limit. Following the same procedure used in the definition of performance indicators, we can adapt that the environment indicator is as given in Table 3

4.2.4. Social indicator (SI)

The social indicators reflect the social aspect of the options under consideration. It will comprise the following two sub-indicators: area indicator and job indicator. The area indicator represents parameter which defines the number of m^2 per unit power. The job indicator sub-indicator represents the number of hours of new job to be opened corresponding to the respective option in the following 10 years. (Fig. 4, Table 4).

5. Single criteria analysis

5.1. Performance indicator

As presented the performance indicator is composed of four sub-indicators, namely, efficiency, electricity cost capital and lifetime sub-indicators. The traditional method for

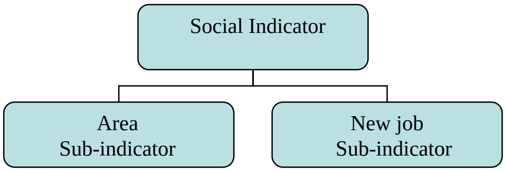

Fig. 4. Social indicator chart.

Table 4

	Name	Definition	Unit
SI_{Area}	Area indicator	Area per kW installed power	m^2/kW
SI_{job}	New job indicator	Number of paid hours per kWh produced in lifetime	h/kWh

Table 5

Option	Efficiency (%)	Electricity cost (Euro/kWh)	Capital cost (Euro/kWh)	Lifetime (Years)
PAFC	40	0.41	1500	5
SOFC	46	0.35	4500	7
Gas turbine	35	0.035	750	20
Photovoltaic	25	0.03	5000	15
Wind	45	0.06	1000	15

the comparison of different systems was always based on a single parameter analysis. In this respect the numerical values of individual sub-indicators for options under consideration are presented in Table 5.

5.1.1. Efficiency sub-indicator

As expected, the efficiency of the system represents the quality measure of the system. The efficiency of systems reflects the effect of quality parameters on the rating among the options. In this exercise the efficiency of the system is defined as the total efficiency and includes all conversion processes from the energy resources to the end-use energy.

The graphical presentation of the efficiency sub-indicators for all options in Fig. 5 introduces SOFC and wind plant options as the priority options in rating among options under consideration.

5.1.2. Electricity cost sub-indicator

The electricity cost in the single parameter analysis is one of the most important parameters for the assessment of the system. It includes the economic aspect of the energy transformation and represents a measure of the quality of the system taking into the account the total cost of the electric energy production, including fuel cost, capital cost and maintenance cost. As can be noticed, the highest electricity cost is obtained for the PAFC and SOFC (Fig. 6).

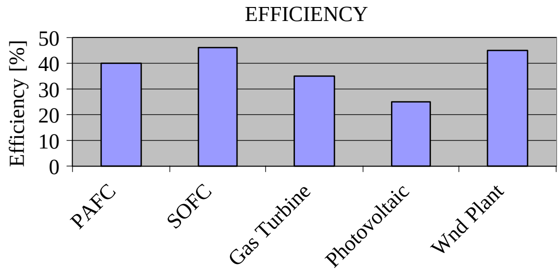

Fig. 5. Efficiency indicator.

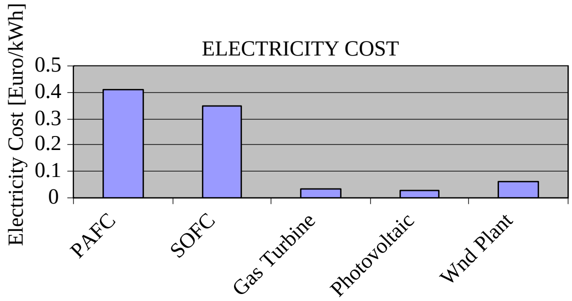

Fig. 6. Electricity cost sub-indicator.

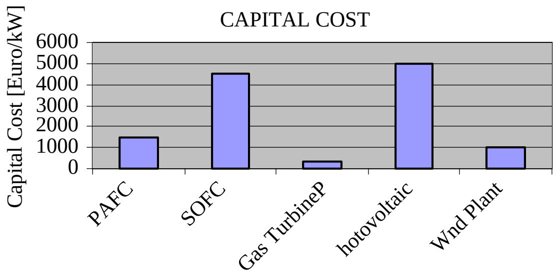

Fig. 7. Capital cost sub-indicator.

5.1.3. Capital cost sub-indicator

The capital cost sub-indicator comprises the material cost of the system which includes the development, design and construction cost of the system. Capital cost rating shows that photovoltaic and SOFC are the most expensive systems under consideration. In general, it should be kept in mind that these two options are also in the early stage in their development so that this capital cost is to a certain extent overestimated in comparison with other options (Fig. 7).

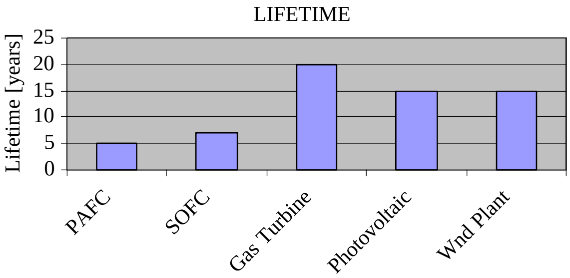

Fig. 8. Lifetime sub-indicator.

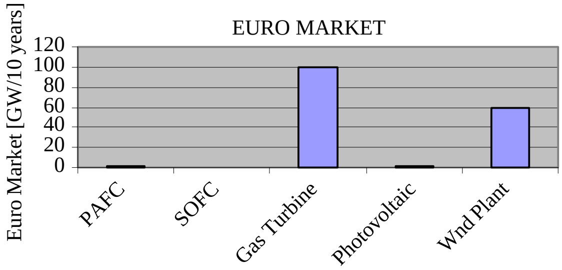

Fig. 9. Euro market indicator.

Table 6
Market indicators

Option	Euro market (GW/10 Years)	World market (GW/10 years)
PAFC	2	40
SOFC	0.5	15
Gas turbine	100	2000
Photovoltaic	1.8	11
Wind	60	160

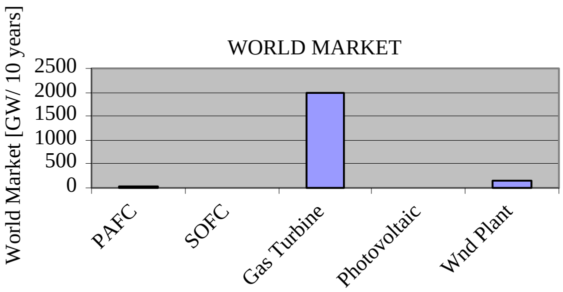

Fig. 10. World market indicator.

5.1.4. Lifetime sub-indicator

The lifetime sub-indicator reflects the maturity of the system. This sub-indicator strongly affects all economically relevant sub-indicators, and its definition is of great importance in the evaluation of the energy systems Estimated values for the lifetime of individual options are only the design characteristics which are used for the evaluation of the systems (Fig. 8).

5.2. Market indicator

Market indicator is introduced in this evaluation as a measure for public acceptance of the system. Also to a certain extent, these sub-indicators reflect the maturity of the system. There are two sub-indicators in this group, namely, Euro market and world market. The numerical values of market sub-indicators are given in Table 6.

5.2.1. EURO market

In this evaluation, special attention was devoted to the Euro market. It is known that the European industry is actively involved in the development of the new energy sources, so that this sub-indicator reflects the priority given to the individual options under consideration. As expected, the gas turbine option is the leading option among those under consideration. The second option is the wind energy option with high market expectation in the future (Fig. 9).

5.2.2. World market

World market sub-indicator is a measure of the potential market in the world scale for the next 10 years. As expected, the highest value of this indicator is obtained for the gas turbine option. It should be noticed that among the other options, world market is not expected to open up high opportunity (Fig. 10).

5.3. Environment indicator

Lately, the main concern in the selection of potential option of power plants are the environment sub-indicators. In this analysis, attention is focused on the following sub-indicators: CO_2, NO_x and Kyoto sub-indicators. As the numerical values for CO_2 and NO_x sub-indicators respective concentrations of the species in the flue gas are used. The third sub-indicator in this group is Kyoto sub-indicator. It represents the measure of contribution of specific options to the Kyoto limit (Table 7).

5.3.1. CO_2 concentration

CO_2 concentration sub-indicator is used as a measure of CO concentration contribution to the environment indicator. Fuel cells options have the highest contribution to the environment indicator. This is the result of a rather low temperature in the fuel cell. In this analysis, it is assumed that the contribution from photovoltaic and wind energy plant is zero (Fig. 11).

Table 7

Option	NO_x (ppm)	CO_2 (ppm)	Kyoto index
PAFC	1	4	0.1
SOFC	0.5	3.5	0.3
Gas turbine	3.5	1.5	20
Photovoltaic	0	0	0.3
Wind	0	0	0.32

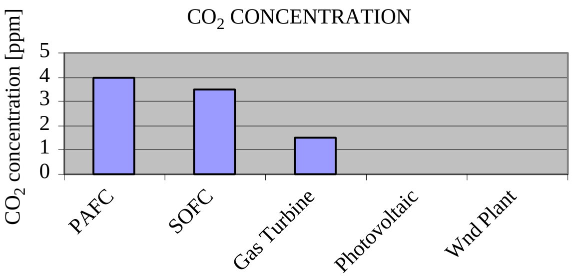

Fig. 11. CO_2 concentration sub-indicator.

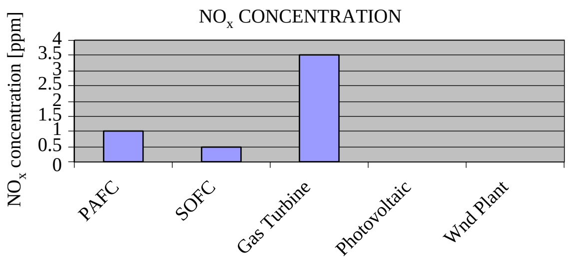

Fig. 12. NO_x concentration sub-indicator.

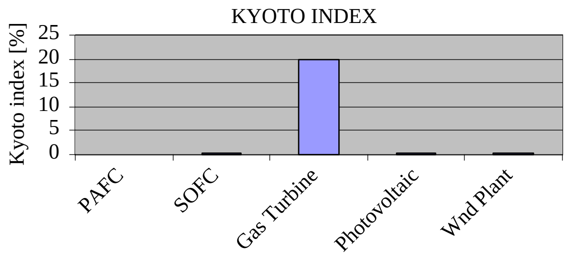

Fig. 13. Kyoto index sub-indicator.

Table 8

Option	Area (m^2/kW)	New jobs (jobs $\times 10^4$)
PAFC	3	4
SOFC	5	1.5
Gas turbine	2	300
Photovoltaic	9	15
Wind	2.5	3

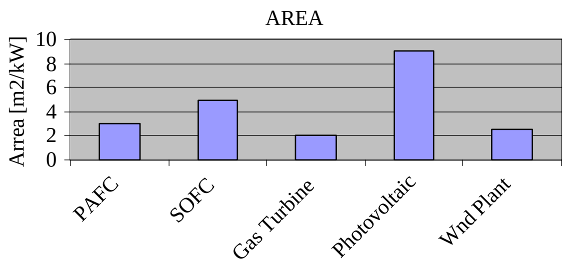

Fig. 14. Area sub-indicator.

5.3.2. NO_x concentration

Again, it is assumed that the NO_x concentration from photovoltaic and wind energy plant options is zero. Due to the high combustion temperature in gas turbine, the highest value of NO_x is obtained for the gas turbine option (Fig. 12).

5.3.3. Kyoto index

Since the gas turbine option is going to have the highest contribution of CO_2 to the total concentration in the atmosphere, it is found that the Kyoto index for the gas turbine option will have the highest value. Due to the rather low participation of the other options under consideration in the total CO_2 concentration, their values will lead to the low value of Kyoto index (Fig. 13).

5.4. Social indicator

Every energy system has effects on the surroundings thus reflecting a social aspect of the energy system. These effects can be positive and/or adverse. In any evaluation of the energy system, it is of great interest to investigate the social aspect of the options under consideration. Obviously, there are a number of social effects which may be of importance for the assessment of the social contribution in the evaluation of energy systems. In this evaluation two sub-indicators are used in the definition of social indicators, namely, area sub-indicator which can be used as the representative of the adverse effect and new job sub-indicators as the positive social effect of the energy system to the surrounding (Table 8).

5.4.1. Area

The high requirement for area to be used for the construction of the respective energy plant is immanent to any energy system. Due to the low intensity of solar energy resource per unit area, the photovoltaic power plant will have the highest of area sub-indicator (Fig. 14).

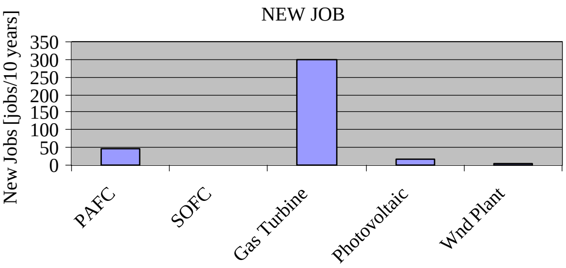

Fig. 15. New job sub-indicator.

5.4.2. New job

Since our evaluation is limited to the first 10 years, the gas turbine option will have the highest contribution to the potential job opening indicator. Also, a high demand of man-power for the design, production and construction of gas turbine power plant will request the new jobs which are the immanent social effect of this option (Fig. 15).

6. Indicators of agglomeration

For the description of objects usually there are a number of sub-indicators, which are used for the specific feature of the object. The individual contribution of these sub-indicators is very difficult to determine with sufficient accuracy [14–16]. In this respect the weighting coefficients are used to determine the importance of individual indicators to the general object index. Even if the weighting coefficient for the individual sub-indicator, is determined it will be difficult to obtain sufficient accuracy in the validation of the indicator to the general object quality parameter. In order to override this deficiency, the agglomeration procedure is adopted which will lead to the aggregation of individual sub-indicators in the main group of indicators defined to the specific performance indicator, market indicator, environment indicator and social indicator. As shown, individual sub-indicators are a subset of the set of indicators reflecting attributes in the description of objects. Under the constraint that the subset of sub-indicators belongs to the set of general indicators as defined by the attributes, it is allowed to use the linear agglomeration function represented as follows:

$$I_{\mathrm{agg}} = \sum_{i=1}^{m} w_i q_i, \tag{1}$$

where I_{agg} is the aggregated indicator, w_i is the weighting coefficient for sub-indicator i, q_i is the normalized value of sub-indicator i.

For the formation of membership functions $q_1(x_1), \ldots, q_m(x_m)$ for every indicator x_i we have to (1) fix two values MIN(i), MAX(i); (2) indicate if the function $q_i(x_i)$ is decreasing or increasing with argument x_i increasing; and (3) choose the exponent's value λ in the formula

$$q_i(x_i) = \begin{cases} 1 & \textit{if } x_i \leqslant \mathrm{MIN}(i), \\ \left(\frac{\mathrm{MAX}(i) x_i - x_i}{\mathrm{MAX}(i) - \mathrm{MIN}(i)}\right)^{\lambda} & \textit{if } \mathrm{MIN}(i) < x_i \leqslant \mathrm{MAX}(i), \\ 0 & \textit{if } x_i > \mathrm{MAX}(i), \end{cases} \tag{2}$$

for the decreasing function $q_i(x_i)$.

The functions $q_1(x_1), \ldots, q_m(x_m)$ formation process finished with a matrix $(q_i^{(j)})$, $i = 1, \ldots, m$, $j = 1, \ldots, k$, where an element $q_i^{(j)}$ is a value of ith particular criterion for jth option. In this analysis it is assumed that the linear functions $q_1(x_1), \ldots, q_m(x_m)$ are used. For q_1, q_2 and q_m membership functions, the decreasing functions are adapted.

The procedure for the determination of weight coefficients is based on the anticipated method for the determination of average values of the weight coefficients for the specific set of indicator values satisfying the imposed constraint. If the scale for the indicator values is defined between 0 and 1 with increment $h = 1/n$, where n is the selected integer then all indicator values will be within this scale. The total set of values in the scale will be $N = W$. The constraint imposed in the priority of indicators will lead to the selection of only those values that satisfy the constraint. The new set formed will allow to determine the average value weight coefficient for each indicator. This is the final result of the procedure for the determination of weight coefficients to be used in the aggregated indicator calculation.

If this procedure is used in the determination of the individual indicators, then the agglomerated values can be obtained for performance indicator, market indicator, environmental indicator and social indicator under specified constraints reflecting the priority of the individual sub-indicators.

6.1. Performance agglomerated indicator

For the evaluation of the performance agglomerated indicator four sub-indicators will be taken into consideration. As defined in the agglomeration procedure, it is necessary to define the respective constrain in order to obtain a specific value of the indicator.

In this exercise, the following constraints will be used for the determination of the performance agglomerated indicator:

CASE 1: (EfI $>$ ECI $=$ CCI $=$ LTI)
CASE 2: (ECI $>$ EfI $=$ CCI $=$ LTI)
CASE 3: (CCI $>$ EfI $=$ ECI $=$ LTI)
CASE 4: (LTI $>$ EfI $=$ ECI $=$ CCI)

In the evaluation of these four cases, only those which are giving priority to the individual sub-indicators are selected. It was aimed to investigate the importance of the individual sub-indicator in the determination of performance aggregated indicator as will be shown in the final results of the evaluation. For each case, two diagrams are obtained

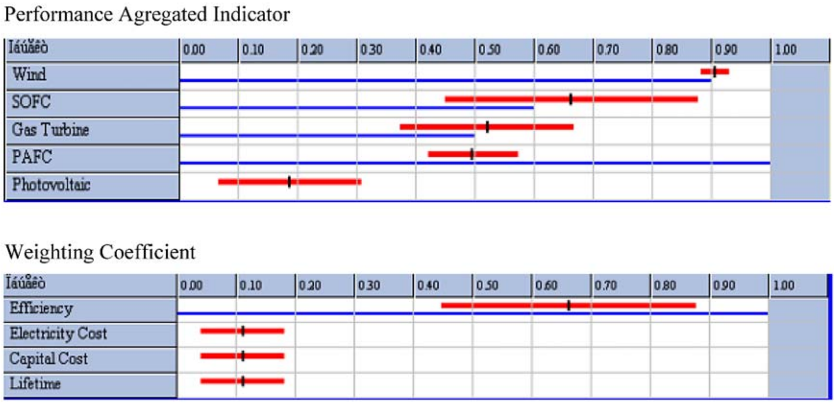

Fig. 16. Performance aggregated indicator—Case 1. (a) Performance aggregated indicator. (b) Weighting coefficient.

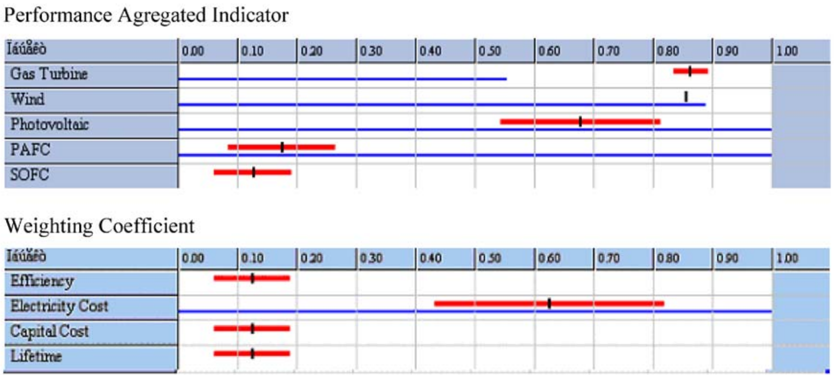

Fig. 17. Performance aggregated indicator—Case 2. (a) Performance aggregated indicator. (b) Weighting coefficient.

presenting values of performance indicator and weighting coefficient values used in the evaluation of the specific case. As it can be noticed, the results obtained for the performance indicators are associated with the respective dispersion of each options. In our further analysis, the value of the performance indicator as obtained for every situation under consideration will be used.

It should be mentioned that these four cases are only the limited number of cases to be used in the evaluation. In the evaluation of the real system the evaluation should include all possible combinations constraints.

Case 1: As can be noticed, this case is designed to demonstrate the determination of the performance indicator if priority is given to the efficiency sub-indicator and others have the same value. Due to the high efficiency of the wind energy system, the highest value for performance indicator in this case is obtained. This is followed by SOFC, gas turbine, PAFC and photovoltaic energy system (Fig. 16).

Case 2: Case 2 is aimed to introduce priority to the electric energy cost sub-indicator. If the priority is given to the electricity cost sub-indicator, the highest value for the performance indicator is obtained for the gas turbine option. It should be noticed that the same value is obtained for the wind energy option. The lowest value is obtained for the PAFC and SOFC systems (Fig. 17).

Case 3: Case 3 is a demonstration for the priority of capital cost sub-indicator. If the priority is given to capital cost sub-indicator, against options gas turbine and wind energy option will have higher values for the performance aggregated indicator (Fig. 18).

Case 4: The last case in the demonstration of priority of individual sub-indicator is the case with priority given to the lifetime sub-indicator. In this case, it can be noticed that the higher values for performance indicator are obtained for gas turbine, wind and photovoltaic options (Fig. 19).

6.2. Aggregated market indicator

The market indicator is composed of sub-indicators taking into consideration the effects of Euro market and world

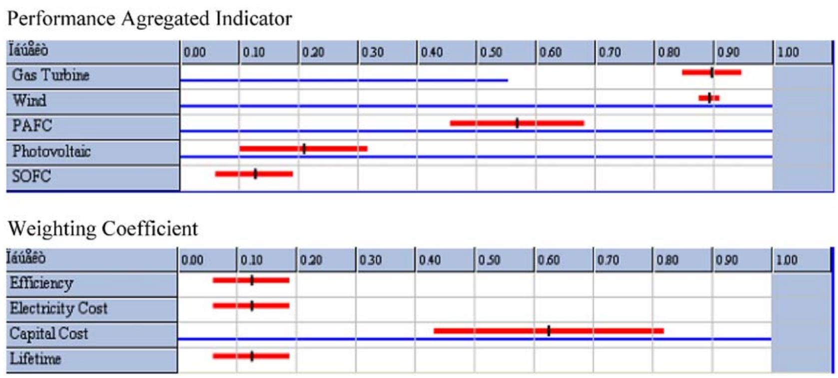

Fig. 18. Performance aggregated indicator—Case 3. (a) Performance aggregated indicator. (b) Weighting coefficient.

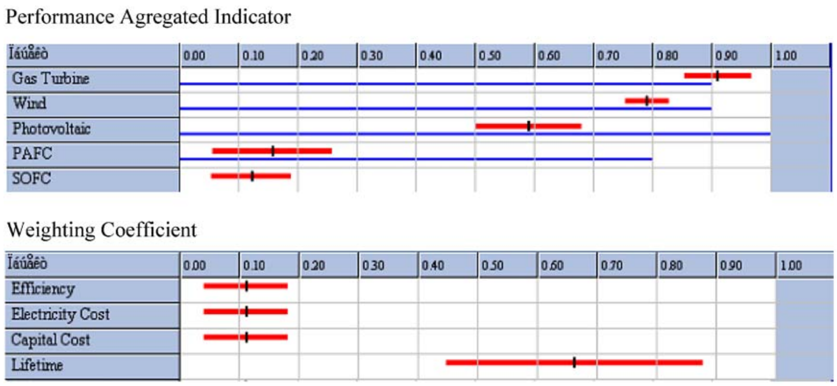

Fig. 19. Performance aggregated indicator—Case 4. (a) Performance aggregated indicator. (b) Weighting coefficient.

market. Market aggregated indicator is analyzed in two cases, namely:

Case 1 (MIEuro > MIWorld)

Case 2 (MIWorld > MIEuro)

Case 1: This case is taking into consideration the determination of the market indicator under constraint if the priority is given to Euro market sub-indicator. As expected, the highest values for market indicator are obtained for the gas turbine and wind energy options (Fig. 20).

Case 2: In this case, the constraint is designed to give priority to the world market sub-indicator. Case 2 is characterized by a very high value for the gas turbine option and other options with rather low values of aggregated market indicator (Fig. 21).

6.3. Environment indicators

In order to obtain environment agglomerated indicator values, the following constraints are taken into consideration:

Case 1 ($EINO_x > EICO_2 = EIKyoto$)

Case 2 ($EICO_2 > EINO_x = EIKyoto$)

Case 3 ($EIKyoto > EINO_x = EICO_2$)

Case 1: This case demonstrates two values for the environment aggregated indicator if priority is given to the NO_x concentration sub-indicator. Since wind energy and photovoltaic options are assumed to have zero contribution of respective sub-indicator, highest values for the environment aggregated indicator are obtained for these two options (Fig. 22).

Case 2: Similarly as for the priority of NO_x concentration sub-indicator, the CO sub-indicator effects on the environment aggregated values are obtained. It can be noticed that wind and photovoltaic options have the same value but other options are very different and SOFC and PAFC options have very low values of environment aggregated indicator (Fig. 23).

Case 3: For the case with priority to the Kyoto sub-indicator, the environment aggregated indicator value is having the highest value for gas turbine options followed by equal values for wind and photovoltaic options. Since a high value for the Kyoto sub-indicator reflects an adverse effect on the environment aggregated indicator, the high value if this indicator in this case should be considered as a

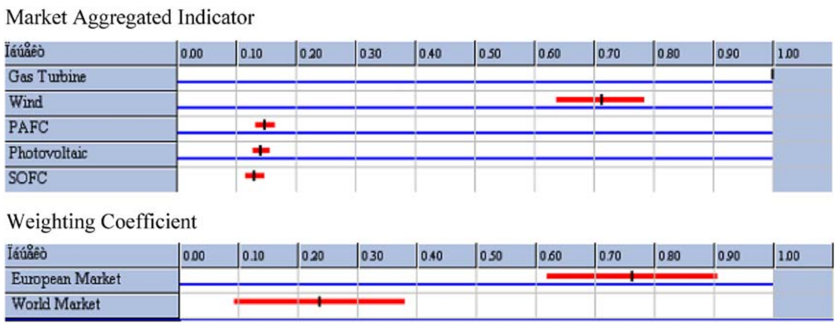

Fig. 20. Market aggregated indicator—Case 1. (a) Market aggregated indicator. (b) Weighting coefficient.

Fig. 21. Market aggregated indicator—Case 2. (a) Market aggregated indicator. (b) Weighting coefficient.

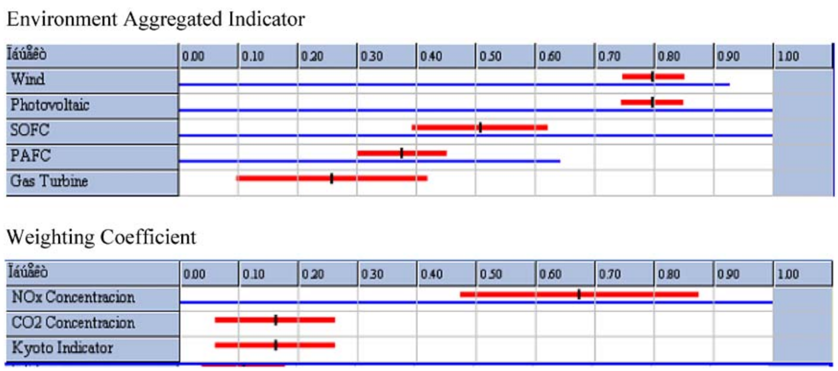

Fig. 22. Environment aggregated indicator—Case 1. (a) Environment aggregated indicator. (b) Weighting coefficient.

negative contribution in the sustainability index evaluation (Fig. 24).

6.4. Social indicators

The social indicator represents two different sub-indicators which are associated with different quality scales. It is of great importance to obtain social aggregated indicator values reflecting the respective constraints. In this evaluation of the social agglomerated indicator values, the following constraints are used:

Case 1: (SIArea > SIjob)

Case 2: (SIjob > SIArea)

Case 1: This case is aimed at investigating the effect of the constraint if priority is given to the area sub-indicator. As expected, the highest value for the social aggregated indicator is obtained for the photovoltaic option. Here it can be noticed that the SOFC option also bears a high value (Fig. 25).

Fig. 23. Environment aggregated indicator—Case 2. (a) Environment aggregated indicator. (b) Weighting coefficient.

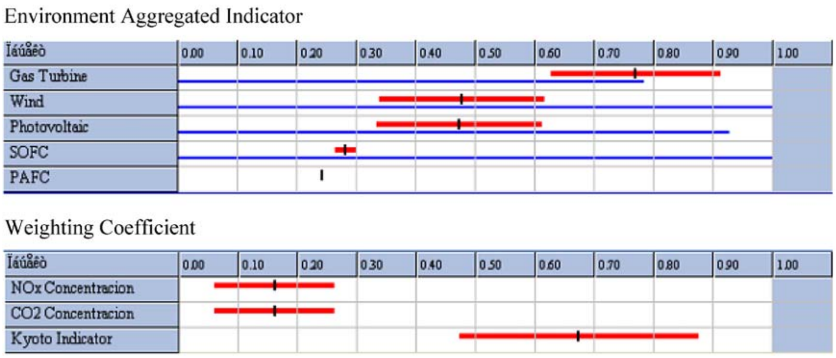

Fig. 24. Environment aggregated indicator—Case 3. (a) Environment aggregated indicator. (b) Weighting coefficient.

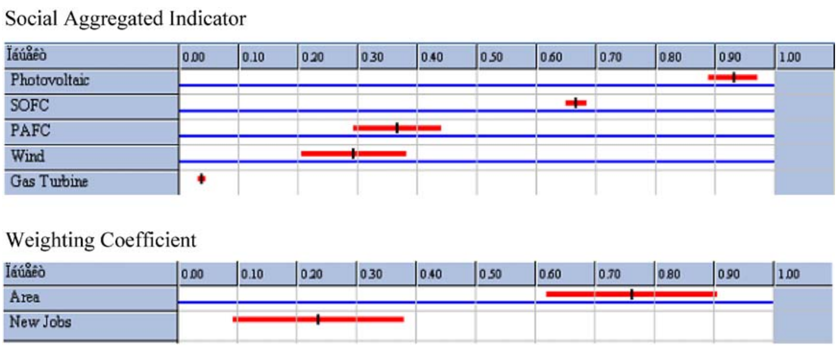

Fig. 25. Social aggregated indicator—Case 1. (a) Social aggregated indicator. (b) Weighting coefficient.

Case 2: Among the social constraints, the most important is job opportunity. This case is designed with priority to the new job sub-indicator. The results obtained imply that Photovoltaic, SOFC, PAFC and Wind options have similar values for the social aggregated indicator (Fig. 26).

7. Multi-criteria sustainability assessment

The multi-criteria assessment is based on the decision-making procedure reflecting the combined effect of all criteria under consideration and it is expressed in the form of a general index of sustainability [17]. Selected number of indicators are taken as a measure of the criteria comprising specific information of the options under consideration. The procedure is aimed to express options property by the respective set of indicators.

7.1. Sustainability index definition

The decision-making procedure comprises several steps in order to obtain a mathematical tool for the assessment of

Fig. 26. Social aggregated indicator—Case 2. (a) Social aggregated indicator. (b) Weighting coefficient.

the rating among the options under consideration. In order to prepare respective data for the hydrogen systems assessment, Table 5 presents the data to be used in the analysis.

The general indices method comprises the formation of an aggregative function with the weighted arithmetic mean as the synthesizing function defined as

$$Q(q;w) = \sum_{i=1}^{m} w_i r_i \qquad (3)$$

where w_i is the weight-coefficients elements of vector $\mathbf{w}$ and r_i is the aggregated indicators of specific criteria.

In order to define the weight-coefficient vector, the randomization of uncertainty is introduced. Randomization produces stochastic realizations from corresponding sets of functions and a random weight-vector. It is assumed that the measurement of the weight coefficients is accurate within the step $h = 1/n$, with n a positive integer. In this case, the infinite set of all possible vectors may be approximated by the finite set $W(m,n)$ of all possible weight vectors with discrete components. In our case, we will use $m = 5$, and $n = 35$ so that the total number of elements of the set $W(m,n)$ is $N(m,n) = 92251$.

For non-numeric, inexact and incomplete information I = OI U II used for the reduction of the set $W\,(m,n)$ of all possible vectors $\mathbf{w}$ to obtain the discrete components set W (I;n,m) is defined as the number of constraints reflecting non-numeric information about mutual relation among the criteria under consideration.

7.2. Evaluation of selected situations

Evaluation is obtained for the following situations:

Run no. 1—PI (Case 1) > MI (Case 1) = EI (Case 1) = SI (Case 1)

Run no. 2—PI (Case 2) > MI (Case 1) = EI (Case 3) = SI (Case 2)

Run no. 3—PI (Case 3) > MI (Case 1) = EI (Case 3) = SI (Case 2)

Run no. 4—PI (Case 4) > MI (Case 1) = EI (Case 3) = SI (Case 2)

7.2.1. Run no. 1—PI (Case 1) > MI (Case 1) = EI (Case 1) = SI (Case 1)

As shown, this run is designed to investigate the effect of the performance indicator on the rating among options under consideration. The performance indicator in this run is obtained under the constraint that the efficiency sub-indicator has priority. The market indicator is calculated under the constraint that priority is given to the EURO market sub-indicator. The environment indicator was obtained under the constraint that priority is given to Kyoto index sub-indicator. The social indicator is determined with the constraint that priority is given to area sub-indicator (Fig. 27).

The first two places on the priority list of general sustainability index rating of options under consideration in this run are obtained by wind and photovoltaic options.

7.2.2. Run no. 2—PI (Case 2) > MI (Case 1) = EI (Case 3) = SI (Case 2)

The situation presented in Run no. 2 is designed to show what effect will be obtained if the priority in performance indicator will be changed and if priority is given to the electricity cost sub-indicator. The market indicator is obtained with the constraint that priority is the same sub-indicator as for Run no. 1. The Environment indicator is determined with priority given to Kyoto sub-indicator. The social indicator was obtained for the priority given to new job sub-indicator. This run will show the sensitivity of the method for multi-criteria assessment of energy system options.

Very high priority is obtained in the gas turbine and wind options. This change in the priority in performance indicator and other indicators has shown to what extent it is important to evaluate any combination of priority in making the final decision in the selection of the potential energy system option (Fig. 28).

7.2.3. Run no. 3—MI (Case 1) > PI (Case 3) = EI (Case 3) = SI (Case 2)

This Run is aimed at introducing the priority of market indicator with Euro market sub-indicator priority. The

Fig. 27. General sustainability index—Run no. 1. (a) General sustainability index. (b) Weighting coefficient.

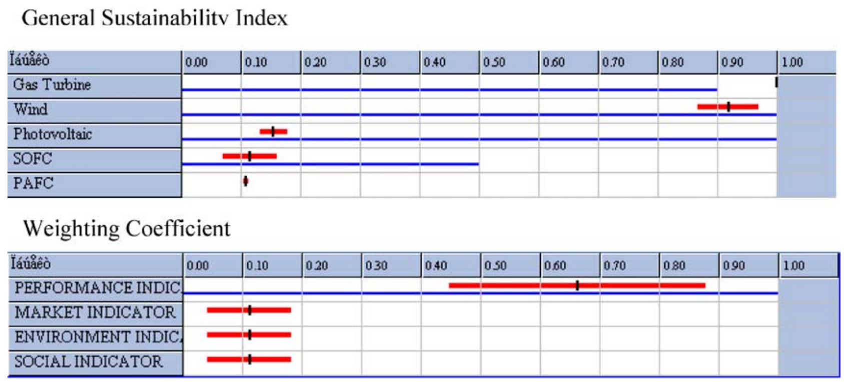

Fig. 28. General sustainability index—Run no. 2. (a) General sustainability index. (b) Weighting coefficient.

performance indicator in this Run is obtained with the constraint of capital sub-indicator as the first priority. The environment indicator is determined with Kyoto sub-indicator priority. The social indicator is calculated for the case with new job sub-indicator priority.

The general sustainability index rating as shown in diagram Fig. 29 gives priority to the gas turbine option and the second place is taken by wind options. A very low rating is obtained for photovoltaic, SOFC and PAFC options (Fig. 29).

7.2.4. *Run no. 4—EI (Case 3) > PI (Case 2) = MI (Case 2) = SI (Case 2)*

In order to show that the photovoltaic option can be highly rated in the general sustainability index rating this Run is designed with priority given to the environment indicators.

Among the first rated options are wind, photovoltaic and gas turbine with a marginal difference in the general sustainability index (Fig. 30).

8. Discussion of multi-criteria evaluation

Multi-criteria evaluation of energy systems is an exercise showing the potential possibility of the analysis of complex systems. In general terms it could be said that the complexity of energy systems can be defined as the multi-dimensional space of different indicators. Every energy system under consideration is an entity by itself, defined by the respective number of parameters which are deterministically related according to the physical laws describing individual processes in the system. The differences expressed by selected indicators are reflecting the complexity of the individual structure of options under consideration. Sustainability indicators take into account the economic, environmental, resources and social aspects of sustainability. They are supposed to help decision-makers to identify problematic areas that should be given priority.

The use of a multi-criteria decision-making procedure requests a new method for evaluation of the potential options of energy systems. Its purpose is mainly oriented to the evaluation of options in order to investigate the effect of

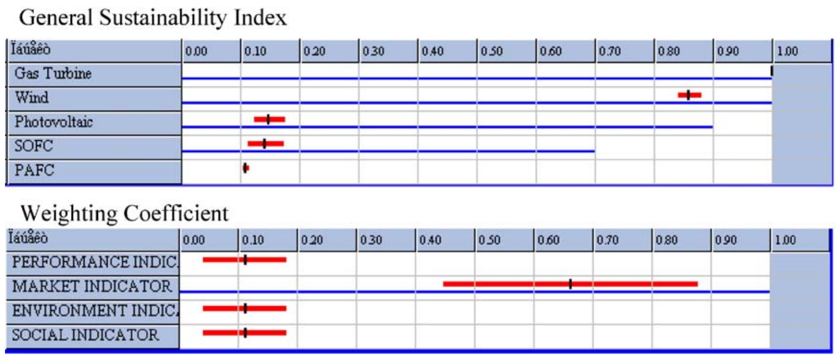

Fig. 29. General sustainability index—Run no. 3. (a) General sustainability index. (b) Weighting coefficient.

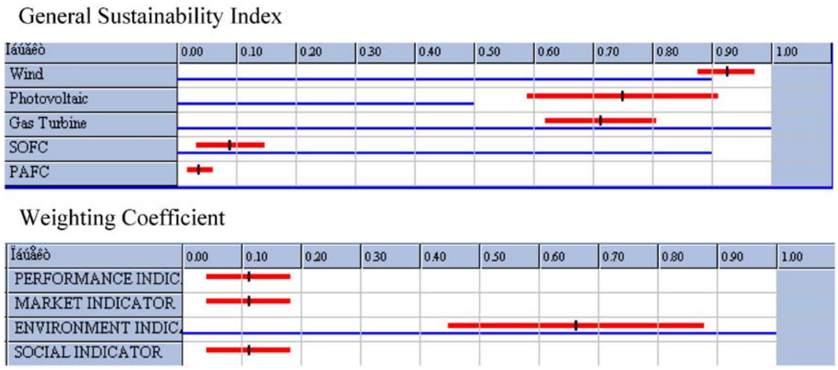

Fig. 30. General sustainability index—Run no. 4. (a) General substainability index. (b) Weighting coefficient.

individual criteria on the priority list for the decision-making process. In the evaluation procedure it is possible to investigate the effects of mutual relation of the criteria on the final priority list. This evaluation procedure could be imagined as a useful tool for the analysis of the individual criteria.

Since each of the indicators represents the aggregated parameter derived from the internal parameters of the system the general sustainability index as defined in this analysis is a measure of complexity of the system. Indicators are deterministically related to the technical and economic parameters of the system, so their aggregation means only convolution of indicators multiplied by respective weighting coefficients. The quality measurement demonstrated in this evaluation has proved that the decision-making process strongly depends on the priority given to the specific indicators used in this analysis. As it was demonstrated in this exercise priority given to the specific indicators may lead to the different rating list of the option under consideration. So, Run Nos. 1 and 2 have led to the different rating just as a result of the difference in the priority of indicators and sub-indicator.

Since this evaluation is only a demonstration of the method and procedure, it would be inappropriate to make any final conclusion on the potential selection of the energy system as it was demonstrated in this evolution. But still it can be concluded that under circumstances demonstrated in this evaluation gas turbine and wind options are presently the most attractive potential systems to be selected among the options under consideration. Also, photovoltaic option is a potentially acceptable solution for the situation where it can be in accordance with the respective local condition. The PAFC and SOFC options are representative of hydrogen energy system. Their rating in this analysis is low, but it should be recognized that they are in the development stage so the present analysis only reflects the present state of the art in the field.

Further development of this methodology will be oriented towards two main directions. First, to the better definition of indicators and their certainty. In particular, attention has to be focused on variables affecting indicators which are space and time dependent. Second, the use of different types of aggregation functions for the general sustainability index may prove to be a way of finding respective functions appropriate for different systems. As regards the evolution of energy systems, further development of this method may be envisaged through its application to the evaluation of future selection of energy systems.

References

[1] Afgan NH, Carvalho MG. Sustainable assessment method for energy systems. Dordrecht: Kluwer Academic Publishers; 2000.

[2] Dunn S. Hydrogen future: toward sustainable energy development. Int J Hydrogen Energy 2002;27:235–64.

[3] Afgan NH, Al Gobaisi D, Carvalho MG, Cumo M. Sustainable energy management. Renewable Sustainable Energy Rev 1998;2(3):125–286.

[4] Afgan NH, Carvalho MG, Hovanov NV. Energy system assessment with sustainability indicators. Energy Policy 2000;28:603–12.

[5] Afgan NH, Carvalho MG. Multi-criteria assessment of new and renewable energy power plants. Energy 2002;27: 739–55.

[6] Afgan NH, Carvalho MG, Prstic S, Bar-Cohen A. Sustainability assessment of aluminium heat sink design. Heat Transfer Eng 2003;24:1–10.

[7] Morse S, McNamara N, Acholo M, Okwoli B. Sustainability indicators: the problem of integration. Sustainable Development 2001;9:1–13.

[8] Veziroglu N. 21 st century energy: the hydrogen energy system, Invited Lecture, Melbourne, Australia: CSIRO, 2003.

[9] Hart D, Brandon N. An introduction to fuel cell technology and economics. Imp Coll Centre Energy Policy Technol, Internal report, 1999.

[10] Kordische K, Simander G. Fuel cells and their application. NY, USA: VCH Press; 1996.

[11] Pilavachi P. An overview of gas turbine technology for power generation in Europe. Proceedings of the New and Renewable Technologies for Sustainable Development, Funchal, Madera, 2002. p. 299–313.

[12] Kazmerski L. Photovoltaic R and D: tour through the 21st century. Proceedings of the New and Renewable Technologies for Sustainable Development, 2002. p. 135–45.

[13] Cotrell J, Pratt W. Modelling the feasibility of using fuel cells and hydrogen internal combustion engines in remote renewable energy system. WINDPOWER 2003.

[14] Hovanov N, Fedotov Yu, Zakharov V. The making of index numbers under uncertainty. In: Pykh YA, Hyat DE, Lenz RJUM, editors. Environmental indices: systems analysis approach. Oxford: EOLSS Publishers Co.; 1999. p. 83–99.

[15] Hovanov N. Analysis and synthesis of parameters under information deficiency. St. Petersburg: St. Petersburg State University Press; 1996 (Monograph, in Russian).

[16] Hovanov N, Kornikov V, Seregin I. Qualitative information processing in DSS ASPID-3W for complex objects estimation under uncertainty. Proceedings of the International Conference “Informatics and Control”. St. Petersburg, Russia, 1997. p. 808–16.

[17] Hovanov AN, Hovanov NV. DSSS “ASPID-3W” Decision Support System Shell, Registered by Federal Agency for Computer Programmes Copyright Protection Russia Federation, 22 September, 1996, Num. 960087.