Available online at www.sciencedirect.com

ScienceDirect

International Journal of Hydrogen Energy 32 (2007) 3183–3193

International Journal of HYDROGEN ENERGY

www.elsevier.com/locate/ijhydene

Multi-criteria evaluation of hydrogen system options

Naim H. Afgan[a,*], Ayfer Veziroglu[b], Maria G. Carvalho[a]

[a]*Instituto Superior Tecnico, Av. Rovisco Pais, 1094 Lisbon, Portugal*
[b]*International Association for Hydrogen Energy, Coral Gables, FL 33146, USA*

Received 17 April 2007; accepted 17 April 2007
Available online 28 August 2007

Abstract

The paper gives an overview of the potential of multi-criteria assessment of hydrogen systems. With respective selection of the criteria that comprise the performance, environment and market 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 multi-criteria procedure is based on the sustainability index (SI) rating that is composed of a linear aggregative function of indicators, of which all have respective weight functions. The hydrogen fuel cell systems have three options, natural gas reforming, photovoltaic and wind energy systems, from which the latter two represent the renewable options. These options are evaluated with a multi-criteria method comprising the following indicators: the performance indicator, the market indicator, the environment indicator and the social indicator. An example of a multi-criteria procedure for the assessment of hydrogen systems proves that the sustainability general index (SGI) rating is an effective tool for decision making compared to single indicators evaluation.

Keywords: Multi-criteria assessment; Hydrogen energy; Hydrogen energy systems

1. Introduction

Sustainable development is a strategic goal of a modern society reflecting contemporary demand for economic, social, political and environmental development. It is of fundamental importance for the world to join this movement and promote future strategy in the economic development, based on the vision of sustainability criteria. The energy strategy in this respect plays the most important role in the design of the sustainability concept development. Access to affordable and reliable energy that is drawn from environmentally acceptable sources of supply is an important feature of sustainable development.

The present dilemma, which reflects different approaches to the potential utilization of hydrogen, greatly attracts the scientists, the engineers and the academic society to discuss the potentiality of the options under consideration. Fossil fuels, nuclear energy, geothermal energy, hydro-potential and solar energy have all been the essential resources of energy. The conversion of primary energy resources to final energy is a chain of processes leading to usable form of energy. Electricity is the widely used form of energy. Today's technology for electricity production basically consists of burning a fuel in order to heat up water to get steam, and turning a turbine to obtain mechanical energy, the form of energy which is then converted to electricity through an induction mechanism. The electricity can be used to produce hydrogen which is then used as a fuel in fuel cells, so that hydrogen becomes the novel energy carrier.

There are two major objections to the hydrogen route for the development of future energy strategies. One is based on the insufficiency of hydrogen as a fuel compared to other energy resources. Oil can be directly pumped out from underground and fortunately it has a huge net energy, which is usually more than 200 times the amount of the energy that is required for its extraction. However, hydrogen has a negative net energy, which means that its production requires more energy than the energy it can actually provide for the same volumes at the same pressure conditions. Moreover, even if hydrogen is the most abundant element in the universe, its production is relatively difficult. Oil is the most concentrated form of hydrogen that is available for human consumption, and contains more hydrogen by volume than the pure hydrogen itself, since the configuration

* Corresponding author. Tel.: +351 21 8418082; fax: +351 21 8475545.
E-mail address: nafgan@navier.ist.utl.pt (N.H. Afgan).

0360-3199/$ - see front matter © 2007 Published by Elsevier Ltd on behalf of the International Association for Hydrogen Energy.
doi:10.1016/j.ijhydene.2007.04.045

of the atoms in the hydrocarbons' structure cover less amount of space. Another argued deficiency of hydrogen is that, it has a very low calorific value, for example about 4 times more amount of hydrogen has to be consumed in transportation in order to travel a given distance. There are several methods to produce hydrogen; via electrolysis of water, splitting of water by light (photolysis) and reforming gas from biomass, natural gas or any other fossil fuel. The potency of hydrogen produced by renewable energy sources creates a new venue for its utilization. In particular, an advantage is realized in the utilization of hydrogen for transportation. Owing to the abundant renewable energy resources, the hydrogen route is gaining economic feasibility as the promising fuel of the future. Additionally, if the environmental impacts of fossil fuel consumption are taken into account, it will be apparent that hydrogen economy can definitely constitute the future energy strategy.

In order to determine the potential options for the future energy strategy, it is of interest to initially evaluate the hydrogen energy system (HES) by utilizing different criteria. A number of methods, which are used in respective sequence in a procedure for presenting quantitative merits for the rating of different power system designs, serve this purpose. Popular methods applied in the evaluation of a power system are: the thermodynamic method, the energy cost evaluation method and the life-cycle method.

"Each of these methods is based on the optimization function, which reflects a single indicator in the evaluation of individual options of the power plant design. It has been noted that the energy system complexity requires that a multi-variable assessment of different aspects of the power system is taken into account. It is clear that besides the economic valorizations of the power system that take place in the modern approach, some other aspects of individual designs of the power system have to be considered, as well. Since the energy production in the power system is based on different physical principles, each power system option will reflect the importance of a different optimization parameter. Moreover, each power system option will make use of different energy sources, of which conversion into final energy option will create a different interaction with its environment" [1].

The decision generating method that is based on the probabilistic assessment of a fuzzy set of indicators that have information deficiency has proved to be a powerful tool for the evaluation of complex systems defined by multi-parameters [2–5]. It has become crucial to compare the desirability of different means of actions that lead to the achievement of sustainable products or to determine "optimal" solutions in multiple cases by utilizing simple criteria or a simple objective function. Multi-criteria decision-making has resulted in numerous evolution schemes and has led to the formation of the vector-maximum problem in mathematical programming.

2. Selection of options and indicators for energy systems

2.1. Option selection

Potential options of the hydrogen systems are objects with a number of attributes defining feedstock, energy resources, hydrogen production, and hydrogen utilization system. Among the energy resources are the fossil fuels, nuclear fuel and renewable energy sources. As described previously, the hydrogen production process comprises of electrolysis, the gas reforming process and the light splitting process. The attribute that describes the hydrogen utilization process includes a fuel cell, a reciprocation engine and a gas turbine. Fig. 1 represents the hydrogen system structure object. It is clear that there are number of objects, which can be designed by taking the potential option of the HES into consideration.

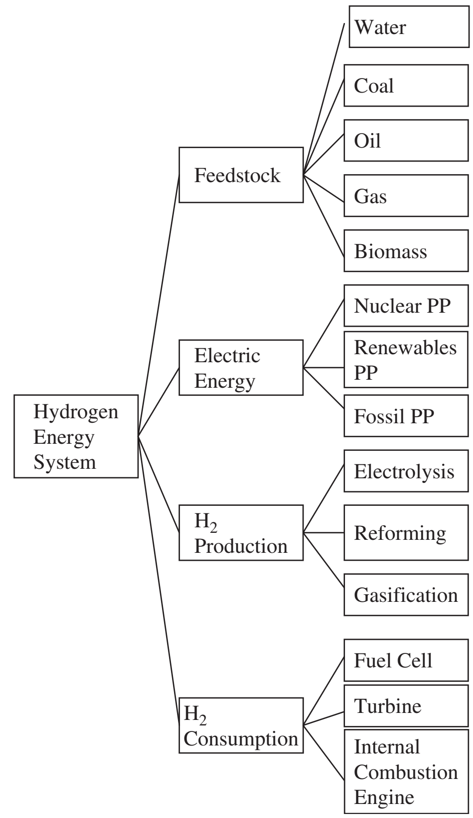

Fig. 1. The hydrogen system structure object.

In the Object Oriented language, the potential options of the HES can be defined as: feedstock (water, coal, oil, gas, and biomass); electrical energy (nuclear PP, renewable PP, and fossil PP), H_2 production (electrolysis, reforming, and gasification); H_2 utilization (fuel cell, gas turbine, and internal combustion engine (ICE)). Ninety objects are utilized in the evaluation of the potential objects, and these define the respective options that have to be taken into consideration.

2.2. The hydrogen system options

In this exercise we focus our attention on the following HES: the fossil-reforming-reciprocation system, the nuclear-electrolysis-fuel cell system, the solar-electrolysis-fuel cell system, the wind-electrolysis-fuel cell system, and the biomass-reforming-gas turbine system [6]. Selection of options is arbitrary with intention to introduce different combination system elements.

The following sections constitute the options that were utilized in the evaluation of the HES.

2.2.1. The fossil-reforming-ICE system (ORSICES)

In the definition of this system it is anticipated that the mean energy resource is oil having a low calorific value of 7000 kJ/kg. The market energy cost of oil is 4 USc/kJ. The efficiency of the oil reforming system is 35 USc/kg H_2 [6]. The efficiency of the reciprocation engine that works with hydrogen fuel is 37%. Combustion of oil during the reforming process is accompanied with the production of chemical products, which are considered as pollutants. In an attempt to justify the effect of the pollution problem related to this HES, the following substances are anticipated to be emitted: CO, SO, and NO. In this option, it is assumed that no storage facility is required. The total investment cost of the system is distributed between the following items: the reforming plant and the reciprocation engine. The technological advancement is defined by the financial resource that is planned for the future development. Schematic representation of this system is shown in Fig. 2.

2.2.2. The nuclear-electrolysis-fuel cell system (NESFCS)

The use of nuclear energy for hydrogen production has been advocated many years ago and promoted as an advantage of the nuclear power plants. Now, as hydrogen approaches towards a strategic acceptance, the familiar idea is again being brought into discussion. The present cost of electricity from modern nuclear power plant is estimated as 7 USc/kWh [6]. Utilization of the relatively inexpensive electricity for electrolysis carried out for hydrogen production has become a challenging opportunity. With an electrolysis efficiency of 70%, the price of hydrogen can be as low as 47 USc/kg. In this hydrogen system the need for storage is of fundamental importance. The estimated cost of large volume hydrogen tanks is $\$399/\mathrm{m}^3$. Phosphoric acid fuel cells (PAFC) have been in ‘commercial’ production for more than five years, with about 200 kW units currently installed or in the stage of production. Although the US Government programs have assisted the purchasers, these have historically been expensive; e.g. having a price of \$3000/kW. The current market price is \$3750/kW and even at this value, it is subsidized internally. The difference in the prices may seem to indicate an increase; in fact it is the first time that the price covers all the costs of production.

The PAFCs represent the first generation of ‘commercial’ fuel cells. Although being successful in terms of technical performance, a debate concerning their cost reduction potential and their applicability as a more competitive option in the future is still continuing. Schematic presentation of a nuclear PACF system is shown in Fig. 3.

2.2.3. The solar-electrolysis-fuel cell system (SESFCS)

The abundant solar energy resources constitute the challenging potential option for hydrogen production. The solar cell cost is the most important element of the photovoltaic (PV) system’s economic viability. The modules account for about 50% of the cost of a PV power plant. The solar cells themselves account for about the half of the module cost, or 20% of the system’s total cost. Thin film polycrystalline technology may make it possible to bring the module cost to about $50\,\mathrm{USD/m^2}$ and the electricity price to 6 USc/kWh. This is a planning target for only 10% efficiency. With the increase of efficiency to 20% the target will be 4 USc/kWh.

Electrolysis is the decomposition of water into hydrogen and oxygen. Electrolyzers essentially consist of a negative and a positive electrode, as well as an electrolyte. Electrolyzers are characterized by their very simple and compact construction. Only 4% of hydrogen is made from water via electrolysis. Since most of the electricity comes from fossil fuels formed from plants that are 30% efficient, and since electrolysis is 70% efficient, one can end up in using four units of energy to create one unit of hydrogen energy: $70\% * 30\% = 20\%$ efficiency. Schematic representation of this system is presented in Fig. 4.

2.2.4. The wind-electrolysis-fuel cell system (WESFCS)

Wind energy can be utilized to provide electricity at low cost. Coupling the wind turbine with a hydrogen generating electrolyzer provides a potential for distributed generation of hydrogen—which has low cost and is environmentally friendly—in comparison to electricity. Wind electricity generation unit has an efficiency of 35% and a lifetime of 20 years. The cost of investment of the wind generation unit is 1000–1100 €/kW, with the cost of land being 300–400 €/m^2. Electricity cost is 0.03–0.07 €/kWh.

The goal is to utilize renewable energy to produce hydrogen from water, via electrolysis. Today’s technology of wind energy systems can perform at 30–40% efficiency which leads to hydrogen production having 25% efficiency. Schematic representation of this system is shown in Fig. 5.

2.2.5. Biomass-electrolysis-gas turbine system (BGCSGTS)

The main goal of the gasification process is production of high quality and quantity gaseous fuels from biomass. The gasification process is performed at high temperatures in the range of 700–1000 °C and under stechiometric conditions ($\lambda < 1$) which do not allow the development of a combustion process and also aim to ensure that all of the fuel is consumed. A gas turbine is used as the electricity generation unit [7]. Schematic representation of this system is shown in Fig. 6.

2.3. Selection of the indicators

For the multi-criteria assessment of the hydrogen system, the following indicators are used:

1. Fuel cost indicator (FCI).
2. Electricity cost indicator (ECI).
3. Fixed cost indicator (FxI).
4. Capital charge indicator (CCI).
5. Environment indicator (EI).

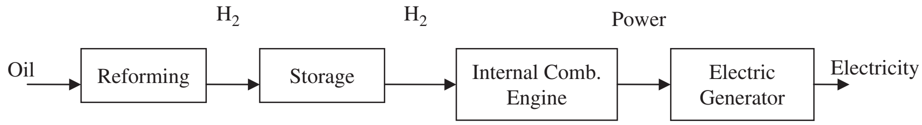

Fig. 2. The fossil-reforming-ICE system (ORSICES).

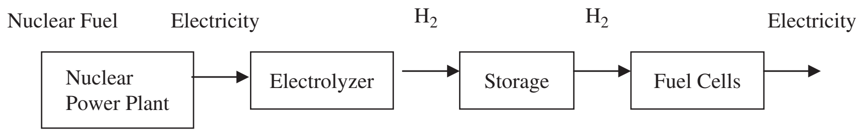

Fig. 3. The nuclear-electrolysis-fuel cell system (NESFCS).

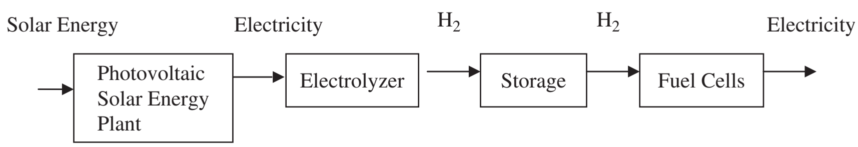

Fig. 4. The solar-electrolysis-fuel cell system (SESFCS).

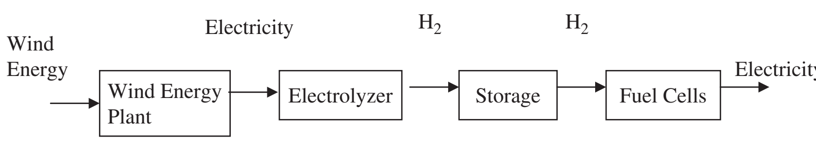

Fig. 5. The wind-electrolysis-fuel cell system (WESFCS).

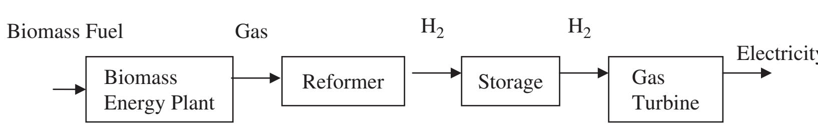

Fig. 6. The biomass-electrolysis-gas turbine system (BGCSGTS).

2.3.1. The FCI

The energy cost constitutes the major part of the operation and maintenance cost in hydrogen production. Every option under consideration is based on a different hydrogen production scheme, which implies that the effect of the fuel consumption is an important indicator in the evaluation of the quality of the hydrogen system. The energy cost indicator is determined from the simplified energy and material balances and capital investment and operating costs. It comprises of two indicators: the fuel cost sub-indicator and the electricity cost sub-indicator. The fuel cost sub-indicator is based on the consumption of a fuel that is utilized during the hydrogen production process.

2.3.2. The ECI

The second indicator includes the electricity cost that is utilized in the hydrogen production chain. As all of the options of the hydrogen scheme require the consumption of electrical energy, the ECI is a very important measure parameter for the assessment of the hydrogen production process. It is anticipated that electrical energy costs from different electric power systems comprise the total electrical energy form the respective power plant. The ECI is defined in USD/kg H_2.

2.3.3. The FxI

The FxI consists of the operation and the maintenance cost. Fixed operating and maintenance costs are estimated as the percentage of the total capital cost per year that is assumed for capital investment and include the operating maintenance cost of all of the elements of the system.

2.3.4. The CCI

The CCI is based on the percentage of the process unit cost. Capital charges are also estimated as the percentages of the total capital charges. Capital charge in this analysis is 18%.

Table 1
Technical data of hydrogen systems

System	Resources	H_2 production		Storage	Electricity production		
		Reforming (m^3 H_2/day)	Electrolysis (m^3 H_2/day)	(m^3 H_2/day)	Fuel cell (kWh/day)	ICE/EG (kWh/day)	Gas turbine/EG (kWh/day)
ORSICES	1.2 t oil/day	3705	0	3705	0	2400	0
NGRSFCS			1042		2400		
NPESFCS	11.65 MWh/day	0	1042	990	2400	0	0
SPESFCS	20.84 MWh/day	0	1042	990	2400	0	0
WPESFCS	8.961 kWh/day	0	1042	990	2400	0	0
BGCSGTS	0.347 m/day Meth.	2004	0	2004	0	0	2400

2.3.5. The EI

The EI is the CO_2 Indicator and is represented by the CO_2 gas production per unit hydrogen. The same procedure that is used in the definition of other indicators can be adapted to the EI. It will include the production that is achieved as a result of the power production, which is needed in the process of hydrogen production.

The numerical values for all of the options under consideration are listed in Table 1 [6].

3. Multi-criteria sustainability assessment

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

In order to make use of data for the assessment of a respective system, it is necessary to convert the data into an indicator. So, the indicator represents the measuring parameter serving to make comparison between the different states or the structures of the system. As an example, the efficiency of the system is an indicator for the quality of energy use in the respective system. Also, we can evaluate different structures of systems by utilizing indicators that represent the respective entities of these systems. In this way the assessment of an intelligent use for the improvement of the system's compatibility with its surroundings is measured by the respective indicators.

The multi-criteria assessment is based on the decision making procedure, which reflects the combined effect of all of the criteria that are under consideration and is expressed in the form of the general index of sustainability [8–11]. A selected number of indicators are taken, numbers being the measures of the criteria that comprise specific information about the options under consideration. The procedure is aimed to express the options' properties by utilizing the respective set of indicators.

3.1. Sustainability index (SI) definition

The decision making procedure consists of several steps that work to obtain a mathematical tool for the assessment of the rating among the options under consideration. Table 1 lists the data that are to be used in the analysis for the preparation of the respective data for the assessment of the hydrogen systems.

The general indices method, which consists of formation of an aggregative function with the weighted arithmetic mean as the synthesizing function, is defined as

$$Q(q, w) = \sum w_i q_i(x), \tag{1}$$

where w_i is the weight-coefficient elements of vector $\mathbf{w}$, $q_i(x)$ the aggregated indicators of specific criteria.

The aggregation function represents a sum of a multiplication between the membership functions of respective indicators and its weighting coefficient corresponds to constraints that exist among indicators. For the formation of the member functions $q_1(x_1), \dots q_m(x_m)$, for every indicator x_i we have: (1) to set two values MIN(i), MAX(i); (2) to indicate if the function $q_i(x_i)$ is decreasing or increasing with the argument x_i increasing; and (3) to choose the exponent's value λ in the formula for the decreasing function $q_i(x_i)$.

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

The formation process of the functions $q_1(x_1), \dots, q_m(x_m)$ is finished with a matrix $(q_i^{(j)})$, $i = 1, \dots, m$, $j = 1, \dots, k$, where an element $q_i^{(j)}$ constitutes a value of ith particular criterion for the jth option. In this analysis it is assumed that the linear functions $q_1(x_1), \dots, q_m(x_m)$ are used. For q_1, q_2, and q_m member functions, the decreasing function is adapted [3].

The weight coefficients are obtained with different constraints. The simplest way to obtain the weight coefficients is to assume the same value for all of the indicators. This means that each indicator contributes to the general indicator with the same weight coefficient.

The weight coefficient vectors are obtained as the result of considering a set of weight coefficients, which are defined as

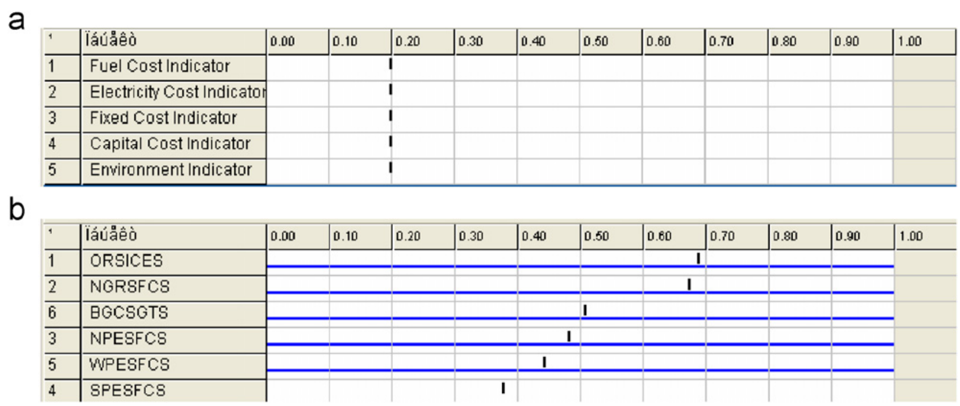

Fig. 7. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 1.

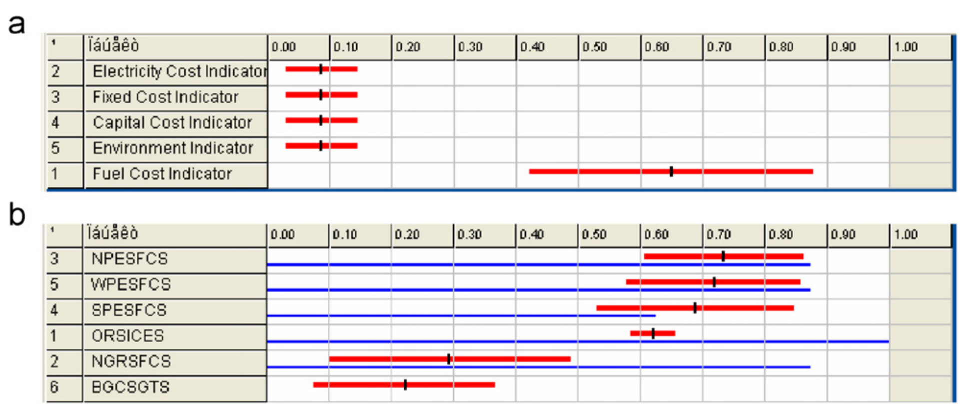

Fig. 8. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 2.

the uncertainty of an arbitrary combination. In order to define the weight-coefficient vector, randomization of the uncertainty is introduced. Randomization is a stochastic process with realizations coming from the corresponding sets of functions and from a random weight-vector. It is assumed that the measurement of the weight coefficients is accurate to within $h = 1/n$ steps, with n being a positive integer. In this case the infinite set of all of the possible vectors may be approximated by the finite set $W(m, n)$ of all possible weight vectors having discrete components. In our case, we will use $m = 5$, and $n = 40$ so that the total number of the elements of the set $W(m, n)$ is $N(m, n) = 92\,251$.

For a nonnumeric, inexact and incomplete information, I=OI U II is used for the reduction of the set $W(m, n)$ of all the possible vectors $\mathbf{w}$ to obtain the discrete components set $W(I; n, m)$, which is defined as the number of constraints reflecting nonnumeric information about the mutual relation among the criteria that are under consideration [12].

3.2. Evaluation results

Case 1: Evaluation of the hydrogen production and utilization scheme is obtained for the following situations:

$$Case\ 1 \quad FCI = ECI = FxI = CCI = EI. \tag{3}$$

This case is the least probable situation in this evaluation; it represents a situation where the weight coefficients of all the indicators have the same value. This situation is very often utilized in the standard evaluation of the potential options and it can be envisaged that it does not represent the best choice when considering different cases (Fig 7).

As it was expected, the case having equal weight coefficients is a unique case in means of the number of the combinations that are taken into consideration in this evaluation. The rating among the options is obtained as the biased one, since it represents the least probable case. It shows ORSICES and NGRSFCS as the result of the highest values of the individual indicators.

Case 2:

$$Case\ 2 \quad FCI > ECI = FxI = CCI = EI. \tag{4}$$

In the evaluation of this case, emphasis is put over the FCI and on other indicators that have the same value of weight coefficients. This implies that the weight coefficient of the fuel indicator is given priority compared to all the other indicators (Fig. 8).

In this case, it can be noticed that there are two groups of hydrogen schemes, namely, the first one consisting of NPESFCS, WSESFCS, SPESFCS and ORSICES and the second one of NGRSFCS and BGCSGTS. Two in this group are hydrogen production from renewable energy, but this group also includes

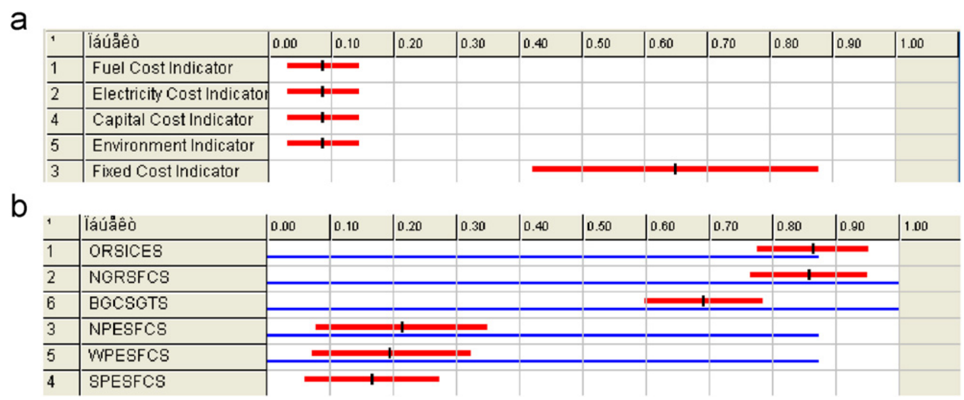

Fig. 9. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 3.

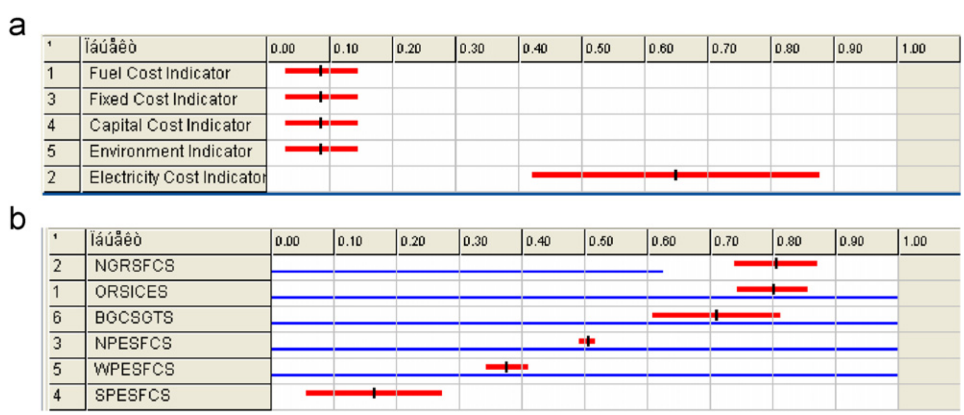

Fig. 10. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 4.

an option of an organic fuel, ORSICES. This proves that the multi-criteria constraint has an effect on the priority list of the option that is under consideration.

Case 3:

$$Case\ 3 \quad ECI > FCI = FxI = CCI = EI. \tag{5}$$

This case is designed with priority given to the ECI. It is of importance to notice that the ECI is a significant factor, which contributes to the final rating among the options. As can be noticed, the electricity cost is contributing in all the options being under consideration (Figs. 9 and 10).

The result obtained in this case gives priority to NGRSFCS, ORFSICES and BGCSGTS. This case is very probable due to the high value of the probability dominance. Common characteristics of these three options are that they have low fixed and capital charge costs. It should be noticed that even these options have high values of EI and their rating is very high.

Case 4:

$$Case\ 4 \quad FxI > ECI = FCI = CCI = EI. \tag{6}$$

Case 4 represents a situation where priority is given to the fixed operation and maintenance costs. This indicator does not have a large contribution to the general index (Figs. 9 and 10).

This case is characterized as having two groups with similar values of the general sustainability index. This shows that even the group of ORSICES, NGRSFCS, and BGCSGT is a hydrogen production system fuelled with organic fuel; it has gained priority compared to the renewable energy scheme group.

Case 5:

$$Case\ 5 \quad CCI > ECI = FCI = FxI = EI. \tag{7}$$

This case represents a situation where the priority of the weight coefficient is given to the CCI and to other weight coefficients that have the same value. This situation reflects the case where we have an expensive capital and we want to investigate how this constraint affects the general sustainability index (Fig. 11).

Again the formation of two groups on the rating list of the general sustainability index can be noticed. The first group includes ORSICES, NGRSFCS, and BGCSGTS; and the second group consists of NPESFCS, WPESFECS, and SPESFCS. It can be noticed that this case is very similar to Case 4. High values of probability of dominance prove that this situation is very probable among all the combinations that we have taken into consideration.

Case 6:

$$Case\ 6 \quad EI > ECI = FCI = FxI = CCI. \tag{8}$$

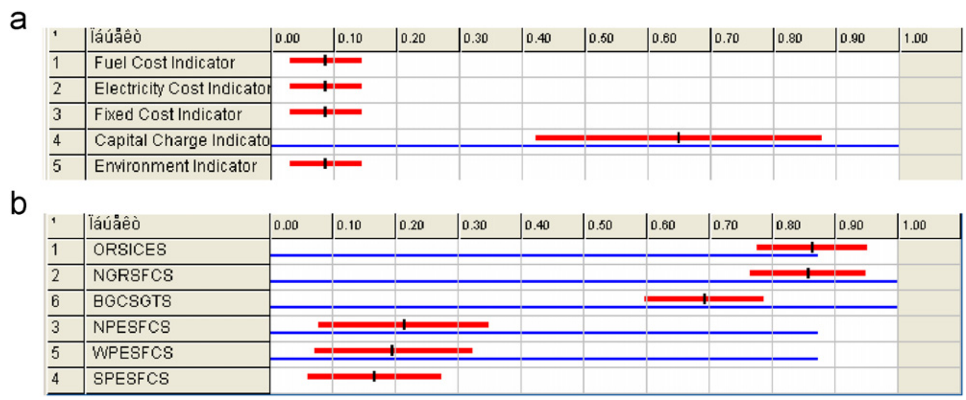

Fig. 11. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 5.

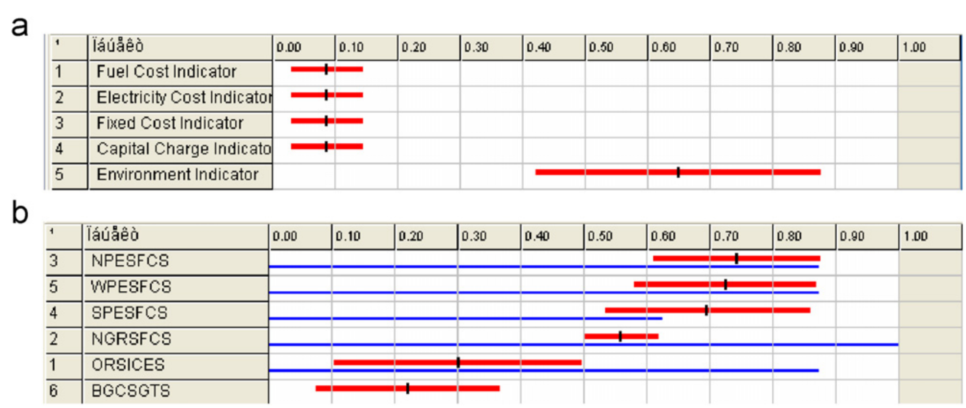

Fig. 12. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 6.

The last case among all of the single priority situations considered in this evaluation is the case having a weight coefficient priority given to the value of the weight coefficient of the EI. It is obvious that this situation reflects the potential effect of the EI on the priority list of the general sustainability index rating (Fig. 12).

Rating of the general sustainability index for this case results in priority given to the NPSFCS. As it would be expected, the renewable energy resources system will have a high position in the rating, among other options that are under consideration. The difference among these options is marginal so that in general, we can consider that the situations having zero emission occupy higher position in the general sustainability index rating.

Case 7:

$$Case\ 7 \quad FxI = CCI > ECI = FCI > EI. \tag{9}$$

The second group of situations analyzed in this exercise is designed by assigning the same value of weight coefficients to the group of indicators. In this case the priority is given to the energy cost, including fuel and electricity cost compared to the fixed and the capital charge cost. The EI weight coefficient has the lowest value (Fig. 13).

It is interesting to notice that in the analysis of this situation, the priority is obtained by the ORSICES option followed by NGRSFCS, BGCSGTS, NPESFCS, WPESFCS, and SPESFCS.

Case 8:

$$Case\ 8 \quad EI > FxI = CCI > ECI = FCI. \tag{10}$$

The second situation in this group is the case with priority given to the CCI compared to the ECI. Again, the EI has the lowest weight coefficient value. This situation represents the case where the total capital cost is given a priority (Fig. 14).

Case 8 represents an interesting result. There are two groups of options that are substantially different in the rating of the general sustainability index. In the first group we can notice mainly ORSICES, compared to the other two options, namely: NGRSFCS, and BGCSGTS. The second group consists of NPESFCS, WPESFECS, and SPESFCS, which are marginally different in their General Sustainability Index values.

Case 9:

$$Case\ 9 \quad EI > ECI = FCI > FxI = CCI. \tag{11}$$

This situation reflects the case where the priority constraint is given to the Environment Indicator followed by the ECI and the CCI as the groups of the same values of weight coefficients (Fig. 15).

Under this constraint on the indicators, the result shows a decrease in the general sustainability index for the options of NPESFCS, WPESFECS, SPESFCS, NGRSFCS, ORSICES, and BGCSGTS, respectively.

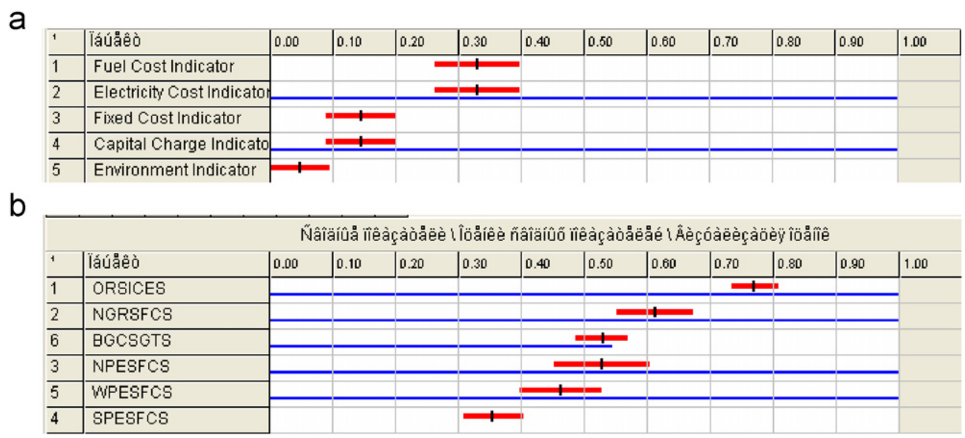

Fig. 13. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 7.

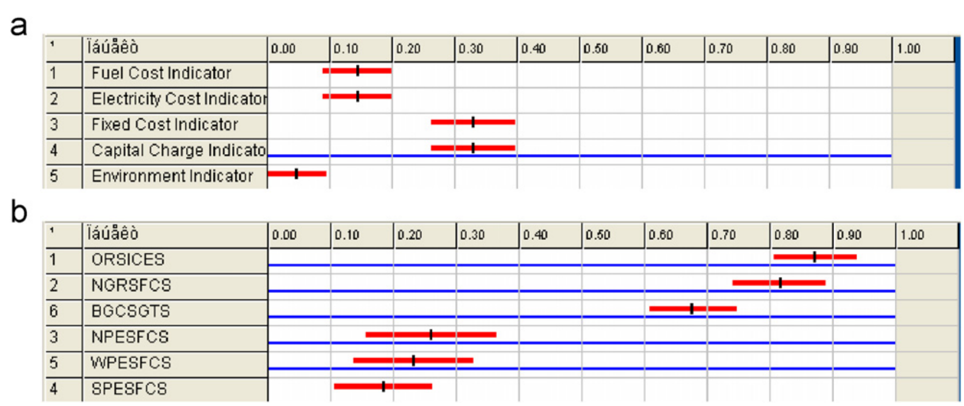

Fig. 14. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 8.

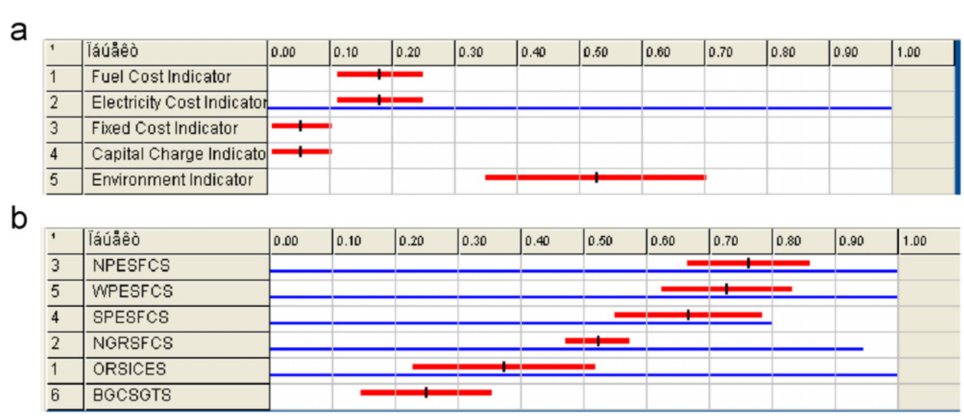

Fig. 15. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 9.

Case 10:

$$\textit{Case}\ 10 \quad EI > FxI = CCI > ECI = FCI. \tag{12}$$

The last case in this analysis is designed to give priority to the EI. The difference between this case and Case 9 is in the change in the given priority on the group with the CCI and the ECI. The aim of this case is to investigate the effect of the inversion of the rating among the fuel and capital indicators, under a constraint implying that the priority is given to the EI (Fig. 16).

It is interesting to see that the effect of inversing the rating among the fuel and the capital indicators makes up a case where the differences among options are marginally different. This finding proves the sensibility of this methodology on a change carried out on the rating among the indicator priorities.

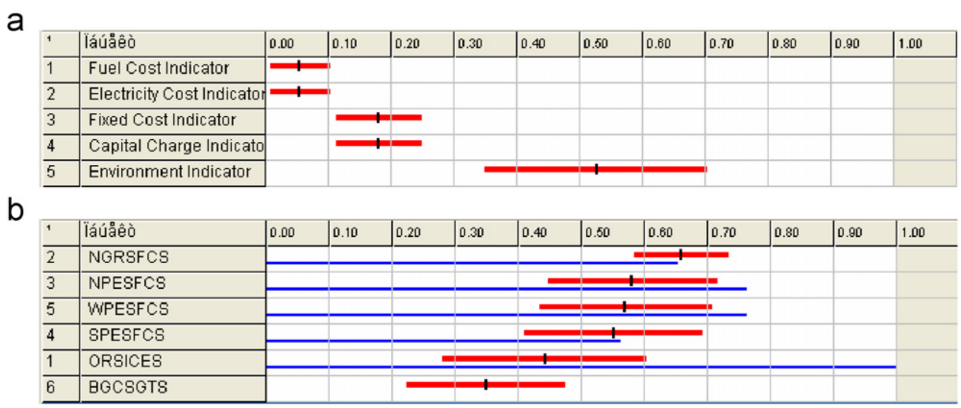

Fig. 16. (a) Weight coefficient diagram and (b) general sustainability index for *Case* 10.

Table 2
Numerical analysis of the indicators

Option	Energy cost		Capital cost		Environment
	Oil ($USD/kg\,H_2$)	Electricity ($USD/kg\,H_2$)	Fixed (O & M) ($USD/kg\,H_2$)	Capital cost (18% yr) ($USD/kg\,H_2$)	CO_2 ($kg/kg\,H_2$)
ORSICES	0.20	0.16	0.58	2.09	19
NGRSFCS	0.58	0.04	0.56	2.07	9.5
NPESFCS	0	2.45	1.09	3.92	0
SPESFCS	0	8.93	1.09	3.92	0
WPPESFCS	0	3.68	1.09	3.92	0
BGCSGTS	0.64	0.22	0.69	1.32	25.4

4. Conclusions

Multi-criteria evaluation of hydrogen systems is an exercise reflecting the potential possibility of the analysis of a complex system. In more general terms, it could be stated that the complexity of the energy systems can be defined as the multi-dimensional space of different indicators. Hydrogen chain is an energy system having a multiple function, which includes hydrogen production, hydrogen storage and hydrogen utilization for electricity production. Every hydrogen system under consideration is the entity itself, defined as the respective number of parameters, which are deterministically related according to the physical laws that describe individual processes in the system. The differences expressed by the selected indicators reflect the complexity of the individual structures of the options under consideration. The general sustainability index considers the economic and the environmental aspect of sustainability. This type of an analysis is supposed to help the decision-makers in the decision-making processes to identify the problematic areas that should be given priority.

With assumption that in all cases the indicator priority is possessing the same weighting factor, the final list of the priorities of the options under consideration will be as shown in Table 2. Also, it can be noticed that due to the change in the indicator priority, the options take different ratings on the priority list. As can be followed from the analysis, the NGRSFCS is the most promising Hydrogen system (Table 3).

Table 3
Final ratings of different HES options

Options	Average value of GSI
NGRSFCS	4.04
ORSICES	3.95
BGCSGTS	3.04
NPESFCS	2.86
WPESFECS	2.66
SPESFCS	2.12

Further development of this methodology will be oriented in two main directions. Initially, effort will be put on better defining the indicators and their certainty. Particular attention has to be focused on the variables, which affect the indicators that are space and time dependent. Then, the utilization of different types of aggregation functions for the general sustainability index may prove to be a suitable way of finding the respective function that will be appropriate for different systems. With regard to the evolution of the hydrogen systems, further development of this method can be envisaged through its application for the evaluation of future selections of the hydrogen systems.

In this paper, the selected number of options is rather limited in order to make the assessment of potential options, but it shows that it is important to make extended analysis, which will include larger number of options. Furthermore, paying special attention to the definition of individual indicators and determining respective numerical values is of great need.

References

[1] Afgan NH, Carvalho MG. Sustainability assessment of hydrogen energy systems. Int J Hydrogen Energy 2004;29(13):1327–42.

[2] Afgan NH, Carvalho MG. Sustainability assessment method for energy systems. Boston: Kluwer Academic Publisher; 2000.

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

[4] Afgan NH, Carvalho MG. Multi-criteria assessment of new and renewable energy power plants. Energy 2002;27(8):759–75.

[5] Afgan NH, Carvalho MG, Prstic S, Cohen AB. Sustainability assessment of aluminum heat sink design. Heat Transfer Eng 2003;24(4):39–48.

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

[7] Simbeck D, Chang E. Hydrogen supply: cost estimate for hydrogen pathway—scoping analysis; 2002, NREL/SR.

[8] Pilavachi P. Indicators for Gas Turbine (Personal Communication).

[9] Hovanov N, Fedotov Y, Zakharov V. The making of index numbers under uncertainty, environmental indices: systems analysis approach. Oxford: EOLSS Publishers Co.; 1999.

[10] Hovanov N. Analysis and synthesis of parameters under information deficiency. St. Petersburg: St. Petersburg State University Press; 1996.

[11] Hovanov N, Kornikov V, Sereign I. Qualitative information processing in DSS ASPID-3W for complex objects estimation under uncertainty, environmental indices: systems analysis approach. 1997.

[12] Hovanov AN, Hovanov NV. DSS ASPID-3W decision support system shell, 1996.