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MULTI-CRITERIA SUSTAINABILITY ASSESSMENT OF CLEAN AIR TECHNOLOGIES

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ABSTRACT

The paper presents a selection of criteria and options for energy technologies assessment based on the Analysis and Synthesis of Parameters under Information Deficiency Method. In order to present an evaluation of the clean air technologies a number of options featuring some of the characteristics measured by the selected sustainability indicators are taken into consideration. For each option under consideration sustainability indicators are defined in order to verify their rating in respect to the specific indicator and also to introduce these data to obtain the generalized index of sustainability rating of all options.

The multi-criteria evaluation of clean air technologies is an exercise showing a possibility of analyzing complex systems. 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. Sustainability indicators take into account the economic and environmental resources and the social aspect of the systems under consideration.

Key words: *clean air, energy system, sustainability indicators, environmental resources*

1. INTRODUCTION

System analysis is both a philosophical approach and a collection of techniques, including simulation developed explicitly to address problems dealing with complex systems. System analysis emphasizes a holists approach to problem solving and the use of mathematical models to identify and solve important characteristic of complex systems. A mathematical model is a set of equations that describe the interrelations among those objects. By solving the equations comprising a model we can mimic or simulate the dynamic behavior of the system.

Like many words for which we have tentative understanding, "system" is difficult to define precisely. In relation to physical and biological sciences, a system is an organized collection of interrelated components determined by a boundary and functionality[1]. A system is defined by its structure and boundaries. It is communicating material, energy and information through its boundaries. The system is defined by internal and external variables. The internal structure of the system and processes defines its functionality, which is determined by internal variables of the system. The external variables are defined by the boundary of the system [2].

Energy system is a complex system with its respective structure and can be defined by different boundaries depending on the problem. In the simple analysis with the only function of the energy system to convert energy resources in the final energy form, the interaction of the energy system is defined by its thermodynamic efficiency [3]. Adding some complexity to the energy system, we can follow the interaction of the energy system and environment. In this respect a good example is the problem of pollution, which is defined as emission of energy and material species resulting from the conversion process. With further increase in complexity of the energy system and establishing respective links through the boundary, there are other entity fluxes between the system and surroundings. Since every energy system has its social function in our life, a link between the energy system and surroundings may be also established taking into account the social interaction between the system environment. Obviously, further addition of complexity of the energy system regarding the interaction may lead to the exchange of different fluxes. In this respect the Onsager relation gives good example of possible relation among the fluxes of interaction between the system and its environment [4]. In the information theory there are attempts to define a non-linear relation between fluxes and its relation to a change in the structure of the system.

In our exercise, we have assumed that the energy system is a complex system which may interact with its surroundings by utilization of resources, exchange of conversion system products, utilization of economic benefits from the conversion process and adsorption of social consequences of the conversion process. Each of the interaction fluxes is a result of a very complex interaction of the elements of the energy system within the system and also an interaction with surroundings [5]. In our analysis we will use synthesized parameters of the system in the form defined in classical analysis of energy system. So, for resources utilization we will use resource indicators, and for the conversion process effect of the CO_2 exhaust gas. The electric energy cost will be used to measure economic benefits of the energy system and NO_x release of the energy system will be used as the social indicator of the energy system [6].

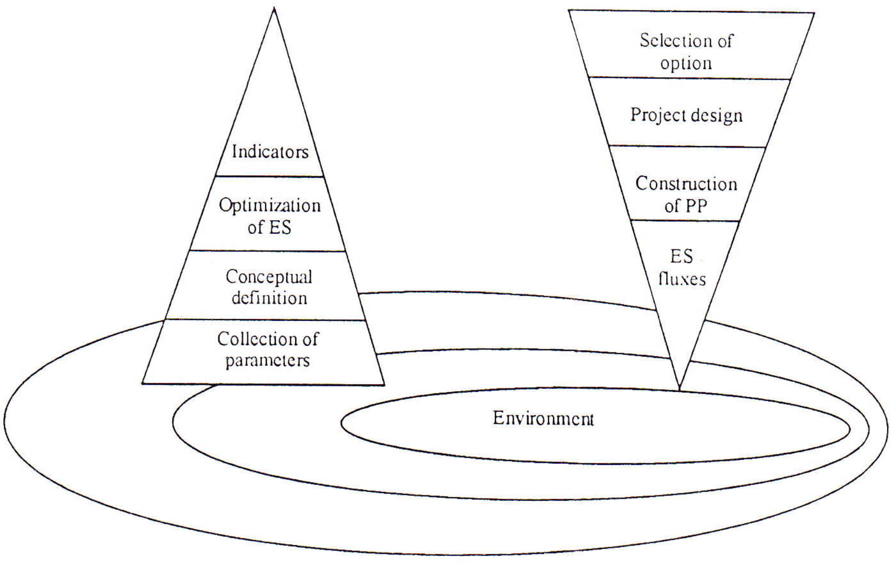

Fig. 1 The process of collection and interpretation of different parameters

In this analysis the indictors are representing a measure of different interactions of the energy system and its surroundings. All indicators are in a deterministic or stochastically relation with their respective parameters of the system. Their interpretation and collection require an organization and systematization of the parameters of the system and environment. The process of collection and interpretation of different parameters, which are synthesized in the respective indicators can be represented graphically as shown in Fig. 1 [5].

It can be noticed that the data collection regarding earth resources, environment pollution parameters, economic system parameters and social structure and quality is the first step in the establishing of the indicators. The second step is defining the energy system concept including definition of structure and interaction between the elements and processes. This will imply a selection of energy conversion process and its interaction with inlet parameters.

By means of the life cycle analysis of the selected energy system the interpretation of the interaction of the system with its economic, environmental and social surroundings can be defined [7]. Since each of the selected indicators represents a collective interpretation of different interactions of the system and its surroundings, their mutual relation could be interpreted as an independent parameter of the system.

The multi-criteria assessment of the energy system is one attempt to establish a measuring parameter, which will comprise different interactions of the system and its surroundings [8]. This may lead to the development of a method, which will help us to understand in deep a specific role of the energy system selection and quality of our life. At the same time this new tool may be used for a universal interpretation of our goal to focus our attention on the sustainable development of an energy system.

2. SUSTAINABILITY ASSESSMENT

In order to make a sustainability assessment of clean air technologies two approaches have been adopted: single criteria assessment and multi-criteria assessment. The first approach is based on the single criteria rating among the options under consideration. The second is based on the analysis and synthesis indicators on the decision making procedure reflecting combined effect of all criteria under consideration and is expressed in the form of a General Index of Sustainability [9,10].

2.1. Option selection

In order to present the evaluation of the clean air technologies a number of options is selected featuring some of the characteristics measured by the selected sustainability indicators. For each option under consideration sustainability indicators are defined in order to verify their rating in respect to the specific indicator and also to introduce these data to obtain the generalised index of sustainability rating of all options.

In this analysis of clean air technologies the following plants are considered

1. Pulverised Coal Fired Power Plant (PCPP)
2. Integrated Gasification Combined Cycle (IGCC)
3. Gas Fired Power Plant with Combined Cycle (NGCC)
4. Natural Gas Combined Cycle with CO_2 Removal (NGCC - CO_2)
5. Natural Gas Combine Heat and Power Production (NGCHP)

These options represent various technologies for generating electricity. A common feature of the presented options is that they can be considered as clean air technologies presently under development. In our analysis it is assumed that each power plant generates 876 GWh per year, which corresponds to the electricity generated during one year by a 100 MW plant running at 100 % capacity. In this analysis an emphasis will be placed on those options of power plants which are sufficiently mature that the reliable data is available [11,12].

2.2. Indicator Definition

The decision making procedure comprises several steps in order to obtain mathematical tool for the assessment of the rating among the options under consideration. In order to prepare relevant data for the clean air technology assessment table 1 presents the data to be used in the analysis.

Table 1 The values of the indicators for different options

Options	Indicators				
	Investment Cost c/kWh	Fuel Cost c/kWh	Energy Cost c/kWh	CO_2 Emission c/kWh	NO_x Health Effect c/kWh
PCTT	1.79	1.72	3.94	239.0	3.6
IGCC	2.17	1.53	4.18	210.0	1.12
NGCC	0.77	2.29	3.44	98.0	0.16
NGCC-CO_2-R	1.35	2.50	4.17	9.71	0.16
NGCHP	0.8	0.88	1.96	97.1	0.36
Max	2.17	2.50	239.0	3.6	4.18
Min	0.77	0.88	9.71	0.16	1.96
Max - Min	1.40	1.62	229.29	3.44	2.22

3. SINGLE CRITERIA ASSESSMENT

It is usually accepted that the comparison of individual options of power plants is defined with a single parameter. This approach limits the understanding of the effect of other parameters which are of importance for the assessment of the systems.

3.1. Investment Cost Comparison

The classical approach to the evaluation of different options of the system is based on the thermodynamic efficiency of systems. With the thermodynamic efficiency merged with economic validation the cost of energy as a single parameter is obtained. Using the cost of energy produced the comparison of the systems can be evaluated. In the classical approach to the evaluation of power plants besides the efficiency of the system as a parameter for evaluation there is also investment cost which effects the decision in the selection of the appropriate option. So, the classical evaluation procedure for the selection of the power plants option is based on two parameters: electricity cost per unit kWh and specific investment per unit kW.

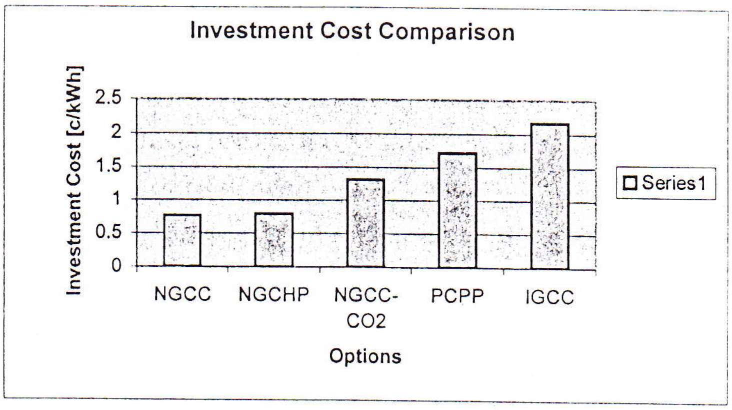

Fig. 2 Investment Cost Comparison

In order to verify the comparison of the options under consideration with respect to the investment cost which comprises information of the material used in the design of different options Fig. 2 shows the investment cost comparison. It can be noticed that NGCC and NGCHP are among best options regarding investment cost.

3.2. Fuel Cost Comparison

The fuel cost is an essential parameter which affects the electrical energy cost. Also, selection of fuel affects resource parameters. As our interest is to focus attention to the use of the resources, the fuel cost is seen as a resource parameter.

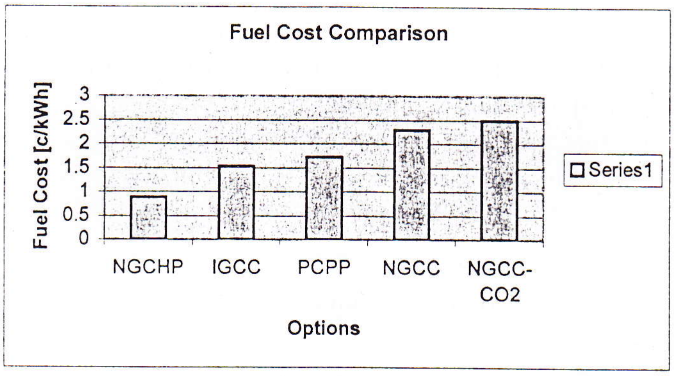

Fig. 3 Fuel Cost Comparison

In this respect the comparison between the options by fuel cost indicator implies the validation of respective options by fuel resource consumption per unit of electrical energy produced. As shown in Figure 3 it can be noticed that NGCHP option is the first on the priority list in the single parameter comparison based on the fuel cost.

3.3. Energy Cost Comparison

Traditionally, economic rating of the options under consideration has been the only assessment parameter in the comparison. It was commonly accepted that only the cost of electrical energy produced by the power plant was the measure of validity of the power plant. In this respect Figure 4 shows the comparison of the options under consideration by the economic indicator.

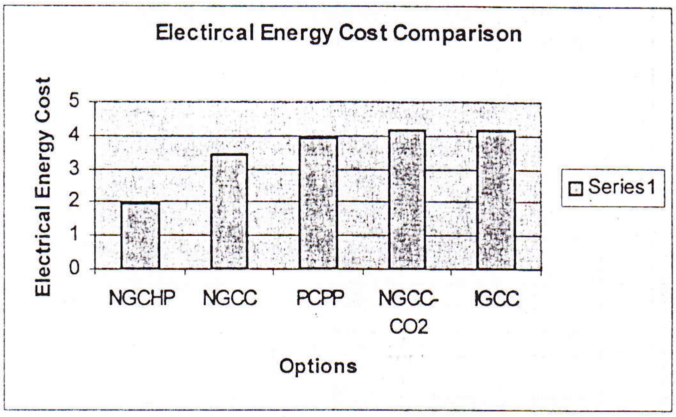

Fig. 4 Electrical Energy Cost Comparison

The economic indicator is based on the life cycle analysis and reflects the total cost of electrical energy. It should be noticed that the total cost of electric energy comprise also the efficiency of the system.

The economic indicator (Fig. 4) is a complex parameter which is deterministically related to the number of parameters which-h affect the total scope of the system.

3.4. CO_2 Emission Comparison

Recently, it has become important to evaluate the CO_2 emission of the plants. With the introduction of the new CO_2 taxation system, it will be possible to include this parameter into the cost of the energy produced in a power plant. This will not be straight forward; some ambiguity will be left for the further evaluation. If CO_2 will be used as the only parameter, the comparison among the power plant systems will reflect the emission of the system. Again, the single parameter is used for the evaluation of a potential option of the power plant under consideration. Also, we can take emission of other combustion products as a parameter for the evaluation of power plant systems. This will lead to different rating of the options under consideration depending on the emission product.

Fig. 5 shows the fuel cost comparison of the options under consideration. It can be noticed that NGCHP has the highest rating and the option of NGCC–CO_2 has the lowest rating. This is obvious result of the CO removal cost which effects the rating of the option with CO_2.

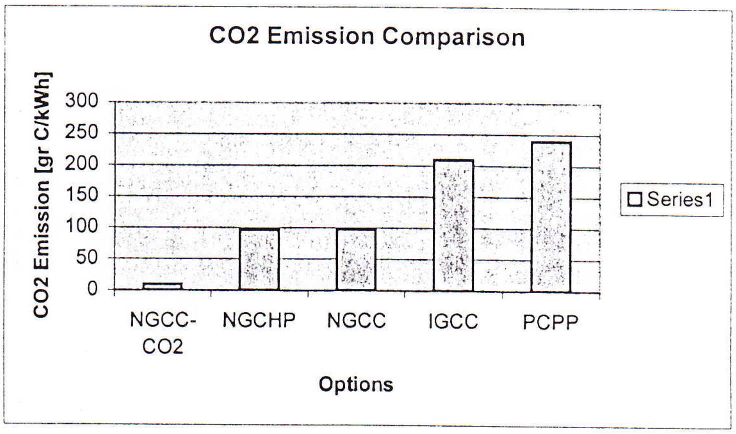

Fig. 5 CO_2 Emission Comparison

3.5. NO_x Health Effect Comparison

In the power plant options under consideration there is an interest to make an evaluation of the social aspect of the power plant. It is known that the major adverse effect of the power plant on the surroundings is due to the health effect of NO_x.

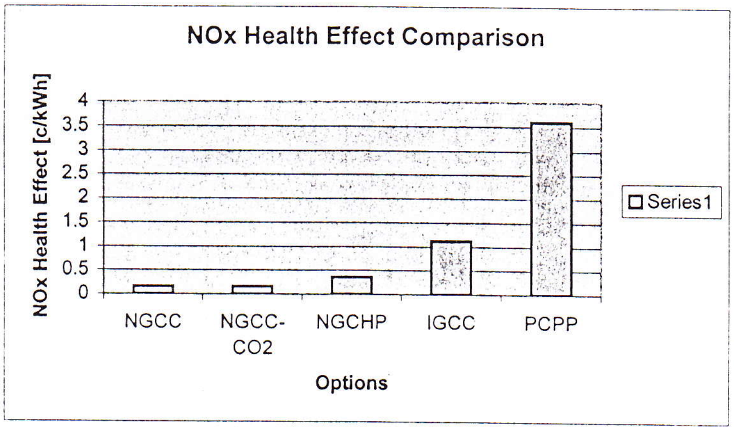

Fig. 6 NOx Health Effect Comparison

The formation of NO_x in a power plant strongly depends on the quality of fuel and its nitrogen content. Also, the design of the boiler furnace effects the formation of NO_x. In order to mitigate the formation of NO_x there are number of techniques used, including the organisation of the combustion process in the furnace, respective design of burners, reburning and flue gas recirculation. From the options under consideration we have selected only those options which reflect the use of different kinds of fuel. In this respect it can be noticed that the effect of gas combustion is to less extent immanent to the NO_x formation. In order to convert the concentration in the flue gases to the health effect a method was used which establishes a linear correlation between the concentration of NO_x and health cost. Figure 6 shows the health cost of different options of the power plants under consideration.

4. MULTI-CRITERIA ASSESSMENT

The multi-criteria assessment is based on the decision making procedure [13,14] reflecting the combined effect of all criteria under consideration and is expressed in the form of a General Index of Sustainability. A selected number of indicators is taken as the measure of the criteria comprising specific information of the options under consideration [15,16,17]. The procedure is aimed at expressing options property by the respective set of indicators.

The next step in the preparation of data for the multi-criteria sustainability assessment is arithmetization of the data.

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

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

for the decreasing function $q_i(x_i)$.

The functions $q_1(x_1),\ldots,q_m(x_m)$ formation process results with a matrix $(q_i^{(j)})$, $i=1,\ldots,m$, $j=1,\ldots,k$, where an element $q_i^{(j)}$ is a value of i-th particular criterion for j-th option. In this analysis it is assumed that the linear functions $q_1(x_1),\ldots,q_m(x_m)$ were used. For q_1, q_2 and q_4 membership functions the decreasing functions are adapted. In table 2 the values of the functions $q_1(x_1),\ldots,q_m(x_m)$ are shown.

Table 2 The values of the functions $q_1(x_1)$, ..., $q_m(x_m)$

Options	Normalized Indicators				
	RI_{Steel}	RI_{fuel}	EN_{CO2}	SI_{Nox}	EcI
PCPP	0.729	0.543	0.000	0.000	0.892
IGCC	0.000	0.398	0.873	0.279	0.000
NGCC	1.000	0.827	0.395	1.000	0.667
NGCC-CO_2	0.392	0.000	1.000	1.000	0.995
NGCHP	0.020	1.000	0.391	0.058	1.000

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

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

where

w_i – weight-coefficients elements of vector **w**

q_i – indicators of specific criteria

In order to define the weight-coefficient vector the randomization of uncertainty is introduced. Randomization produces stochastic sets with realizations from the corresponding sets of functions and a random weight-vector. It is assumed that the measurement of the weight coefficients is accurate to within a steps h = 1/n, with n being 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 = 40 so that the total number of elements of the set W(m,n) is N(m,n) = 92251.

The nonnumeric, inexact and incomplete information is used for the reduction of the set W(m,n) of all possible vectors **w** to obtain the discrete components set W(I;n,m). It is defined as a number of constraints reflecting nonnumeric information about mutual relation among the criteria under consideration.

5. SELECTION OF CASES

In order to make an assessment of options it is necessary to define constraints which are imposed regarding the preference of the criteria. There are three groups of Cases to be taken into consideration, namely the Case when priority is given to a single indicator and others are kept constant, the second group with priority given to the individual indicators and others are rated successively and the third group comprises a selected relation between the indicators in order to obtain a preselected ratio between the options.

Group I

Case 1 – $I = I_1$ $\{w_1 = w_2 = w_3 = w_4 = w_5\}$

Case 2– $I = I_2$ $\{w_1 > w_2 = w_3 = w_4 = w_5\}$

Case 3 – $I = I_3$ $\{w_4 > w_1 = w_2 = w_3 = w_5\}$

Case 4 – $I = I_4$ $\{w_5 > w_2 = w_3 = w_4 = w_1\}$

Group II

Case 5 – $I = I_5$ $\{w_1 > w_2 > w_3 > w_4 > w_5\}$

Case 6 – $I = I_6$ $\{w_4 > w_1 > w_2 > w_3 > w_5\}$

Group III

Case 7 – $I = I_7$ $\{w_5 > w_1 > w_2 = w_3 > w_5\}$

Case 8 – $I = I_8$ $\{w_3 > w_1 > w_2 > w_4 = w_5\}$

Group I

Case 1 – $I = I_1$ $\{w_1 = w_2 = w_3 = w_4 = w_5\}$

Case 1 is characterized by the equal weighting functions value for all criteria. This implies that no preference is given to any criterion and as the non-numerical information is used equal value is given to all indicators. It is obvious that this case is not very realistic, but it shows what the outcome of this type of a constraint would be. Since there is only one combination which satisfies this constraint it is obvious that the dispersion equals zero.

General Index Sustainability reflects an additive function of normalized indicators so that the rating of options is a simple addition of the normalized values of indicators to individual options. In this assessment NGCC is the first on the list with the highest priority, followed by NGCC-CO2, NGCHP, PCPP and IGCC. It is interesting to notice that the NGCC option has priority in this respect due to the highest of all values of normalized indicator. Figure 7 shows the General Index and respective probability among the options for Case 1.

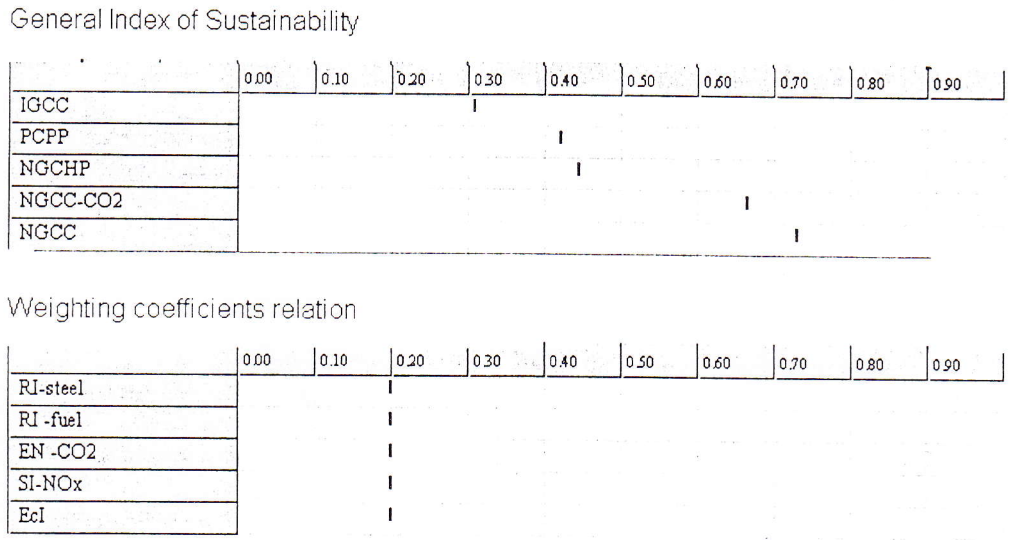

Fig. 7 General Index of Sustainability and Weighting Coefficients Relation for Case 1

Case 2 – $I = I_2$ $\{w_4 > w_1 = w_2 = w_3 = w_5\}$

Case 2 is designed with an investment indicator having priority in relation to other indicators. All other indicator's weighting coefficients are the same. It could be noticed that only a limited number of situations within the total number of combination fulfills this condition. Only 7 combinations among 82251 are taken into consideration to define weighting coefficients for this case. It should be registrated that in all other cases with similar constrains, the number of combinations is the same.

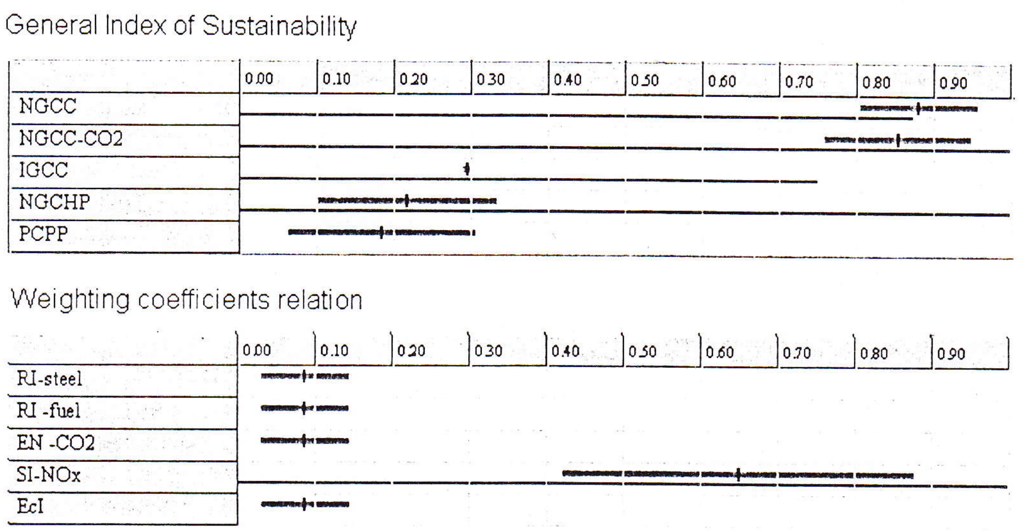

Fig. 8 General Index of Sustainability and Weighting Coefficients Relation for Case 2

Case 3 – I = I_3 {$w_1 > w_2 = w_3 = w_4 = w_5$}

Case 3 is designed to emphasize investment cost indicator in comparison to other indicators having the same weighting coefficients. As it can be noticed there is no change in the comparison of the first priority but only in 4th and 5th position on the rating list. Again NGCHP has priority as in many other cases under consideration. This is a result of a dominant position of the NGCHP option in regards to any indicator. The second position is taken by NGCC but with a rather high dispersion and low probability to the position of first place of NGCHP.

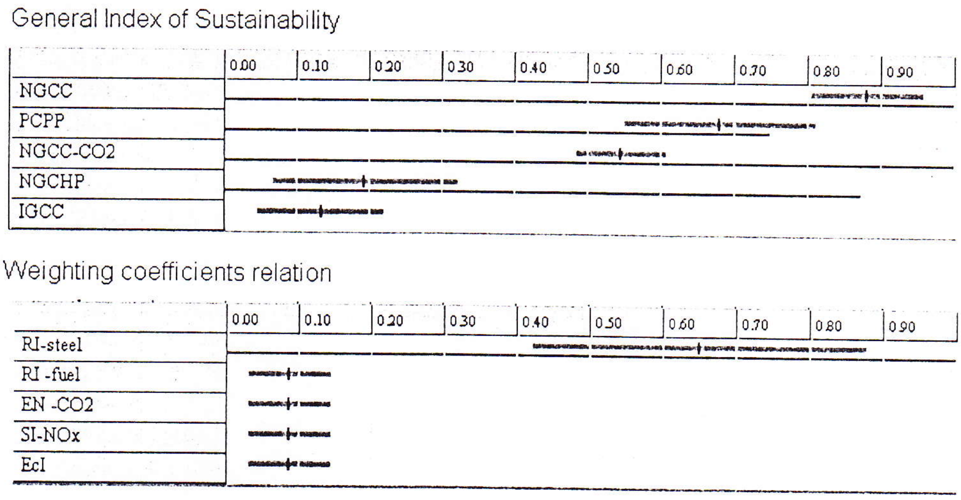

Fig. 9 General Index of Sustainability and Weighting Coefficients Relation for Case 3

Case 4 – I = I_4 {$w_5 > w_2 = w_3 = w_4 = w_1$}

Case 4 represents the relation between the constraints defined by the priority of health indicator and other indicators having the same weighting coefficients. It is also of interest to investigate other combinations of constraints which might effect the priority list.

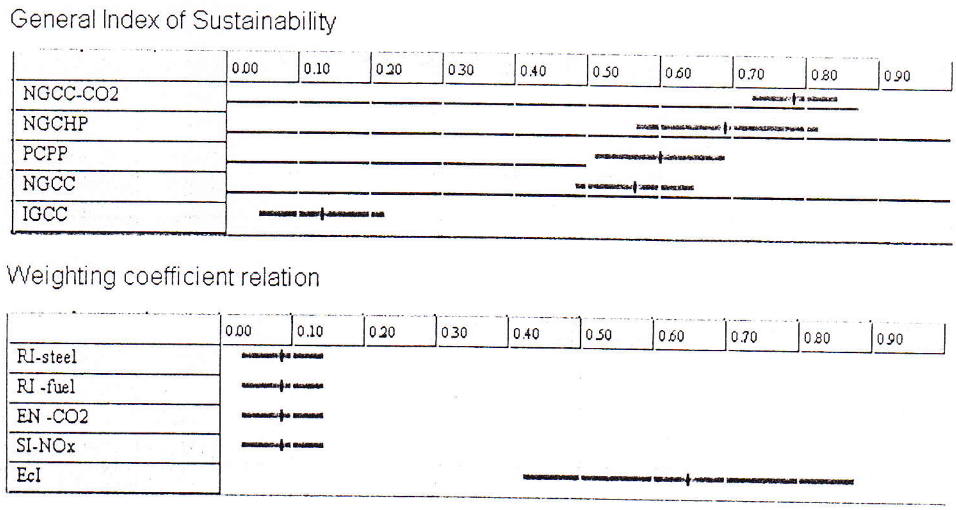

Fig. 10 Sustainability General Index and Weighting Coefficients Relation for Case 4

The results obtained for this case do not introduce any new feature to the priority list. NGCHP is again placed first on the priority list with a very high value of the general index. The other options are less pronounced and with a rather low index.

Group II

Case 5 – I = I_5 {$w_1 > w_2 > w_3 > w_4 > w_5$}

Case 5 is designed to give priority to the investment cost followed by fuel cost indicator, energy cost indicator CO_2, environment indicator and NO_x, health indicator. As it can be seen, this assessment leads to the priority of NGCC with CO_2 removal, followed by NGCC, IGCC, PCPP and NGCHP. It is of interest to notice that the same list of priority is obtained with the single priority list with fuel indicator.

The assessment with multi-criteria indicators and non-numerical constraints among the indicators as specified in Case 5, shows the priority of the option NGCHP with CO_2 removal. Figure 11 shows the general index and the respective probability among the options of Case 5.

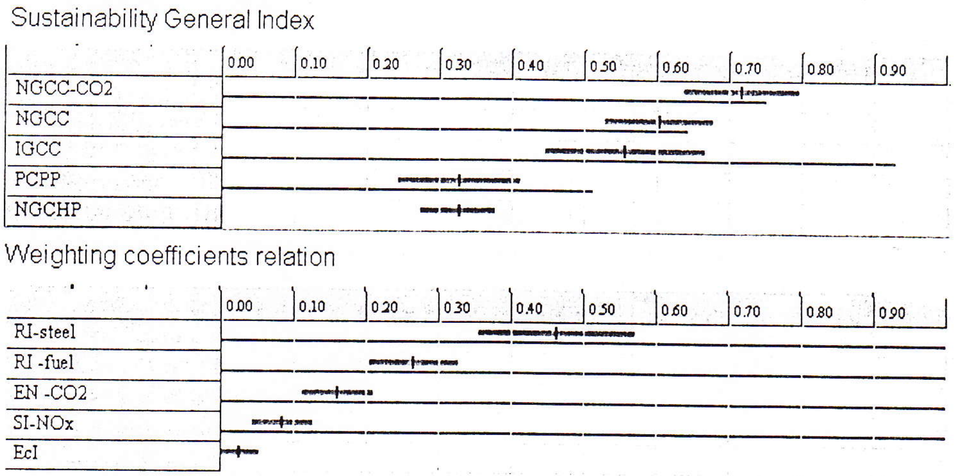

Fig. 11 General Index of Sustainability and Weighting Coefficients Relation for Case 5

Case 6 – I = I_6 {$w_5 > w_1 > w_2 > w_3 > w_4$}

The design of Case 6 is based on the request to emphasize the importance of the economic indicator in relation to other indicators. In particular attention is paid to giving priority to the economic indicator in relation to the investment and fuel indicators. Since the economic indicator essentially comprises fuel and investment indicator, there is a change in the priority list in relation to Case 5. Also, there are some changes in the value of weighting coefficients and their dispersion.

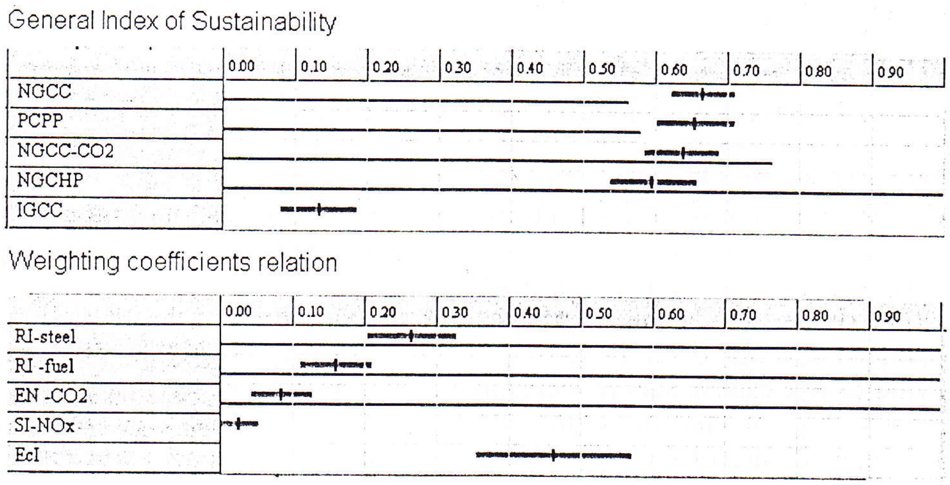

Fig. 12 Sustainability General Index and Weighting Coefficients Relation for Case 6

Case 6 is also characterized by higher values of the general index of sustainability of the options. This implies that obtained ranking of the options is less pronounced than in other cases. It is also noticed that in Case 6 the dispersion of the general indexes is lower with a lower probability of the compliance by the options. Again, it is the NGCC option to be the first on the priority list with PCPP, NGCO-CO2 and NGCHP not differing substantially. IGCC has a substantially lower rating. This proves that the economic criterion strongly effects the rating of IGCC option. Figure 12 shows the general index of sustainability and the respective probability among the options of Case 6.

Case 7 – $I = I_7$ $\{w_4 > w_1 > w_2 > w_3 > w_5\}$

Case 7 is characterized by the priority of the environment indicator. It presents an alternative which emphasizes the importance of the CO_2 environment indicator and its role in the priority list. It is of importance to recognize the effect of the environment indicator on the priority list. The NGCC-CO2 option is the first on the priority list. It is interesting to investigate why this changes in the priority of indicators do not change the selected option. Since NGCHP proves to be high priority in a number of cases under consideration, it may be concluded that its weighting coefficient in all cases is high. This is probably the result of the high value of the indicators in comparison with other options. Also, it may be the result of a large number of situations reflecting arithmetization of all indicators. Finally, it may be the result of a large contribution of the resource and economic indicators in the general index sustainability. Figure 13 shows the general index and the respective probability among the option of Case 7.

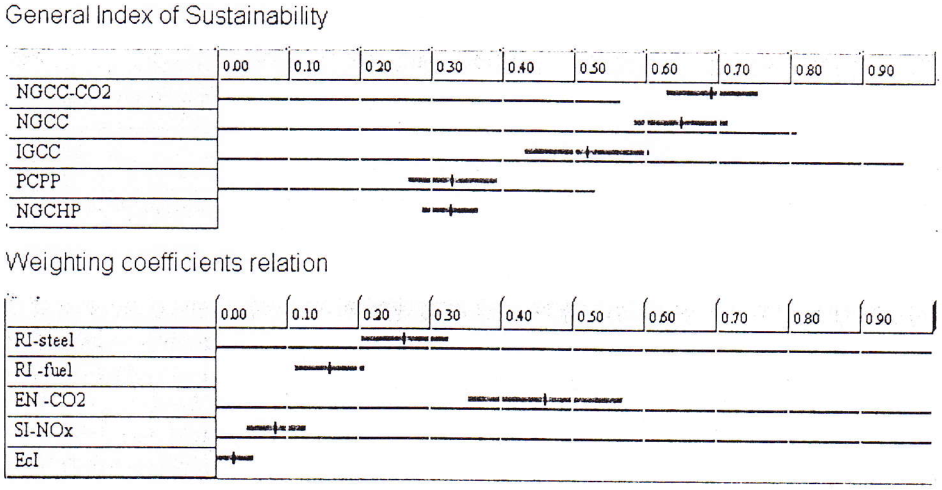

Fig. 13 General Index of Sustainability and Weighting Coefficients Relation for Case 7

Case 8 – $I = I_8$ $\{w_5 > w_1 > w_2 = w_3 > w_5\}$

Case 8 is aimed at investigating the effect of the health indicators on the priority list. By using the health effect as the first priority criterion in the comparison with other criteria it is expected that the importance of these criteria in the selection of the priority option will be shown. The health criteria has lead to the priority of the NGCHP option. It may be noticed that all other options have lower rating and higher dispersion. The characteristic of this case is also reflected in a higher position of the NGCC and IGGCC options. One of the characteristics of this case is also that all options have higher values of the general index. Figure 14 shows the general index and the respective probability among the options of Case 8.

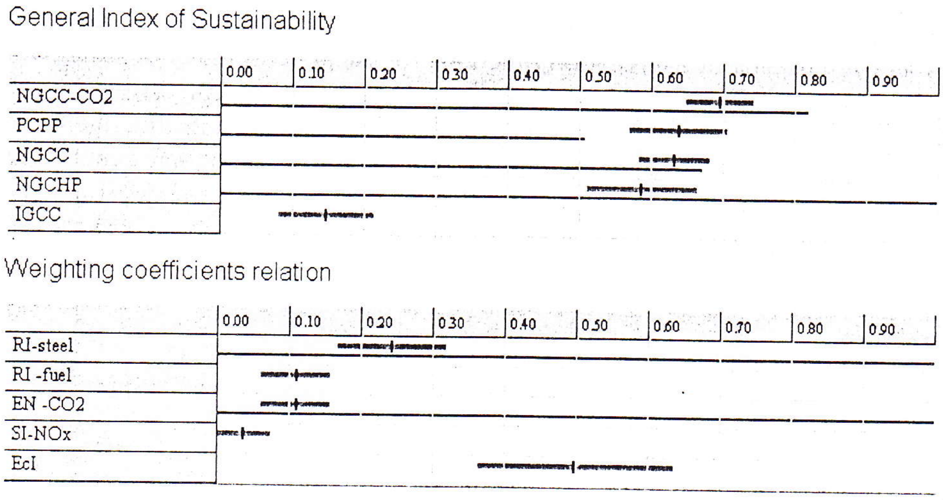

Fig. 14 General Index of Sustainability and Weighting Coefficients Relation for Case 8

It is of interest to notice that under this constraint the priority has the option NGCC-CO2. Figure 14 shows the general index and the respective probability of dominancy among the options of Case 8.

6. DISCUSSION OF MUTICRITERIA EVALUATION

The multi-criteria evaluation of clean air technologies is an exercise showing a possibility of the analysis of complex systems. Generally, it could be said that the complexity of the clean air technology can be defined as multidimensional space of different indicators. Every energy system under consideration is an entity by itself, defined by a respective number of parameters which are deterministically related according to the physical laws describing individual processes in the system. The differences expressed by the selected indicators reflect complexity of the individual structure of the options under consideration. The sustainability indicators take into account the economic, environmental, resources and social aspect of sustainability. They are supposed to be of help to decision-makers in decision-making processes while identifying problematic areas that should be given priority.

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

Since each of the indicators represents an aggregated parameter derived from the internal parameters of the system the general index of sustainability as defined in this analysis is a measure of the complexity of the system. The indicators are deterministically related to the technical and economic parameters of the system, so their aggregation means only convolution of indicators multiplied by the respective weighting coefficients. Certain arbitrariness in the decision- making procedure is immanent to this type of evaluation. In this respect this procedure of selecting an option of energy system will require some further development.

It is required that the indicators are defined by the life cycle analysis in order to satisfy the wholeness of the indicator interpretation. A close link to the life cycle analysis may lead to a better quality of the decision-making process.

Further development of this methodology will be oriented to two main directions. Firstly, to the better definition of the indicators and their certainty. A particular attention has to be paid to the variable effecting indicators which are space and time dependent. Secondly, the use of a different type of aggregation functions for the general index of sustainability may prove to be a way of finding a respective function 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 the future selection of energy systems.

It is obvious that further development off the decision-making method will be of great interest for the energy system evaluation. It should be emphasized that the multi-criteria assessment of energy systems may lead to a better quality of life locally, regionally and globally.

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