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Energy system assessment with sustainability indicators

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Abstract

The paper presents an attempt to select, define and apply a set of sustainability indicators for the energy system assessment. Starting from the general sustainability concept, a set of indicators is defined reflecting specific criteria for the energy system evaluation. Particular attention is devoted to the resource, environment, social and economic criteria. Among these groups of criteria there are individual indicators emphasising respective aspect of the sustainability concept. This approach has its limitation due to the lack of data for serious consideration of the system. But it should be anticipated that these excises might serve as the guidance for the eventual future application. Also, this methodology for the assessment of energy system will become an useful tool only if it proves useful in the engineering practice. The example under consideration is an island with only individual consumption to be satisfied with solar, wind, biomass and oil-fired power plant which represent four options under consideration. The set of indicators is defined and determined with the aim to demonstrate the method of decision making procedure in selecting the option which meet selected indicators numerical values and constrain reflecting the non-numeric information of weighting factor for the determination of general criteria for the selection of appropriate option. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The sustainability assessment methodology has to be demonstrated in order to become the tool in the engineering practice. This section is devoted to an attempt to evaluate the sustainability of energy system and show how it can be used in the everyday engineering practice. The approach has its limitation due to the lack of data for the serious consideration of the system. However, it should be anticipated that these excises might serve as the guidance for eventual future application.

It should be kept in mind that this example is based on the date collected in the available literature, with insufficient reliability. Also, it should be emphasised that all data are normalised with the total energy production. In particular this may be important in the assessment of resources.

System selection is also one of the key issues. In order to make the analysis simple, it is anticipated to take into consideration a limited geographic area with rather low level of population index.

The application of sustainability indicators for the assessment of isolated island energy structure is an application of the use of the methodology presented. In this respect, the island is defined by the area and number of habitants and with respective economic activity defined by the GNP. It assumed that water has to be produced with the desalination plant.

2. Definition of sustainability criterion

The criteria for the energy system sustainability assessment have to reflect four aspects, namely: resource aspect, environment aspect, social aspect and economic aspect (Afgan *et al.*, 1998). In this respect, the sustainability assessment of energy system will comprise the evaluation of those parameters which are a reflection of the integral concept of sustainability. As any other complex system the energy system is defined with constrains which reflect its function, technology, geography, property and capacity.

In the definition of sustainability criteria for the energy system the following aspects were taken into

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consideration in the definition of the criteria (Geiz and Kutzmark, 1998):

- It should reflect sustainability concept. This will imply that the indicators for the criteria represent quantities, which have relevancy to the sustainability. This will imply that the energy system dematerialization in the design may be seen as the introduction of knowledge based systems, use of virtual library, digitalised video, use of on-line diagnostic systems, development of new sensor elements and development of new combustion technologies.
- It will be defined with indicators which can be measured as physical parameters and are available as the data which are possible to obtain in quantitative or qualitative form.
- It should be based on timely information. Indicators have to be the information which is relevant to the time. This will mean that the energy system and its subsystems have to meet sustainability through every stage of the life cycle. It is known that the energy system work under different conditions in order to meet load change, environment change, social change. It is obvious that there will be different cycles for each of the mentioned time scale.
- It is based on the reliable information. In this respect the indicators have to be the data which you must trust because they may be the milestone for the important decision to be made.
- It reflects a strategic view. Since the sustainability is not a quick fix of current problems and it is a way of choosing actions today that will cause problems tomorrow. As regards the energy system, it may be interpreted as: mixed energy concept with optimization of local resources, urban and industrial planning with transport optimization and use of renewable energy sources.
- It gives possibility to perform optimisation of the system to minimise energy cost, available material, government regulations, financial resources, protection of the environment, together with safety, reliability, availability and maintainability of the system.
- It reflects longevity of design. Complex energy system is commonly composed of different subsystems and individual equipment elements. It has been recognized that the life of the elements and subsystems is not equal. In this respect optimal selection of the life cycle for elements and subsystems may lead to the retrofitting procedure which will reflect need for the sustainable criterions application.

2.1. *Sustainability indicators*

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 non-sustainable processes informing design-makers of the quality of products and monitoring impacts to 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 (Voinov, 1997).

In order to cope up with the complexity of sustainability related issues for different systems the indicators have to reflect the wholeness of the system as well as the interaction of its subsystems. Consequently, indicators have to measure the intensity of the interactions among elements of the system and system and its environment. In this view, there is a need for the indicator sets related to the interaction processes that allow an assessment of the complex relationship of every system and its environment. This will imply that complexity indicators will be defined reflecting links among internal parameters and external parameters of the system. This may be interpreted in the thermodynamic vocabulary as the intensive and extensive parameters of the system.

The effective indicator has to meet characteristics reflecting the problem and criteria to be considered. Its purpose is to show how well the system is working. Indicators are strongly dependent on the type of the system they monitor.

It is known that any numerical number, semantic expression or mathematical sign is information. Also, positive or negative sign of the variable are also information.

Collecting information and its processing will convert them into data. So, the data represent agglomerated information, which are partially or finally processed.

In order to use the data for the assessment of the respective system, it is necessary to convert them into an indicator. So, the indicator represents the measuring parameter for the comparison between different states or structure of the system. Also, we can evaluate different structures, of the systems by the indicator. In this direction is the assessment of intelligence use in the improvement of the system compatibility with its surrounding measured by the respective indicators.

In order to quantify the criteria for the sustainability assessment of any design of energy system the indicators are defined to meet this requirement. In this respect, the efficiency of resources use and the technology development are of fundamental importance. The efficiency of energy resource use is a short term approach which may give return benefit in the near future. As regards the technology development, a long-term research and development is needed. In some cases it will require respective social adjustment in order to meet requirements of the new energy sources.

3. Indicators definition

For the sustainability assessment of energy system the following indicators are used.

- Resource indicator — RI.
- Environment indicator — EI.
- Social indicator — SI.
- Efficiency indicator — FI.

3.1. Resource indicators

The resource indicators (Pearce and Turner, 1990) for the energy system will comprise four elements, including: fuel resources; stainless-steel resource; cooper resource and aluminium resource. The indicators reflecting individual element of the resource indicator are defined as the total amount of the respective material resource used in the design of the system divided by the total annual energy production. This means that the following elements will compose the resource indicator.

The fuel indicator will comprise the total organic fuel needed for the annual energy production including fuel consumption for energy production and energy needed for the respective materials production. In this respect, the definition of resource indicators are shown in Table 1.

3.2. Environment indicators

The environment indicators are composed of three elements, namely. CO_2, NO_x SO_2 indicator. Following the same procedure used in the definition of resource indicators, we can adapt the environment indicators which are given in Table 2.

3.3. Social indicators

The social indicators reflect the social aspect of the options under consideration. It will comprise the following three indicators: job indicator, standard indicator and community indicator. The job indicator element represents the number of new job to be opened corresponding to the respective option. The standard indicator element reflects the potential increase of the standard of living in the community. The community indicator element takes into consideration the community benefits due to individual option. The social indicator are defined and shown in Table 3.

3.4. Economic indicators

Economic indicators are based on the elements, including: effectiveness indicator, investment indicator, energy unit cost indicator. The effectiveness indicator element is defined as the thermodynamic efficiency of the

Table 1
Resource indicators

	Name	Definition	Unit
RI_{fuel}	Fuel resource indicator	The amount of fuel consumed in tons divided by the energy produced in lifetime	kg/kWh
RI_{CS}	Carbon steel resource indicator	The amount of carbon steel in tons, used in the construction of the plant divided by energy produced in lifetime	kg/kWh
RI_{Coop}	Cooper resource indicator	The amount of cooper in tons, used in the construction of the plant divided by the energy produced in lifetime	kg/kWh
RI_{Al}	Aluminum resource indicator	The amount of aluminium in tons, used in the construction of the plant divided by the energy produced in lifetime	kg/kWh

Table 2
Environment indicators

	Name	Definition	Unit
EI_{CO_2}	Carbon dioxide environment indicator	The amount of carbon dioxide in tons produced by the plant divided by the energy produced in lifetime	kg/kWh
EI_{NO_x}	Nitrogen oxide environment indicator	The amount of nitrogen oxide in tons produced by the plant divided by the energy produced in lifetime	kg/kWh
EI_{SO_2}	Sulfur dioxide environment indicator	The amount of sulfur dioxide in tons produced by the plant divided by the energy produced in lifetime	kg/kWh
EI_{waste}	Waste environment indicator	The amount of waste in tons produced by the plant divided by the energy produced in lifetime	kg/kWh

Table 3
Social indicators

	Name	Definition	Unit
SI_{job}	New job indicator	Number of paid hours per kWh produced in lifetime	hours/kWh
SI_{Inv}	Capital indicator	The amount of capital per kWh produced in lifetime	USD/kWh
SI_{Div}	Diversity and vitality indicator	Number of respective entity per kWh produced in lifetime	Number/kWh

Table 4
Economic indicators

	Name	Definition	Unit
EcI_{Effic}	Efficiency economic indicator	The efficiency of the system divided by the energy production	1/kWh
EcI_{inv}	Capital investment indicator	Amount of USD invested in the respective option divided by the energy production in lifetime	USD/kWh
EcI_{com}	Community economic indicator	Gain of GNP for the community per unit kWh	USD/kWh

system. It will include the energy efficiency conversion from the energy resources to the final energy. The investment cost indicator is aimed to obtain valorisation of the investment per unit power. The energy unit cost indicator will comprise the cost of the energy per unit kW production. Following the adapted procedure the economic indicators are presented in Table 4.

4. Energy system assessment

4.1. Energy consumption system

The total demand of energy for the island is obtained from individual consumption. Individual energy consumption is defined by the number of people living on the area and specific energy consumption reflecting the standard of living. The parameters effecting individual energy consumption are: number of people, area and specific consumption.

4.2. Energy production systems

The energy structure includes the following four energy sources: solar energy (Markvart, 1994), wind energy (Walker and Jenkens, 1997), biomass energy (Werko-Brobby and Hagen, 1996) and option with electric power production in oil fired thermal power plant.

Solar energy sources are based on photoelectric conversion of solar energy based on insulation and respective surface covered by the solar collectors. The solar energy conversion efficiency is used as the parameter reflecting the possibility of technology development. Insulation, surface and efficiency are used as the parameters reflecting possible options to be taken into a consideration.

Wind energy source is defined by the average wind velocity and diameter of the wind mill. It is assumed that the wind is produced in the wind farm defined by the number of fields.

Biomass energy source is obtained by the assumption of the agriculture waste obtained from the pre-defined area. It is adapted in the range of biomass yield from the minimum to the maximum value with respecting heat values. The efficiency of the thermal plant is taken in the range between minimum and maximum values. Biomass is used as a fuel in thermal power plant with respective efficiency.

Oil resource in thermal plant is used for the cases when local energy source is not sufficient to satisfy local demand. It is assumed that imported oil is used in order to estimate its requirement.

4.3. Energy object structure

The object oriented structure of the ENERGY object representing Production and Consumption as the subclass of the ENERGY object is presented in Fig. 1. Subclasses Production and Consumption are composed of the sub-subclasses Solar, Wind, Biomass and Oil and Individual, Industry and Desalination with respective attributes. The attributes are defined by the corresponding Minimum and Maximum values defining the range of the parameters to be used in the description of any individual option to be taken into consideration.

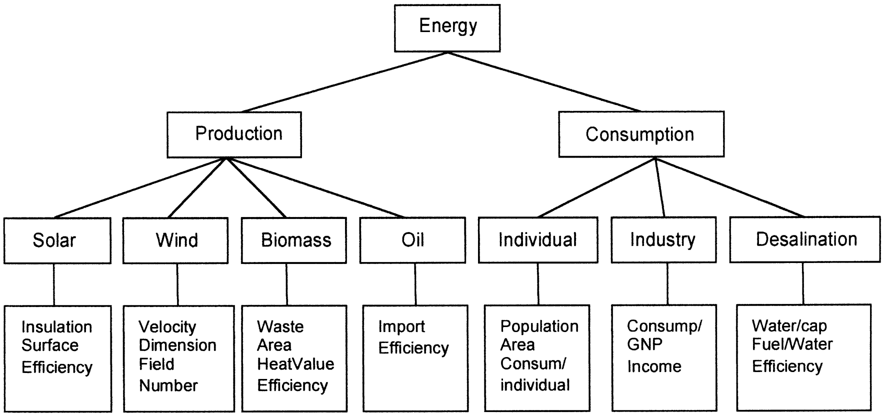

Fig. 1. ENERGY object.

Table 5
Min and Max values for ENERGY object

				Min.	Max.
Production	Solar	Insulation	W/m^2	80	100
		Surface	m^2	1000	2000
		Efficiency	-	0.1	0.15
	Wind	Velocity	m/s	10	40
		Diameter	m	2	4
		Field	m^2	400	200
		Number	-	20	40
	Biomass	Waste	t/km^2 year	100	500
		Surface	km^2	5	10
		HeatValue	kcal/kg	1000	4000
	Oil	Rate	t/year	0	1000
		Efficiency	-	0.25	0.4
Consumption	Individual	Individual	Man/km^2	55	200
		Area	km^2	10	20
		Con/capita	kWh/cap year	250	2000

In Table 5 are shown the data presenting Minimum and Maximum values for the respective attributes of ENERGY object.

Using the data presented in Table 5 the following energy production and consumption rate can be obtained for different energy sources. Table 6 presents the Minimum and Maximum values of the respective energy sources.

For further analysis a number of potential option will be taken into consideration which are representing specific cases which are incompatible with respect to demand and production alternative.

Table 6
Min and Max values for energy sources

Production		Power		Energy	
		Min. (kW)	Max.	Min. (kWh/year)	Max.
	Solar	8	30	0.0688×10^6	0.25×10^6
	Wind	75	800	0.645×10^6	6.88×10^6
	Biomass	29	1160	0.145×10^6	5.81×10^6
	Oil	0		0	8.8×10^6
Consumption					
	Individual			0.125×10^6	8×10^6

4.4. *Energy system options*

For the specific geographical site with the defined demand for electric power several options are taken into consideration. It is aimed at making an assessment of all potential options using the respective criteria for sustainable development. In this respect the following options are taken into consideration.

1. Solar PV unit.
2. Wind power plant.
3. Biomass power plant.
4. Thermal power plant.

The nominal power production for the units under consideration is 0.125×10^6 kWh/year. For the respective power production the following energy sources are assumed.

The thermal power plant is a CI internal combustion engine with HV = 24 MJ/kg.

Solar power plant — average insolation $q = 100\ \mathrm{W/m^2}$.

Wind power plant — average wind velocity $w = 20$ m/s.

Biomass fueled power plant with biomass HV = 15 MJ/kg.

5. Evaluation of the sustainability indicators

The energy consumption assumption is that the total need of energy in the region under consideration is 0.125×10^6 kWh/year and is used only for domestic use.

Next step in the assessment of the energy system is to determine sustainability indicators. In this respect, the following indicators are taken into a consideration: fuel resource indicators, CO_2 environment indicator, job social indicator and cost economic indicator (Table 7).

5.1. The assessment procedure

The assessment procedure is based on the Decision support system (DSS) (Hovanov, 1996). This procedure is based on the General Indices Method. The essence of the method is aggregation of some specific criteria

$$q_1\ (x_1), \ldots, q_m\ (x_m).$$

Each of them is estimated as the fixed quantity of multi-attribute options under consideration.

The procedure of DSS is based on a list of initial parameters of the indicators $x_i^{(j)}$ and a list of options under investigation as shown in Table 8. Then we must enter a matrix $(x_i^{(j)})$, $i = 1, \ldots, m$, $j = 1, \ldots, k$, where element $x_i^{(j)}$ is a value of ith indicator for jth option. For each Indicator x_i some elementary statistics are calculated:

$$\operatorname*{MIN}_j\ \{x_i^{(J)}\},\ \operatorname*{MAX}_j\ \{x_i^{(j)}\},\ \mathrm{Mean}\,(i) = \frac{1}{k}\sum_{j=1}^{k} x_i^{(j)},$$

$$\mathrm{StDev}\,(i) = \sqrt{\frac{1}{k}\textstyle\sum_{j=1}^{k}[x_i^{(j)} - \mathrm{Mean}(i)]^2}.$$

The following step consists in 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 that the function $q_i(x_i)$ is decreasing or increasing with argument x_i increasing; (3) to choose the exponent's value λ in the formula

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

for the increasing function $q_i(x_i)$. or in the formula

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

for the decreasing function.

The functions $q_1(x_1), \ldots, q_m(x_m)$ formation process being 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 the 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_4 membership function the decreasing functions are adapted. In Table 8 are shown values of the functions $q_1(x_1), \ldots, q_m(x_m)$ representing respective normalised indicators for options under consideration.

The general criteria is defined as

$$Q = Q\ (q_1, q_2, q_3,\ \ldots, q_m),$$

representing the aggregation function of the multi-criteria indicator.

Table 7
Options under consideration

Option		RI kg/kWh	EI kg/kWh	SI min/kWh	EcI c/kWh
Solar	1	0.0075	0.0186	1.6	10.6
Wind	2	0.0029	0.0052	2.2	4.4
Biomass	3	0.0015	0.332	4.5	16
Oil	4	0.152	0.47	2.3	10.6
Max		0.152	0.47	4.5	16
Min		0.0015	0.0052	1.6	4.4
Max–min		0.1505	0.4648	2.9	11.6
StDev		0.0741	0.2317	1.2715	4.7413

Table 8
Values of normalised indicators

Options	RI	EI	SI	EcI
Solar	0.7342	0.8394	0.0000	0.4516
Wind	0.9662	1.0000	1.0000	1.0000
Biomass	1.0000	0.3610	0.3333	0.0000
Oil	0.0000	0.0000	0.8333	0.4839

Table 9
Numeric estimation of weight-coefficients

Sustainability indicators	Min.	Max.	Weight-coefficient	Standard deviation
RI	0.000	1.000	0.250	0.212
EI	0.000	1.000	0.250	0.212
SI	0.000	1.000	0.250	0.212
EcL	0.000	1.000	0.250	0.212

The specific criteria are synthesized into a general criteria as an aggregation function, which is presented in the form of additive convolution. If it will be adapted that each of the criteria is weighted by the respective factor, the sum of criteria multiplied with the corresponding factor will lead to the sustainability assessment of the selected option. The multiplication factors should be normalized and their sum is equal to 1.

For the case under consideration the general sustainability indicator will lead to the following:

$$Q(q, \omega) = \sum_n \omega_n q_n,$$

where ω_n is the weighting factor for the nth criterion and q_n the nth criterion for sustainability assessment.

In this exercise, we will present only the data which are with equal weighting factors for all criteria under consideration. This will imply that non-numerical data are not available so that there is no information about the preference in criteria. This is not a realistic case and will not reflect the objective ground for the sustainability assessment of energy system. But even under this constrain the priority list of potential options can give us some guidance in the assessment of energy system. In particular, it may lead the assessment of the contribution of the individual criteria to the assessment of energy system.

This procedure can be repeated for any group of the selected parameters of the energy system. In this case, a number of options could be generated which will allow application of the method for the analysis and syntheses under information deficiency. This will allow use of the non-numeric information which are reflection of the differences in weighting factor and their mutual relation.

6. Discussion of the APSID — 3W program results

The analysis is based on the results obtained by the "Analysis and Synthesis of Parameters under Information Deficiency" ASPID-3W Program (Hovanov and Hovanov, 1996; Hovanov et al., 1997). In this analysis, we will take into consideration different alternative as regards weighting factors. The general index for sustainability assessment of the contribution of individual criteria to the sustainability assessment is considered appropriate to use in the following expression:

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

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

It is assumed that there are non-numerical information so that $I \neq 0$ related to the weighting of the contribution of individual indicators. In other words, let us take non-numerical information as regards the relation among the individual weighting factors in the form of non-equity system

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

for weighting factors w_1, w_2, w_3, w_4.

In our analysis of the effect of individual criteria on the general index of sustainability four different cases are assumed which will reflect changes in the mutual relation of the weighting factors on the decision-making process (Hovanov and Hovanov, 1996).

The following cases are taken into consideration:

1. *Case* 1: $I_1 = 0$ — there is no information about admissible weight-coefficients at our disposal
2. *Case* 2: $I = I_2 = \{w_1 > w_2 > w_3 > w_4\}$ — specific criteria (specific indices) are strictly ranked by their influence on general sustainability index.
3. *Case* 3: $I = I_3 = \{w_2 > w_4 > w_1 > w_3\}$ — we have the ordinal information I_3 about weight-coefficients.
4. *Case* 4: $I = I_4 = \{w_1 = w_2 > w_3 > w_4\}$ — we have the ordinal information I_4 about weight-coefficients.

For all the cases the input data for DSSS ASPID-3W are the same.

Number of object (options of the energy system) $k = 4$.

Number of initial attributes (sustainability indicators) $m = 4$.

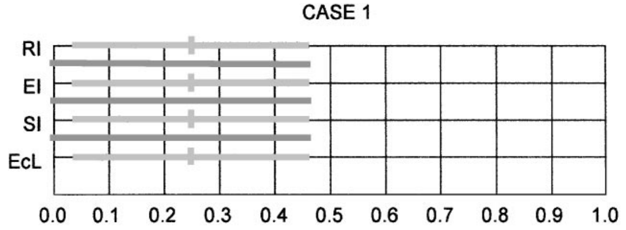

Fig. 2. $\bar{w}_i(I_1)$ of weight-coefficients, their standard deviations $s_i(I_1)$, and probabilities $p(r, s; I_1)$ of pair-wise dominance of the corresponding random weights $\tilde{w}_r(I_1)$, $\tilde{w}_s(I_1)$ for case 1.

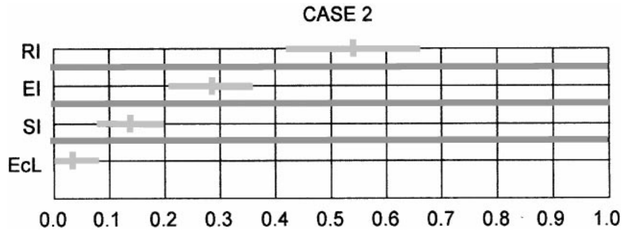

Fig. 4. $\bar{w}_i(I_2)$ of weight-coefficients, their standard deviations $s_i(I_2)$, and probabilities $p(r, s; I_2)$ of the pair-wise dominance of the corresponding random weights $\tilde{w}_r(I_2)$, $\tilde{w}_s(I_2)$ for case 2.

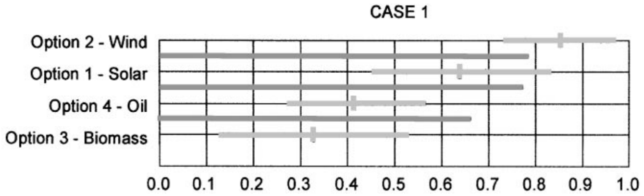

Fig. 3. General indices of sustainability for case 1.

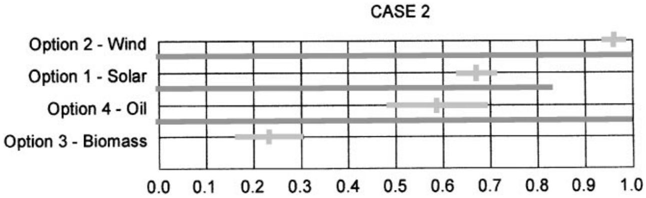

Fig. 5. General indices of sustainability for case 2.

Table 10
Reliability of general indices for sustainability assessment dominance

	Solar	Wind	Biomass	Oil
Solar	0.000	0.216	0.823	0.775
Wind	0.784	0.000	0.999	0.998
Biomass	0.177	0.001	0.000	0.335
Oil	0.225	0.002	0.665	0.000

Number of steps $n = 20$ (So, it is supposed that the measurement of coefficients is accurate within the step $h = 1/n = 0.05$.

Number of possible variants (of all weight-vectors $w = (w_1, \ldots, w_m)$)$N(4;20) = 1771$.

Case 1: Case 1 represents the alternative for sustainability assessment of the energy system based on the assumption that weighting factors are equal for all criteria as shown in Table 9 and graphically presented in Fig. 2. This will imply that no non-numerical information are available.

The assumption that there is no information admissible weight-coefficients in our disposal ($I = I_1 = 0$) implies equal values $\bar{w}_1(I_1), i = 1, \ldots, m$, for all weight-coefficients. But it is not the simple case where we plainly suppose that all weight are equal. No, in our case standard deviations (which are measuring "uncertainty" of weight-estimation) are taken into a consideration. The amount of non-numerical information $\mathrm{Inf} = 0.0000$.

Weight-coefficients visualization is presented in Fig. 2.

Following the procedure adapted by the ASPID-3W Program, the normalized values of indicators are determined and shown in Table 8.

From the presented data it can be concluded that in case 1 with $I = 0$, Option 2 — wind energy is having the highest value of general index for sustainability assessment. It can be noticed that this option is having a minimal value of standard deviation, which represents the accuracy of the obtained rating among the options under consideration. Blue lines in Fig. 3 represent the probability of options dominance. The probability values $P(r, s)$ with $r, s = 1, \ldots, 4, r \neq s$ are presented in Table 10. General indices of sustainability for Case 1 are presented in Table 11 and graphically shown in Fig. 3.

Case 2: Case 2 represents an alternative with non-numerical information reflecting the relation among the individual weighting factors.

$$I = I_2 = \{w_1 > w_2 > w_3 > w_4\},$$

reflecting relation among the individual weighting factors. In this case the preference in rating of individual factors is given with the intention to show how the priority among indicators effect the finale rating of the options under consideration. Now set $W\,(4, 20, I_2)$ has only 47 elements so that from the number of all possible variants $N = 1771$ only $N\,(I_2) = 47$ and $\mathrm{Inf} = 5.2358$, meets the specified relation among the weighting factors.

Graphical representation of weight coefficients and respective probability of the Sustainability Indicators for $I = I_2$ is shown in Fig. 4.

Graphical presentation if general sustainability index including probability and standard deviation for the option under consideration having $I = I_2$ is shown in Fig 5.

Adding a non-numerical information to the procedure for the rating by Sustainability Index the options under consideration does not change the priority list but it has added certainty to the selected option by decreasing its standard deviation. Besides this conclusion, the

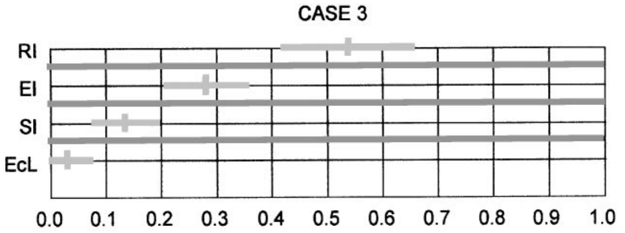

Fig. 6. $\bar{w}_i(I_3)$ of weight-coefficients, their standard deviations $s_i(I_3)$, and probabilities $p(r, s; I_3)$ of pair-wise dominance of the corresponding random weights $\tilde{w}_r(I_3)$, $\tilde{w}_s(I_3)$ for case 3.

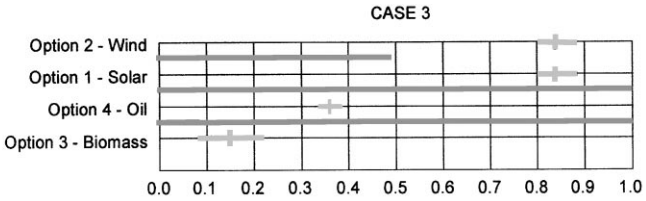

Fig. 7. General indices of sustainability for Case 3.

Table 11
Values of the general index of sustainability

Options	Min.	Max.	General sustain. index	Standard deviation
Solar	0.000	1.000	0.643	0.188
Wind	0.9662	1.000	0.854	0.114
Biomass	0.000	1.000	0.333	0.200
Oil	0.000	0.833	0.419	0.146

non-numerical information give possibility to investigate the importance of the individual criteria in the decision making procedure. For the sustainability assessment of energy systems under consideration it results in the selection of the Option 2 — Wind Energy is a natural choice which can sustain different criteria (Figs. 4 and 5).

Case 3: Case 3 represents the alternative for the sustainability assessment based on non-numeric information giving priority to environment and economic criteria.

$$I = I_3 = \{w_2 > w_4 > w_1 > w_3\} -$$

This implies that priority is given to the environment criteria and economy criteria followed by resource criteria and social criteria. Number of sets of weighting factors corresponding to these non-numeric information is $N(I) = 47$.

Graphical representation of weight coefficients with standard deviation and respective probability of the Sustainability Indicators for $I = I_3$ is shown in Fig. 6.

Graphical presentation of the General Sustainability Index for case 3 with $I = I_3$ is shown in Fig. 7.

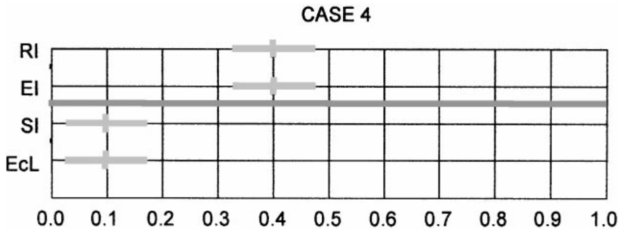

Fig. 8. $\bar{w}_i(I_4)$ of weight-coefficients, their standard deviations $s_i(I_4)$, and probabilities $p(r, s; I_4)$ of pair-wise dominance of the corresponding random weights $\tilde{w}_r(I_4)$, $\tilde{w}_s(I_4)$ for case 4.

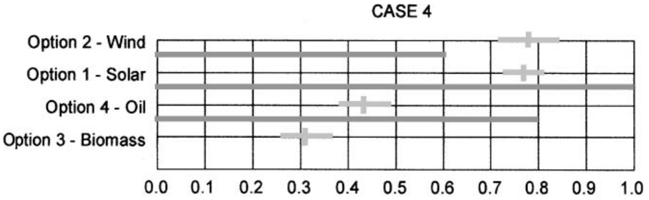

Fig. 9. General indices of sustainability for case 4.

With the emphasise on the environment and economic criteria the difference between option 2 and option 1 is becoming very small so that there is no difference in the rating of these two options. It could be noticed that the standard deviation has become smaller and probability for option 2 has gain substantial confidence.

Case 4: Case 4 is designed as the alternative to reflect the priority to be given to the resource and economic criteria in comparison with the environment and social criteria.

$$I = I_4 = \{w_1 > w_2 = w_3 > w_4\}.$$

Selection of the weight-coefficients relations in this case is determined by the intention to investigate what effect will have priority given the resource and economic criteria in relation to the environment and social criteria.

Graphical presentation of the weight-coefficients and their standard deviation for case 4 with $I = I_4$ is given in Fig. 8.

Graphical presentation of the general sustainability index for case 3 with $I = I_4$ is shown in Fig. 9.

Since case 4 is designed with priority given to the resource and environment criteria the obtained results are supposed to reflect its dominance and significance for the final decision of the priority list. The change in priority is noted so that option 1 is having higher rating than option 2, but very small advances and reliability. Again, this proves that the selection of option 2 can sustain different priority with sufficient accuracy.

7. Discussion of the results

As it can be noted from Table 5 the selection of options is aimed to make comparison between the different energy sources used for the production of energy to satisfy the minimum energy need for the undeveloped rural area. The availability of energy sources on the island under consideration are introduced as the input values corresponding to the specific location.

The criteria defined by fuel resource indicator is aimed to rank options by the amount of organic fuel resources needed to produce a lifetime energy for the respective energy source. From Table 7 it can be noted that the thermal energy option has the maximum value of the fuel resource indicator.

The environment criteria is defined by the amount of CO_2 produced per lifetime energy production. Also,it can be noted that the wind energy option is having a maximum value of this criterion. This shows that the wind energy option is having the least adverse affect on the environment.

The job social indicator is used for the definition of the social criteria for the energy system assessment. Since, the maximum value of social indicator corresponds to the wind energy source, it proves that this option is the most favourable option from the social criteria assessment.

The cost economic indicator is applied for the economic assessment. The solar option is having the maximum value of economic indicator and is the first on the priority list of economic indicators.

As it could be noted the standard deviation for all criteria are very large in comparison with values corresponding to the individual criteria. This will add substantial uncertainty in the assessment of the energy system with the criteria used in this example.

In order to verify the effect of weighting factor in the general criteria for the sustainability assessment the four cases are analyzed.

Case 1: $I_1 = 0$
Case 2: $I = I_2 = \{w_1 > w_2 > w_3 > w_4\}$
Case 3: $I = I_3 = \{w_1 < w_2 < w_3 < w_4\}$
Case 4: $I = I_4 = \{w_1 > w_2 = w_3 > w_4\}$

For case 1, from Fig. 2 it is obvious that the wind energy option has a maximum value of general sustainability index with the assumption of same weighting factor for all criteria under consideration. For case 2 even more the selection of the wind energy option is emphasized as it can be seen from Fig. 5. It shows that the standard deviation of General Sustainability Index is less pronounced. In case 3, although weighting coefficients are giving substantial priority to the environment criteria the general sustainability index for solar and wind energy are the same as shown in Fig. 7. Case 4 shows that under certain constrain the priority list can be changed. Due to the high value of resource weighting coefficient the solar option has obtained priority.

With non-numeric information related to weighting factors mutual relation, it will be possible to obtain a better quality of the assessment procedure. Four demonstrated cases are arbitrarly selected to demonstrate the effect of the weighting factors relation on the decision of the priority among the options under consideration. It should be mentioned that the analysis of effect of non-numerical information on the decision making process in selecting specific option for energy system may lead to a remarkable confidence in the decision making process.

8. Conclusions

Sustainable energy development is the ultimate goal of modern society in order to meet the ever growing demand for new energy resources. In particular it was recognized that the complexity of the global system will require special attention to the interaction between life support systems.

It was demonstrated that there is the possibility to define the consistent set of sustainability indicators to be used in the assessment of energy system. In this respect, four groups of indicators were presented which reflect the resource, environment, social and economic criteria.

The deficiency of the reliable data for the sustainability assessment lies in the demonstration of the methodology for sustainability assessment of the energy system which is based on the simple energy system with limited number of indicators. The selection of the energy resource for the small island has shown the application of decision making procedure based on the non-numeric information about the weighting factor for the individual criteria.

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