SUSTAINABILITY ASSESSMENT IN THERMAL ENGINEERING

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ABSTRACT

Development of sustainability concept in energy field has become driving force for the development of new energy strategy in the world. This development reflects future need for the adoption of energy system structure, which is in compliance with long-term strategy of our civilisation. The sustainability concept includes harmonised constrains of economical, ecological, social and resource aspect of global development.

This lecture is devoted to an attempt to present the sustainability method for energy system evaluation. In this respect the general concept of sustainability will be defined and assessment procedure is designed to reflect different constrains to be met by the energy system under consideration.

The thermal engineering is the basic engineering field for the energy system design, operation, diagnostic and evaluation. The sustainability concept of energy system is defined by the respective criteria derived from the basic laws of thermal engineering. These criteria include: efficiency assessment, environment assessment, resource use assessment and social aspect of energy strategy.

1. INTRODUCTION

Sustainability definition was with us from the early days of religious books where human conscious is instructed to follow harmonised activities which leads to the balanced interaction between the human society and its environment. There are number of religious plies which are expressing the need for the human behaviour without compromising with future of the divine.

In modern life, it was recognised that the future development has some constrains which impose the need for a new strategy in planning and forecasting future development[1,2,3]. On the first place, it was recognised that Malthusian model of resource use has to be deserted and new constrains have to be adapted taking into a consideration limited availability of natural resources. Beside constrains reflecting natural resources scarcity, it was recognised the importance of environmental, social, economic and cultural aspect of future strategy. Among the systems, which have attracted global attention, is the energy system, which by its complexity has been linked to any human commodity and welfare. In this respect the study of energy system development has become subject of global concern.

The most commonly accepted definition of sustainable development came from a 1987 report by the U.N. World Commission on Environment and Development (UNCED): it is development "that meets the needs of the present without compromising the ability of future generations to meet their own needs." This general definition has been used to identify more specific policies and reinforced the integral relationship between economic development and resource conservation which define sustainability as "the emerging doctrine that economic growth and development must take place, and be maintained over time, within the limits set by
ecology, the interrelations of human beings and their works, the biosphere and the physical and chemical laws.

The concept and application of sustainability evolved further during UNCED's 1992 Earth Summit in Rio de Janeiro, where 120 nations agreed to an agenda for the actions needed to sustain global development into the twenty-first century. Agenda 21, Chapter 35 “development requires taking long-term perspectives, integrating local and regional effects of global change into the development process, and using the best scientific and traditional knowledge available”

2. CRITERIA AND INDICATOR SELECTION

Energy system is a complex system which requires appropriate approach for the evaluation of quality of the system. The complexity of energy system can be described by the number of criteria reflecting different characteristics of the system. Complex system describe a variety of systems of high technological and intellectual importance. The desire to understand such systems has encountered significant challenges in scientific and technological community. Success in this effort is based on simplicity if interaction between the elements of the system.

In this respect multi-criteria method is an appropriate tool to be used in the assessment of energy system. Multi-criteria assessment method is based on the respective criteria defined by indicators. Indicators are parameters, which quantitatively determine mutual relation between different options under consideration. Usually criteria are reflecting quality of the option within the domain of indicators. So, indicator is expressing numerically the property of the options under consideration. The selection of criteria and corresponding indicators depend on the system and impose the need for their definition.

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

2.1 Criteria

In the definition of sustainability criteria for the energy system a following was taken into a consideration in the definition of the criteria.

- To reflect sustainability concept. This will imply that the indicators for respective criteria represent quantities, which have relevancy to the sustainability.
- To be defined with indicators, which can be measured and are available as physical parameters representing the data, which are possible to obtain with respective quantitative or qualitative form.
- To be based on timely information. The indicator has to be the information, which is relevant to the time to act. 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, etc.
- To be based on the reliable information. In this respect the indicators have to be the data, which you must trust because they may be the milestones for the important decision to be made.
- To reflect strategic view. Since the sustainability is not a quick fix of current problems and it’s the way a choosing actions today that will cause problems tomorrow.

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

In order to quantify criteria for the sustainability assessment of any design of energy system the element indicators are defined to meet this requirement. In this respect, the efficiency of resources use and the technology development are of the fundamental importance. It is obvious that the efficiency of energy resource use is a short-term approach, which may give return benefit in the near future. As regard the technology development, the 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

Sustainability indicators are by definition parameters which are used to describe respective criteria aimed to the specific qualification of the system [4]. In this respect the indicators for energy system are reflecting those properties of the system, which are used to define the system sustainability concept. For the sustainability assessment of energy system a following indicators are used:

- Resource Indicator - RI
- Environment Indicator - EI
- Social Indicator - SI
- Efficiency Indicator - FI

3.1 Resource Indicator

The resource indicator can be defined as the amount of material used to perform specific function. Material comprises, the construction material for specific equipment and material as the energy resource needed for respective function. Each element of thermal equipment represents the metallic construction build of the material by extraction from the available resources. The material is obtained by the processing of the respective material in the form defined by its function. In the processing of resource material adequate energy is needed to be spend for its finale form production. This energy is called energy produced by the system during its lifetime.

It obvious that beside the fuel as energy source for energy production, there are other resources, which have to be used in the design of energy system. Carbon steel, stainless steel, cooper, aluminium are among the material used in different energy systems.

Following this methodology, it can be concluded that resource consumption indicators are reflecting respective materials used in the design of system.

3.2 Environment Capacity Indicator

The environment capacity is function of number of parameters reflecting specific design it is of special interest to the determine the value of the parameter which correspond to the optimal option for the specific design. This will represent the environment capacity indicator for the assessment of the specific design. Also, the environment capacity will be divided on the species participating in the pollution capacity, namely CO₂, SO₂, NOₓ, and waste. For each of the contributing gas the respective indicator will be defined and will be used in the total assessment of its contribution to the environment capacity consumption. Species Environment Indicators are defined as the amount of specific species divided by energy production in lifetime.

3.3 Social Indicators

Social indicators are designed to reflect the social aspect of the energy system options. In this respect it is understood that every energy system attributed with respective social parameters which are reflecting the changes in social environment. In this approach we will
take only those parameters which are obvious, as number of new opening for a job, degree of local participation in the projects and use of the indigenous resources. Quality of social indicators is strongly depending on the case under consideration. So as in this case we are dealing with variety of energy sources their social affect is represented with those indicators which are possible to obtain for the individual source. The Job Social Indicator represents number of paid hours per kWh for the option under consideration.

The next group of the social indicators is the size of the economy as measured GNP and GDP. In the sustainability indicator interpretation this will imply indicators reflecting the local economy benefit. In this respect it is of importance to estimate the mount of capital which will be introduced locally with the respect energy system construction. This will reflect the benefit which will come with the option under consideration. The benefit obtained will be directly proportional local economy. In this case the indicator will be defined as the amount money per kWh produced with the energy system option under consideration. Invested Capital Social Indicator \( (SI_{Inv}) \) represent the amount of capital per kWh for the option under consideration.

Among social indicators are also those which are suppose to describe the diversity and vitality of the local job base. In this respect we need to know the number and variability in size of employers, the number end variability of industry types and variability of skill levels required for jobs. Diversity and Vitality Social Indicator \( (SI_{div}) \) will be defined as the number of respective entity per kWh for the respective option.

### 3.4 Economic Indicators

It is known that for any investment the main attribute reflecting its quality is expressed by the respective economic parameters. There are number of method how to evaluate the attractiveness of various investment in energy system. Among those are: payback method, average rate at the return method, internal rate at the return method, present value method and life cycling costing approach. In the definition of economic indicators we will use the life cycle cost analysis to consider the cost over life of the system. It takes account of the “time value” of money. By definition the economic indicators will be divided in two groups, namely, capital investment and operation and maintenance expense. In this respect the Investment Social Indicator \( (SI_{Inv}) \) is defined as the amount of USD invested in the respective option divided by the energy production in life-time.

Every investment is suppose to bring some gain of GNP to the local community due to the increase economic activities in the region. In this respect it of interest to formulate the indicator which will explicitly show what the specific option of the energy source may bring to the local community. Community Social Indicator is defined as the gain of Gross National Product divided by energy production in lifetime.

### 3.5 The Assessment Procedure

The assessment procedure is based on the Decision Support System (DSS) [5,6,7]. This procedure is based on the General Indices Method. The essence of 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. 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 \(i\)-th Indicator for \(j\)-th option. For each Indicator \(x_i\) some elementary statistics are calculated:

\[
\min_j \{x_i^{(j)}\}, \max_j \{x_i^{(j)}\}, \quad \text{Mean}(i) = \frac{1}{k} \sum_{j=1}^{k} x_i^{(j)}, \quad \text{StDev}(i) = \sqrt{\frac{1}{k} \sum_{j=1}^{k} [x_i^{(j)} - \text{Mean}(i)]^2}.
\]

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 \(\text{MIN}(i), \text{MAX}(i)\); (2) to indicate is the function \(q_i(x_i)\) decreasing or increasing with argument \(x_i\) increasing; (3) to choose the exponent’s value \(\lambda\) in the formula

\[
q_i(x_i) = \begin{cases} 
0, & \text{if } x_i \leq \text{MIN}(i), \\
\left(\frac{x_i - \text{MIN}(i)}{\text{MAX}(i) - \text{MIN}(i)}\right)^\lambda, & \text{if } \text{MIN}(i) < x_i \leq \text{MAX}(i), \\
1, & \text{if } x_i > \text{MAX}(i)
\end{cases}
\]

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

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 \(i\)-th particular criterion for \(j\)-th option. In this analysis it 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 function are adapted. In the TABLE 9 are shown values of the functions \(q_1(x_1), \ldots, q_m(x_m)\).

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.

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 1.

For the case under consideration the General Sustainability Indicator will lead to the following

\[
Q = \sum_{n} \omega_n q_n
\]

where

- \(\omega_n\) weighting factor for the \(n\)-th criterion
- \(q_n\) \(n\)-th criterion for sustainability assessment.

In this exercise we will present only 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 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 individual
criteria to the assessment of energy system.

4. DEMONSTRATION OF SUSTAINABILITY ASSESSMENT IN THERMAL
ENGINEERING

In order to demonstrate sustainability assessment in energy engineering a following system
are taken into a consideration: renewable energy systems, thermal energy systems and
desalination systems. Criteria for evaluation are defined reflecting resource, environment, social
and economic aspect of the option under consideration. For each system several options are
taken into a consideration.

4.1 Renewable Energy Systems

Evaluation of the energy system [8,9] is demonstrated for the power plant options based on
solar, luvoul, biomass and oil energy sources which are designed to satisfy energy demand of
small island. For the specified insulation, wind parameters, biomass resources and imported oil
respective power plants are designed and numerical values for the design parameters for individual options are determined. For the total capacity of P = 0.125 x 10^6 kWh a following options are analysed:

- Option 1  Solar Power Plant
- Option 2  Wind Power Plant
- Option 3  Biomass Power Plant
- Option 4  Diesel Power Plant

In the evaluation of options a following Indicators are taken into a consideration:

- Resource Indicator  RI
- Environment Indicator  EI
- Social Indicator  SI
- Efficiency Indicator  Efi

For the options under consideration the sustainability assessment procedure is applied. Graphical presentation if General Sustainability Index including probability and standard deviation for options under consideration having for a following relation between the criteria, are taken into consideration:

4.1.1 Case 1

\[ I = I \{w_{RI} = w_{EI} = w_{SI} = w_{Efi}\} \]

Case 1 represents alternative for sustainability assessment of energy system based on the
assumption that weighting factors are equal for all criteria and General Sustainability Index is
graphically presented on Fig.1. This will imply that no non-numerical information are available.
Fig. 1. General Indices of Sustainability for Case 1.

4.1.2 Case 2

\[ I = I_2 \{w_{RI} > w_{EI} > w_{SI} > w_{EF} \} \]

Case 2 represents an alternative with non-numerical information reflecting relation among the individual weighting factors. Graphical presentation of the General Sustainability Index for the Case 2 for the options under consideration is shown on Fig. 2. It can be noticed that different relation of the criteria weighting factors are effecting decision making process. In this respect it is of interest to emphasise that selection of the relation among the criteria plays important role in the decision making process.

Fig. 2. General Indices of Sustainability for Case 2

4.2 Sustainability Assessment of Aluminium Heat Sink Design

The evaluation of the aluminium heat sink design is presented as follows [10]. Three heat sink designs, each dissipating 100 W (within ±5 W) were chosen to which require the smallest pumping power (D1), consume the least mass (D2), and utilise the lowest total energy (D3).

<table>
<thead>
<tr>
<th>Options</th>
<th>Option definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-1</td>
<td>Smallest pumping power</td>
</tr>
<tr>
<td>D-2</td>
<td>Least mass used</td>
</tr>
<tr>
<td>D-3</td>
<td>Lowest total Energy</td>
</tr>
</tbody>
</table>

Table 1, Sustainability Indicators for Heat Sink Design
<table>
<thead>
<tr>
<th></th>
<th>[kg/comp]</th>
<th>Indicators [kWh/comp]</th>
<th>Indicators [kWh/comp]</th>
<th>Indicators [cents/comp]</th>
<th>Indicators [cents/comp]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D 1</td>
<td>0.664</td>
<td>1.2</td>
<td>54.9</td>
<td>284</td>
<td>12</td>
</tr>
<tr>
<td>D 2</td>
<td>0.124</td>
<td>9.6</td>
<td>10.2</td>
<td>48</td>
<td>96</td>
</tr>
<tr>
<td>D 3</td>
<td>0.163</td>
<td>3</td>
<td>13.5</td>
<td>70</td>
<td>30</td>
</tr>
</tbody>
</table>

**Case 1**

The Case 1 represent situation when we assume that all weighting coefficients are having the same value. This is not realistic situation since there is only one combination among total number of the weight-coefficient vectors generated in this analysis. In all diagrams colour lines are: black - value of Sustainable Index; red – Standard Deviation of Sustainable Index ; blue – Probability of Dominancy. Fig.3 presents Sustainability Index and Weighting function values for the Case 1

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**Figure 3, Sustainability Index and Weighting Coefficients for CASE 1**

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**Case 2**

$RI = OBI = FEI = PCI = OCI$

Sustainability Index

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**Figure 4, Sustainability Index and Weighting Coefficients for CASE 2**

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Fig.4 presents Sustainability Index and Weighting function values for the Case 2. It can be noticed that priority for this case is obtained for Option 3 – the lowest total energy, followed by Option 2 and Option 1. The high value of the probability as the
measure of reliability proves that this combination is realistic case within the total number of combination under consideration.

In order to investigate effect of different cases with priority given to one of the indicators, it was constructed number of situations which reflecting priority of individual indicators with other indicator keeping the same. Among the first in this group is the Case 2 with priority given to Resource Indicator.

### 4.3 Thermal Power Plants

Tried example in demonstration of the sustainable assessment method application is thermal power plant options. In this analysis of clean air technologies [11] a following plants are considered:

- Option 1 Pulverised Coal Fired Power Plant (PCPP)
- Option 2 Integrated Gasification Combined Cycle (IGCC)
- Option 3 Gas fired power plant with combined cycle (NGCC)
- Option 4 Natural Gas Combined Cycle with CO2 Removal (NGCC - CO2)
- Option 5 Natural Gas Combine Heat and Power Production (NGCHP)

The assessment of clean air technologies is based on criteria defined with a following indicators:

- Resource Indicator for steel: $R_{steel}$
- Fuel Resource Indicator: $R_{fuel}$
- Environment Indicator: $E_{CO2}$
- Health Social Indicator: $SI$
- Efficiency Indicator: $E_{cl}$

Following Cases are taken into consideration:

#### 4.3.1 Case 1

$I = I_1 \{ w_{RI_{steel}} > w_{RI_{fuel}} > w_{EI} > w_{SI} > w_{E_{cl}} \}$

The Case 1 is designed to give priority to the Investment Cost followed by Fuel Cost Indicator, Energy Cost Indicator, CO2 Environment Indicator and NOx Health Indicator. It could be noticed that the general priority it is given to the economic and resources indicators in comparison to environment indicators reflecting CO2 and NOx effects. As it can be seen, this assessment leads to the priority to NGCHP followed by NGCC, NGCC with CO2 removal, PCPP and IGCC. 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 multicriteria indicators and nonnumerical constrains among the indicators as specified in the Case 1, shows that the priority options of option NGCHP. Figure 5 shows the General Index and respective probability among the options for the Case 1.

![Fig. 5 General Sustainability Index for Case 1](image-url)
4.3.2 Case 2

\[ I = I_2 \{ w_{\text{El}} > w_{\text{Rs}} > w_{\text{Rif}} > w_{\text{Sl}} > w_{\text{EcI}} \} \]

The Case 2 characterized by the priority of the environment indicator. It presents alternative which emphasize importance of CO₂ Environment Indicator and its role in the priority list. It is of importance to recognize the effect of environment indicator on the priority list. NGCHP option is first on the priority list. It is interesting to investigate the reason why this changes in priority of indicators do not change selected option. Since NGCHP proves to be with high priority in number of cases under consideration, it may be concluded that its weighting coefficient in all cases is high. This probably result of high value of the indicators in comparison with other options. Also, it may be result of large number of situations reflecting aritmetization of all indicators. Finally, it may be result of large contribution of resource and economic indicators in the Sustainability General Index.

![Fig.6 General Sustainability Index for Case 2](image)

Figure 6 shows the General Index and respective probability among the option for the Case 2.

4.3.2 Case 3

\[ I = I_3 \{ w_{\text{Rif}} > w_{\text{Rs}} > w_{\text{El}} > w_{\text{Sl}} > w_{\text{EcI}} \} \]

In other to investigate the effect of individual criteria to the general index for specific cases, these cases are designed to focus attention to the reflection of those criteria on the rating of the option under consideration. The Case 3 is designed with Investment indicator having priority in the relation to the other indicators. All other indicators weighting coefficients are the same. It could be noticed that only limited number of situations within the total number of combination is satisfying this condition. Only 7 combinations among the 82251 are taken into a consideration to define weighting coefficients for this case, Fig. 7

![Fig.7 General Sustainability Index for Case 3](image)

It is of interest to notice that under this constrain the priority is options. Figure 7 shows the General Index and respective probability among the options for the Case 3.
5. CONCLUSIONS

Sustainable energy development is an ultimate goal of modern society in order to meet ever growing demand for the 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 possibility to define the consistent set of sustainability indicators to be used in the assessment of energy system. In this respect, it was presented tree groups of the indicators which reflect the resource, environment, social and economic criteria.

Multicriteria evaluation of clean air technologies is an exercise showing potential possibility of the analysis of complex systems. In the general terms it could be said that the complexity of clean air technology can be defined as the multidimensional space of different indicators. Every energy system under consideration is entity by itself, defined by the respective number of parameters which are deterministically related according the physical laws describing individual processes in the system.

REFERENCES

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