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Sustainability assessment of a hybrid energy system

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ABSTRACT

A hybrid energy system in the form of the Object structure is the pattern for the structure of options in the evaluation of a hybrid system. The Object structure is defined as: Hybrid Energy System {[production (solar, wind, biomass, natural gas)] [utilization(electricity, heat, hydrogen)]}.

In the evaluation of hybrid energy systems only several options are selected to demonstrate the sustainability assessment method application in the promotion of the specific quality of the hybrid energy system.

In this analysis the following options are taken into a consideration:

1. Solar photo-voltaic power plant (PV PP), wind turbine power plant (WTPP) biomass thermal power plant (ThSTPP) for electricity, heat and hydrogen production.
2. Solar PV PP and wind power plant (WPP) for electricity and hydrogen production.
3. Biomass thermal steam turbine power plant (BThSTPP) and WPP for heat and hydrogen production.
4. Combined cycle gas turbine power plant for electricity and hydrogen production.
5. Cogeneration of electricity and water by the hybrid system.

The sustainability assessment method is used for the evaluation of quality of the selected hybrid systems. In this evaluation the following indicators are used: economic indicator, environment indicator and social indicator.

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1. Introduction

The promotion of sustainable development is a European affirmation in the international arena. Sustainability is an example of the European policy and the expression of a "European way". However, the current situation, where sustainability is more an intention than a practice, there are risks for such European affirmation (Green Paper on a European Strategy for Sustainable, 2006).

The sustainability ranges from the policy making in the top to the engineering practices in the bottom. The policy, in a top-down approach, may be successful if served by the tools, methods and skills that may make it real in practice. The present approach intend to contribute the development of a bottom-up approach, skills, methods and tools able to make the implementation of the sustainability in European policy: by applying methods in demonstrative cases (Green Paper on Energy Efficiency, 2005), by providing tools that make it possible to treat sustainability indexes in macro-policy making, to evaluate sustainability in the development assessment, by disseminating best practices.

The proposed approach will provide research groups throughout Europe and to a number of young professionals the practical development and implementation of skills, methods and tools to assess sustainability in a given but critical sector—Energy.

2. Scientific, technological and societal context

The single most important aspect in the European Union (EU) energy system is its high dependency on imported fuels for primary energy sources. The EU imports around 70% of the oil it needs, 43% of the natural gas and 50% of the coal. Oil is mainly used in transportation, and the power sector is the main user of natural gas and coal.

The current power production capacity installed in Europe is based on several sources: natural gas (18%), oil (6%), coal (26%), nuclear (33%), hydro (12%) and other renewable (3%). The current trends in power production point to an increased use of natural gas and renewable, slight increase in nuclear and decrease in coal and oil consumption. Two factors are expected to influence future trends in the European energy sector: the need to meet the Kyoto commitments and the issue of security of energy supply, reflected

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on the green paper: Towards a European Strategy for the Security of Energy Supply (Hemmes et al., 2007).

In view of this, the sustainability of energy supply system cannot be viewed simply on the basis of its environmental impact but must also take into consideration the need to assure that the system has the capacity to meet the requirements set by the consumers, not only in terms of installed power and availability, but most importantly in the capacity to use different primary sources, indigenous and imported.

As mentioned before, the European capacity to supply the primary energy source is very limited in the case of conventional fuels (fossil); however, the use of renewable energies is not yet fully developed. The technologies (wind, hydro, solar, geothermal, biomass) are available and can potentially contribute with a large share of the total energy supply. The main limiting factor so far has been cost. Conventional fuels are very cheap and the investments made in the infrastructure put the pressure on the local authorities to maximize the investments made. The sustainability of the energy system (Afgan and Carvalho, 2000, 2007) should also be evaluated taking these factors into consideration, and that would show that the indigenous energy sources, although more costly, are much more sustainable.

The sustainability has been reinvented as the key word to describe a political discourse concerning quality of life issues, limitation of natural resources and the sense of the commitment to the future generations. Our ever-growing interest has led us to the redefinition of the main discourse in our development strategy in order to adapt our future to the irreversible changes which are immanent to our civilization. As an example, sustainable development is sometimes closely linked to the rejection of the ‘‘development’’ and mere economic modernization is being a new approach for the management of social structure change. This vision of sustainability is reflecting only the resources aspect of sustainability and is neglecting the environmental and social effect of the notion of sustainability.

3. Energy sustainability criteria

There have been a number of attempts to define criteria for the assessment of the sustainability of the market products. In this respect, the Working Group of UNEP on Sustainable Development has come out with qualitative criteria for the assessment of the product design (UNEP Working Group Report, 1997).

A complex energy system is commonly composed of different subsystems and individual equipment elements. It has been recognized that the lifetime of elements and subsystems is not equal. In this respect, the optimal selection of the life cycle for elements and subsystems may lead to the retrofitting procedure which will reflect the need for the sustainable criterion application. Examples for this criterion are: modular design of subsystems, standardization of elements, lifetime monitoring and assessment, co-ordination of suppliers and buyers.

This will mean that the energy system and its subsystems have to be designed to meet sustainability through every stage of the life cycle (World Energy Council, 2006). It is known that the energy system is designed to work under different conditions in order to meet load changes, environment change, social changes, etc. It is obvious that there will be different cycles for each of the mentioned time scale processes. In this respect the system has to fulfil its function without failing to meet sustainability requirements. As an example, we can see: water cooling temperature change; social change leading to the requirement to decrease the load to meet sustainability criteria; building pumping power station for energy saving at night; period of thermal power plant (PP) technical minimum, etc.

4. Multicriteria evaluation of energy systems

System analysis is both a philosophical approach and a collection of techniques, including simulations developed explicitly to address problems dealing with complex systems. System analysis emphasizes a holistic approach to problem solving and use of mathematical models to identify and solve important characteristics of complex systems. A mathematical model is the set of equations that describes the interrelations among those objects. By solving the equations describing a model of the system, we can mimic or simulate the dynamic behaviour of the system (Afgan et al., 1998, 2005).

An energy system is a complex system with a respective structure and can be defined by different boundaries depending on the problem. In a simple analysis with only a function of the energy system designed to convert energy resources into the final energy form, the interaction of the energy system is defined by its thermodynamic efficiency. Adding the respective complexity to the energy system, we can follow the interaction between the energy system and environment. In this respect, a good example is a pollution problem, which is defined as the emission of energy and material species resulting from the fuel conversion process. With further increase in complexity of the energy system and by establishing respective communication through the boundary, there are other entities fluxes between the system and surroundings. Since every energy system has a social function in our life, its link may also be established between the energy system and surroundings taking into consideration the social interaction between the system and environment. Obviously, additional complexity in the energy system may lead to the exchange of different fluxes. In this respect, the Onsager relation (Progogine, 1966) gives a good example of the possible relation among the fluxes of interaction between the system and its environment.

In our analysis, we have assumed that the energy system is a complex system which may interact with its surroundings by utilizing resources, exchange conversion system products, utilize economic benefits from conversion process and absorb the social consequences of conversion process. Each of the interaction fluxes is a result of the very complex interaction between the elements of the energy system within the system and with the surroundings. In our analysis we will use synthesized parameters for the system in the form defined in classical analyses of energy systems. In this analysis, we will use the indicator for resources utilization as the resource indicators, and for the conversion process effect on the environment the CO_2 concentration in exhaust gas. The electric energy cost will be used to measure the economic benefits of energy system and NO_x release of the energy system will be used as its social indicator. It is proved that the NO_x concentration in the air is affecting human health and can be correlated with health expenses (Brown, 2002).

Multi-criteria assessment of the energy system (Shi et al., 2007; Afgan et al., 2000) is the method to establish a measuring parameter, which comprises different interactions between the system and its surroundings. This may lead to the development of a method which will help us to understand in deep the specific role of energy system selection and quality of our life.

The multi-criteria assessment is based on the decision-making procedure reflecting the combined effect of all criteria under consideration and is expressed in the form of General Index of Sustainability. A selected number of indicators are taken as a measure of the criteria comprising specific information of the options under consideration. The procedure is aimed to express options property by the respective set of indicators (Hovanov, 1996).

4.1. Sustainability index definition

The decision-making procedure comprises several steps in order to obtain a mathematical tool for the assessment of the rating among options under consideration (Hovanov et al., 1997).

The first step in the preparation of data for the multi-criteria sustainability assessment is arithmetization of the data. This 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 whether the value of function $q_i(x_i)$ is decreasing or increasing with argument x_i; (3) to choice the exponent's value λ in the formula

$$q_i(x_i) = \begin{cases} 0 & \text{if} \quad x_i \leqslant Min(i), \\ \left(\frac{x_i - Min(i)}{Max(i) - Min(i)}\right)^{\lambda}, & \text{if} \quad Min(i) < x_i \leqslant Max(i), \\ 1 & \text{if} \quad x_i > Max(i) \end{cases}$$

for the increasing function $q_i(x_i)$.

The functions $q_1(x_1), \ldots, q_m(x_m)$ formation process is 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 i-th particular criterion for the j-th option. In this analysis it assumed that the linear functions $q_1(x_1), \ldots, q_m(x_m)$ are used for the membership functions with the decreasing function.

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

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

where w_i is the weight-coefficients elements of vector **w**, and q_i the indicators of specific criteria.

In order to define the weight-coefficient vector the randomization of uncertainty is introduced. The randomization process is a stochastic realization of the corresponding sets of functions and a random weight-vector. It is assumed that the measurement of weight coefficients is accurate to within the steps $h = 1/n$, 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.

For nonnumeric, inexact and incomplete information I = OI U II. (Information are ordinal information, or Incomplete information so Information is union of all information.) Information is used for the reduction of the set $W(m,n)$ of all possible vectors **w** to obtain the discrete components set $W\ (I;n,m)$ and is defined with the number of constraints reflecting nonnumeric information about mutual relation among the criteria under consideration.

5. Energy hybrid system

A hybrid energy system produces power from more than one generating source such as wind-driven turbines and solar panels, biomass plant and hydro turbine. The system stores excess power in battery storage units, and could be configured also to use power from the local electric power grid when the reserve power storage (batteries) is low. Our systems provide the right combination of wind, biomass and solar energy generation and system components. These systems take the guess work out of selecting and installing a renewable energy generation because every system should be tailored to meet the power generation needs of the specific energy resources available at the specific site.

The energy demand in the developing regions is an essential problem for economic development in a number of countries (Urban et al., 2007). This applies to the developed and developing countries. Usually, these regions are short in energy resource and are mainly depending on the renewable energy resources. A single, energy resource is not commonly justified to meet the need for sufficient energy production. In this respect the hybrid system has proved to offer the potential possibility for energy production from different energy production systems. Putting together several energy systems is the potential option for meeting the demand for energy in the region and is apromising energy strategy in many countries.

The hybrid energy system composed of several sub-systems is an imminent option in the design of the long-term strategy for the underdeveloped regions (Urban et al., 2007). There are a number of potential structures of the hybrid system composed of the individual elements of the system. So, it can be taken that the hybrid system is the composed structure of different energy systems supplied by the respective energy source. In this analysis attention will be focused on the following energy systems: solar photo voltaic power plant (PVPP), Biomass PP, NGPP and wind PP (WPP). Fig. 1 shows the potential structure of a hybrid system. If it is anticipated that the hybrid system is defined as Object structure, then the hybrid system can be presented as

Hybrid energy system {[Solar PV PP(Electricity, Hydrogen, Heat)][Biomass PP(Electricity, Heat)][Natural Gas PP(Electricity, Hydrogen, Heat)][Wind PP (Electricity, Hydrogen))]}, giving the possibility to form a number of different hybrid energy systems with respective attributes. This will give us the possibility to design options to be used in this analysis.

5.1. Selection of hybrid system options

As it can be noticed from the Object structure of a hybrid energy system, there are a great number of potential hybrid system options with different energy system elements. In the demonstration of the potential options to be taken in this analysis, we have selected the following options:

1. Solar PV PP, wind turbine power plant (WTPP), biomass thermal steam turbine power plant (BTLSTPP) for production of electricity and hydrogen (Celik, 2003).

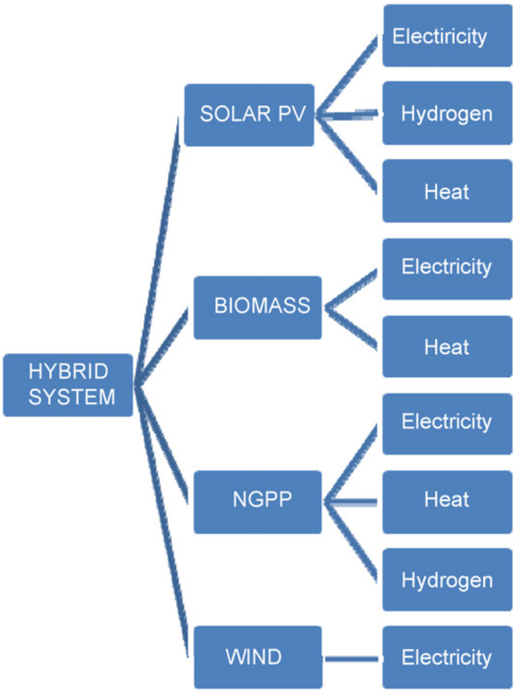

Fig. 1. Hybrid energy system structure.

2. Diesel and Wind PP for production of electricity and hydrogen (McKenni and Olsen, 1999).
3. BTLSTPP and WPP for production of electricity and hydrogen (Juarad and Saenz, 2002; Pilavachi et al., 2006).
4. Combined cycle gas turbine power plant for electricity and hydrogen production (El-Nashar, 2001; Al-Sofy, 2007).
5. Cogeneration of electricity and water by the hybrid system.

A simple description of the potential options for the evaluation of hybrid system is presented as follows:

1. Solar PV PP, wind turbine PP biomass thermal STPP for production of electricity, heat and hydrogen.
   The hybrid system with solar PV, wind turbine and biomass steam turbine is aimed to produce electricity, heat and hydrogen as shown in Fig. 2. The electricity produced by the solar PV is merged with the electricity produced by the wind and biomass power plant. It is assumed that the hybrid energy production is designed with the following participation of individual sources: solar PV 26%, WPP 26%, Biomass fuelled power plant 48% (Celik, 2003). Part of the electricity produced by the hybrid energy system is used for hydrogen production.
2. Diesel and wind PP for production of electricity and hydrogen.
   This hybrid energy system consisting of the combined diesel and wind generator is proved to be economically and environmentally advantageous (McKenni and Olsen, 1999). The assessment of such asystem compared with other options of hybrid systems with the selected indicators is an effective method for the optimal hybrid system selection.
   The wind–diesel hybrid system is relatively simple. It comprises the wind turbine specified capacity and diesel generator. For this analysis a total wind capacity of 450 kW and a diesel generator of 1700 kW are anticipated. Therefore the wind penetration of "online" capacity is 26% Fig. 3.
3. Biomass thermal STPP and wind PP for production of electricity and hydrogen.
   This hybrid system is designed as the combination of biomass thermal STPP and wind PP with the aim to facilitate zero CO_2 emission. It comprises 26% wind power and 74% biomass fired PP (Juarad and Saenz, 2002). This combination of the renewable energy sources is suitable for the area where biomass planting is economically justified.

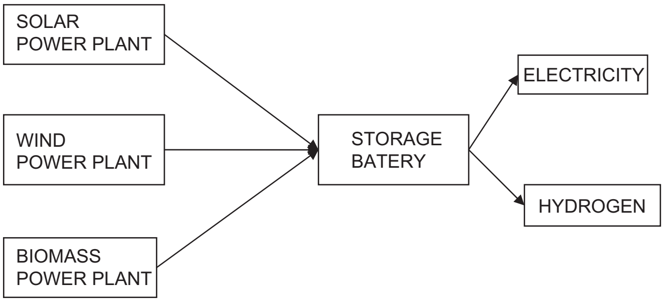

Fig. 2. Solar PV PP, wind turbine PP biomass thermal STPP for production of electricity and hydrogen.

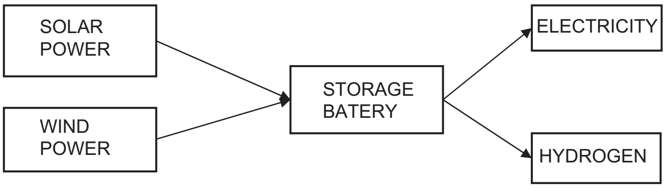

Fig. 3. Solar PV PP and wind PP for production of electricity and hydrogen.

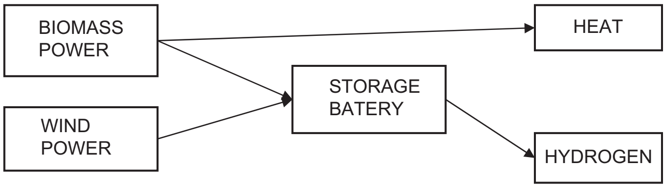

Fig. 4. Biomass thermal STPP and wind PP for production of heat and hydrogen.

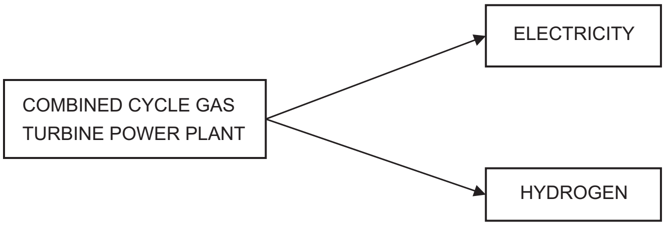

Fig. 5. Combined cycle gas turbine power plant for electricity and hydrogen production.

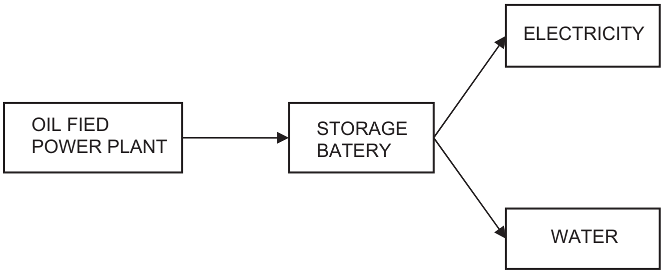

Fig. 6. Cogeneration of electricity and water by oil fired power plant.

   This system includes a boiler fired with biomass and steam turbine of the respective capacity. The biomass thermal STPP and the wind PP produce electricity, which accommodates its use for the hydrogen and local electricity production. The schematic structure of this hybrid system is shown in Fig. 4.
4. Combined cycle gas turbine power plant for electricity and hydrogen production.
   In order to have the possibility to compare the hybrid energy system with the classical power plant, the combined cycle gas turbine power plant is used. It is anticipated that gas turbine power generation is about 66% and steam turbine power generation 34% with 56% efficiency (Pilavachi et al., 2006). Investment cost is 1000 \$/kW. CO_2 and NO_x emissions are 0.38 and 0.415 kg/MWh,, respectively. The schematic structure of this plan is shown in Fig. 5.
5. Cogeneration of electricity and water by the oil fired system power plant.
   There are several potential options for the cogeneration plant for electricity and water production. It is of particular interest to investigate the options for the cogeneration plant for electricity and water production in islands. In this respect, in this analysis we have used the cogeneration plant with the oil fired boiler and steam turbine as the option to be compared with hybrid energy systems (El-Nashar, 2001; Al-Sofy, 2007) (Fig. 6).

5.2. Energy system indicators

Measuring sustainability is a major issue as well as a driving force of the discussion on sustainability development. The tool for reliable sustainability measurement is a prerequisite for

Table 1
Hybrid energy system indicators

Options	Efficiency (%)	Electricity cost ($/kWh)	Investment cost ($/kW)	CO_2 emission (kg/MWh)	NO_x emission (Kg/MWh)
PV–wind–biomass PP	43.28	12.16	1960	0.00	0.406
Wind–diesel PP	46.48	24.28	1450	0.59	2.00
Biomass–wind PP	68.56	8.00	1464	0.00	0.406
Combined cycle PP	56.00	4.00	65	0.38	0.415
Cogenerated cycle PP	36.00	6.20	1000	0.85	2.00

identifying non-sustainable processes. Informing decision-makers of the quality of products and monitoring impacts to the social environment play an essential role in evaluation of the system. 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.

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

5.3. *Indicators definition*

For the sustainability assessment of an energy system, the following indicators are used (Table 1):

1 Economic indicator—EI
  1.1 Efficiency sub-indicator
  1.2 Electricity cost sub-indicator
  1.3 Investment cost sub-indicator
2 Environment indicator—EI
  2.1 CO_2 emission sub-indicator
3 3. Social indicator—SI
  3.1 NO_x emission sub-indicator

5.3.1. *Economic indicators*

Economic indicators are based on the following sub-indicators, including: effectiveness sub-indicator, investment sub-indicator and energy unit cost sub-indicator. The effectiveness sub-indicator element is defined as the thermodynamic efficiency of the system. It will include the energy efficiency conversion from the energy resources to the final energy. The investment cost sub-indicator is aimed to obtain valorization of the investment per unit power. The electricity energy unit cost sub-indicator will comprise the cost of electricity per unit kWh production.

5.3.2. *Environment indicators*

The environment indicator is represented by the respective sub-indicators, namely: CO_2 emission sub-indicator. Following the same procedure used in the definition of economic sub-indicators, we can adapt that the environment indicator is given in the same way.

5.3.3. *Social indicators*

The social indicators reflect the social aspect of the options under consideration. It will comprise the NO_x sub-indicator as the measuring parameter for the adverse health effect of energy production.

5.4. *Case selection*

In the evaluation of selected options there is a number of potential constraints to be introduced among the criteria in the multi-criteria assessment of the options under consideration. The constraints are defined by the priority among indicators. In this respect there are a large number of cases reflecting selected constraints among indicators. In this analysis the first three cases are with the priority of individual indicators taken into consideration. The next two cases are designed with stepwise priority give to indicators. The following cases are used in this evaluation:

Case 1. Weight coefficients constraint: efficiency$>$ electricity cost $=$ investment cost $=$ CO_2 emission $=$ NO_x emission.

Case 1 corresponds to the situation when the priority is given to the efficiency indicator and other indicators are having the same value. It is of interest to notice that the option biomass-wind PP and combined cycle PP with marginal difference are in the first place on the General Index list. The wind–diesel PP option and solar PV–wind–biomass PP option are in the second place. Cogeneration PP is in the last place of the General Index priority list Fig. 7.

Case 2. Weight coefficients constraint: electricity$>$cost efficiency $=$ investment cost $=$ CO_2 emission $=$ NO_x emission.

Case 2 is designed to give priority to the electricity cost sub-indicator. As it can be noticed the combined cycle option has priority on the General Index rating list. Biomass–wind, cogeneration and PV–wind-biomass PP options are on the General Index list with stepwise decreasing values. The lowest value of the General Index is obtained for the wind–diesel option. Fig. 8

Case 3. Weight coefficients constraint: Investment cost$>$efficiency $=$ electricity cost $=$ CO_2 emission $=$ NO_x emission.

Case 3 represents results if priority is given to the investment sub-indicator. As it can be seen, this case represents the same rating list as it could be obtained with single investment indicator rating. (Fig. 9).

Case 4. *Weight coefficients* constraint: CO_2 emission$>$efficiency $=$ electricity cost $=$ investment cost $=$ NO_x emission.

Case 4 represents the situation if priority is given to the CO_2 emission indicator. The first place on the General Index rating list is combined cycle and biomass–wind options. The PV–wind-biomass and wind–diesel options are defined with the stepwise decreasing of the General Index values. Fig. 10.

Case 5. Weight coefficients constraint: NO_x emission$>$efficiency $=$ electricity cost $=$ investment cost $=$ CO_2 emission.

Case 5 is designed with priority given to the NO_x sub-indicator, reflecting the health effect on the options under consideration. The first three options on the priority list are having marginally different General Index values and can be treated as a single

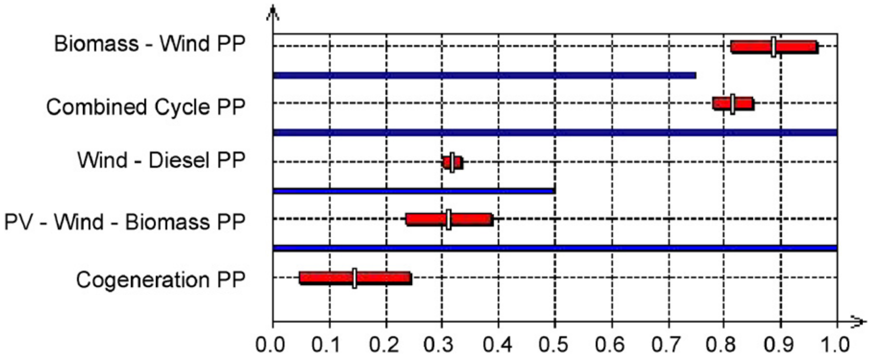

Fig. 7. General Index for Case 1.

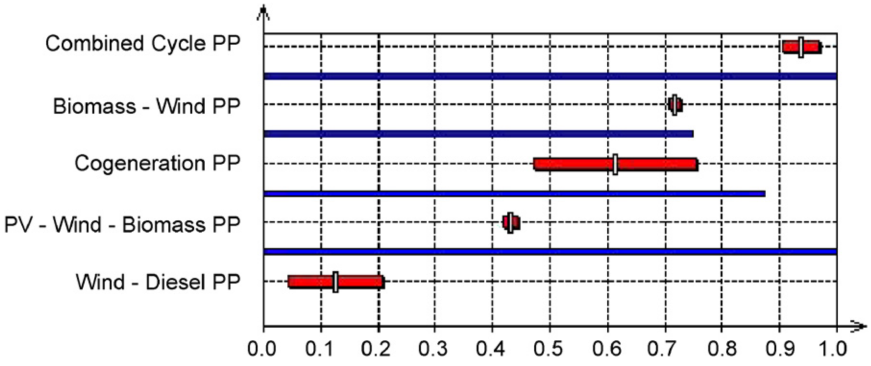

Fig. 8. General Index for Case 2.

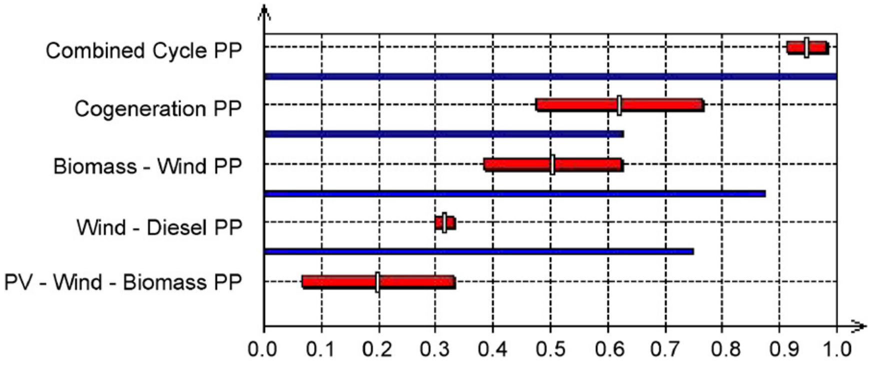

Fig. 9. General Index for Case 3.

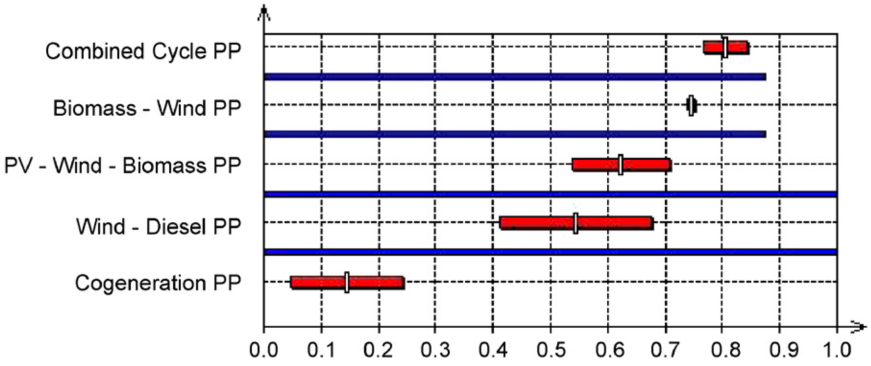

Fig. 10. General Index for Case 4.

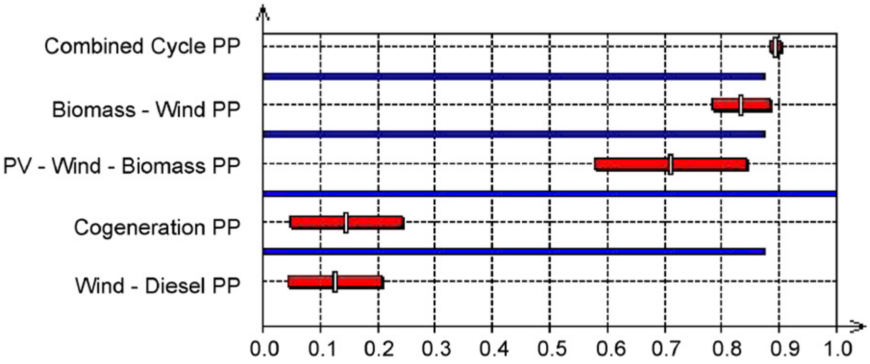

Fig. 11. General Index for Case 5.

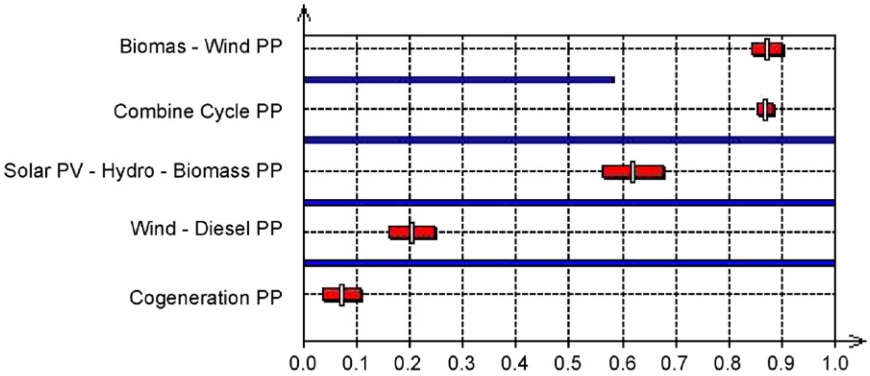

Fig. 12. General Index for Case 6.

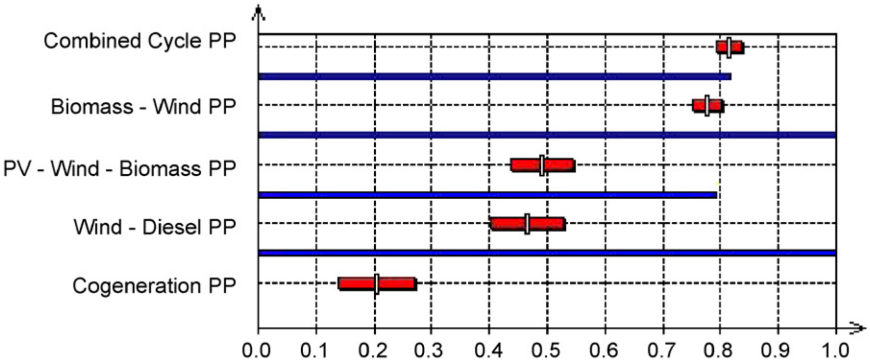

Fig. 13. General Index for Case 7.

group. The cogeneration option and wind–diesel option are having the lowest values on the priority list (Fig. 11).

Cases 6 and 7 are devoted to the analysis of the effect of changes of constraints on the priority list of the General Index. It is obvious that there is a large number of potential cases with different rating among the sub-indicators. In this demonstration we have selected only cases representing electricity cost and CO_2 emission priority.

Case 6. Weight coefficients constraint: electricity cost > efficiency > investment cost > CO_2 emission > NO_x emission.

Case 7. *Weight coefficients* Constraint: CO_2 emission > efficiency > electricity cost > Investment cost > NO_x emission.

Cases 6 and 7 are designed with indicators priority formed by the decreasing constraints between individual sub-indicators (Figs. 12 and 13). In Case 6 priority is given to the electricity cost, followed by the efficiency, the electricity cost, investment cost and CO_2 emission sub-indicators. Case 7 reflects the situation if the priority is given to the CO_2 sub-indicator. It is of interest to notice that the combined cycle and biomass–wind options in Cases 6 and 7 are having priority on the General Index list.

6. Conclusions

The multi-criteria method for the evaluation of hybrid energy system shows the potential possibility for the determination of the Sustainability Index rating. It implies quantification of the Sustainability Index as the parameter for the quality assessment of the energy system under consideration. In particular, the assessment of hybrid energy system with a large number of potential options can be justified with high level of confidence. Also, the agglomeration of the sub-indicators offers the possibility to use an extensive number of sub-indicators in verifying their effect on the sustainability priority list. It is of special interest to emphasize that the multi-criteria method as presented in the paper is independent of human effect on the decision-making process.

The demonstrated exercise proves the feasibility of the multi-criteria method in the evolution of the hybrid energy system. The selected number of cases is arbitrary in our case, but in any other evaluation it can be taken as a useful parameter in obtaining a better basis for the decision making. Also, it can be noticed that the selection of indicators and sub-indicators is an important factor which affects the quality of evaluation. It should be emphasized that this type of evaluation is only the basis for the decision-making procedure.

References

Afgan, N.H., Carvalho, M.G., 2000. Sustainability Assessment Method for Energy Systems. Kluwer Academic Publisher, New York.

Afgan, N.H., Carvalho, M.G., 2007. Quality, Sustainability and Indicators of Energy Systems. Begell House Publisher.

Afgan, N.H., Al Gobaisi, D., Carvalho, M.G., Cumo, M., 1998. Sustainable energy management. Renewable and Sustainable Energy Review 2, 235–286.

Afgan, N.H., Carvalho, M.G., Hovanov, A.N., 2000. Energy system assessment with sustainability indicators. Energy Policy 28, 603–612.

Afgan, N.H., Carvalho, M.G., Hovanov, N., 2005. Modelling of energy system sustainability indicators. Thermal Science 9 (2).

Al-Sofy, M.A., 2007. Integrated production of water, electricity and fuel, In: Symposium Proceedings: Toward Innovative Desalination and Power Generation in Kuwait, December 9–11, 2007, Kuwait.

Brown, K., 2002. Calculation and Reference Relation to Health and Environmental Cost. University of Alberta, Edmonton, Canada.

Celik, Ali Naci, 2003. Tech-economic analysis of autonomous PV—wind hybrid energy systems, using different sizing method. Energy Conversion and Management 44, 1951–1965.

El-Nashar, Al.M., 2001. Cogeneration for power and desalination—state of the art review. Desalination 134, 7–28.

Green Paper on Energy Efficiency, 2005. European Commission, COM(2005)265, Final.

Green Paper on a European Strategy for Sustainable Development, 2006. Competitive and Secure Energy, 8 March 2006.

Hemmes, K., Zahariah-Wolf, J.L., Geidl, M., Anderson, G., 2007. Toward multi-source and multi-product energy system. International Journal of Hydrogen Energy 33, 1322–1338.

Hovanov, N., 1996. Analysis and Synthesis of Parameters under Information Deficiency. St. Petersburg State University Press, St. Petersburg (Monograph, in Russian).

Hovanov, N., Kornikov, V., Seregin, I., 1997. Qualitative information processing in DSS ASPID-3W for complex objects estimation under uncertainty. In: Proceedings of the International Conference "Informatics and Control," St. Petersburg, Russia, pp. 808–816.

Juarad, F., Saenz, J.R., 2002. Possibilities for biomass power plant and wind system integration. Energy 27 (10), 966–985.

McKenni, E., Olsen, T.L., 1999. Performance and economics of wind–diesel hybrid energy system, NREL/SR-500-24663, July 1999.

Pilavachi, P.A., Rompeas, C.P., Minett, S., Afgan, N.H., 2006. Multi-criteria evaluation for CHP system options. Energy Conversion and Management 47, 3519–3529.

Progogine, I., 1966. In: Donnely, R.J., Herman, R., Prigogine, I. (Eds.), Evaluation Criteria, Variational Properties and Fluctuations, Non-equlibrium Thermodynamics Variational Techniques and Stability. The University of Chicago Press, Chicago.

Shi, Jun-Hai, Zhu, Xin-Jin, Cao, Guang, 2007. Design and techno-economical optimization for stand-alone hybrid power systems with multi-objective evolutionary algorithms. International Journal of Energy Research 31, 315–328.

UNEP Working Group Report, 1997. Sustainable Development Commission.

Urban, F., Bender, R.M.J., Moll, H.C., 2007. Modeling energy system for developing countries. Energy Policy 35, 3473–3482.

World Energy Council, 2006. Comparison of Energy Systems using Life Cycle Analysis. World Energy Council, London.