International Journal of Sustainable Energy
Vol. 26, No. 4, December 2007, 179–193

Biomass-fired power plant: the sustainability option

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Biomass use for power generation has become an attractive option for the increase of energy production with the increase of efficiency, decrease of environment degradation and waste utilization. Justification of the biomass use benefits requires a multi-criteria assessment based on the evaluation of economic, environmental, technological and social aspects. In this respect, the need for the evaluation of biomass-fired power plant is of great interest for the validation of benefits of biomass resources.

The paper presents an outline of a multi-criteria method for the evaluation of the General Sustainability Index as the quality measurement of different potential options of the biomass-fired power plant and their comparison with other new and renewable power plants. A number of options are evaluated with appropriate selection of indicators reflecting economic, environment, technological and social parameters. Among options under consideration there are those reflecting mixed fuel of biomass and fossil organic fuel power plants. Special attention is devoted to the use of constraints giving priority to individual criteria.

It is shown that the potential quality merit, which describes the priority of individual options under specific constraint is the potential tool for the energy system evaluation. This decision-making procedure enlightens the potential priority of biomass-fired power plants in comparison with other renewable energy sources.

Keywords: Biomass power plant; Sustainability assessment; Economic; Environment; Technology and social indicators; Decision making procedure

1. Introduction

Biomass provides about 14% of world energy resources or about 25 million barrels of oil equivalent per day (Mboe/day). It is the most important source of energy in developing countries (Afgan *et al.* 1998). In general, it is rather difficult to estimate biomass resources because it strongly depends on the natural vegetation. Detailed analysis shows that if it is assumed 35 GJ/capita for developing countries, the land required per capita at biomass yield 2, 5 and 10 t/ha/year, will be 1.0, 0.5 and 0.2 ha/capita, respectively. This means that the low-yield biomass production will require a large land area to be used for the required energy production. It is estimated that for the biomass use for energy production it would be needed minimum 5 t/ha/year yield and could be used for the energy production in areas where the local energy consumption is substantially below the average for developing countries. Commodities

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International Journal of Sustainable Energy
ISSN 1478-6451 print/ISSN 1478-646X online
http://www.tandf.co.uk/journals
DOI: 10.1080/14786450701550434

such as lighting, water for people, water for live stock and irrigation are of the primary interest for the biomass electricity production.

Biomass energy production can be obtained through different routes for biomass conversion processes. The great versatility of biomass as a feedstock is evident from the range of wet to dry materials which can be converted into various solid, liquid and gaseous fuels using biological and thermo-chemical conversion processes. Solid fuels are wood, charcoal, crop and forestry residual, agro-industrial and municipal wastes and briquettes. Biomass-derived liquids are mainly ethanol and methanol. Gases are mainly biogases from anaerobic digesters, gasifiers-producing gases which can be used for electricity generation and possibly coupled to an efficient gas turbine system.

This analysis is devoted to the assessment of biomass-fired power plant taking into consideration economic, environmental and social criteria. (Wereko-Brobby and Hagen 1995, Bain *et al.* 2003). In this respect the evaluation will include a number of energy systems which will include: stand alone biomass-fired system, co-firing biomass/coal system, and modern coal-fired power plant. The analysis is based on the multi-criteria assessment method using three groups of indicators: economic, environmental and social.

2. Options selection

The multi-criteria assessment of energy system requires definition of the system under consideration (Afghan and Carvalho 2000, Afghan *et al.* 2000). As the energy system is a complex system it needs to use a respective method for the quality determination. This is subject to the definition of indicators which are relevant to the description of different aspects of energy systems. So, the first step in evaluation of energy systems is the definition of systems to be taken into consideration. In our analysis of biomass energy systems, we will focus our attention on the following energy systems:

1. Direct biomass-fired power plant using biomass residual;
2. Pulverized coal-fired steam cycle power plant;
3. Natural gas combined cycle power plant;
4. Co-firing biomass residual and coal power plant;
5. Biomass-fired integrated gasification with combined cycle system;
6. Wind power plant.

Technologies for the biomass conversion could be classified into three large groups: thermo-chemical conversion, physical–chemical conversion and bio-chemical conversion.

In this paper we will select a number of options from summary survey information where 20 biomass power plants are presented (out of which 18 are in the United States, one is in Canada, and one is in Finland) that represent some of the leaders in the industry (Bain *et al.* 2003).

We will focus our attention on the following energy systems.

2.1 *Direct biomass-fired power plant using biomass residual*

Direct fired combustion technologies are option designed as the fixed bed combustors with fuel charged on the bottom are suitable only for smaller sizes of plant (up to 5 MW) and biomass fuels with small ash contents (disintegrated wooden mass, sawdust).

The combustion in furnace with the traveling grate stocker is suitable for the biomass with high content of humidity and ash, as well as for a wide range of particle sizes and shapes (without fine fractions, under the 5 mm). It is important to control and regulate the volume of air along the grate, according to zones of drying, gasification and coke residual combustion.

The prepared biomass suitable for combustion is used in the pulverized combustion. The process of combustion should be realized in a way to avoid high temperatures of combustion, because the ashes of some biomass types are meltable at temperatures under 800 °C.

The combustion in furnace with traveling grate stocker is simpler, cheaper and more suitable for low nominal sizes of the plants, but they could work in a wide range of power. On the other hand, power plants of FBBC and CFBC are more suitable for usage of biomass with high content of humidity and various mixtures of biomass (as well as other fuels). The plants (FBBC and CFBC) work with higher efficiency and produce lower emission of CO i NOx; and if it is necessary, the reduction of SO_2 emission could be achieved by very simple methods (Ministry for Science, Technology and Development of Republic Serbia, 2000).

In this evaluation, the technology with fixed bed combustion, the biopower plants of 75 MW and total efficiency $\eta = 30\%$ will be used. Boiler technology with travelling grate stoker combustion of biomass is included. Steam temperatures for the biomass-fired boilers are 399 °C–527 °C.

2.2 *Pulverized coal-fired steam cycle power plant*

A reduced efficiency due to the carbon loss is a major factor in comparing a stoker-fired to a pulverized coal-fired boiler (PC boiler). A properly designed PC boiler can maintain an efficiency loss due to unburned carbon of less that 0.4% (Singer 1981). The PC unit offers a lower carbon loss because of the increased combustion efficiency obtained with the finer coal particles that enter the furnace. Another factor favoring PC firing is the fact that many high-ash coals with a low-ash fusion temperature create a clinkering problem when burned on a stoker. Also, the modern pulverized coal-fired power plant incorporates several clean air technologies. Control of particulate emission, sulfur oxides, and nitrogen oxides must also be evaluated in the comparative installed costs of different types of coal-fired equipment.

Under the PC-fired power plant we will take 105 MW plant with the lignite fuel combustion at steam pressure $p = 137$ bars and steam temperature $T_{steam} = 450$ °C. The total efficiency of the plant is $\eta = 33\%$. The emission of CO_2 of the plant is assumed to be 1.06 kg/kWh.

2.3 *Natural gas combined cycle power plant*

Combined cycle is one of a number of combinations of gas turbines, steam generators (or other heat recovery equipment), and steam turbines assembled for the reduction in plant investment cost or improvement of cycle efficiency in the power-generation process. In principle the natural gas-fired power plant is used to improve its efficiency by increasing the working fluid temperature by the high-temperature gas turbine. Open cycle gas turbines are used to satisfy both the peaking and reserve requirements of the utility industry because of their quick-starting capability and low capital cost.

The total efficiency of gas turbine energy system fueled with natural gas is $\eta = 36\%$. The installation cost is estimated to be 2500 \$/kW.

2.4 *Coal/Biomass co-firing power plant*

In the study of biomass, co-firing means addition of biomass to the base fuel, mainly coal. Technically, the combustion of biomass could be realized in several ways: mixing of biomass and coal on dumping, using of separate lines for transport and coal and biomass charge, gasification of biomass and later combustion of gas in the furnace. The maximal portion of biomass is relatively small (in the pulverized power plants up to 5% and in the cyclone furnace up to 20% of biomass) mostly because of the bad influence of biomass to the mills work.

Advantages of this technical option are cheaper used fuels (biomasses in regard to replaced coal), directly reduced emission of SO_2 and ash, together with the ash reduction of heavy metals emission, as well as reduction of CO_2 emission. However, in the scope of economic aspect, it is the lower price of biomass as fuel that can compensate for both the necessary high investments and certain reduction of total efficiency of power plant, too (caused by high humidity of biomass).

The lowest-cost option for the use of biomass is cofiring with coal in existing boilers. We have chosen boiler technology where cofiring has been practiced, tested, or evaluated, and include tangentially fired pulverized coal (PC) boilers. Many trials have shown that effective substitutions of biomass energy can be made for up to 15% of the total energy input, in our case 15% from wood and 85% from coal, with little more than burner and feed intake system modifications to existing stations. The total efficiency to electricity would be 36% and the power of the biopower plant is 75 MW. Steam temperature for the PC boiler is 540 °C. Investments are expected to be in 1360 \$/kW.

2.5 *Biomass-fired integrated gasification with combined cycle system*

The main goal of gasification process is the production of gaseous fuel from the solid fuel, in this case from the biomass. The gasification process is performed at the high temperature of 700–1000 °C and under the stechiometric conditions ($\lambda < 1$), which do not allow to develop the combustion process or to consume all fuel.

The main products of the gasification process of biomass are: CO, CO_2 CH_4, CnHm, H_2 and nitrogen. Ratio of some components in products of gasification depends on a few parameters: type of gasificator, characteristics of the fuel part of biomass, temperature of the gasification process, oxidization level of fuel components occurred during the pyrolysis, types of the oxidizing compound (air or oxygen), and addition of the vapor.

This process gives high efficiency of electricity production in a gaseous power plant than in the classic power plant during the combustion of biomass and steam cycle. Besides, this process enables considerably lower emission of harmful gases and particles.

For this attractive biopower option based on gasification, size of biopower plant is 75 MW and total efficiency would be $\eta = 36\%$. Cost of this power plant is estimated to be 2750 \$/kW and electricity costs of 0.03 \$/kWh.

2.6 *Wind energy system*

The important parameter in the design of wind power plant is the wind velocity. It varies in time and space, and requires special procedure for its averaging in order to meet a wide range of the wind fluctuation. Power change is subject to the wind fluctuation and since its values vary by third power the estimate of local power potential is not simple. Each turbine has nominal power that corresponds to the designed wind velocity. It depends on local conditions and frequency of wind occurrences during the year (Djajić 2002).

The development of wind generators tends towards larger capacity, *e.g.* those with rotor of 15–20 m in diameter yield 50–100 kW, while the output of those with diameter 50–60 m is 1 MW, thus making wind generators more and more present in electro-energetic network.

3. Selection of indicators

In this analysis, a following agglomerated indicators are used: economic, environmental, technological and social indicators. Each of the indicators is comprised of several sub-indicators describing specific characteristics of the systems under consideration. In order to present agglomerated values of individual option the special procedure is introduced for the definition of economic, environmental, technological and social indicators (Afgan *et al.* 2004).

The procedure for the determination of the agglomerated indicators is based on the statistical validation of contribution of individual sub-indicators (Afgan and Carvalho 2004). The individual contribution of sub-indicators is difficult to determine with sufficient accuracy. In this respect the weighting coefficients are used to determine importance of individual indicator to the general object index. In order to override this deficiency the agglomeration procedure is adopted which will lead to the aggregation of individual sub-indicators in the main group of indicators defined to the specific Economic indicator, Environment indicator, Technological Indicator and Social indicator. As it is shown individual sub-indicators are a subset of the set of indicator-reflecting attributes in the description of objects. Under the constraint that the subset of sub-indicators belong to the set of general indicators as defined by the attributes, it is allowed to use the linear agglomeration function represented as follows:

$$I_{\text{agg}} = \sum_{i=1}^{m} w_i q_i \tag{1}$$

where

I_{agg} – Aggregated indicator
w_i – weighting coefficient for sub-indicator i
q_i – normalized value of sub-indicator i

Formation of 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 if 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 (Hovanov *et al.* 1997, Nikolai *et al.* 1999, Afgan *et al.* 2005)

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

for the deceasing function $q_i(x_i)$.

Procedure for the determination of weight coefficients is based on the method for determination of average values of the weight coefficients for the specific set of sub-indicator values satisfying imposed constraints. The constraints imposed in the priority of sub-indicators will lead to the selection of only those values which satisfy constraints. The new set formed will allow the determining of the average value weight coefficient for each sub-indicator. This is the final result of the procedure for determination of weight coefficients used in the aggregated indicator calculation.

This procedure is used in the determination of agglomerated values for the Economic indicator, Environmental indicator, Technology indicator and Social indicator under specified constraints reflecting the priority of sub-indicators.

3.1 *Economic indicator*

The economic indicator comprises a tree of sub-indicators which are relevant to the economic assessment of energy system. Among those are: efficiency, electricity cost and investment cost. The efficiency of the system is considered as the integral parameter which is reflecting performance of the system as thermodynamic system. The electricity cost sub-indicator represents the total energy cost and is a measure of the quality of the system. The investment cost comprises material cost, design and construction cost of the system. The data presented in the table 1 are derived from a literature survey (Bain *et al.* 2003) of the biomass system. Biomass/Coal and Biomass/Gas systems are considered as the biomass co-fired system with 15% biomass. For the relative validation of biomass system, this evaluation uses coal-fired and gas-fired power plants (Walker and Jenkins 1995, Pruschek 1998) and wind power plants (Elliasson 1999).

The agglomerated economic indicator is defined as follows (table 2):

$$\mathrm{EcI}_{\mathrm{aggr}} = \sum w_n.\mathrm{EcI}_n \tag{3}$$

3.2 *Environment indicator*

The environment indicator has become a governing parameter in the evaluation of energy system. Among the Green House Gases the CO_2 concentration in flue gases of the power plant is the most important characteristic for the environment assessment of energy system (Bain *et al.* 2003). The CO_2 cycle in utilization of biomass shows one of the main advantages of the biomass system in power plant systems. NO_x and SO_x concentration in flue gas is contributing to the adverse effect of the utilization of biomass. For this reason, the evaluation of concentration of these gases in the biomass energy system is of primary interest for the quality assessment of the biomass energy system. The data presented in table 3 correspond to the utilization of the wood residual biomass.

Table 1. Economic indicators EcI.

	Efficiency %	Electricity cost \$/kWh	Investment \$/kW
Biomass PP	30	0.084	1747
Coal-fired PP	33	0.039	1100
Gas-fired PP	36	0.021	2500
Biomass-Coal PP	36	0.045	1360
Biomass-Gas PP	36	0.03	2750
Wind PP	28	0.08	1100

Table 2. Agglomerated economic indicators.

	Constrains		
	Efficiency > Electricity Cost = Investment	Electricity Cost > Efficiency = Investment	Investment > Efficiency = Electricity Cost
Biomass PP	0.113	0.091	0.354
Coal fired PP	0.656	0.743	0.893
Gas fired PP	0.837	0.837	0.325
Biomass-Coal PP	0.604	0.627	0.731
Biomass-Gas PP	0.824	0.779	0.311
Wind PP	0.162	0.162	0.675

Table 3. Environmental indicator EnI.

	CO_2 Concentration kg/kWh	NO_x Concentration kg/kWh (10^{-6})	SO_x Concentration kg/kWh (10^{-6})
Biomass PP	−0.40	408.24	36.29
Coal-fired PP	1.06	3125	6486
Gas fired PP	0.50	413	1.814
Biomass-Coal PP	0.89	2798.7	5534
Biomass-Gas PP	0.6	720	22.68
Wind PP	0.00	0.00	0.00

Table 4. Agglomerated environment indicators.

	Constraints		
	$CO_2 > NO_x = So_x$	$NO_x > CO_2 = SO_x$	$SO_x > CO_2 = NO_x$
Biomass PP	0.949	0.866	0.871
Coal fired PP	0.000	0.000	0.000
Gas fired PP	0.704	0.775	0.784
Biomass-Coal PP	0.036	0.009	0.009
Biomass-Gas PP	0.485	0.674	0.745
Wind PP	0.939	0.966	0.892

The agglomerated environment indicator (table 4) is defined as follows

$$\mathrm{EnI}_{\mathrm{aggr}} = \sum w_n.\mathrm{EnI}_n \tag{4}$$

3.3 *Technological indicator*

Renewable technologies include modern biomass, solar, wind, hydro and geothermal technologies. The R&D data for the development of renewable technologies are not well defined because there is no universally accepted definition of R&D. The technological indicator comprises two sub-elements: Development Capital and Market elements.

The Development capital sub-indicator is determined from the data obtained from the Research & Development Budget in IEA (Nakcenovic *et al.* 1998, World Energy Council 2000, UNDP 2000). The amount of development budget for the fossil fuel power plant development is divided between gas (50%) and coal-(50%) fired power plant systems. The utilization of renewable energy sources is divided between solar, wind and biomass systems. It is anticipated that the biomass utilization is divided between direct biomass (50%), biomass/coal-fired (25%) and biomass/gas (25%).

The market indicator is based on the forecast of energy consumption in the period of the next 50 years. It is assumed that the gas consumption in the power sector will be 50% of total gas consumption. For coal consumption, it is assumed that 80% of coal consumption will be used for power production. For the biomass consumption it is assumed that 30% will be used in power sector. This consumption will be divided between direct biomass 50%, biomass/coal 25% and Biomass/gas 25%.

The agglomerated technological indicator (table 5) is defined as follows:

$$\mathrm{TeI}_{\mathrm{aggr}} = \sum w_n.\mathrm{TeI}_n \tag{5}$$

3.4 *Social indicator*

Presently it is becoming very urgent to take into consideration the social aspect in the evaluation of power plants. In this respect, in this analysis, a following social sub-indicators are taken into consideration: New Job opportunity, Area required and Health effect on the surrounding population.

The New Job sub-indicator comprises the number of jobs to be open per unit MW (World Energy Council 2000). The data are derived from the evaluation of similar data for the classical fossil fuel power plant. The high requirement for the area to be used for the construction of a power plant is imminent for any power generation system. In this analysis data are taken for the ABB study (UNDP 2000). In this evaluation, the health parameter is derived from the NO_x concentration in the surrounding of the power plant.

The agglomerated environment indicator is defined as follows:

$$\mathrm{SoI}_{\mathrm{aggr}} = \sum w_n.\mathrm{SoI}_n \tag{6}$$

4. Results and discussion

As it was defined in section 2, the biomass systems are to be compared with different options of the classical fossil energy system and wind energy system as the representative of other renewable energy systems. The multi-criteria evaluation of biomass energy systems is based on the decision-making procedure and implies the need to define respective criteria and corresponding indicators.

The aggregated economic, environment, technological and social indicators comprise the specific properties given to the sub-indicators and are used in the analysis of priority of options under consideration. As the measuring indices for the quality evaluation of the options the General Sustainability Index is used.

The decision-making procedure comprises several steps in order to obtain mathematical tools for the assessment of the rating among the options under consideration. In order to prepare respective data for the biomass systems assessment the tables 5–8 present the data to be used in the analysis.

The General Index Method comprises the formation of an aggregative function with the weighted arithmetic mean as the synthesizing function defined as

$$Q(q; w) = \sum_{i=1}^{m} w_i q_i \tag{7}$$

Table 5. Technological indicator TeI.

	Development capital \$/year (10^{12})	Market MW (10^3)
Biomass PP	0155	420
Coal-fired PP	0.35	106
Gas-fired PP	035	382
Biomass-Coal PP	0.078	9
Biomass-Gas PP	0.078	9
Wind PP	0.0465	8.7

Table 6. Agglomerated technological indicator.

	Constrains	
	Development capital > Market	Market > Development capital
Biomass PP	0.555	0.861
Coal-fired PP	0.849	0.511
Gas-fired PP	1.00	1.00
Biomass-Coal PP	0.106	0.092
Biomass-Gas PP	0.105	0.092
Wind PP	0.02	0.064

Table 7. Social indicator SoI.

	New Job/MW	Area km^2/kW	Health c/kWh
Biomass PP	0.825	5.2	0.47
Coal fired PP	0.6	0.4	3.6
Gas fired PP	0.3	0.38	0.16
Biomass-Coal PP	0.8	1.124	3.22
Biomass-Gas PP	0.384	1.03	0.806
Wind PP	0.2	0.78	0.00

Table 8. Agglomerated social indicators.

	Constrains		
	NewJob > Area = Health	Area > NewJob = Health	Health > NewJob = Area
Biomass PP	0.800	0.287	0.680
Coal fired PP	0.713	0.791	0.772
Gas fired PP	0.298	0.699	0.692
Biomass-Coal PP	0.828	0628	0.492
Biomass-Gas PP	0.252	0.465	0.138
Wind PP	0.242	0.615	0.682

where

w_i – weight-coefficients elements of vector **w**
q_i – aggregated indicators of specific criteria and respective constraints

In order to define the weight-coefficient vector the randomization of uncertainty is introduced. Randomization produces stochastic with realizations from corresponding sets of functions and a random weight-vector. It is assumed that the measurement of weight coefficients is accurate to within steps $h = 1/n$, with n a positive integer. In this case the infinite set of all possible vectors may be approximated by the finite set $W(m, n)$ of all possible weight vectors with discrete components. In our case, we will use $m = 4$, and $n = 40$ so that the total number of elements of the set $W(m, n)$ is $N(m, n) = 92251$.

Evaluation is obtained for the following situations:

Case 1 **EcI 1** (Efficient > El.Cost = Inv.Cost) = **EnI 1** ($CO_2 > No_x = So_x$) = **TeI1** (DevCap > Market) = **SoI1** (Job > Area = Health)

Case 1 reflects constraints when priority is given to the Economic Indicator and Environment, Technological and Social Indicators have the same value. Also, in the derivation

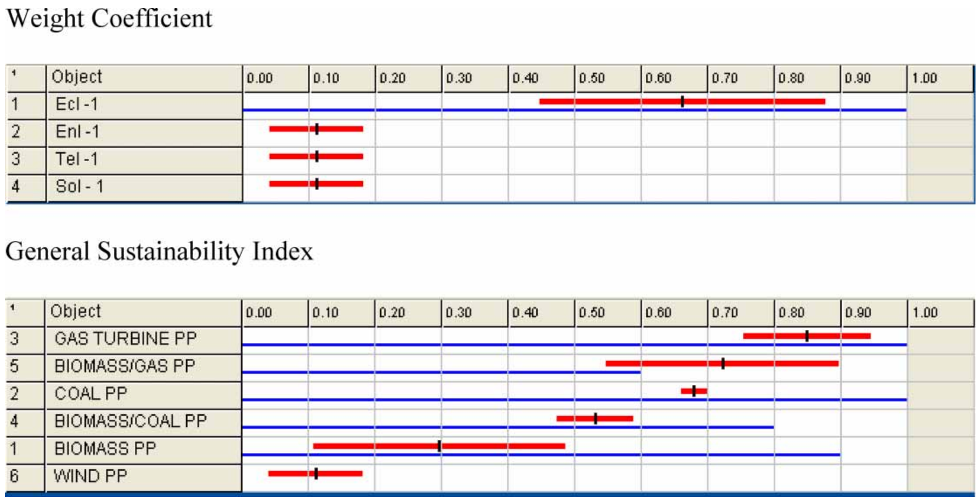

Figure 1. Weight coefficients and general sustainability index for Case 1.

of individual agglomerated indicators the priority is given to the specific sub-indicators as specified in the Case 1 (figure 1) definition.

Under these constraints the priority is obtained by the Gas Turbine option which is followed by the Biomass/Gas, Coal, Biomass/Coal, Biomass and Wind option.

Case 2 **EcI 2** (El.Cost > Eff = Inv.Cost) = **EnI1**($CO_2 > NO_x = SO_x$) = **TeI1** (Dev Cap > Market) = **SoI 1** (Job > Area = Health)

Case 2 is designed very similarly to Case 1, besides the change in priority of sub-indicators for the Economic Indicators (figure 2). After this change, we can notice that the Gas Turbine PP option is still in the first place even though there is a change in the second place being taken by the Coal PP option. Also, it is noticed that the fossil-fired power plant has higher priority

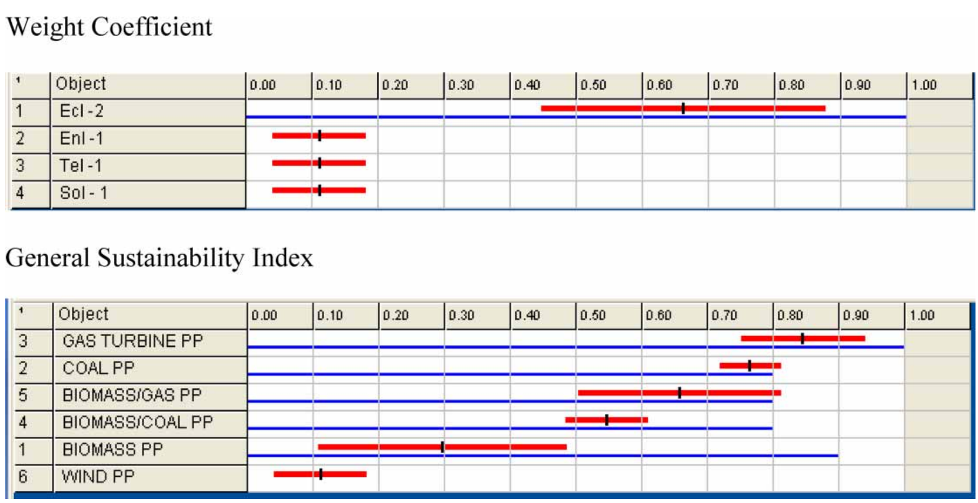

Figure 2. Weight coefficients and general sustainability index for Case 2.

than Biomass power plants. It is becoming obvious to what extent the change in priority could change the position on the priority list in the evaluation of options under consideration.

Case 3 **EcI** (Inv.Cost > El.Cost = Eff) = **EnI 1** (CO_2 > No_x = So_x) = **TeI 1** (Dev Cap > Market) = **SoI 1** (Job > Area = Health)

Case 3 reflects the introduction of change in the Economic Indicator with priority given to the Investment sub-indicator (figure 3). The priority in this case is obtained by Coal Power Plant option. It should be noticed that due to the strong effect of the Investment sub-indicators the first tree places on the priority list are taken by options with low values of investment per kW. Under this constraint the Biomass/coal option is highly rated on the priority list, which may be taken as the positive quality of the biomass use.

Case 4 **EnI 1** (CO_2 > No_x = So_x) > **EcI1**(Eff > El.Cost = Inv.Cost) = **TeI2**(Market > DevCap) = **SoI3** (Health > Job = Area)

Case 4 aims to present the effect of the Environment indicator on the priority list (figure 4). As is expected, Biogas and Wind PP options are on the first two places on the priority list with the marginal difference between them. This can be understood as the potential possibility to use the biomass power plant as the substantial contribution to the Kyoto protocol verification.

Case 5 **TeI 1** (Market > DevCap) **EcI**(Eff > El.Cost = Inv.Cost) = **EnI1**(CO_2 > No_x = So_x) = **SoI3** (Health > Job = Area)

The priority list affected by the Technological Indicator is presented in Case 5. Biomass and Gas Turbine PP are potential options to be considered in the future strategy of the development of energy systems (figure 5). It is very important to notice that the priority list in this case is reflecting strong influence of the potential market and future strategy in the assessment of potential.

Case 6 **SoI 3** (Health > Job = Area =) > **EcI1** (Eff > El.Cost = Inv.Cost) = **EnI1** (CO_2 > No_x = So_x) = **TeI2**(Market > DevCap)

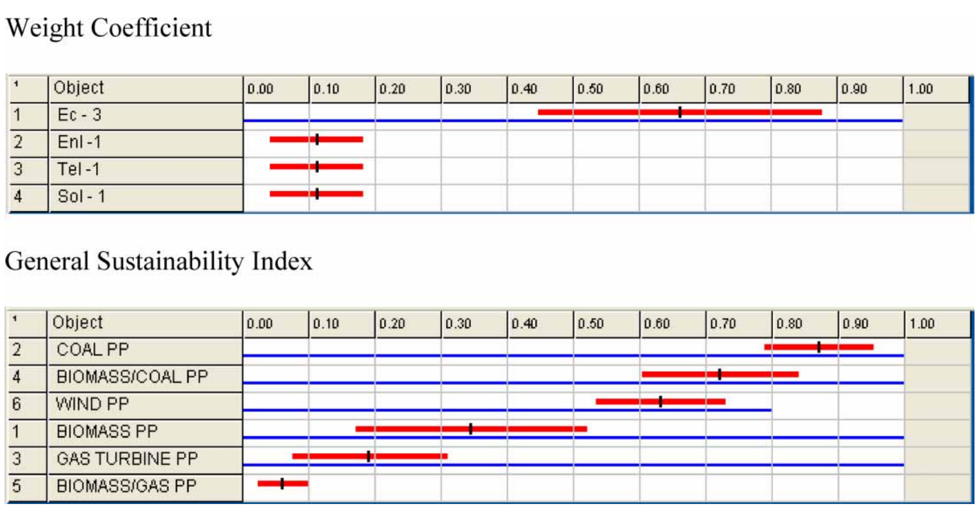

Figure 3. Weight coefficients and general sustainability index for Case 3.

Figure 4. Weight coefficients and general sustainability index for Case 4.

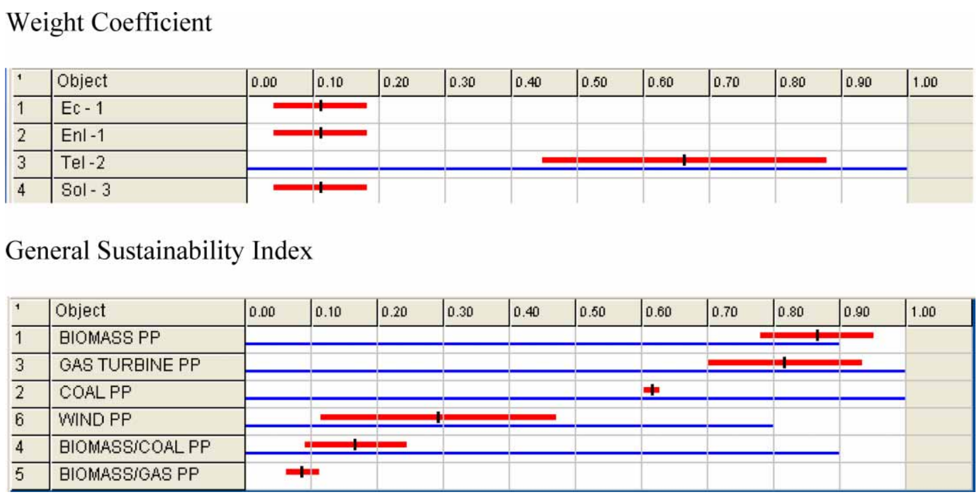

Figure 5. Weight coefficients and general sustainability index for Case 5.

Case 6 is making visible potential effects of the Social Indicators on the future strategy of the development of energy systems (figure 6). New Job, Area and Health sub-indicators are of primary interest to be fully understood in the evaluation of the potential options of energy systems. It should be noticed that Coal, Biomass, Wind and Gas Turbine options are in the same group on the priority list.

Case 7 **EcI 1** (Eff $>$ El.Cost $=$ Inv.Cost) $=$ **TeI2**(Market $>$ DevCap) $>$ **EnI1**(CO_2 $>$ No_x $=$ So_x) $=$ **SoI1**(Job $>$ Area $=$ Health)

Next two cases are designed with the aim to investigate the effect of combined priority of the indicators. In this respect Case 7 is giving priority to the Economic and Technological indicators with priority given to efficiency and market sub-indicators, respectively (figure 7). This can be explained as the priority given to economy and technology developments in comparison to environmental and social aspects of the options under consideration.

It is noticed that Coal and Biomass PP plant are at the top of the priority list.

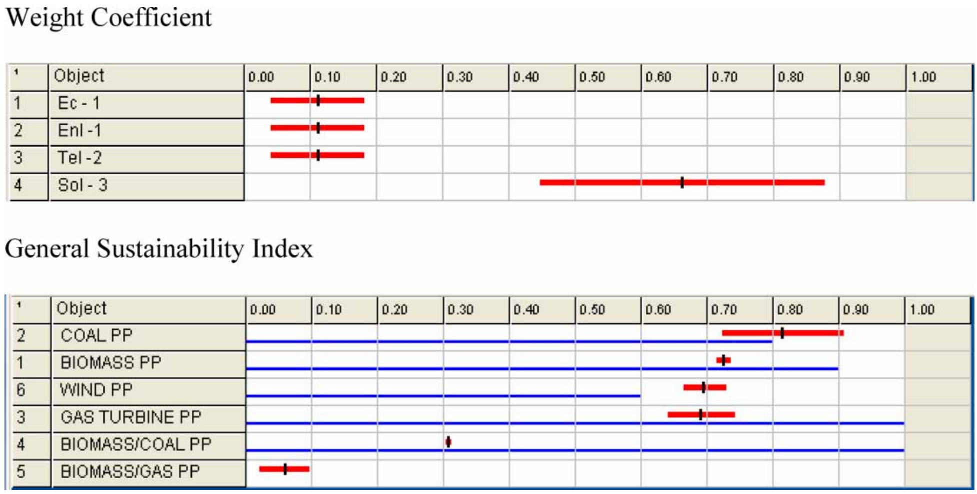

Figure 6. Weight coefficients and general sustainability index for Case 6.

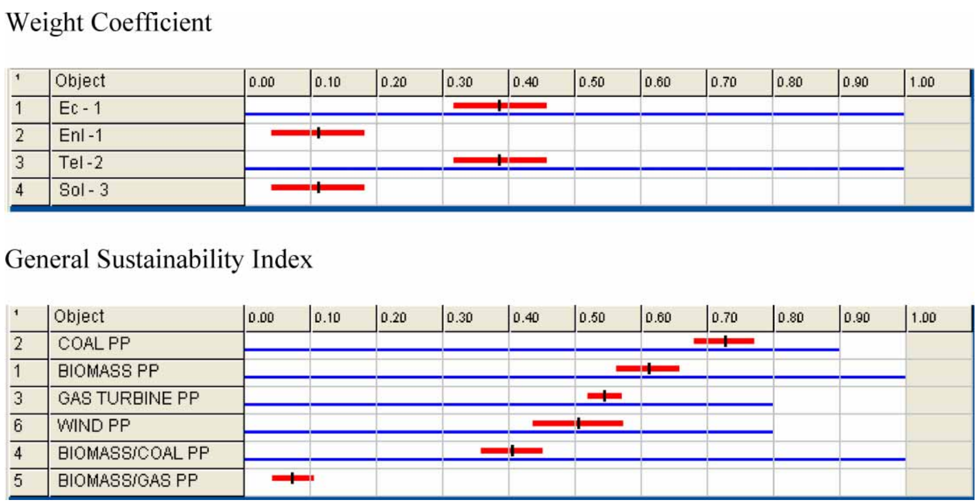

Figure 7. Weight coefficients and general sustainability index for Case 7.

Case 8 **EcI 2** (El.Cost > Eff = Inv.Cost) = **EnI1**(CO_2 > No_x = So_x) > **TeI1**(Market > DevCap) = **SoI1**(Job > Area = Health)

This Case is an attempt to validate the effect of Economical and Environmental Indicators on the priority list. Under these constraints Gas Turbine PP, Biomass PP options and Biomass/Gas are taking a first tree place on the priority list (figure 8).

It is of interest to emphasize that Case 8 is a good example, which proves that Biomass PP options may be taken as the promising options which can meet economic and environment constraints in the selection of new energy sources.

Case 9 **EcI 3** (Inv.Cost > El.Cost = Eff) = **TeI1**(Market > DevCap) > **EnI1**(CO_2 > No_x = So_x) = **SoI1**(Job > Area = Health)

If the priority is given to the Economic Indicator with Investment sub-indicator, and the Technology Indicator with Market sub-indicator, the General Sustainability Index priority list

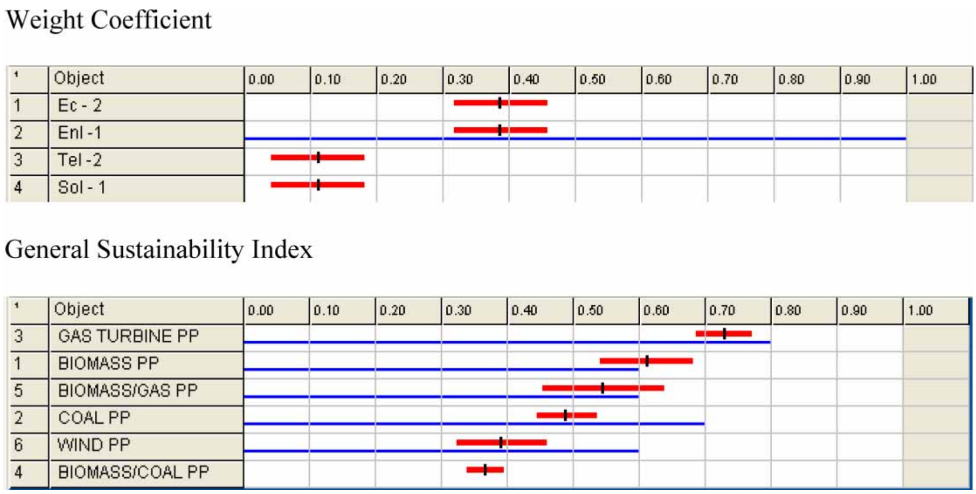

Figure 8. Weight coefficients and general sustainability index for Case 8.

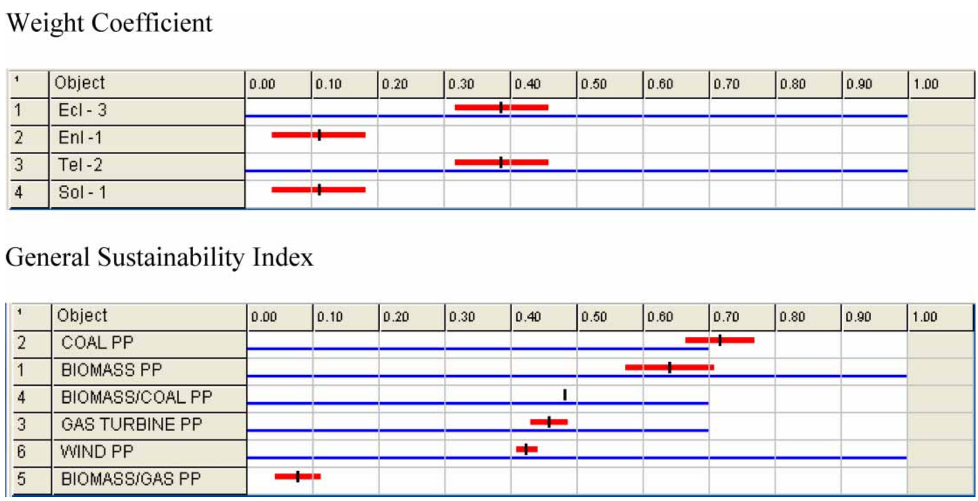

Figure 9. Weight coefficients and general sustainability index for Case 9.

will be taken by Coal PP and Biomass PP (figure 9). Since Economic Indicator with Investment sub-indicator priority and Technology Indicator with Market sub-indicator priority are linked with potential expectation in future development, it is of interest to recognize that the Coal PP and Biomass PP options are of substantial importance for the future strategy. It will reveal that future strategy will be based on the coal- and biomass-fired power plant and at the same time to meet ecological and social constraints.

5. Conclusions

The evaluation of potential biomass utilization is of great importance for the development of future energy strategy. As biomass resources are the potential option in the programming future clean air strategy, it is important to be in a position to quantify the quality of biomass energy systems.

The multi-criteria decision-making procedure is a tool which offers the possibility to introduce the valorization of potential energy system options and investigate constraints which are of importance for the design of future energy strategies.

In this analysis, the biomass energy system as Biomass Direct combustion, Biomass/Coal and Biomass/Gas power plant are used to compare with fossil fuel coal-fired and gas-fired power plants. As the representative of the renewable energy sources system the Wind energy power plant is used.

From the analysis of the individual cases defined with specific priority of the indicators and evaluation of the presented options, a conclusion was derived as regards to the utilization of the biomass energy system. It was shown that the biomass energy system is in most of the considered cases highly rated among the options. In particular, it was proved that biomass energy systems in the cases with Economic Indicator, with Investment sub-indicator priority, and Technology Indicator, with Market sub-indicator priority, are linked with potential expectation in future development. Also, it is of interest to emphasize that Case 8 is a good example which proves that the Biomass PP option may be taken as the promising option which can meet economic and environment constraints in the selection of new energy sources. It is recognized that the Coal PP and Biomass PP options are of substantial importance for the future strategy. It will reveal that future strategy will be based on the coal- and biomass-fired power plant and at the same time will meet ecological and social constraints.

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