ENERGY INDICATORS IMPACT IN MULTI-CRITERIA SUSTAINABILITY ANALYSE OF THERMAL POWER PLANT UNIT

by

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This paper presents method for sustainability assessment of thermal power plant unit using multi-criteria analysis with aim to create base for business decision. Seven options of possible status of thermal power plant „Kolubara A" unit No. 2 with energy indicators of sustainable development were shown. Energy indicators of sustainable development consists of sets of resource preservation, economic, environmental, and social indicators. Sustainability assessment often fails to account for social influence on energy system. Considering to this, special focus will be on social indicators, their definition, forming, and impact on multi--criteria sustainability analysis. Analysis of quality of the selected options (energy systems) in respect to sustainable development by compare of their general index of sustainability is presented. Methodology of multi-criteria analyse of thermal power plant unit can show decision makers how to find best available options when the social indicators impact is leading. The aim of this paper is to choose the criteria for the evaluation of the available options, determine the relative importance of specific criteria and present methodology of multi-criteria analysis in the decision-making process.

Key words: *sustainable development, thermal power plant, social indicators, multi-criteria analysis*

Introduction

Sustainable development has been defined best by the Brundtland Commission *as development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. Energy is central improved social and economic well-being, and is indispensable to most industrial and commercial wealth generation. It is key for relieving poverty, improving human welfare and raising living standards. Today, there is wide consensus that concept of sustainable development brings the hope of renaissance of our planet but also that next ten years are critical to implementation of that concept [1]. Achieving sustainable economic development on a global scale will require the judicious use of resources, technology, appropriate economic incentives, and strategic policy planning at the local and national levels. Energy system is complex system with adequate structure and can be

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defined by different boundaries depending on the type of the problem. If only function of energy system is conversion of resources into final energy form, then the system is only defined by thermodynamics efficiency. Since every energy system has social function in our life, its link can be established between energy system and its environment taking into consideration social interactions between system and environment [2].

Electric Power Industry of Serbia (EPS) is the biggest enterprise in Serbia. Installed power generation capacity is 8,359 MW [3]. In thermal power plants (TPP) run by EPS was produced 34.509 GWh in 2014. Thermal Power Plants Nikola Tesla Company (TPPNT) is the biggest producer of electric energy in south-east Europe and is integral part of EPS. It has 14 units of installed power of 3,288 MW and produces more than 50% of total Serbian electricity production per year. Five organizational units works within TPPNT: TPPNT A in Obrenovac (6 units of total power of 1.650 MW), TPPNT B on Usce (2 units, each of 620 MW), TPP *Kolubara* in Veliki Crljeni (five units of total power of 271 MW), TPP *Morava* in Svilajnac (one unit of 125 MW), and Railway transport which transports more than 28 million tons of lignite from open pit mine (OPM) *Kolubara* [3].

The oldest TPP which operate in EPS is *Kolubara A*. Management of EPS is planning to shut down two units due to very long life time of their exploitation and low efficiency. Among those units is A2 TPP *Kolubara* power of 32 MW. Shutting down this unit would cause a fall in production of electric energy and loss of jobs. This paper shows sustainability analyzis by multi-criteria method and possibilities of further operation and life-time extension of TPP *Kolubara A*, Veliki Crljeni.

Possible options for revitalization or new facility of TPP *Kolubara A* unit No. 2

In this paper seven options of possible status of this unit for life-time extension for 20 years has been proposed. For each proposed option are formed indicators and sub-indicators for better understanding of various aspects of sustainable development. The proposed options are:

Revitalization of thermal unit 2 in the condensational regime – Option 1

This revitalization include new membrane wall in a furnace, new high pressure piping system, new electrostatic precipitator, new turbine (high pressure cylinder, middle pressure cylinder, and low pressure cylinder) and modernization of the majority of automatic and electric equipment. Fuel for combusting is lignite (LHV = 7,000 kJ/kg) [4] and process of combusting is same as in existing facility. After revitalization unit fulfils all environmental requirements for this kind of large combustion plant. Gross heat rate (gross specific consumption of fuel energy) is 12,500 kJ/kWh and electric energy self-consumption is 11.5%.

Revitalization of thermal unit 2 on the basis of co-combustion coal (lignite) and solid recovered fuel in the condensational regime – Option 2

Revitalization in this option is the same as in Option 1 but includes all equipment for a partial replacement of coal with solid recovered fuel (SRF) in the process of co-combustion [4]. In the co-combustion process, 5% of the energy needed for the production of electricity would be received from SRF.

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Revitalization of thermal unit 2 on the basis of co-combustion coal (lignite) and biomass in the condensational regime – Option 3

Revitalization in Option 3 is the same as in Option 1 but includes all equipment for co-combustion of local biomass with lignite. This option is included in order to exploit the potential impact of waste biomass use in large combustion plants. With this option, the total amount of energy needed to generate electricity, 95% is derived from coal (lignite) and the rest from biomass [5].

Revitalization of thermal unit 2 on the basis of co-combustion coal (lignite) and waste in the condensational regime – Option 4

Processes of digging out, transporting, and drying Kolubara coal in OPM *Kolubara* generate a large quantity of dried coal dust and other waste material which makes the work much more difficult and pollutes environment [6]. Possible co-combustion of lignite and waste matters created in OPM *Kolubara* operating process could bring numerous positive social, economic and environmental effects. The total amount of energy needed to generate electricity, 90% is derived from coal (lignite) and the rest from waste coal matters. Revitalization in the Option 4 is the same as in Option 1 but includes all equipment for co-combustion lignite with waste coal materials.

Thermal unit 2 gas-combusted in condensational regime (combined cycle gas-steam facility) – Option 5

For this option, new unit with natural gas powered turbine and boiler utilisator with steam turbine is planned. Gross heat rate of the unit is 7,000 kJ/kWh and electric energy self-consumption is 7% [7].

Production of electric energy from wind generators of 32 MW power (new facility) – Option 6

This option take into account new 32 MW wind powered facility instead old lignite fired unit No. 2 TPP *Kolubara A*. As there is no useful wind potential in the Kolubara region new 16 wind turbine each 2 MW power level are planned to be located on the hills near city of Vrsac, Serbia, with annual average wind velocity of 5 m/s [8]. Annual energy generation potential is estimated at the level 37, 910 MWh.

Production of electric energy from solar energy (photovoltaic – new facility) – Option 7

This option is based on 32 MW photovoltaic facility instead of old unit No. 2. Solar facility is planned to be located in the OPM *Kolubara* region with global horizontal irradiation 1400 kWh/m^2 per year [9, 10]. It will consist of 400 panels each 80 kW with annual energy generation 84 000 kWh per year per panel.

Sustainability indicators for proposed options of unit 2 TPP *Kolubara A*

Purpose of indicator is to describe the work of the system. Indicator is measurement parameter for comparing different conditions or structures of the system. The issue of sustain-

ability is very complex and indicators must reflect the wholeness of system as well interactions between its sub-systems [11, 12]. In this paper are selected, defined, and calculated economic, environmental, social, and resource indicators (tab. 1) for assessing the sustainability of the unit A2 TPP *Kolubara* for the projected lifetime of the plant of 20 years for previously shown options. In addition to these indicators the following sets of sub-indicators for each of the indicators are formed.

Table 1. Sustainability indicators and sub-indicators for proposed options

Options	Resource indicator		Economic indicator	
	I_{coal} [ton]	$I_{production\ of\ electric\ energy}$ [kWh]	$I_{electricity\ price}$ [€ per kWh]	$I_{investment}$ [€ per kWh]
Option 1	7,437,941	3,681,600,000	0.03	0.0022
Option 2	6,958,970	3,624,960,000	0.032	0.0024
Option 3	6,959,970	3,624,960,000	0.033	0.0026
Option 4	6,695,084	3,681,600,000	0.0295	0.0023
Option 5	4,489,367	4,166,400,000	0.088	0.0046
Option 6	1,280	758,145,062	0.0067	0.042
Option 7	1,500	672,000,000	0.0094	0.1

Options	Environmental indicator				Social indicator					
	I_{CO_2} [kgCO$_2$ per kWh]	I_{SO_2} [gSO$_2$ per kWh]	I_{NO_x} [gNO$_x$ per kWh]	$I_{dust\ matters}$ [mg per Nm^3]	I_{salary} [€ per kWh]	$I_{employee}$ [–]	$I_{project\ in\ l.\ c.}$ [€ per kWh]	$I_{injury\ on\ the\ work}$ [1 per year]	$I_{sick\text{-}leave}$ [h per year]	I_{supply} [–]
Option 1	1.51	20.2	1.3	0.55	0.0059	90	0.0004	4	9,260	0.9
Option 2	1.46	19.3	1.29	0.51	0.0064	95	0.00055	5	10,750	0.8
Option 3	1.44	19.3	1.29	0.48	0.0065	100	0.0005	6	11,830	0.8
Option 4	1.55	22.9	1.32	0.41	0.0065	100	0.00068	5	10,290	0.9
Option 5	0.42	0.07	0.41	0.01	0.0016	25	0.00024	2	1,286	0.3
Option 6	0.0013	0.017	0.0011	0	0.0057	15	0.001	1	772	0.3
Option 7	0.0017	0.022	0.0014	0	0.0084	20	0.00074	1	1,029	0.3

　　　　Resource indicator contains the following sub-indicators.
–   Coal sub-indicator, I_{coal} [t], which shows the extent of consumption of lignite in process of production of electric energy in unit A2 TPP *Kolubara*.
–   Indicator of production of electric energy, $I_{production\ of\ electric\ energy}$ [kWh], shows how much neto electric energy is produced in projected lifetime of facility.

　　　　Environmental indicator contains the following sub-indicators.
–   The CO_2 sub-indicator, I_{CO_2} [kgCO$_2$ per kWh], shows emission of CO_2 per neto kWh of electric energy.
–   The SO_2 sub-indicator, I_{SO_2} [gSO$_2$ per kWh], shows emission of SO_2 per produced neto kWh of electric energy.

– The NO_x sub-indicator, I_{NO_x} [g_{NO_x} per kWh], shows emission of NO_x per neto kWh of electric energy.
– Dust matters sub-indicator, $I_{dust\ matters}$ [g per kWh], shows emission of particulate dust matters per neto produced kWh of electric energy.

      Economic indicator contains the following sub-indicators.

– Sub-indicator of electricity price, $I_{electricity\ price}$ [€ per kWh], which is formed on the basis of costs that influence the production of electric energy: cost of fuel, labour, and maintenance.
– Investment sub-indicator, $I_{investment}$ [€ per kWh], shows the required amount of investment per neto produced kWh of electric energy depending on options that is considered.

      Social indicator contains following sub-indicators.

– Salary indicator, I_{salary} [€ per kWh], represents cost of labor force per neto kWh of electric energy generated during lifetime of the considered unit option.
– Employee indicator, $I_{employee}$ [–], represents number of employees.
– Project sub-indicator in local community, $I_{project\ in\ l.\ c.}$ [€ per kWh], which is formed on the basis of how much is appropriated for projects in local community per neto produced kWh.
– Injury sub-indicator on the work, $I_{injury\ on\ the\ work}$ [1 per year], which is formed on the basis of number of injuries per year.
– Sick-leave sub-indicator, $I_{sick-leave}$ [hours per year], which is formed on the basis of the number of hours which employees spend on the sick-leave per year.
– Sub-indicator of the safety of supply, I_{supply}, represents the value linked to resources, import of fossil fuel and possibility of exploitation (renewable energy sources).

Social indicators

      Every energy system affects the surrounding reflecting social aspect of an energy system [7, 13]. The social aspect of an energy system is an important factor defining the quality of the system. It can bring new jobs, investment and infrastructure, among others. Besides the adverse effect of the energy system on the environment, it can be a driving force for social changes [14-16].

      While the ecological and economic indicators which could be precisely quantified, the quantification of the social aspects is much more different. In this domain, social aspects do require a much more extensive discussion. The aim of this paper was to analyse and presents the indicators that have social dimensions of sustainability by including different values and interests of local communities. In order to determine the best option in the decision-making process, impact of social indicator in the multi-criterion analysis was based on different priorities for six social sub-indicators, tab. 2.

The ASPID method multi-criteria sustainability
analyse of chosen options

      Multi-criteria decision making is a well-known branch of decision making. It is a branch of a general class of operations research models that deal with decision problems under the presence of a number of decision criteria. Multi-criteria analyses present techniques designed in order to integrate the economic, environmental, and social aspects in sustainability assessment.

      This paper shows an example of the analysis and synthesis of parameters under information deficiency (ASPID) method of multi-criteria analysis. In this process, the priorities

are defined by decision-maker in order to their interests and needs by weight coefficients that represent a share in the final result [13, 17]. It is possible to evaluate considered options by using this method in situations when there are un-complete, non-countable or interval (incorrect) information with different levels of reliability. It is performed on the basis of determined specific criteria, q, and with the aid of weight coefficients [17]. Using ASPID method, ranked options from the aspect of sustainability and find best solution can be obtained.

In order to determine influence of specific criteria the category of weight coefficients is introduced while multi-criteria assessment of option is expressed with aid of aggregate function $Q_+(q;w)$ of the following form:

$$Q_+(q;w) = \Sigma w_i q_i \tag{1}$$

where w_i represents weight coefficient.

Weight coefficients are chosen from some final set:

$$\left\{ 0, \frac{1}{n}, \frac{2}{n}, ..., \frac{n-1}{n}, 1 \right\}. \tag{2}$$

N is a number of all possible choices of weight coefficients of set {0, 1/n, 2/n, …, (n – 1)/n, 1}, then:

$$N = \binom{n+m-1}{m-1} = \frac{(n+m-1)\,!}{n\,!(m-1)\,!} \tag{3}$$

where n is the number of sections, which is divided on a segment of 0 to 1. In this paper is applied segment divide 0-1 on 70 sections, and m – the starting number of attributes and specific criteria. In the considered case m = 4.

Exactness of an average general estimation $Q_+[q^{(j)}]$ of the jth object's preferability may be measured by the standard deviation:

$$S_j = S[q^{(j)};I] = \sqrt{\frac{1}{N(I;m;n)} \sum_{s=1}^{N(I;m;n)} \left\{ Q_+^{(s)}[q^{(j)}] - \overline{Q_+[q^{(j)}]} \right\}} \tag{4}$$

where: $|\{s:...\}|$ is the number of elements of the finite set $\{s:...\} \subseteq \{1, ... , N(I; m, n)\}$.

The synthesis function for general index sustainability (GIS) calculation is also used on second level of calculation. On this level, normalization of all indicators for each options and under conditions of pre-defined constrains that represent non-numerical information about interrelation between criteria were performed:

$$Q(q;I) = \frac{1}{N(I;m;n)} \sum_{s=1}^{N(I;m;n)} Q[q;w^{(s)}] \qquad w^{(s)} \in W(I, m, n) \tag{5}$$

where $Q\,(q, I)$ is the average value of GIS, q – the criteria, $N(I, m, n)$ – the number of elements of the set $W(m, n)$, w – the weight coefficient, $W(m, n)$ – the infinite set of all possible weight coefficients, m – the number of attributes (criteria), n – the positive integer, and I – the non-numerical and inexact information.

Sustainability analysis of the proposed options

In this paper, three cases are analysed (tab. 2) and based on them, GIS of each option are calculated by using ASPID method.

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Table 2. Indicators priority

	Social indicator > Environmental indicator = Economic indicator = Resource indicator
	Social sub-indicator importance
Case 1	$I_{\text{salary}} > I_{\text{employee}} > I_{\text{project in l.c.}} = I_{\text{injury on the work}} = I_{\text{sick-leave}} > I_{\text{safety of supply}}$
Case 2	$I_{\text{safety of supply}} > I_{\text{salary}} > I_{\text{employee}} > I_{\text{project in l.c.}} = I_{\text{injury on the work}} = I_{\text{sick-leave}}$
Case 3	$I_{\text{sick-leave}} > I_{\text{salary}} > I_{\text{employee}} > I_{\text{safety of supply}} > I_{\text{project in l.c.}} > I_{\text{injury on the work}}$

Between four indicators (resource preservation, economic, environmental, and social) presented in this paper, priority is given to social indicator while others are equal in importance. Each indicator contains sub-indicators, tab. 1. In all considered cases resource preservation, environmental and economic sub-indicators are equal in importance while importance of social sub-indicators are variable from case to case, tab. 2. In this way, calculated value of GIS for different cases can be compared and it is possible to see how social indicators affect GIS of each option. When the social indicator has the highest value of the weight coefficient ($w = 0.64$) and the environmental, economic and resource indicators have the value of the weight coefficient of 0.12, the priority list of the options are presented. The weight coefficients and their standard deviation have same values for each case, fig. 1.
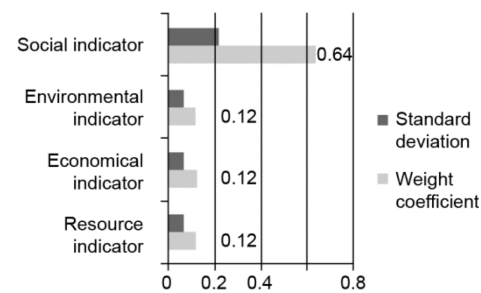

Figure 1. Weight coefficient and standard deviation

Figure 2. The GIS – Case 1

Multi-criteria analysis results – Case 1

Table 2 shows priority of social sub-indicators for case 1. By using multi-criteria analysis, GIS is calculated and values are shown in fig. 2.
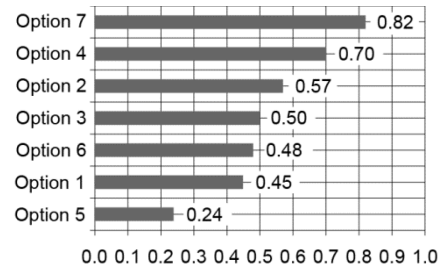
When priority is given to social sub-indicators of salary, I_{salary}, and employee, I_{employee}, the option 7 (photovoltaic) has the highest values of GIS, 0.82 and option 4 (co-combustion of coal and waste), 0.7, fig. 2) The lowest level of sustainability for Case 1 has Option 5 (gas-combusted).

Multi-criteria analysis results – Case 2

Figure 3 presents options ranked with respect to priority for social indicator in the case 2, tab. 2. For this case, the social sub-indicator of safety of supply has priority regarding sub-indicators of salary, employee, local community, injury on the work and sick-leave.

Option 4 (co-combustion coal and waste) has estimated as the best option as well as Option 1 (coal combustion in condensational regime) which is top of the priority list so that GIS have values of 0.79 and 0.72, respectively, fig. 3. At the bottom of the priority list is Option 5 (combined gas-steam facility) and Option 6 (electric energy from wind generators).
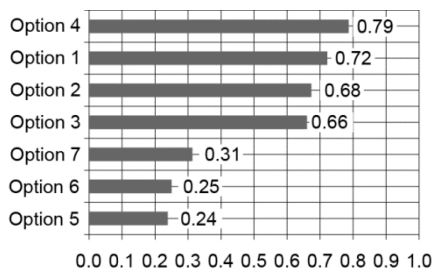
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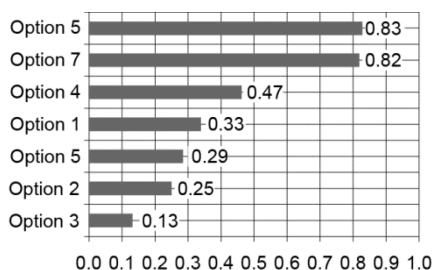Škobalj, P. D., *et al.*: Energy Indicators Impact in Multi-Criteria Sustainability …
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Figure 3. The GIS – Case 2

Figure 4. The GIS – Case 3

Multi-criteria analysis results – Case 3

In case 3, constraint were defined to give priority to the social indicator while economic, resource and environmental indicators have the same values of weight coefficients. In the process of agglomerations of the social sub-indicators according to the defined conditions, tab. 2, the following had priority: sickleave, $I_{sick\ leave}$, salary, I_{salary}, employee, $I_{employee}$, and safety of supply, $I_{safety\ of\ supply}$.

Figure 4 shows that Option 6 (electric energy from wind generators) and Option 7 (photovoltaic) have the GIS highest values: 0.83 and 0.82, respectively. Option 3 performs the worst on the priority list with GIS value of 0.13.

Conclusions

Making business decision or decision in general are among the most important and most delicate human activities. Most models designed for calculating best option are based on one criterion which becomes unacceptable. Muti-criterial analyse for assesment of sustainability of options of possible status of unit 2 TPP *Kolubara* by ASPID methodology is presented in in this paper. Selecting, defining, and quantifying appropriate energy indicators describe the quality of the considered options in terms of sustainability. Presented methodology is based on the determination of the GIS for the seven selected options (energy systems). Special priority is given to social indicators and their impact is leading through parameters which are used in multi-criteria analyse. Quality assessment of examined options using the GIS depends on proper choice of given priority to some of the weight coefficients. Subset of 14 sub-indicators is also formed. In this paper three cases were analysed. For each case was given priority to social indicator while social sub-indicators have different priorities. Options were ranked based on obtained value of GIS. Based on presented results it can be concluded that Option 4 (co-combustion of coal and waste matters), and Option 7 (production of electric energy from solar energy, photovoltaic) have highest values of general index of sustainability, in almost all cases while Option 5 (combined cycle gas-steam facility) has lowest GIS in almost all cases. This case study of the TPP *Kolubara A* shows recommendations to decision maker to choose best options if priority is given to social policy.

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