SUSTAINABILITY ASSESSMENT OF POWER PLANTS USING AN ANALYTIC HIERARCHY PROCESS

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ABSTRACT

This paper is focused on defining a sustainability assessment of power plants integrating different classes of indicators (selection criteria) in an Analytic Hierarchy Process (AHP) analyzing ten different basic power plants considered among the most affordable in the actual technical and social panorama considering fossil and nuclear fuels as well as renewable sources. The approach is based on different levels of criteria. Tangibles and intangibles are considered at first. Different depth of classes are considered in the proposed AHP framework in order to better face the different nature of the managed indicators. At the bottom of the tree appear the ten considered power plants options. The proposed approach has to be considered a sort of basic framework, a guidance for future applications requiring specific definition and management of data available in the explicit field considered where this methodology can turn into an useful tool for the assessment of energy system in the engineering practice. In this case, a further sensitivity analysis should be performed in order to best fit the model to the considered context.

Keywords: Sustainability, Analytic Hierarchy Process (AHP), Indicators, Sensibility Analysis.

1. Introduction

Evaluation of power plants according to several different criteria in order to meet sustainability has become a basic concern in modern industrial as well as ecological requirements. In this field the complexity of the considered energy systems requires multivariable assessment taking into account the overall performance of the power plants: the valorization of a power plant and its comparison to different options requires an updated approach considering different features concerning the individual design of the power plants as well as the capability of express an explicit estimate of their performance. In the following the authors proceed selecting an adequate set of power plants technologies and propose an AHP based approach with the aim of involve simultaneously a large variety of criteria considering technical, environmental, ecological and socio-economic aspects of the faced problem. Some criteria have been furtherly decomposed into sub-criteria to finally establish a hierarchical framework able to better face the different nature of the indicators managed.

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2. The context.

Focusing our interest on power plants systems, evaluation of sustainability involves a large number of criteria whose selection and comparative balancing can be developed referring to several frameworks depending on different factors considering also the geographic area in which the plants may be located. The power plant impact on the living standard has been investigated by Chatzimouratidis and Pilavachi (2007), (2008a,b).

Several other aspects have been considered for the overall assessment of different types of power plants: capacity (Pilavachi, Stephanidis, Pappas, Afgan 2009), efficiency (Beer, 2007), availability (Ogaji, Sampath, Singh and Probert, 2002) as well as maintenance (Wang 2007) for specific types of power plant. Chatzimouratidis and Pilavachi (2007) have proposed an evaluation of the influence of non-radioactive emissions released into atmosphere using an AHP-based approach. Different studies on multi-criteria assessment of energy power plants (Afgan and Carvalho, 2001) have been considered in the scientific literature. The aim of the present paper is to propose a multicriteria decision making assessment which incorporates and integrates specific performance indicators different for nature (technological, social, economic and quality). The authors suggest also a global indicator of the type more is better which helps decision makers to rank selected power plants in terms of sustainability.

3. Alternatives and indicators selection.

In this paper the authors develop a sustainability analysis of ten types of power plants. Coal/lignite, oil, natural gas turbine (NGT) and natural gas combined cycle systems (NGCT) are compared to five different renewable energy power plants and the nuclear power plants are also included. The aim of the study is to balance the performance of systems against two basic criteria: tangible and intangible factors. Tangible factors comprise technological and economic criteria which are decomposed into different types of sub-indicators. Intangible factors integrate quality and social indicators to incorporate the impacts of selected alternatives on living standards. Technology and sustainability of power plants are assessed among 4 different sub-indicators. The system with the highest value of each indicator represents the alternative with the best performance in term of sustainability. Efficiency characterizes the ratio of output to input energy and it is expressed in % terms. The authors consider the electrical energy as useful output obtained from power sources. The ratio between the quantity of time that a power plant is able to produce electricity over a specific time horizon and the amount of time in the period point outs the availability of the system. It is expressed as a percentage. The capacity (%) is the ratio between the total electricity produced by a plant over a period and the amount of electricity which it could produce if the system should run at full time. The availability refers to the time while the capacity considers the amount of electricity produced. The reverse-to-production ratio (R/P) indicates the availability, expressed in terms of years, of a specific fuel according to the real consumption and the annual utilization increase/decrease rate of each non-renewable energy source for electric power generation. The economic indicator is decomposed into 5 specific sub-indicators and the power plant with the highest value of each factor is the best one in terms of economic performance. Installation costs (capital costs) include the land, construction and equipments costs. They don't incorporate labor and maintenance cost. The operation and maintenance costs (O&M) comprise the labor costs and energy costs for the power plant operation. They are classified into fixed and variable costs: the fixed ones are related to the costs per year not dependent by the quantity of electricity produced; variable costs are directly related to the amount of electricity. Fuel costs indicate the found spent for the supply of raw material essential for system operation. They incorporate the costs of waste produced by fuel processing, extraction and transportation. The economic indicators include the electricity and the external costs. External costs incorporate the cost of negative quantifiable impacts of power plant activities on the human health and environment. In particular, they represent the funds paid for the restoration of negative impacts of systems on human health and ecosystem and they are calculated based on the life cycle external costs of power plants (OECD, 2003). The evaluation procedure has been developed collecting and adequately integrating data from current technical and scientific literature, as well as, experts judgments Table 1 shows data associated to technological and economic indicators

Table 1. Technological and economic indicators (Chatzimouratidis and Pilavachi 2008a and 2008b)

Plant	Capital €/kW	Fuel €cent/kWh	Variable O&M €cent/kWh	Fixed O&M €cent/kWyr	External €cent/kWh	Electricity c/kWh	Efficiency %	Availability %	Capacity %	R/P Year
Coal/lignite	975	1,31	0,183	19,00	8,40	5,4	39,4	85,4	70,8	164,0
Oil	483	1,84	0,233	6,25	6,75	5,0	37,5	92,0	26,2	40,5
NGT	612	2,34	0,27	10,83	2,00	4,0	39,0	91,0	16,6	66,7
NGCT	587	2,34	0,233	10,00	1,33	4,0	54,8	91,0	38,2	66,7
Nuclear	1.590	0,27	0,033	30,00	0,49	4,0	33,5	96,0	90,5	70,0
Hydro	2.417	0,00	0,486	72,5	0,56	8,0	80,0	50,0	29,6	Infinite
Wind	1.250	0,00	0,417	25,00	0,16	7,0	35,0	38,0	32,1	Infinite
Photovoltaic	4.167	0,00	1,667	16,67	0,24	75,0	9,4	20,0	22,4	Infinite
Biomass	1.667	2,05	0,708	60,83	2,65	14,0	28,0	80,0	70,0	Infinite
Geothermal	2.158	0,00	0,025	83,33	0,20	8,0	6,0	95,0	82,5	Infinite

The incidence of intangible factors on the sustainability of power plants has been evaluated. The quality indicator is decomposed into 5 different types of sub-indicators and the power plant with the lower value of these indicators is the best ones in term of performance. Radioactivity indicates the amount of uranium, radium and thorium or the quantity of radioactive gases released into atmosphere by power plants. Land requirement measures the area occupied by power plant and it includes the land required for fuel production. On the other hand, the sub-indicator area includes the ratio between area and installation capacity. Decision makers may consider the incidence of non-radioactive emissions on the goal developing a subjective and objective assessment. The objective assessment is expressed in terms of price for each kilogram of specific selected substance released in the atmosphere above a predefined limit (Chatzmouratidis & Pilavachi, 2007). Price is an external cost caused by systems in the EU-15 during their life cycle, including construction, decommissioning and fuel supply. The subjective assessment is based on subjective judgments concerning the damage caused by the emissions of non-radioactive substance to human health and environment. The non-radioactive substances selected in this paper are: non-methane volatile organic compounds (NMVOCs), carbon dioxide (CO_2), nitrogen oxide (NO_X), sulphur dioxide (SO_2), particular matter (PM). The substances are related to power plants in terms of amount released into atmosphere expressed as mg/kWh. Accident fatalities refer to lost lives of workers and public over the period from 1970 to 1992. The authors consider the normalized number of lost lives for each type of power plant over that period. In order for the figures to be comparable, deaths of workers and public for that period are measured for each TW of established power for each type of power plant per year. Social indicator is decomposed into 3 different sub-indicators. Job creation indicates the new employees related to 500 MW. Compensation rate shows the recompense give to the social community influenced directly by the installation and operation of systems. In this paper it is considered as a benefit and it is calculated on the base of external costs of power plants. Job creation and compensation rate are a measure of positive influence of power plants on people’s living standards. In this study the social acceptance is a qualitative criterion and decision makers express their judgments using the Saaty’s scale

Table 2. Saaty’s scale.

Importance intensity	Definition	Meaning (A compared with B)
1	Equal importance	A is equally important to B
3	Moderate importance	A is moderately more important than B
5	Strong importance	A is strongly more important than B
7	Very strong importance	A is very strongly more important than B
9	Extreme importance	A is extremely more important than B

Table 3 shows available data referring to quality and social indicators. Table 4 contains the available data referring to subjective and objective assessment of non-radioactive emissions and Table 5 shows pair-wise comparisons for social acceptance indicator.

Table 3. Quality and social indicators (Chatzimouratidis and Pilavachi 2008c and 2008d)

PLANT	LAND	AREA	NMVOC	CO	NOX	SO_2	PM	Job creation	Compe. rate
	km^2/1000MW	km^2/kW	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	New-employees/500 MW	eurocents/kWh
Coal/lignite	2,5	0,40	24	986.000,00	2.986,00	16.511,00	347	2.500,00	8,40
Oil	2,5	0,30	18	1.131.178,00	5.253,00	81.590,00	128	2.500,00	6,75
NGT	2,5	0,04	118	560.000,00	1.477,00	152,00	34	2.460,00	2,00
NGCT	2,5	0,04	118	450.000,00	756,00	152,00	6	2.460,00	1,33
Nuclear	2,5	0,01	0	21.453,00	51,00	27,00	2	2.500,00	0,49
Hydro	750,0	0,13	0	22.696,00	23,00	33,00	5	2.500,00	0,56
Wind	100,0	0,79	0	17.652,00	32,00	54,00	20	5.635,00	0,16
Photovoltaic	35,0	0,12	70	49.174,00	178,00	257,00	101	5.370,00	0,24
Biomass	5000,0	5,20	80	58.000,00	1.325,00	76,00	269	36.055,00	2,56
Geothermal	18,0	0,03	0	18.913,00	280,00	20,00	0	27.050,00	0,20

Table 4. Subjective and Objective assessment for non-radioactive emissions (Chatzimouratidis and Pilavachi, 2007)

Emission	Subjective		Objective
	Human health damage %	Environmental damage %	Costs €/kg
NMVOC	20	0	1.124,00
$CO_{2\text{-eq}}$	0	70	0,02
NO_X	20	15	3.054,00
SO_2	10	15	3.442,00
PM	50	0	14.698,00

Table 5. Pair-wise comparisons related to social acceptance for power plants (Chatzimouratidis and Pilavachi 2008c and 2008d)

	Coal	Oil	NGT	NGCT	Nuclear	Hydro	Wind	Photo.	Biomass	Geoth.
Coal	**1,00**	1,00	0,33	0,20	3,00	0,33	0,20	0,20	0,33	0,20
Oil	1,00	**1,00**	0,33	0,20	3,00	0,33	0,20	0,20	0,33	0,20
NGT	3,00	3,00	**1,00**	0,33	3,00	0,33	0,20	0,20	0,33	0,20
NGCT	5,00	5,00	3,00	**1,00**	5,00	0,33	0,20	0,20	0,33	0,20
Nuclear	0,33	0,33	0,33	0,20	**1,00**	0,20	0,11	0,11	0,20	0,11
Hydro	3,00	3,00	3,00	3,00	5,00	**1,00**	0,33	0,33	3,00	0,33
Wind	5,00	5,00	5,00	5,00	9,00	3,00	**1,00**	3,00	3,00	1,00
Photo.	5,00	5,00	5,00	5,00	9,00	3,00	0,33	**1,00**	3,00	1,00
Biomass	3,00	3,00	3,00	3,00	5,00	0,33	0,33	0,33	**1,00**	0,33
Geoth.	5,00	5,00	5,00	5,00	9,00	3,00	1,00	1,00	3,00	**1,00**

Data reported in tables 3-4-5 are not directly related because managed in different branches of the AHP tree-based logical structure.

4. Analytic Hierarchy Process in sustainability analysis.

In order to assess the performance of power plants, an adequate hierarchy of evaluation factors has been defined for the application of AHP. Top level encloses the goal of the analysis: the assessment of sustainability of the 10 power plants. Level 2 comprises the two basic criteria. Tangible factors are decomposed in technology and sustainability (T&S) and economic indicators; intangible factors incorporate quality and social indicators. The macro-categories of indicators are located at the third level of the hierarchy. The fourth level of the tree encloses the specific indicators selected. At the bottom are located the power plants selected by decision makers: coal/lignite (1), oil (2), natural gas turbine (3), natural gas combined cycle (4), nuclear (5), hydro (6), wind (7), photovoltaic (8), biomass (9) and geothermal (10). Figure 1 shows the hierarchy tree.

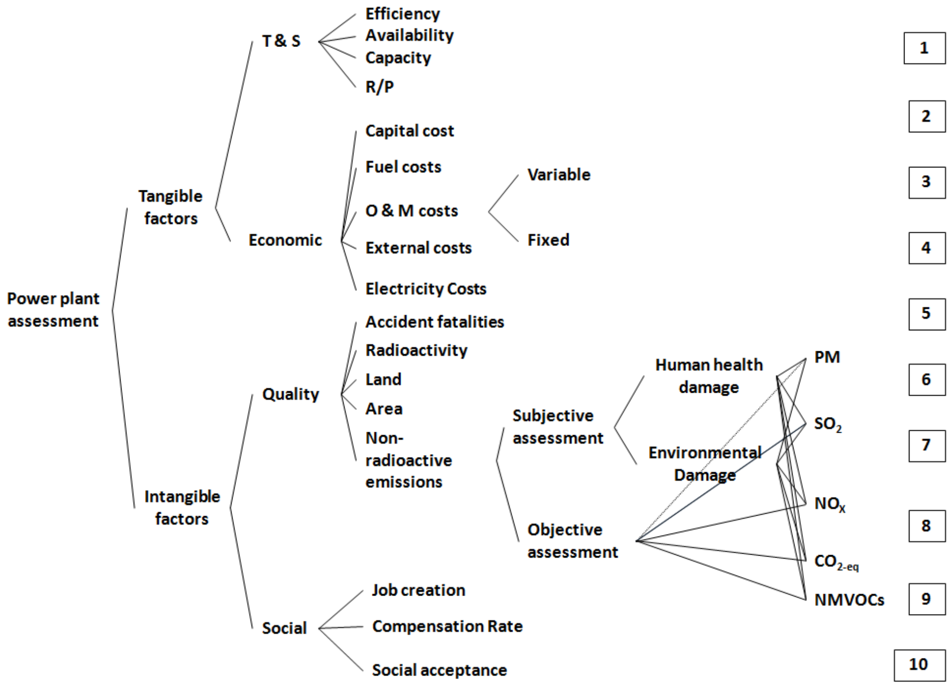

Figure 1. Hierarchy tree

To evaluate the incidence of selected power plants on the goal, decision makers calculate criteria and sub-criteria weights subjectively by pair-wise comparison of the elements located at the same level of the hierarchy. They set the local weights of tangible and intangible factors at 50% and they assign equal local importance to the macro-categories of indicators (T&S 50%, economic 50%, quality 50% and social 50%). They set efficiency, availability, capacity and R/P at 25%; capital, fuel, external, O&M and electricity at 20%; fatalities, radioactivity, land, area and non-radioactive emissions at 20%; job creation, compensation rate and social acceptance at 33,33%. Variable and fixed O&M costs have equal importance therefore the local weight is 50%. Equal incidence (50%) is attributed to subjective and objective assessment and to human health and environmental damage. To achieve the local weights of specific pollutants, with the respect of objective assessment, decision makers use data reported in Table 4 and they develop pair-wise comparisons obtaining following incidences: NMVOCs 25%, CO_2 50%, NO_X 11%, SO_2 11% and PM 3%. By implementing AHP, the authors have obtained following local weights whit the respect of human health damage: NMVOCs 11%, CO_2 50%, NO_X 11%, SO_2 25% and PM 3%. The incidence of emissions with the respect of environmental damage is: NMVOCs 35%, CO_2 3%, NO_X 14%, SO_2 14% and PM 35%. Decision makers give more importance to the pollutants with the lower price. In the same way, the authors assign more relevance to emission with the lower percentage referring to human health and environmental damage. Decision makers calculate the inconsistence of each pair-wire comparison matrix and they verify that the value of consistency ratio value is < 10%. Implementing the AHP-based approach, decision makers achieve the overall weights of power plants reported in Figure 2.

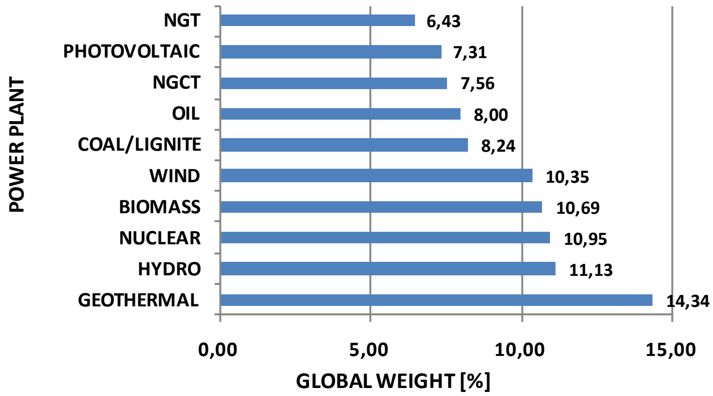

Figure 2. Global weights of power plants

Geothermal plants are the most sustainable with a score of 14,34%. Hydro, nuclear, biomass and wind totalize a weight of about 10%. A score around 8% is reached by coal/lignite and oil power plants and NGCT, photovoltaic and NGT obtain a score below 7,6%.

Conclusion

The evaluation of 10 types of power plants with regard to their sustainability was carried out by the application of the AHP. The assessment of selected systems depends on several criteria and the authors have proposed different tangible and intangible factors, technological, environmental, social and quality, to compare and evaluate performance of power plants considering coal/lignite, oil, natural gas turbine, natural gas combined cycle and nuclear against five different renewable energy systems. Further developments will concern a sensibility analysis with the aim to evaluate specific scenarios achieved modifying the weights of criteria and sub-criteria represented into the proposed hierarchy tree. Scientific literature proposes a review on multi-criteria decision making to resolve sustainability problem, integrating the AHP approach with Fuzzy logic and to classify sustainability indicators (Wang J. J, You-Yin Jing, Chun-Fa Zhang, Jun-Hong Zhao, 2009)

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