

SUSTAINABILITY ASSESSMENT OF HYDROGEN ENERGY SYSTEMS USING AN ANALYTIC HIERARCHY PROCESS

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ABSTRACT

The aim of the proposed paper consists in defining an Analytic Hierarchy Process (AHP) able to integrate different classes of indicators (selection criteria) in order to assess the sustainability of five basic energy systems. The criteria (market, performance, environmental and social indicators) are located at the second level of hierarchy tree proposed and they are decomposed in specific sub-indicators which represent the sub-criteria situated at the third level. At the bottom of the tree appear the five alternatives selected and compared: phosphoric acid fuel cells (PAFC), solid oxide fuel cells (SOFC), natural gas turbine (GT), photovoltaic (PV) and wind energy systems (WE). Reference data used to perform the evaluation procedure have been collected and integrated from current technical and scientific literature. A sensitivity analysis allows the evaluation of different scenarios by changing, step by step, the relative perceptual importance of criteria and sub-criteria.

Keywords: Sustainability, Analytic Hierarchy Process (AHP), Indicators, Sensitivity 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. The complexity of the considered energy systems requires multivariable assessment taking into 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 (Afgan and Carvalho, 2000 and 2003).

2. Selection of option of energy system

Focusing our interest on hydrogen systems, a comparison between hydrogen-based and different new and renewable energy systems is developed in this paper selecting a number of meaningful options referring to a set of indicators significant for the assessment of the considered systems. In selecting appropriate options, the following systems will be considered: phosphoric acid fuel cells (PAFC), solid oxide fuel cells (SOFC), natural gas turbine system (GT), photovoltaic system (PV) and wind energy system (WE).

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PAFCs are in 'commercial' production since more than 20 years ago with typical sizes of 400-500 kilowatts of electricity and 1,700,000-2,000,000 Btu per hour of heating. Overall efficiency considering also heat production can be about 90%. Emissions can be considered in the following specific values: NO_x: 0.035 lb/MWh (0.016 kg/MWh); CO: 0.008 lb/MWh (0.004 kg/MWh); CO₂: 1120 lb/MWh (508 kg/MWh); SO_x Particulate matter / VOCs are negligible. PAFC use a platinum catalyst: at 10% to 15% of the current installed costs of a PAFC power plant, causing costs for the PAFC power plants remain above \$4,000/kW (Fuel Cells, 2000)

SOFC cells use a solid oxide material as the electrolyte to conduct negative oxygen ions from the cathode to the anode. SOFCs operate at very high temperatures, 500-1,000°C, thus not requiring expensive platinum catalyst material, as is currently necessary in PAFCs. Solid oxide fuel cells have a wide variety of applications from use as auxiliary power units in vehicles to stationary power generation with outputs from 1kW to 2 MW range allowing for flexibility in service for commercial users providing also heat for space heating and hot water. DOE target requirements are 40,000 hours of service for stationary fuel cell applications at a factory cost of about \$400/kW for a 10 kW coal-based system (NETL's Fuel Cells Webpage) without additional requirements. Lifetime effects (phase stability, thermal expansion compatibility, element migration, conductivity and aging) must be addressed. The Solid State Energy Conversion Alliance 2008 (interim) target for overall degradation per 1,000 hours is 4.0 percent (Fuel Cell Stacks Still, 2009).

GT fueled with natural gas consist mainly of large-scale simple-cycle and combined-cycle gas turbine power plants followed by smaller Distributed Generation (DG) systems. Industrial GT range in size from truck-mounted mobile plants to very large and complex stationary systems. In this comparison a simple GT system is considered in order to prevent advantages obtained by additional complexity of the energy system: the total efficiency of the system is $\eta=0,47$ with an inlet temperature of about 850-900°C.

Solar-PV farms today range from 10-60MW up to 150 MW (Jacobson M.Z., 2009). Between 2004 and 2009, PV capacity increased at an annual average rate of 60% to about 21 GW, a tiny fraction of the 4800 GW total global power-generating capacity from all sources (REN21, 2010). The capacity considered for the decentralized electric solar plant ranges from a Min of 30 kW to Max<5000 kW.

The WE system considered in this comparison concerns the horizontal-axis wind turbine which represent approximately 95% of the capacity installed in the wind plants (REN21, 2010).

3. Indicator selection

Four basic indicators (Afgan and Carvalho, 2004) are considered for the sustainability assessment performed in this paper: performance, market, environmental and social indicators. The performance indicator is decomposed into 4 different sub-indicators namely, efficiency, total energy cost, capital cost and lifetime. Efficiency of the system considers all conversion processes from energy resource to the end-use resource. The electricity costs represent the costs of energy production and they include fuel cost, capital cost and maintenance cost. Capital cost measures the investment per unit energy produced in the lifetime of the system and it comprises the material cost of the system including development, design and construction cost of the system. Lifetime represents the maturity of the system. The market indicator provides a measure of the market penetration in the Europe and world scale in the next 10 years. Environmental referred indicators regard: CO₂, NO_x and Kyoto indicator. CO₂ and NO_x refer to the respective concentration in flue gases. Kyoto indicator reflects the contribution of the respective systems to the Kyoto Protocol specific limit. Social indicator considers 2 different sub-indicators: area, which represents the land occupied per kW of power installed, and new job, which indicates the number of paid hours per kWh produced in lifetime. Indicators are reported in Table 1

Table 1. Sustainability indicators.

Name	Definition	Unit
Efficiency	Carnot Efficiency	%
Electricity cost	Electric energy cost per unit kWh	Euro/kWh
Capital cost	Capital cost per unit kWh	Euro/kWh
Lifetime	Lifetime of the plant	Years
European market	Number of GW per next 10 years	GW/10 years
World market	Number of GW per next 10 years	GW/10 years
CO ₂	CO ₂ concentration	Ppm
NO _x	Nitrogen oxide	Ppm
KYOTO	Contribution to Kyoto limits	%
Area	Area per kW installed power	M ² /kW
New job	Number of paid hours per kWh produced in lifetime	h/kWh

4. Decision making in sustainability analysis.

Multi Criteria Decision Making (MCDM) is required to solve complex problem of sustainability of systems and obtain a compromise between several and conflicting criteria. The MCDM AHP-based approach, proposed by Saaty (Saaty 1980) requires the decision makers to implement the following steps: 1) define the problem and determinate the purpose; 2) structure a decision hierarchy in which at the top level compare the goal of the assessment. Criteria and sub-criteria are located at intermediate levels and the lowest level considers the alternatives analyzed; 3) construct a set of pair-wise comparison matrices containing subjective judgment about the relative importance of the elements (criteria and sub-criteria) located on the same level of hierarchy. In this way decision makers obtain the local weigh of the elements assessed by the comparison matrix; 4) use the priorities obtain by the comparison to determinate the global weight which represents the influence of the alternatives selected on the goal. Decision makers express subjective judgments according to the Saaty's scale (Table 2).

Table 2. Saaty's scale

Importance intensity	Definitio n	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

5. AHP-based approach.

In order to assess the performance of energy systems, an adequate hierarchy has been defined for the application of AHP. Top level encloses the goal of the analysis: the assessment of sustainability of the 5 energy systems. Level 2 comprises four different basic criteria: market, performance, environmental and social indicators, decomposed into different sub-indicators located at the third level of the hierarchy tree. The alternatives assessed appear at the lowest level of the hierarchy: PAFC, SOFC, GT, PV and WE. Criteria weights are calculated subjectively by pair-wise comparison of the elements located at the second level of the hierarchy and, initially, indicators are set to equal importance: 25%. In the same way, the relative importance of sub-criteria selected is set at 50% for market and social sub-indicators; 33,33% for environmental and 25% for performance sub-indicators. Hierarchy tree is represented in Figure 1.

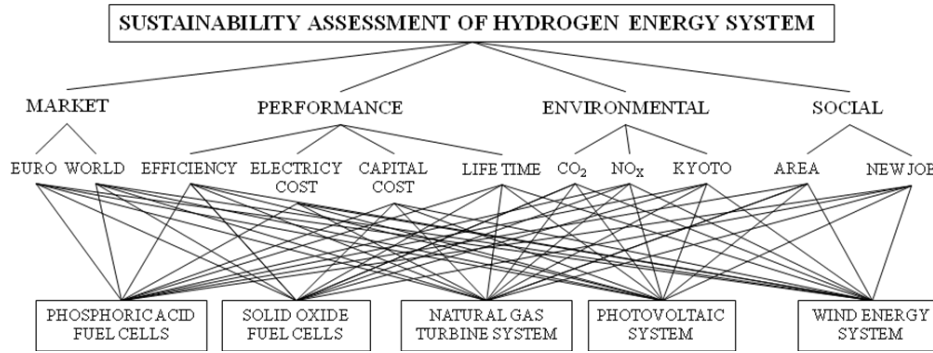


Figure 1. Hierarchy tree

The overall evaluation of energy systems analyzed is obtained using data reported in Table 3. Results of analysis are in Figure 2

Table 3. Available data to assess the sustainability of alternatives (Afgan, Carvalho, 2004).

Option	Efficie. %	Electric €/Kwh	Capital €/Kwh	Lifetime Years	Euro GW	World GW	NO _x ppm	CO ₂ ppm	Ky %	Area m ² /kW	New job h/kWh
PAFC	40	0,41	1550	5	2	40	1	4	0,1	3	4
SOFC	46	0,35	4500	7	0,5	15	0,5	3,5	0,3	5	1,5
GT	35	0,035	750	20	100	2000	3,5	1,5	20	2	300
PH	25	0,03	5000	15	1,8	11	0	0	0,3	9	15
WE	45	0,06	1000	15	60	160	0	0	0,32	2,5	3

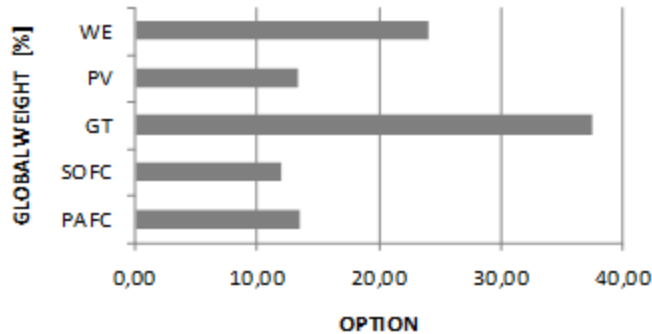


Figure 2. Incidence [%] of system on overall sustainability.

With a score of 37,43% GT reveal as the most sustainable systems followed by the wind energy systems with a score of 24,05%. PAFC and PV get a 13 score % while SOFC get a 11,92% score.

6. Sensitivity analysis.

Sensitivity analysis is a able to evaluate the influence of changing criteria ad sub-criteria weights on the results obtained by AHP-approach based. When the assessment procedure is subjective or a large uncertainty affects the faced problem, several different cases should be examined. In this paper, a sensitivity analysis is developed to evaluate the results variation when the weights of criteria and sub-criteria may change according to the evaluation criteria. Initially criteria and sub-criteria have the same relative importance. In the first scenario the authors, step by step, set 100% of importance to each criteria.

Euro and Market have 50% of importance; efficiency, electricity, capital and life time 25%; CO₂, NO_x and Kyoto 33,33%; Area and newjob 50%. The results obtained are showed in Figure 3

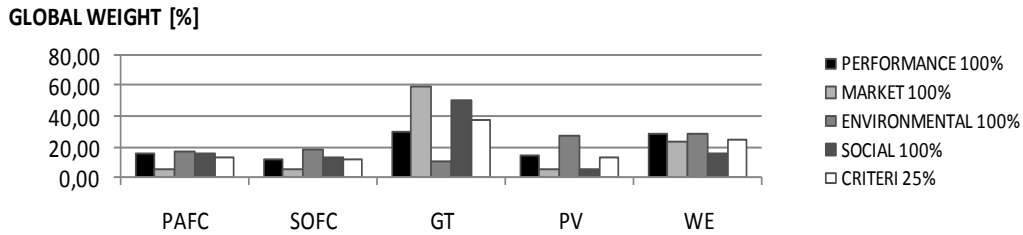


Figure 3. Influence [%] of alternative changing criteria weights.

When decision makers set 100% of relative importance to performance criteria, GT carry out a 30,09% score and the best performance in term of sustainability. WE reach a score of 28,73%. Also, PAFC and PV scores achieve respectively 14,40% and 15,55%. SOFC reach the worst performance at 11,20%. GT achieve the best performance (59,54%) when market indicators are set at 100%. WE achieve 23,39% while other systems weights reach 5,69%. If environmental indicators are set at 100% of importance, WE and PV achieve similar significance (27%) followed by SOFC at 17,91%. PAFC reach third place at 16,86% while GT get 9,97%. GT reach the best performance (50,11%) when social indicators are set to 100%. In this case WE, SOFC and PAFC scores range between 12,80% and 16,12%. PV reach the worst performance at a score of 5,43%.

Figure 4 shows results obtained when decision makers assign 100% of importance to performance criteria and, step by step, they change the value of relative sub-criteria. Figure 4 also reports the case in which the environmental criteria have the 100% of importance and the value of its sub-indicators are changed.

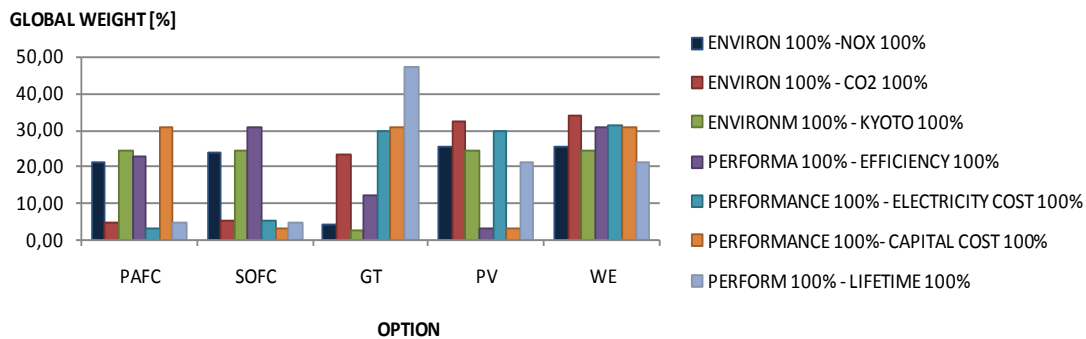


Figure 4. Incidence [%] of option

When decision makers set performance and efficiency at 100%, SOFC and WE show the best performance with a score of 30,91% while PAFC reach 23,06%. A score around 30% is reached by GT, PV and WE, when electricity costs are set at 100%. If 100% of the local importance in attributed to capital costs, PAFC, GT and WE reach similar value of score. Setting lifetime score to 100%, GT are the best systems with a score of 47,20% while PV and WE follow with a score of 21,35%. Considering the different combination of criteria and sub-criteria reported in figure 4, the all alternatives obtain a score below 12%. When decision makers set 100% of importance to environmental criteria and to CO₂ sub-criteria, PV and WE get a weight of about 30%. A score between 21,00 and 25,5% is achieved by PAFC, SOFC, PV and WE when decision makers give the 100% of importance to NO_x and to Kyoto; GT reach a very low 4%. Cases with scores below 6% are not subject to further attention.

Figure 5 shows results obtained when decision makers set 100% of importance to social criteria and, step by step, they change the value of relative sub-criteria. In the same Figure is reported the case in which the market criteria has the 100% of importance and authors changes the value of its sub-indicators.

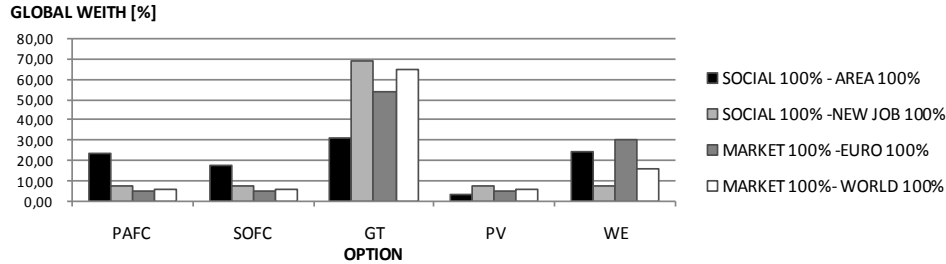


Figure 5. Incidence of alternatives when Market criteria and Social have 100% of importance

In every case GT have the best performance in sustainability assessment: when 100% of importance is set to both social criteria and new job sub-criteria, GT get 69,23% on the overall assessment and other systems perform 7,69%. When the authors set 100% of importance to market criteria and world sub-criteria, GT have a global weight of 65,10% and the other systems have a score below 11%. GT have an influence of 53,97% when the 100% of relative importance of criteria is set to market and Euro sub-criteria has a weight of 100% (in this case WE have a score of 30,62% and the others system are below 5,14%). GT occupy the first place of the rank (30,98%) also when decision makers give 100% of importance to social criteria and area sub-criteria. In this case WE, PAFC and SOFC get a score between 18% and 25%. In this scenario, the systems with the worst performance are PV with a score of 3,17%

7. Conclusion.

A critical difficulty in assessing performance of complex industrial systems may be focused on the capability of expressing a single estimation measure, as well as considering a multiple set of parameters, according to an “engineering” approach. Such a task may be even more complex to face when intangible factors have to be estimated in order to define a standard evaluation criteria useful for technicians as well as for social decision makers. AHP is an optimal tool to employ in such a context. In this paper the authors have proposed an AHP approach to compare and evaluate performance of energy systems. The analysis has been developed considering also a sensitivity analysis in order to provide several feasible scenarios to decision-makers. Further developments will concern a more complex approach considering a Fuzzy-AHP based method, able to face a more complex variability of performance factors and a more detailed scenario referred to an enlarged variety of the systems subject to comparison.

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