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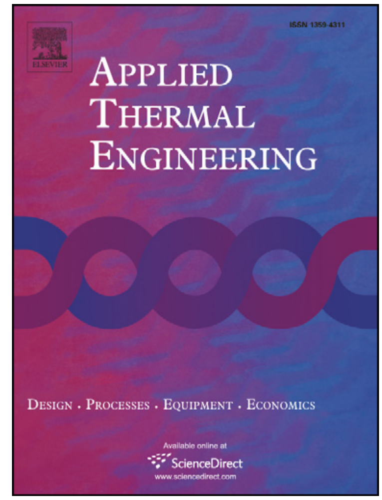

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Multi-criteria evaluation of hydrogen and natural gas fuelled power plant technologies

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Abstract

This paper evaluates nine types of electrical energy generation options with regard to seven criteria. The options use natural gas or hydrogen as a fuel. The Analytic Hierarchy Process was used to perform the evaluation, which allows decision-making when single or multiple criteria are considered.

The options that were evaluated are the hydrogen combustion turbine, the hydrogen internal combustion engine, the hydrogen fuelled phosphoric acid fuel cell, the hydrogen fuelled solid oxide fuel cell, the natural gas fuelled phosphoric acid fuel cell, the natural gas fuelled solid oxide fuel cell, the natural gas turbine, the natural gas combined cycle and the natural gas internal combustion engine.

The criteria used for the evaluation are CO_2 emissions, NO_X emissions, efficiency, capital cost, operation and maintenance costs, service life and produced electricity cost.

A total of 19 scenarios were studied. In 15 of these scenarios, the hydrogen turbine ranked first and proved to be the most preferred electricity production technology. However since the hydrogen combustion turbine is still under research, the most preferred power generation technology which is available nowadays proved to be the natural gas combined cycle which ranked first in five scenarios and second in eight. The last in ranking electricity production technology proved to be the natural gas fuelled phosphoric acid fuel cell, which ranked in the last position in 13 scenarios.

Keywords: Power Generation; Hydrogen; Natural gas; Analytic Hierarchy Process; Single-criterion analysis; Multi-criteria analysis

1. Introduction

Clean, low-cost power generation; these are the trends of the energy market today, in a highly competitive environment with rising environmental concerns. Concepts like energy policy and green house gas emissions reduction, that used to exist in scientific discussions only, are now already a part of the national and international political scene. The warnings of the scientific community are now been taken into consideration and have a permanent place in conferences relevant to energy and the environment.

The increasing world power consumption, over 80% of which is generated by means of fossil fuel combustion processes, has raised the CO_2 concentration in the atmosphere more than 30% above the level of the pre-industrial era [1]. Expected demand for electricity would require during the coming two decades the installation of as much power generation capacity as was installed in the entire 20th century [2]. Considering this, the world community has

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already taken measures to reduce CO_2 and other green house gas emissions. Such reductions are possible by developing more efficient technologies, using renewable energy sources and utilizing new, cleaner fuels.

Natural gas is a widely used fossil fuel that is cleaner than coal and petrol. There is abundance of natural gas and its utilization is constantly increasing in the last 50 years [3]. Power plants that utilize natural gas have significantly lower emissions than other fossil fuel plants.

Hydrogen on the other hand, is viewed as the fuel of the future and has been recently gaining a lot of attention. A great number of studies have been carried out concerning issues to be addressed in order to facilitate the introduction of hydrogen in the energy balance [4]. Alternative fuels including hydrogen-enriched fuels were studied for use in power generation [5]. The effect of hydrogen injection as additional fuel in gas turbine combustors was evaluated [6]. Power plants that utilize hydrogen could potentially have absolutely zero emissions. However, hydrogen is more of an energy carrier than a fuel (because its production requires energy) and hydrogen technologies cannot yet be considered mature and are relatively more expensive.

This paper uses the Analytic Hierarchy Process (AHP) methodology to evaluate different power plant technologies that use natural gas or hydrogen as a fuel using economic, environmental and technological criteria. The AHP is a common tool for single- and multi-objective decision-making problems and has the ability to simplify complex problems. In the past, the AHP has been used before in several studies to evaluate power generation plant technologies, such as the evaluation of power plants with regard to their non-radioactive emissions [7] and with regard to the impact on the living standard [8]. It has also been used to perform a comparison between conventional and renewable power technologies [9] and to make a sustainability comparison of fuel cell systems SOFC, PAFC, MCFC with respect to environmental, societal and economic impacts [10]. Methods other than AHP have also been used in the past to evaluate power plants. A multi-criteria evaluation of plants that produce hydrogen and use it as a fuel was presented [11] and a sustainability assessment of the phosphoric acid and solid oxide fuel cells was carried out and then compared with new and renewable energy systems [12].

2. Description of Power Technologies

Nine different energy generation options were selected for evaluation. It should be noted that there are differences in the levels of maturity of the technology of these options. Therefore the data on emerging technologies may be preliminary and less reliable than the data of more mature technologies. However, it is interesting to see how upcoming and developing technologies perform compared to mature and established ones. It should also be noted that for the hydrogen options under consideration, it is assumed that hydrogen is supplied through a distribution network and is not produced on site. Below follows a brief description of these options.

2.1. Hydrogen combustion turbines

In the recent years, there is an effort to build hydrogen fuelled turbine power plants and companies are funded to study such technologies. Toshiba is currently developing a hydrogen combustion turbine under the Japanese World Energy Network research program (WE-NET). Toshiba’s technology uses combustion chambers to burn hydrogen with pure oxygen in order to produce steam (H_2 + ½ O_2 = H_2O). The steam is then used in steam turbines to produce work.

2.2. Hydrogen internal combustion engines

Hydrogen internal combustion engines (H_2 ICE) operate under the same principles as all reciprocating internal combustion engines. Due to hydrogen's properties, H_2 ICEs are generally more efficient.

2.3. Hydrogen fuelled phosphoric acid fuel cells

Phosphoric acid fuel cells (PAFC) are chemical energy conversion devices. They directly convert the chemical energy of a fuel into electricity. Hydrogen fuelled PAFCs are fed with pure hydrogen and thus have no need for a fuel reformer. This lowers their capital as well as operation and maintenance (O&M) costs, makes them more efficient and extends their service life.

2.4. Hydrogen fuelled solid oxide fuel cells

As above, solid oxide fuel cells (SOFC) directly convert the chemical energy of a fuel into electricity. SOFCs fed with pure hydrogen have lower capital and operation and maintenance costs and are more efficient.

2.5. Natural gas fuelled phosphoric acid fuel cells

Natural gas fuelled PAFCs operate the same way like the hydrogen fuelled ones. Natural gas fuelled PAFCs are mainly comprised of the energy conversion unit (fuel cell) and a fuel reformer. Natural gas is fed into the fuel reformer and is converted into a hydrogen rich gas, which is then fed in the energy conversion unit.

2.6. Natural gas fuelled solid oxide fuel cells

SOFCs can operate on a variety of fuels, including natural gas, without the need of an external fuel reformer (unlike PAFCs). The fact that they operate at high temperatures (600-1000^oC), allows SOFCs to reform fuels into hydrogen rich gases internally, eliminating the need for a complex reformer. Only a simple reformer is required to remove impurities from the fuel.

2.7. Natural gas turbine

Natural gas turbines (NG turbines) burn natural gas with compressed air to produce high temperature and pressure exhaust gasses, which rotate a turbine. The turbine produces work which is used to rotate the air compressor and to power an electrical generator.

2.8. Natural gas combined cycle

Natural gas combined cycle power plants combine gas and steam turbine technologies. They utilize the waste heat of a natural gas turbine to produce steam, which rotates a steam turbine in order to produce additional energy. Other arrangements are possible as well.

2.9. Natural gas internal combustion engine

Natural gas internal combustion engines (NG ICE) burn natural gas in a combustion chamber (cylinder) to produce thermal energy. The thermal energy is then converted into work through an array of appropriate components.

3. Overview of the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a structured tool that helps the user deal with complex decisions. It is based on mathematics and human psychology and was developed by Thomas L. Saaty in the 1970s [13].

In the first step of the process, a hierarchy is built by analyzing the problem into a goal, criteria and decision alternatives. In the next step, each decision alternative is evaluated with regard to each criterion. After that, each criterion is given a numerical weight representing the importance of the criterion. In the last step of the process, numerical values are calculated for each decision alternatives. These values represent the ability of each alternative to achieve the decision goal.

4. Description of criteria

The criteria used for the evaluation of the selected energy production technologies are efficiency, CO_2 emissions, NO_X emissions, capital cost, operation and maintenance costs (O&M costs), electricity cost and service life. All criteria data were collected from the bibliography unless otherwise mentioned.

All economic data were found in US dollars and were all converted to February 2008 US dollars and then in February 2008 Euros.

4.1. Efficiency

The efficiency criterion is the quality measure of the system. It represents the percentage of the fuel's lower heating value (LHV) that is converted to useful electrical energy. A graphical representation of the efficiency values for all nine options is shown in Fig. 1.

As shown in Fig. 1, the option with the highest efficiency is the hydrogen combustion turbine followed by the hydrogen fuelled PAFC and SOFC. The options with the lowest efficiency are the natural gas internal combustion engine and the natural gas turbine.

4.2. CO_2 emissions

The CO_2 emissions criterion represents the amount of carbon dioxide that is released from the power plant in the atmosphere as a byproduct of the energy conversion process. It is measured in g/kWh. A graphical representation of the CO_2 emissions for all nine options is given in Fig. 2.

CO_2 emissions for hydrogen turbine, hydrogen fuelled PAFC and hydrogen fuelled SOFC are 0 g/kWh. This is because hydrogen is a carbon free fuel and thus no carbon oxides are formed. Hydrogen ICEs emit traces of CO_2 due to the combustion of the oil that leaks in the engine's cylinders. However these emissions are very low and are assumed to be 0 g/kWh in this study. As shown in Fig. 2, the option with the highest CO_2 emissions is the natural gas internal combustion engine, followed by the natural gas fuelled phosphoric acid fuel cell. Since the hydrogen combustion turbine and the hydrogen internal combustion engine don't use a carbon-based fuel, they have zero CO_2 emissions.

4.3. NO_X emissions

The NO_X emissions criterion represents the amount of nitric oxides (NO) and nitrogen dioxides (NO_2) that is released from the power plant in the atmosphere as a byproduct of the energy conversion process. It is measured in g/kWh. A graphical representation of the NO_X emissions for all nine options is given in Fig. 2.

As shown in Fig. 2, the option with the highest NO_X emissions is the natural gas turbine. The hydrogen combustion turbine combusts hydrogen with pure oxygen, therefore no NO_x is produced by the combustion process.

4.4. Capital cost

The capital cost criterion represents the total cost of the power plant and includes the cost of all equipment and all installation costs. It is measured in euros per installed kilo-watt (€/kW). A graphical representation of the capital cost for all nine options is given in Fig. 4.

As shown in Fig. 4, fuel cell technologies are extremely expensive compared to the other technologies. The natural gas combined cycle and the natural gas turbine have the lowest capital cost.

4.5. O&M costs

The O&M costs criterion represents the operation and maintenance costs and includes replacement parts costs and labor costs for the operation and maintenance of the power plant. It does not include fuel cost. It is measured in €/kWh. A graphical presentation of the O&M costs for all nine options is given in Fig. 5.

No data for the O&M costs criterion of the hydrogen turbine could be found. Therefore the O&M costs for the hydrogen turbine are assumed to be 0.0057 €/kWh, approximately 24% higher than the natural gas turbine, in the same way as it's capital cost. The natural gas combined cycle and the natural gas turbine have the lowest O&M costs, whereas the phosphoric acid fuel cell has the highest.

4.6. Electricity cost

The electricity cost criterion represents the cost of the produced electric energy of the power plant and is calculated based on the fuel cost (assuming a cost of 0.04231 €/kWh for natural gas and a cost of 0.122 €/kWh for hydrogen), the O&M costs, the power plant cost and the power plant's service life. It is measured in €/kWh. A graphical presentation of the electricity cost for all nine options is given in Fig. 6.

The electricity cost for all nine options was calculated taking capital cost, O&M costs, fuel costs and service life into consideration. As shown in Fig. 6, the natural gas combined cycle has the lowest electricity cost, whereas the hydrogen internal combustion engine has the highest.

4.7. Service life

The service life criterion refers to the year the power plant can operate before the equipment needs to be replaced. It is measured in years. A graphical representation of the service life for all nine options is given in Fig. 7.

As shown in Fig. 7, turbine power plants have the longest service life whereas fuel cells have the shortest.

Table 1 shows all numerical data for all nine options.

5. Hierarchy tree

In order to evaluate each energy generation option, a hierarchy tree has been built for the application of the AHP. The hierarchy tree is shown in Fig. 8.

On the top level of the hierarchy tree is the goal, which is the choice of the best energy generation option. On the next lever are the criteria used for the evaluation, efficiency, CO_2 emissions, NO_X emissions, capital cost, O&M costs, electricity cost and service life. The decision alternatives, H_2 Turbine, H_2 ICE, NG PAFC, NG SOFC, NG Turbine, NG ICE and NG CC, appear at the lowest level.

7. Analysis of the results

For each case, the criteria weights are given in Table 2, while the results of the evaluation are presented in Table 3.

7.1. Base case

In the base case, the weight factors were distributed subjectively. However, an attempt was made for the weight factors to reflect the current trends of the energy market. Therefore, the economic criteria (capital cost, O&M costs, electricity cost) were considered the most significant, followed by the environmental criteria (CO_2 emissions and NO_x emissions).

7.2. Equally distributed weights

In this case (case 1) the weights were distributed evenly among the nine criteria. Each criterion received 14.3% weight.

7.3. Single criterion analysis

Seven single criterion cases were studied (cases 2-8). In these cases, a single criterion receives full emphasis while the other six criteria are ignored.

In cases 2 to 8, full emphasis is given respectively to the efficiency, the CO_2 emissions, the NO_X emissions, the capital cost, the O&M costs, the electricity cost and the service life criteria.

7.4. Multi-criteria analysis

Ten multi-criteria cases were studied. In cases 9 to 15, 60% emphasis is given respectively to the efficiency, the CO_2 emissions, the NO_X emissions, the capital cost, the O&M costs, the electricity cost and the service life criteria while the remaining 40% is equally distributed among the rest of the criteria.

In case 16, 30% emphasis is given to the capital cost and the CO_2 emissions criteria and the remaining 40% is equally distributed among the rest of the criteria.

In case 17, 30% emphasis is given to the capital cost and the electricity cost criteria and the remaining 40% is equally distributed among the rest of the criteria.

In case 18, 30% emphasis is given to the electricity cost and the CO_2 emissions criteria and the remaining 40% is equally distributed among the rest of the criteria.

8. Conclusions

In this paper, nine energy generation options were evaluated with regard to seven criteria. The energy generation options were the hydrogen combustion turbine, the hydrogen internal combustion engine, the hydrogen fuelled phosphoric acid fuel cell, the hydrogen fuelled solid oxide fuel cell, the natural gas fuelled phosphoric acid fuel cell, the natural gas fuelled solid oxide fuel cell, the natural gas turbine, the natural gas combined cycle and the natural gas internal combustion engine. The criteria used for the evaluation were efficiency, CO_2 emissions, NO_x emissions, capital cost, O&M costs, electricity cost and service life. The Analytic Hierarchy Process was used to perform the evaluation. A total of 19 scenarios were studied.

The most dominant electricity generation technology proved to be the hydrogen combustion turbine, which ranked in the first place in 15 out of 19 scenarios. This was to be expected since the hydrogen combustion turbine promises to deliver ultra clean and low cost power generation, despite the high price of hydrogen, which is about three times more expensive than natural gas. Considering the fact that hydrogen prices are expected to drop as its production methods are evolving [1], the cost of the hydrogen turbine's generated electricity is expected to be very competitive in the future. However the hydrogen turbine is not a currently available technology, as it is still under research, and its actual performance characteristics when it becomes commercially available could be very different from the ones used in this paper.

The second most preferable power generation option proved to be the natural gas combined cycle, which ranked first in 5 out of 19 scenarios and second in 8. Had the hydrogen combustion turbine not been taken into consideration in this paper, the natural gas combined cycle would have ranked first in 12 scenarios. In most of these scenarios, focus is given primarily on the economic and secondarily on the environmental criteria. This shows that the natural gas combined cycle is a very competitive power generation technology.

The phosphoric acid fuel cell ranked in the last place in 13 out of 19 scenarios. This was to be expected since this cell has a very high capital cost and O&M costs combined with a short service life and produces rather high emissions compared to other technologies.

References

[1] G. Marbán, T. Valdés-Solís, Towards the hydrogen economy, International Journal of Hydrogen Energy 32 (12) (2007) 1625-1637.

[2] N. Lior, Energy resources and use: the present situation and possible paths to the future, Energy 33 (6) (2008) 842-857.

[3] N.H. Afgan, P.A. Pilavachi and M.G. Carvalho, Multi-criteria evaluation of natural gas resources, Energy Policy 35 (1) (2007) 704-713.

[4] P. Hennicke and M. Fischedick, Towards sustainable energy systems: the related role of hydrogen, Energy Policy 34 (11) (2006) 1260-1270.

[5] Gökalp and E. Lebas, Alternative fuels for industrial gas turbines (AFTUR), Applied Thermal Engineering 24 (11-12) (2004) 1655-1663.

[6] G.L. Juste, Hydrogen injection as additional fuel in gas turbine combustor, Evaluation of effects, Hydrogen Energy 31 (14) (2006) 2112-2121.

[7] A. I. Chatzimouratidis, P. A. Pilavachi, Objective and subjective evaluation of power plants and their non-radioactive emissions using the analytic hierarchy process, Energy Policy 35 (8) (2007) 4027-4038.

[8] A. I. Chatzimouratidis, P. A. Pilavachi, Multicriteria evaluation of power plants impact on the living standard using the analytic hierarchy process, Energy Policy 36 (3) (2008) 1074-1089.

[9] B. A. Akash, R. Mamlook, M. S. Mohsen, Multi-criteria selection of electric power plants using analytical hierarchy process, Electric power systems research 52 (1) (1999) 29-35.

[10] M. S. Mannan, S. A. Ashfaque and Y. Guo, Engineering for sustainable development and its application to fuel cell systems, 18th International Congress of Chemical Engineering, CHISA 2008, Volume 4 - PRES 2008, page 1125.

[11] N. H. Afgan, A. Veziroglu, M. G. Carvalho, Multi-criteria evaluation of hydrogen system options, International Journal of Hydrogen Energy 32 (15) (2007) 3183-3193.

[12] N. H. Afgan, M. G. Carvalho, Sustainability assessment of hydrogen energy systems, International Journal of Hydrogen Energy 29 (13) (2004) 1327-1242.

[13] T. Saaty, The Analytic Hierarchy Process, McGraw-Hill, New York, 1980.

[14] M. Fukuda, Y. Dozono, Double Reheat Rankine Cycle for Hydrogen Combustion, Turbine Power Plants, Journal of Propulsion and Power 16 (4) (2000), 562-567.

[15] S. Verhelst, R. Sierens, A quasi-dimensional model for the power cycle of a hydrogen fuelled ICE, International Journal of Hydrogen Energy 32 (15) (2007) 3545-3554.

[16] P. Zegers, former Head of Unit of the European Commission, Private communication, 10 May 2008.

[17] EG&G Technical Services, Fuel Cell Handbook, Seventh Edition, US Department of Energy, November 2007.

[18] G. Bidini, C.N. Grimaldi, F. Mariani, Experimental analysis of the actual behaviour of a natural gas fuelled engine Caterpillar (CAT)-3516, Applied Thermal Engineering 20 (5) (2000) 455-470.

[19] A. D. Hawkes, L. Exarchakos, D. Hart, M. A. Leach, D. Haeseldonckx, L. Cosijns, W. D'haeseleer, Fuel Cells, European Sustainable Electricity (EUSUSTEL), Work Package 3, http://www.eusustel.be/wp.php#wp3, last access: 21 October 2008.

[20] J. Islas, The gas turbine: A new technological paradigm in electricity generation, Technological Forecasting and Social Change 60 (2) (1999) 128-148.

[21] A. Moreno, Hydrogen and fuel cells in CCS power plant, ENEA, Department of Energy Technologies, for Energy, Renewable Sources and Energy Saving, 2007.

[22] College of the Desert, Hydrogen use in Internal Combustion Engines (Module 3), December 2001, http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/pdfs/fcm03r0.pdf, last access: 21 October 2008.

[23] S. M. Costello, Costello Holdings LLC, Private communication, 23 November 2007.

[24] Ch. Korres, Heliostat LLC, Private communication, 10 December 2007.

[25] US Army Corps of Engineers, Phosphoric Acid Fuel Cells, Construction Engineering Research Laboratory, December 2000.

[26] M. Ameri and M. J. Heidari, The Application of Solid Oxide Fuel Cell for Power Generation in Iran: Feasibility and Cost Analysis, The 2nd Joint International Conference on "Sustainable Energy and Environment (SEE 2006)" 21-23 November 2006, Bangkok, http://www.jgsee.kmutt.ac.th/see1/presentation/Oral%20presentation_SEE2006/A001.pdf, last access: 29 October 2008.

[27] Congress of the United States, A CBO Paper – Prospects for Distributed Electricity Generation, September 2003.

[28] J. M. Torrey, J. F. Westerman, W. R. Taylor, F. H. Holcomb, J. Bush, Detailed fuel cell demonstration site summary report, Department of Defense, US Army Corps of Engineers, June 2006.

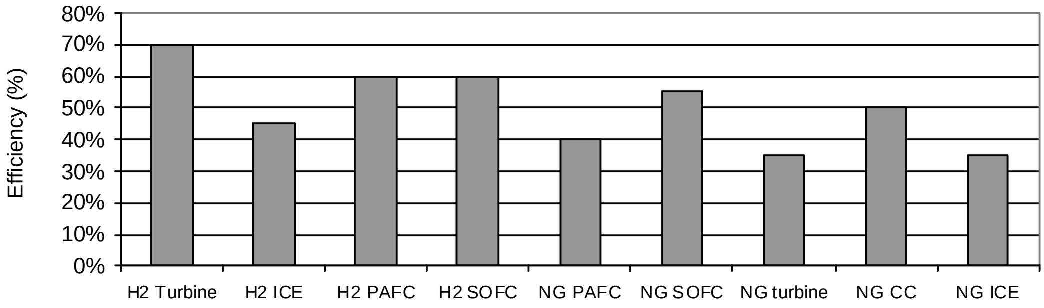

Fig. 1. Efficiency for nine types of electricity generation technologies

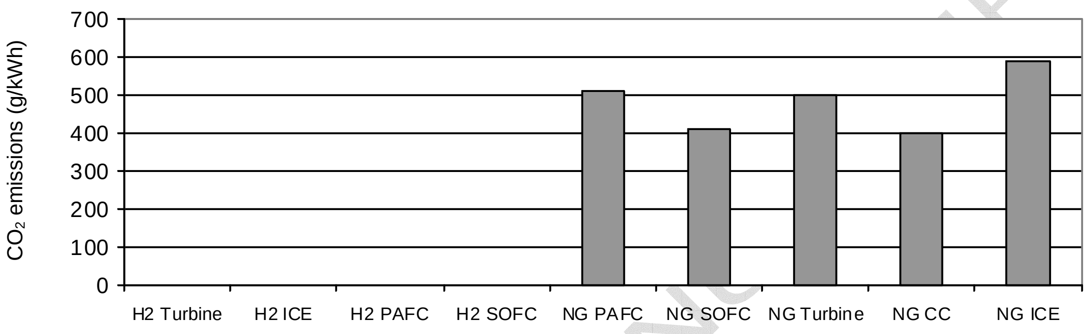

Fig. 2. CO_2 emissions for nine types of electricity generation technologies

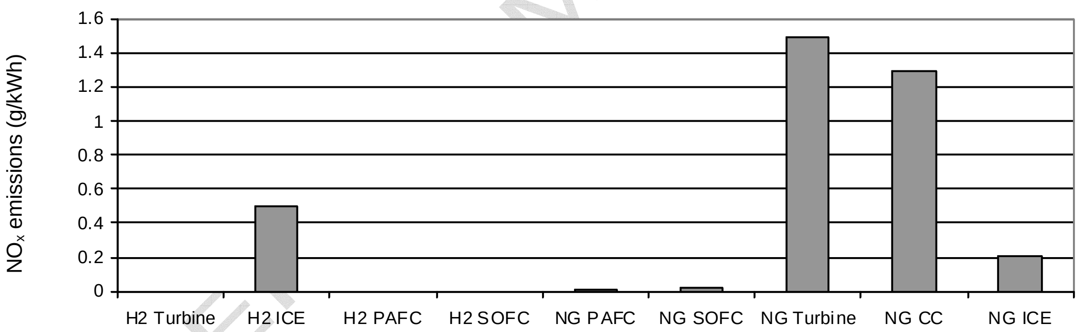

Fig. 3. NO_X emissions for nine types of electricity generation technologies

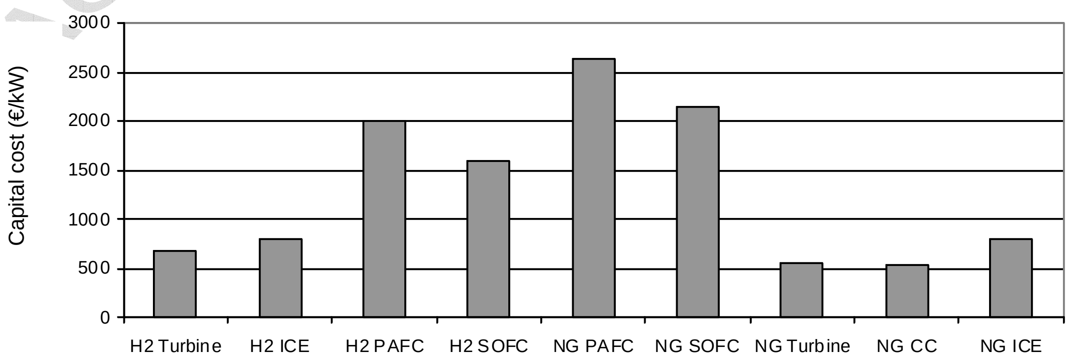

Fig. 4. Capital cost for nine types of electricity generation technologies

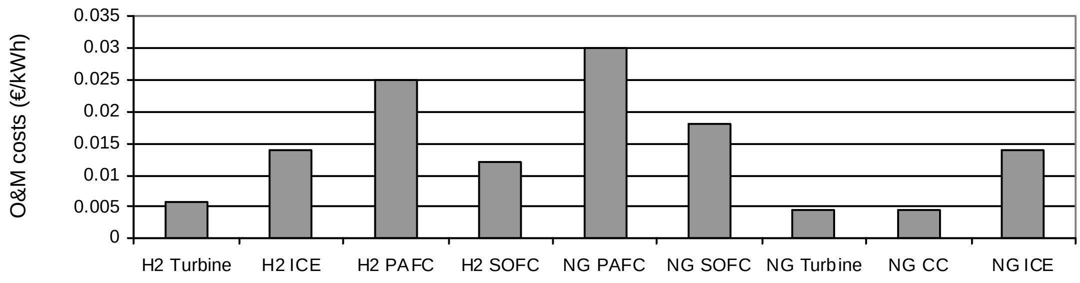

Fig. 5. O&M costs for nine types of electricity generation technologies

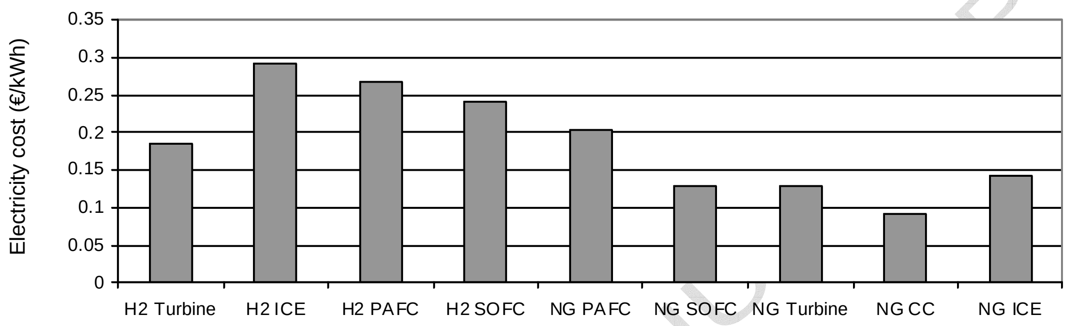

Fig. 6. Electricity cost for nine types of electricity generation technologies

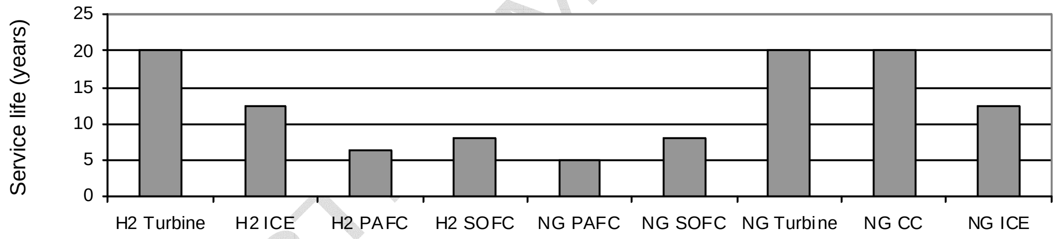

Fig. 7. Service life for nine types of electricity generation technologies

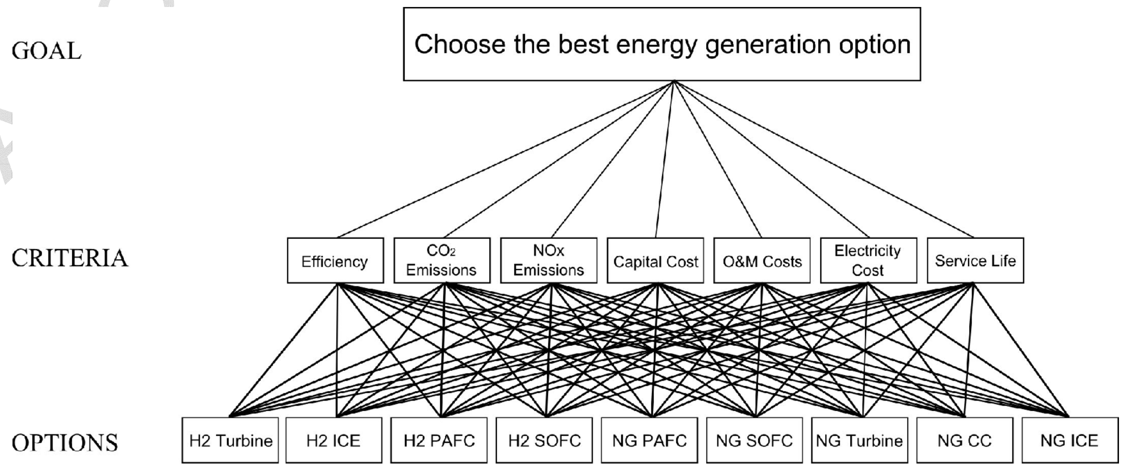

Fig. 8. The hierarchy tree of the problem

Table 1. Criterion values for all nine types of electricity generation technologies

Option	Efficiency (%)	CO_2 Emissions (g/kWh)	NO_X Emissions (g/kWh)	Capital Cost (€/kW)	O&M Cost (€/kWh)	Electricity Cost (€/kWh)	Service Life (years)
H_2 Turbine	70 [14]	0	0	680 [23]	0.0057	0.184	20 [27]
H_2 ICE	45 [9, 15]	0	0.5 [22]	794 [24]	0.014 [24]	0.2929	12.5 [27]
H_2 PAFC	60 [16]	0	0 [16]	2000 [16]	0.025 [16]	0.268	6.25 [16]
H_2 SOFC	60 [16]	0	0 [16]	1600 [16]	0.012 [16]	0.24	8 [16]
NG PAFC	40 [11]	510 [19]	0.0135 [19]	2645 [25]	0.03 [28]	0.202	5 [17]
NG SOFC	55 [17]	410 [19]	0.023 [19]	2140 [26]	0.018 [26]	0.1284	8 [17]
NG Turbine	35 [11]	500 [20]	1.5 [20]	550 [27]	0.0046 [27]	0.129	20 [27]
NG CC	50 [20]	400 [20]	1.3 [20]	531 [27]	0.0046 [27]	0.09252	20 [27]
NG ICE	35 [18]	590 [18]	0.21 [21]	794 [27]	0.014 [27]	0.1429	12.5 [27]

Table 2. Criteria weights for each case studied.

Case	Criterion Efficiency	CO_2 Emissions	NO_X emissions	Capital Cost	O&M Costs	Electricity Cost	Service Life
Base Case	10%	12.5%	10%	25%	10%	25%	7.5%
Case 1	14.3%	14.3%	14.3%	14.3%	14.3%	14.3%	14.3%
Case 2	100%	0%	0%	0%	0%	0%	0%
Case 3	0%	100%	0%	0%	0%	0%	0%
Case 4	0%	0%	100%	0%	0%	0%	0%
Case 5	0%	0%	0%	100%	0%	0%	0%
Case 6	0%	0%	0%	0%	100%	0%	0%
Case 7	0%	0%	0%	0%	0%	100%	0%
Case 8	0%	0%	0%	0%	0%	0%	100%
Case 9	60%	6.7%	6.7%	6.7%	6.7%	6.7%	6.7%
Case 10	6.7%	60%	6.7%	6.7%	6.7%	6.7%	6.7%
Case 11	6.7%	6.7%	60%	6.7%	6.7%	6.7%	6.7%
Case 12	6.7%	6.7%	6.7%	60%	6.7%	6.7%	6.7%
Case 13	6.7%	6.7%	6.7%	6.7%	60%	6.7%	6.7%
Case 14	6.7%	6.7%	6.7%	6.7%	6.7%	60%	6.7%
Case 15	6.7%	6.7%	6.7%	6.7%	6.7%	6.7%	60%
Case 16	8%	30%	8%	30%	8%	8%	8%
Case 17	8%	8%	8%	30%	8%	30%	8%
Case 18	8%	30%	8%	8%	8%	30%	8%

Table 3. The results of the evaluation for each case studied.

Case	**Technology under evaluation**								
	H_2 Turbine	H_2 ICE	H_2 PAFC	H_2 SOFC	NG PAFC	NG SOFC	NG Turbine	NG CC	NG ICE
Base Case	16.7%	10.4%	8.2%	11%	4.7%	10%	12.5%	15%	11.4%
Case 1	18%	11%	9.4%	12.1%	4.8%	9.9%	11.1%	13.7%	10%
Case 2	25.9%	7.4%	18.5%	18.5%	3.7%	14.8%	0%	11.1%	0%
Case 3	20.3%	20.3%	20.3%	20.3%	2.8%	6.2%	3.1%	6.6%	0%
Case 4	15.1%	10%	15.1%	15.1%	14.9%	14.8%	0%	2%	13%
Case 5	16.3%	15.3%	5.3%	8.7%	0%	4.2%	17.4%	17.5%	15.3%
Case 6	17.1%	11.3%	3.5%	12.7%	0%	8.4%	17.9%	17.9%	11.3%
Case 7	11.4%	0%	2.4%	5.4%	9.4%	17.3%	17.3%	21.2%	15.8%
Case 8	23.6%	11%	0.4%	3.4%	0%	3.4%	23.6%	23.6%	11%
Case 9	21.7%	9.3%	13.6%	15.1%	4.3%	12.2%	5.9%	12.5%	5.4%
Case 10	19.2%	15.9%	15.1%	16.4%	3.7%	8%	6.9%	9.9%	4.8%
Case 11	16.2%	10.4%	12.8%	13.9%	10.9%	12.9%	4.5%	6.7%	11.8%
Case 12	17%	13.4%	7.1%	10.2%	2.1%	6.7%	14.6%	15.8%	13%
Case 13	17.5%	11.1%	6.1%	12.4%	2.1%	9.1%	14.9%	16%	10.7%
Case 14	14.6%	5.3%	5.8%	8.6%	7.2%	13.7%	14.3%	17.5%	13%
Case 15	20.7%	11%	5%	7.8%	2.5%	6.7%	17.2%	18.5%	10.5%
Case 16	18.1%	14%	10.7%	13%	3.2%	7.8%	10.9%	13.1%	9.2%
Case 17	16.2%	9.8%	7%	9.9%	4.6%	10%	13.9%	16.1%	12.5%
Case 18	17.1%	10.7%	10.3%	12.5%	5.3%	10.7%	10.6%	13.7%	9%