Bulletin of the *Transilvania* University of Braşov • Vol. 9 (58) - 2016
Series I: Engineering Sciences

A STUDY FOR CHOOSING THE HYDROGEN PRODUCTION METHOD IN ROMANIA BY USING MULTI-CRITERIA DECISION ANALYSIS

A. HOŢUPAN[1] C. BACOŢIU[2]

Abstract: *Producing hydrogen by using two complementary sources represents an important step in solving present and future problems that Romania has to tackle, taking into account the continuous reduction of natural gas reserves. This paper tries to provide an instrument to select the best method to obtain hydrogen in Romania, by using the ELECTRE multi-criteria decision analysis.*

Key words: *hydrogen, choice, MCDA, Electre*

1. Introduction

Choosing a solution concerning hydrogen implementation in the Romanian economic circuit would bring major benefits: virtually endless reserves, low atmospheric pollution, parallel use of natural gas and hydrogen until the financial effort required for hydrogen implementation will pay off, and finally Romania will gain the energetic independance.

Hydrogen may be considered as a synthetic fuel in a future era [1] that will follow after the fossil fuel economy system and can be used as a complementary source of energy, in order to balance the natural gas deficit that Romania has to face from now on.

The required hydrogen flow might be produced by using three methods: water electrolysis, steam reforming of methane or partial oxidation of methane.

Energy sources for producing hydrogen in Romania [2],[4] Table 1

<table>
<tr><td>Renewable energy
Solar
Wind</td><td></td><td rowspan="2">Need electricity input for water electrolysis</td><td rowspan="2"></td><td rowspan="3">Hydrogen</td></tr>
<tr><td>Nuclear energy</td><td>Radioactive wastes</td></tr>
<tr><td>Fossil fuels
Natural gas</td><td>Need energy input</td><td>Steam reforming of methane

Partial oxidation of methane</td><td>Carbon emissions</td></tr>
</table>

[1] Building Services Engineering Faculty, Technical University of Cluj-Napoca.
[2] Building Services Engineering Faculty, Technical University of Cluj-Napoca.

Obviously, there are many other methods used worldwide, but the selection of these three options was made by taking into consideration Romania's energetic resources [2].

This paper wants to present a multi-criteria decision analysis (MCDA) tool that can be used for selecting the optimum method for producing hydrogen in our country. Table 1 presents Romania's energetic resources that could be used in order to obtain hydrogen.

2. Finding the „Best" Method for Producing Hydrogen by Using MCDA

Multi-criteria decision analysis (MCDA) methods have been developed to support the decisions makers in their complex decision processes. Some MCDA methods provide techniques for finding a compromise solution. They are not "miracle" tools, in the sense that sometimes, each decision maker has to feed them with subjective information. Therefore, the results are not always unique because they are dependent of decision maker's preferences. If the results are arguable, new scenarios may be taken into account, by negotiating on those preferences.

The ELECTRE 1 (ELimination Et Choix Traduisant la Realité) MCDA method was used in order to create a software instrument which will assist us for selecting the "best" method of producing hydrogen in Romania. Obviously, this is a *choice* paradigm.

ELECTRE 1, created by Bernard Roy in 1968, belongs to the outranking family of methods. The outranking methods are based on pairwise comparisons of the "potential actions" (i.e. options). So, every option must be compared to all other options. Eventually, strong outranking relationships will emerge and inferences for the "winner" can be made.

The main steps for solving a MCDA problem are the following:

-assess the decision objective/target and make an inventory of all potential actions (options);

-select the family of criteria for supporting the decision, then allocate the weights;

-evaluate each option with respect to each criterion (grades);

-run the aggregation procedure.

Step 1

Our objective is to find the „best" method of producing hydrogen in Romania. As said before, three methods will compete in our analysis, therefore these hydrogen production options will be identified as P1, P2 and P3. Finally, one of them will be the "winner". Now, a short description of each method is necessary:

P1 – Water electrolysis

Water electrolysis is a method of producing hydrogen which involves an electro-chemical process and consists of passing electrical current through water. By the means of a ion transfer technology, water is separated into hydrogen and oxygen.

H_2O --- > $H_2 + ½ O_2$

The reactors used for water electrolysis have special compartments in order to both obtain the purest possible products and optimize the processes that are taking place at each electrode.

Technologies using renewable sources of energy (such as solar panels or wind turbines) could generate electricity in order to produce hydrogen via water electrolysis without any pollutant emissions, also offering high efficiencies.

Another alternative is the use of nuclear energy for obtaining the electricity needed by the water electrolysis process [4], [5], [8] according to Table 1.

The purity of the hydrogen obtained by this method is 99,99% .

P2 – Steam reforming of methane

This type of process uses high temperature steam as energy applied on the raw source (methane gas) containing hydrogen. Nowadays, this procedure is widely used for producing hydrogen, the reason being the well-managed array of involved technologies (e.g. steam production).

The process has two stages:

Stage 1: $CH_4 + H_2O$ --- > $CO + 3 H_2$

Stage 2: $CO + H_2O$ --- > $CO_2 + H_2$

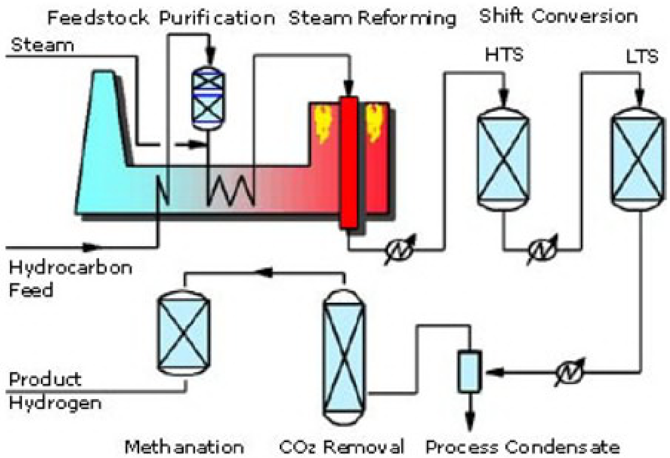

Fig. 1. *The procedure for steam reforming of methane [9]*

For more details:

Stage 1 – reforming the methane with high temperature steam, obtaining a synthesis gas which represents actually a mixture of hydrogen and carbon monoxide. This process takes place inside a reforming reactor (reformer), which is like a huge furnace containing tubes filled with nickel catalyst. The input consists of steam and methane and the reaction develops at temperatures in the range of 650 – 1000 ˚C and pressures of about 40 bar. Unfortunately, a large quantity of CO_2 is also produced alongside with hydrogen. Normally, the reaction products percentage distribution is about 75% H_2, 15% CO and 10% CO_2.

Stage 2 – a water-gas shift reaction is used in order to produce hydrogen and carbon dioxide from stage 1 carbon monoxide. This reaction runs in the presence of steel catalyst, in two phases: the high temperature shift which takes place at 350 ˚C and the low temperature shift which takes place at approximately 190 - 210 ˚C [3].

The hydrogen produced this way contains certain impurities, e.g. small quantities of carbon dioxide, carbon monoxide and hydrogen sulfide. Depending on the application, hydrogen may require a purification treatment before consumption (obviously, methane itself might be purified prior to Stage 1). The standard procedure can be optimised by adding an adsorbant which would significantly reduce CO_2 emissions, allowing an additional quantity of hydrogen to be obtained at lower temperatures.

The efficiency of the reforming process is only 70 – 75%. The reason is partly due to the high temperature required by the endotherm reaction. An important heat quantity is lost by an inefficient use of the sensible heat of reaction products (syngas). This sensible heat might be harvested by the means of a heat exchanger, but the corrosive nature of syngas makes this option very problematic to build and implement.

P3 – Partial oxidation of methane

This type of hydrogen production process (Figure 2), having a 70% efficiency, consist in a partial oxidation of methane (which is a exothermic reaction) and a water-gas shift reaction (like discussed in P2).

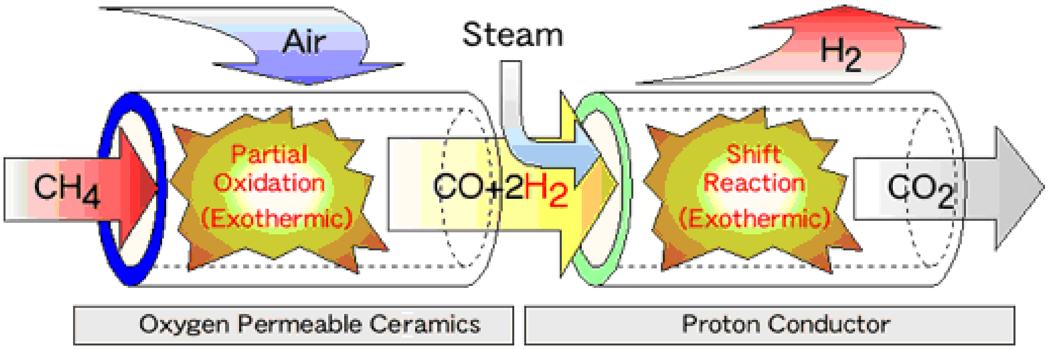

Fig. 2. *The procedure for partial oxidation of methane [10]*

Thus, there is no need for bringing energy from outside and the reaction product is the syngas. This reaction must be strictly controlled in order to only allow a partial oxidation, i.e. the reaction products should only be CO and H_2, without H_2O.

Stage 1: $CH_4 + ½\ O_2 \rightarrow CO + 2\ H_2$

Stage 2: $CO + H_2O \rightarrow CO_2 + H_2$

The benefits of this method of producing hydrogen are low energy consumption and a simple reformer design. [3].

The main drawback of this procedure is the mixing of produced hydrogen with the neutral gas N_2.

Step 2

The decision maker must decide what are the criteria that should be used in order to compare the potential actions/options. It is recommended that those criteria should be coherent, exhaustive/comprehensive and non-redundant. Their number should not be greater than 10.

Our choice was:

C1: the cost of the investment

C2: raw material/source used for producing hydrogen

C3: purity of obtained hydrogen

C4: environmental protection

C5: efficiency

For these criteria we considered the following weights:

Criteria:	C1	C2	C3	C4	C5
Weights:	2	2	3	2	4

Step 3

In order to evaluate each option with respect to each criterion we have used a performance matrix, which had to be filled in with grades:

V=very good

G=good

M=medium

S=satisfying

N=not good (unsatisfying)

This kind of grading may be highly subjective, it is the decident's view according to his information/knowledge.

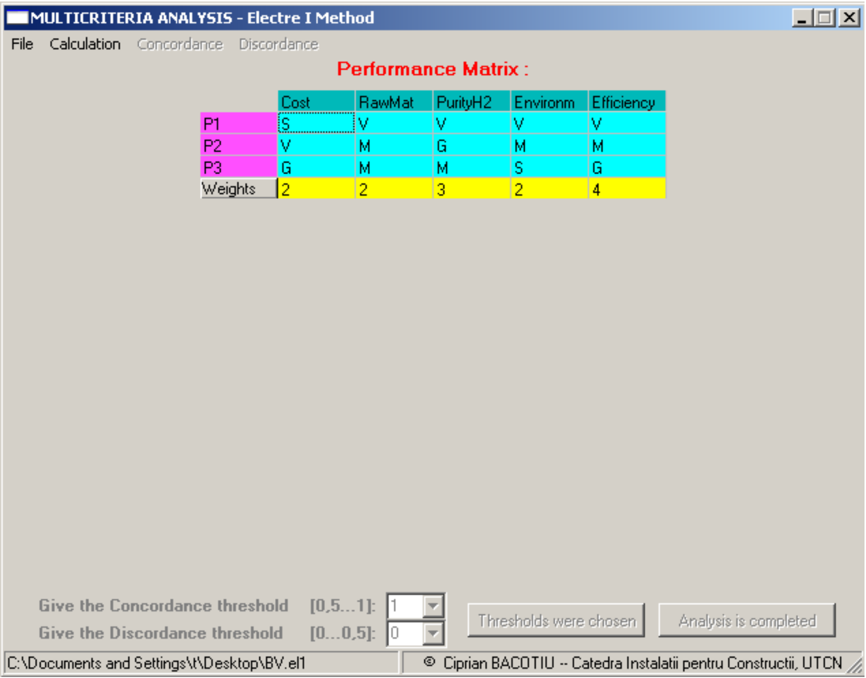

Fig. 3. *The performance matrix (AMEL1 tool)*

Step 4 ELECTRE 1 follows a partial aggregation procedure, using the outranking relationship as basis, together with concordance and discordance indexes and finally with sensitivity analysis.

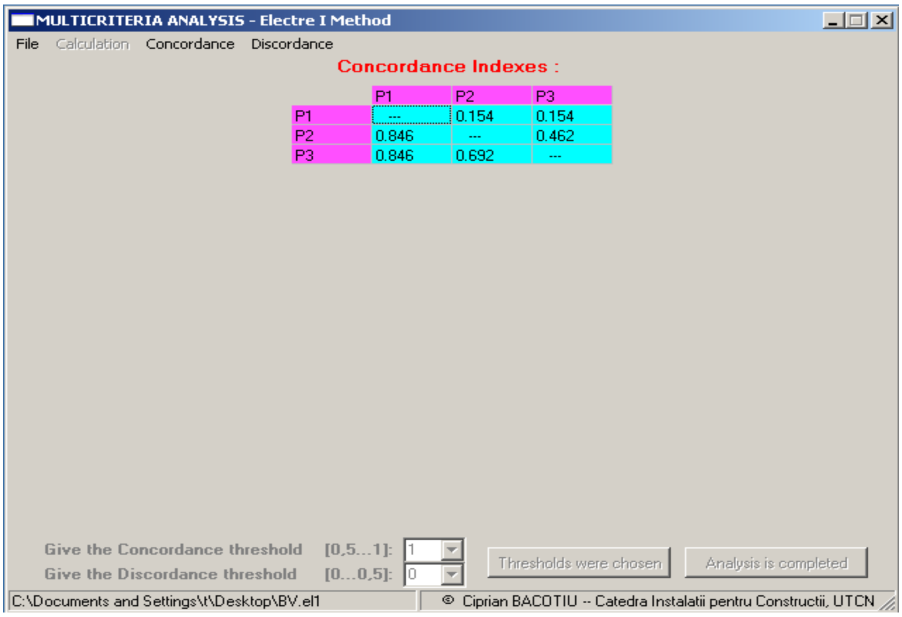

Fig. 4. *Concordance indexes (AMEL1 tool)*

The assertion 'X outranks Y' means that X is at least as good as Y with respect to the majority of the criteria (this is a concordance requirement), without being too inferior with respect to the rest of the criteria (this is a non-discordance requirement).

The detailed description of the method, the calculation of the concordance and discordance indexes and the meaning of the sensitivity analysis can be found in [6],[7].

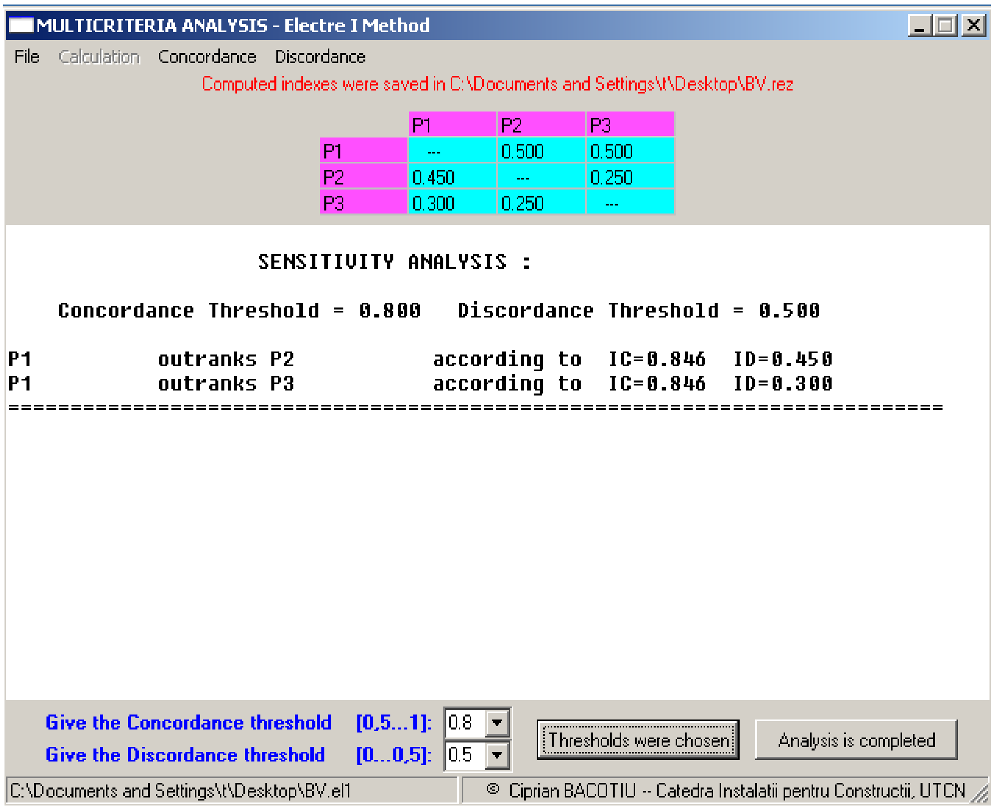

Fig. 5. *Sensitivity analysis (AMEL1 tool)*

Based on [7], we developed in our department a software tool called AMEL1, which was used to identify the „best” option for producing hydrogen in Romania.

We present the results file in Figure 6. Concerning the computed indexes, each matrix respects a convention, i.e. *column option outranks row option.*

For each possible outranking relationship we tried to discover if there exist big concordance indexes simultaneously with small discordance indexes. So, the sensitivity analysis is based on setting concordance thresholds (CT) and discordance thresholds (DT) which act like filters, allowing us to pinpoint the strongest outranking relationships.

We started with severe thresholds, setting CT=0.8 and DT=0.2. No relationship satisfied these conditions.

Then we relaxed a little bit the thresholds, setting CT=0.7 and DT=0.3. A first result emerged, i.e. P1 is better than P3. We cannot tell anything about P2 yet.

Then we continued with CT=0.7 and DT=0.4. Nothing new appeared

Finally, we continued to lower the discordance threshold, keeping the same CT. So, with CT=0.7 and DT=0.5 we obtained the outranking relationship between P1 and P2. It seems that P1 is better than P2, but with a pretty strong „opposition”, because the discordance index is high (0.45).

Conclusion: competition was fierce, there is no clear winner ... but we may suggest that P1 is the best choice.

```
                    PERFORMANCE MATRIX :
           Cost       RawMat     PurityH2   Environm   Efficiency
P1         S          V          V          V          V
P2         V          M          G          M          M
P3         G          M          M          S          G

                    CONCORDANCE Indexes :
           P1         P2         P3
P1         -----      0.154      0.154
P2         0.846      -----      0.462
P3         0.846      0.692      -----

                    DISCORDANCE Indexes :
           P1         P2         P3
P1         -----      0.500      0.500
P2         0.450      -----      0.250
P3         0.300      0.250      -----

                    SENSITIVITY ANALYSIS :
    Concordance Threshold = 0.800   Discordance Threshold = 0.200
======================================================================
                    SENSITIVITY ANALYSIS :
    Concordance Threshold = 0.700   Discordance Threshold = 0.300

P1         outranks P3          according to  IC=0.846  ID=0.300
======================================================================
                    SENSITIVITY ANALYSIS :
    Concordance Threshold = 0.700   Discordance Threshold = 0.400

P1         outranks P3          according to  IC=0.846  ID=0.300
======================================================================
                    SENSITIVITY ANALYSIS :
    Concordance Threshold = 0.700   Discordance Threshold = 0.500

P1         outranks P2          according to  IC=0.846  ID=0.450
P1         outranks P3          according to  IC=0.846  ID=0.300
======================================================================
```

Fig. 6. *The results file produced by the AMEL1 MCDA tool*

3. Conclusions

ELECTRE methods are relevant when facing decision problems with more than two criteria and especially if the performances of the criteria are expressed in different units and the decision maker cannot define a common scale.

Our study came to the conclusion that none of the analysed methods is an absolute winner. Several future scenarios must be taken into account, by slightly modifying some grades in the performance matrix. The battle is still going between P1 (water electrolysis, which implies huge investments) and P2 (steam reforming of methane, which assures only a part of the required flow, because of the limited methane resources).

An acceptable compromise solution could be a combination of these two methods, which may lead to hydrogen production from two complementary sources, both in the vicinity of Cernavodă nuclear power plant.

References

1. Ball, M., Wietschel, M.: *The hydrogen economy: Opportunities and Challenges*, Cambridge University Press, 2009.
2. Badea, Gh., Hoţupan, A., et. al.: *Soluţii energetice alternative pentru România* (*Alternative energetic solutions for Romania*). In *Ştiinţa Modernă şi Energia*, Cluj-Napoca, 2007, p.52-59.
3. Badea, Gh., Hoţupan, A., et. al.: *Producerea hidrogenului utilizând tehnologii termochimice* (*Hydrogen production by using termo-chemical technologies*), In *Instalaţii pentru construcţii şi confortul ambiental*, Timişoara, 2010, p. 52-57.
4. Furu L., Roş V., et. al.: *Analysis of the various methods for obtaining hydrogen* (*Analiza diferitelor metode de obţinere a hidrogenului*) – a XI-a Conferinţă Naţională "Profesorul Dorin Pavel – fondatorul hidro-energeticii româneşti", Sebeş, 2011, p.115-120..
5. Lazăr R.E., Ştefănescu I., et. al.: *Paşi către o economie bazată pe hidrogen I* (*Steps towards a hydrogen based economy I*) In *Revista Instalatorul* nr. 11/2006.
6. Maystre L.Y.: *Methodes multicritere ELECTRE*, Presses polytechniques et universitaires romandes, Lausanne, 1994.
7. Scharlig A.: *Pratiquer Electre et Promethee*, Presses polytechniques et universitaires romandes, Lausanne, 1996.
8. Şurianu D.: *Economia Hidrogenului – de la utopie la realism* (*The hydrogen economy – from utopia to realism*) Available at http://www.agir.ro/buletine/292.pdf Accessed: October 2016.
9. http://www.making-hydrogen.com/steam-reforming-hydrogen.html. Accessed: october 2016
10. .http://ceram.material.tohoku.ac.jp/~takamura/research_e.html. Accessed: october 2016