

# Multi-Criteria Analysis of Hydrogen Infrastructure Supply Pathways

## *Abstract*

*This paper presents a multi-criteria analysis performed to simulate a realistic decision-making process on the hypothetical situation of a mid-size country examining the feasibility of several options to produce, distribute and dispense hydrogen to a given fleet of fuel cell vehicles. The objective of the methodology chosen is to rank and test the sensitivity of the hydrogen supply pathways based on economic, environmental and other relevant criteria. The sensitivity was tested in four scenarios, different weights being assigned to the fourteen decision-making criteria. The two cases presented are an average oil price scenario of 30 US\$/bbl (Case 1) and of 40US\$/bbl (Case 2) over the entire life cycle of the project. The results show that it is very difficult to beat the existing energy supply system of gasoline/diesel for vehicles in terms of cost even when considering near future technologies. Increased environmental sensitivity generally favors hydrogen supply alternatives but a rank reversal is most easily accomplished when energy security is highly weighted. Natural gas alternatives (via steam reforming) seem to be most competitive overall, particularly in the near future.*

## **1 Introduction**

Much has been written on the development, barriers and opportunities of hydrogen technologies in the last decade. Many observers see hydrogen as a future alternative fuel or energy carrier of great interest for economic, environmental and energy security reasons. The principal drivers include the growing world energy demand, the associated environmental problems from the energy uses and the dependence of many sectors on finite energy resources (particularly transport on fossil fuels). The development of a supply infrastructure to produce, distribute and dispense hydrogen is viewed as a critical factor in a possible transition from a largely fossil fuel-based to a hydrogen-based economy.

After an extensive literature review, some quantitative life-cycle data were found on numerous pathways (i.e. technologies and processes) for hydrogen production, distribution and dispensing. Some authors attempt to evaluate one or more of these alternative pathways to yield insights into the possible future development of the supply infrastructure using one or more indicators of performance or cost. However, few works attempt to perform an integrated assessment of all relevant indicators. Moreover, it is difficult to find data for hydrogen alternatives that are comparable and detailed enough for strictly quantitative types of analyses, such as econometrics. In this case, a multi-criteria analysis was seen as an ideal approach because it can handle a mix of quantitative and qualitative data to systematically evaluate the alternatives based on likely decision-making criteria. The added value of this work, therefore, is its application of a systematic

methodology to simulate a realistic decision-making process based on a hypothetical situation. The numerous simplifying assumptions and associated limitations will be described below.

Our analysis considers the situation of the government of a hypothetical mid-size country that is examining the feasibility of several options to produce, distribute, and dispense hydrogen to a given fleet of fuel cell vehicles. This analysis assumes that the amount of hydrogen needed to supply the country's mobility needs is equal to 1,200,000 kilogram per day over the entire life of the project. Moreover, it is assumed that the country can exploit large coal reserves and some gas reserves as feedstock or energy sources, but it does not have any petroleum reserves. It is therefore assumed to be a petroleum-importing country with related concerns about energy supply security.

## 2 Hydrogen supply pathways

The government has to decide whether to continue using currently available fuels (i.e., gasoline and diesel) or invest in a hydrogen production technology and associated supply infrastructure. In the decision-making process, not only economic criteria but also environmental quality (especially the reduction of greenhouse gas emissions) and energy security are considered. As for the infrastructure, the country is considering a budget constraint of US\$3,000 per kilogram of hydrogen per day for capital costs.<sup>1</sup> The transition to a hydrogen supply system can be realized through 19 possible pathways, listed in Table 1 along with the reference (no-build) alternative.

*Table 1: Hydrogen Supply Pathways Considered*

Alternatives	Plant Scale	Energy Source	Technology	Carbon Sequestration	Production Process	Distribution Process
<b>Alt.0</b>	Existing	Petroleum	Current	No	Gasoline/ Diesel	Existing
<b>1-CGCN</b>	Centralized	Natural Gas	Current	No	Steam Reforming	Pipeline
<b>2-CGFN</b>	Centralized	Natural Gas	Future	No	Steam Reforming	Pipeline
<b>3-CGCY</b>	Centralized	Natural Gas	Current	Yes	Steam Reforming	Pipeline
<b>4-CGFY</b>	Centralized	Natural Gas	Future	Yes	Steam Reforming	Pipeline
<b>5-MGCN</b>	Mid-Size	Natural Gas	Current	No	Steam Reforming	Truck
<b>6-MGFN</b>	Mid-Size	Natural Gas	Future	No	Steam Reforming	Truck
<b>7-MGCY</b>	Mid-Size	Natural Gas	Current	Yes	Steam Reforming	Truck
<b>8-MGFY</b>	Mid-Size	Natural Gas	Future	Yes	Steam Reforming	Truck
<b>9-DGCN</b>	Distributed	Natural Gas	Current	No	Steam Reforming	On-Site
<b>10-DGFN</b>	Distributed	Natural Gas	Future	No	Steam Reforming	On-Site
<b>11-CCCN</b>	Centralized	Coal	Current	No	Oxidation	Pipeline
<b>12-CCFN</b>	Centralized	Coal	Future	No	Oxidation	Pipeline
<b>13-CCCY</b>	Centralized	Coal	Current	Yes	Oxidation	Pipeline
<b>14-CCFY</b>	Centralized	Coal	Future	Yes	Oxidation	Pipeline
<b>15-CNFN</b>	Centralized	Nuclear	Future	No	Water Thermal Splitting	Pipeline
<b>16-MBCN</b>	Mid-Size	Biomass	Current	No	Gasification	Truck
<b>17-MBFN</b>	Mid-Size	Biomass	Future	No	Gasification	Truck
<b>18-MBCY</b>	Mid-Size	Biomass	Current	Yes	Gasification	Truck
<b>19-MBFY</b>	Mid-Size	Biomass	Future	Yes	Gasification	Truck

Each alternative includes all the stages that are necessary to produce, distribute and dispense the hydrogen and differs from the others in at least one of the following aspects:

<sup>1</sup> This arbitrary figure is roughly an average of daily capital costs per kilogram of hydrogen estimated from the data available in the NRC 2004 paper for all production pathways.

### 1) *Plant Scale (centralized, mid-size, or distributed)*

- Centralized plants, with a 2.5-year construction time, are assumed to produce 1,200,000 kilograms per day (enough for nearly 2 million cars).
- Mid-size plants, with a 2.5-year construction time, produce 24,000 kg/d (enough for 40,000 cars).
- Finally, distributed plants have a 1-year construction time and a total production capacity of 480 kg/d, supporting 800 cars.

### 2) *Energy Source (petroleum, natural gas, coal, nuclear, or biomass)*

- Natural gas and coal represent the most common feedstock at the moment, but they pose some problems because they generate carbon dioxide as a by-product of the production process and do not reduce the dependency on fossil fuels, a result that most countries would like to achieve. For these reasons, different energy sources such as nuclear energy and biomass are also considered as potential feedstocks.
- At very large scale, the main supply options include carbonaceous fuels and nuclear energy. Both natural gas and renewables can offer production possibilities (especially biomass-based energy sources) in midsize plants. Finally, distributed production might rely on primary energy from natural gas.

### 3) *Technology Development Status (current or future)*

- Most of the alternatives are considered for both current and future states of technology development, with the exception of hydrogen production from a nuclear thermal reforming of water, which does not currently exist.
- The current state is based on technologies and processes that could be implemented in the present, without any breakthrough.
- The future state is based on technological improvements that could be achieved if R&D programs proceed as expected in the near future. It is important to note that these R&D improvements are not guaranteed, and thus the estimates are meant to represent what could *possibly, but not necessarily*, be achieved in the near future.

### 4) *Carbon Sequestration*

- Natural gas, coal and biomass alternatives also consider an option of carbon sequestration to reduce the emissions of CO<sub>2</sub> and its associated environmental impacts.
- Since sequestration would be too costly for distributed plants, this option is considered only for midsize and central station production facilities.

### 5) *Production Process (steam reforming, partial oxidation, thermal splitting, or gasification)*

- In our analysis, steam reforming is associated with natural gas as the energy source. Natural gas is first catalytically treated with hydrogen to remove sulfur compounds. It is then reformed by mixing it with steam and passing it over a nickel-on-alumina catalyst, making CO and hydrogen. This step is followed by catalytic water-gas shift to convert the CO to hydrogen and CO<sub>2</sub> (emission). Finally, the hydrogen gas is purified with pressure swing adsorption (PSA). The first advantage of generating hydrogen from natural gas for our country would be the availability of the feedstock and infrastructure. Further, natural-gas-to-hydrogen conversion technology is at an advanced stage of development, especially for large plants. On the contrary, relying on natural gas (a nonrenewable resource) for hydrogen production would force the country to increase imports in the future or when its reserves are exhausted.
- Partial oxidation of coal with steam in a high-temperature and elevated-pressure reactor consists of three steps: gasification, production of a synthesis gas (a mixture of hydrogen and CO) and processing of CO with water to produce additional hydrogen and CO<sub>2</sub> (emission). In addition to the advantages and disadvantages listed above (feedstock and infrastructure availability, commercial experience, carbon dioxide emissions), partial oxidation would be more flexible in comparison to other processes because it could allow polygeneration of electricity and hydrogen.

- Nuclear energy could produce hydrogen through thermal splitting of water, that releases no CO<sub>2</sub> emissions but with relatively low energy efficiency. In our analysis, it is assumed that this production process could be made more efficient in the future by significantly raising the water temperature before splitting the molecules, in a range of 700°C to 1000°C. The main advantage of using nuclear as an energy source is that water splitting does not generate any polluting emissions or particulate releases. However, the country does not have any uranium reserves, so relying only on nuclear energy would raise issues of dependency on uranium imports in the future. Nuclear waste disposal schemes and public concerns regarding radiation risks are also considerations.
- Gasification, a thermal conversion technology where a solid fuel is converted into a combustible gas, is among currently available technologies for converting biomass into hydrogen. The main gasification processes include oxygen-blown gasification, pyrolysis and biological gasification. Biomass gasifiers are currently designed to operate at low pressure and are limited to midsize scale operations due to the heterogeneity of biomass, its localized production and the relatively high costs of gathering and transporting the feedstock. Hydrogen production from biomass is an attractive technology as the primary energy is solar with no net CO<sub>2</sub> being released (except for transport). Furthermore, different forms of biomass (bioenergy crops, residues including municipal waste, etc.) could be used in different combinations. However, the current concept of biomass-to-hydrogen conversion process has several possible limitations including low energy efficiency, high costs, soil erosion and impact on biological diversity.

6) *Distribution Process (via pipeline, by truck, or on-site in case of distributed production)*

- The distribution process is strictly related to the scale of production. The centralized manufacture of hydrogen requires a means of transportation as well as intermediate storage capabilities, while distributed manufacture requires only storage at the vehicle facility.
- Since centralized plants produce gaseous hydrogen at sites remote from the user points, they would require the building of a pipeline system. However, pipeline transmission of hydrogen is expected to be highly capital-intensive because of the need for pipes at least 50 percent greater in diameter to achieve the equivalent transmission rate.
- For midsize plants, distribution would be by cryogenic trucks, because the low volumes of hydrogen would not justify the construction of a pipeline system.
- Distributed plants generate hydrogen on-site at the filling station and therefore require no specific distribution system. This last alternative is less capital-intensive than the building of a pipeline coupled to large, dedicated hydrogen manufacturing plants, and is also more economic than continued over-the-road shipping.

### 3 Methodology

A multi-criteria analysis is a well-documented approach to support a decision-making process. The objective of the methodology selected is to rank and test the sensitivity of the hydrogen supply pathways based on economic, environmental and other relevant criteria. It was selected because of the mix of quantitative and qualitative well-to-tank data available (i.e., production, distribution, and dispensing).

In our analysis we used the software VISPA (Valutazione integrata per la scelta tra progetti alternativi), developed by Politecnico di Milano. After having defined pathways and indicators, we assigned each indicator a utility function, to quantify the level of satisfaction of the community for the different alternatives. This method allows us to pass from the initial data set to a new matrix, whose values range from zero to one. In this way, decision-makers are able to make comparisons that otherwise would not be possible because each indicator is originally expressed in a different

unit of measurement. When the new matrix is created, the sensitivity analysis is carried out by assigning a weight to every indicator, according to its relative importance for the decision-maker. Finally, the software ranks the different alternatives in order of preference.

### 3.1 Data Source

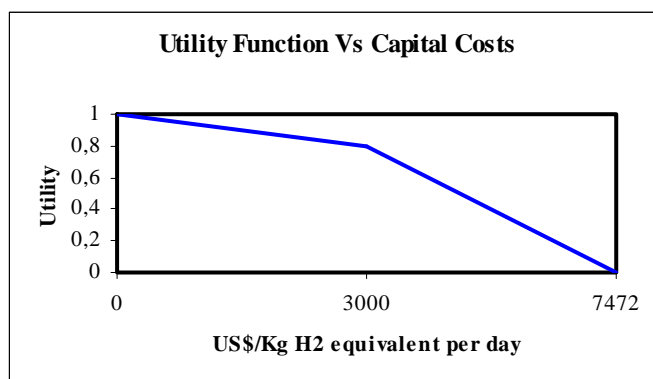
Our primary data source for costs and CO<sub>2</sub> emissions was the report “The hydrogen economy: opportunities, costs, barriers and R&D needs”, published in March 2004 by the US National Research Council of the National Academies. The data used reflects assumptions for the United States, but is also applicable elsewhere.

### 3.2 Indicators

The government uses 14 economic, environmental and qualitative indicators as decision-making criteria. Each of them has a utility function, whose values go from zero to one, that quantifies the level of satisfaction of the entire community for the different alternatives. The shape of the utility function is strictly related to the choice of maximizing (upward slope) or minimizing (downward slope) the indicator.

#### *Economic indicators*<sup>2</sup>

- 1) *Capital investments* (Unit: US\$ per kg of H<sub>2</sub> per day) – The utility function of this indicator has a downward trend that changes its slope at 3,000 US\$/kgH<sub>2</sub>/d, because we initially assumed that this amount corresponds to the country’s daily budget constraint for capital costs. Utility is equal to one if no investments in hydrogen technologies are made, because there is no need to develop a new infrastructure from scratch. Utility is also high if costs are lower than the disposable budget; if they are higher, utility decreases more rapidly and the function becomes steeper. Finally, a utility equal to zero is reached when Alternative 18 (Mid-size biomass centralized plant with carbon sequestration) is realized.



- 2) *Production costs* (Unit: US\$/kg H<sub>2</sub>) – this utility function is downward sloping. Its highest value is attained when Alternative 12 (Coal, centralized, current technology, without carbon sequestration) is realized, while the lowest one corresponds to Alternative 18.
- 3) *Distribution costs and dispensing costs* (Unit: US\$/kg H<sub>2</sub>) – Distribution costs are associated to the transportation of hydrogen by pipeline or cryogenic truck to the filling station, while dispensing costs are related to the compression, storage and dispensation of hydrogen at the

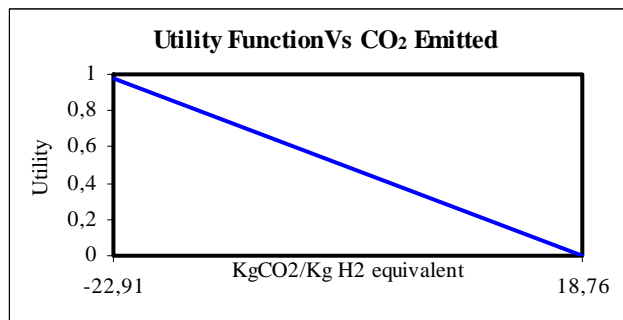
<sup>2</sup> These indicators need to be minimized, with the exception of carbon tax.

filling station. Midsize plants with current technology have the highest distribution and dispensing costs, while distributed plants obviously have the lowest costs because they produce hydrogen on site and dispense it directly on board.

- 4) *Carbon sequestration* (Unit: US\$/kg CO<sub>2</sub>) – We assumed that the cost of transporting and sequestering CO<sub>2</sub> is about 0.01 US\$/kg of carbon dioxide. Among the technologies involving carbon sequestration, the lowest cost is associated to the centralized steam reforming plant with future technology. Alternative 18 has the highest costs for carbon sequestration.
- 5) *Carbon Tax* (Unit: US\$/kg CO<sub>2</sub>) – A tax on CO<sub>2</sub> emissions, at a rate of about 0.05 US\$/kg of carbon dioxide emitted, is imposed on polluting companies and cannot be incorporated in retail prices. In our analysis the decision-maker wants to maximize carbon tax proceeds in order to finance other environmental or hydrogen R&D projects and to discourage companies from polluting. For this reason the carbon tax utility function has an upward slope.

### ***Environmental indicators***<sup>3</sup>

- 6) *CO<sub>2</sub> Emissions* (Unit: kg CO<sub>2</sub>/kg H<sub>2</sub> equivalent) – Estimates of CO<sub>2</sub> emissions are related only to the fuel production and distribution chain, without taking into account tank-to-wheel emissions.<sup>4</sup> The greatest utility corresponds to Alternative 18, which has negative emissions for the generation of hydrogen from biomass with carbon sequestration. This occurs because growing the biomass takes CO<sub>2</sub> from the atmosphere and the carbon dioxide emitted from the gasification process is sequestered. The highest carbon emissions are, not surprisingly, associated with a hydrogen production technology that uses coal as an energy source (Alternative 11).



- 7) *Criteria Emissions* (Unit: %) – This indicator represents the potential change in criteria emissions (as a weighted average by toxicity for NO<sub>x</sub>, CO and VOC) from the supply chain compared to the reference scenario (assuming all hydrogen is consumed by comparable vehicle fleets).
- 8) *Energy Efficiency* (Unit: %) – This indicator represents the total energy output over the total energy input for the supply chain. The more efficient is the process, the higher the utility. Well-to-tank energy efficiency of gasoline over petroleum still represents the best option, while Alternative 15 (Nuclear water thermal splitting) is the least efficient.

<sup>3</sup> All these indicators need to be minimized, except energy efficiency.

<sup>4</sup> For Alternative 0, estimates refer to the carbon dioxide released into the atmosphere per gallon of gasoline produced, considering that the energy content of 1 kg of H<sub>2</sub> is approximately equal to that of 1 gallon of gasoline.

- 9) *Land Consumption/Intrusion* (0=no additional intrusion, 6=max additional intrusion) – This qualitative indicator measures the additional impact the building of a new hydrogen infrastructure could have on the environment. In deciding the value each alternative should be given, we made several assumptions:
- Centralized plants are more intrusive than midsize and distributed ones, because they require the building of a pipeline system dedicated to hydrogen transportation. Among centralized plants, nuclear ones are the most intrusive, because they create some concerns regarding waste disposal.
  - Distributed alternatives are the least intrusive because they may reuse existing facilities.
  - CO<sub>2</sub> sequestration makes use of old wells and thus causes no additional intrusion.
  - Future technologies will lower environmental intrusion.
- 10) *Decommissioning Impact* (0=no additional impact, 2=highest additional impact) – This is a qualitative indicator of the relative level of environmental impact including clean-up, dismantling, waste disposal and other activities after operations at a hydrogen production, distribution or dispensing facility have stopped. It is referenced to additional decommissioning impact over the baseline (i.e., alternative zero). The selected values are a function of the feedstock used in the production process rather than the scale of the plant. In this logic, nuclear (Alternative 15) is the only pathway with the highest additional impact because of the long lasting impacts posed by its waste. There can also be large, long-term impacts for nuclear facilities, but they are not well understood since few nuclear facilities have been decommissioned to date. Coal and biomass pathways receive an intermediate score because of the expected additional impact of their facilities and waste after operations cease. Natural gas pathways, however, are expected not to create any additional impact over the current gasoline/diesel supply systems.

#### *Other qualitative indicators*<sup>5</sup>

- 11) *Construction Time* (0=no time, 6=max time) – Besides linking construction time to the plant scale, we made the following hypotheses:
- Carbon sequestration adds to the project time.
  - Nuclear plants are the most time-consuming, because of prolonged permitting periods due to public opposition.
  - Future technologies lower construction time.
- 12) *Infrastructure risk* (0=no additional risk, 6=highest additional risk) - This qualitative indicator measures the risk of potential accidents that could occur if a new hydrogen infrastructure was built, considering both their frequency and severity. Because a great number of distributed plants is necessary to supply the entire country, we assumed that their total risk is higher. This could also be due to the problematic organization of an effective monitoring on the functioning of the plants. Furthermore, future technologies lower infrastructure risk.
- 13) *Energy Security* (0=no additional energy security, 2=max additional energy security) – Since our hypothetical country only has big coal reserves, additional energy security is maximized when alternatives employing this feedstock are implemented. On the other hand, the fact of

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<sup>5</sup> All these indicators need to be minimized, with the exception of energy security.

being dependent on oil and uranium imports makes the country more vulnerable, thus supplying no additional energy security.

### 3.3 Scenarios

In our sensitivity analysis four different scenarios, with different weights assigned to the fourteen decision-making criteria, are taken into consideration. We initially assumed that an average price of 30 US\$/bbl would remain constant over the entire life cycle of the project (Case 1).

In scenario A, all objectives are given the same importance, except for capital investment costs, whose importance is doubled relative to the other parameters because, besides their considerable impact on the country's budget, they are upfront costs. In the budget-sensitive (B) scenario the decision-maker assigns a higher weight to the costs linked to the development of a new infrastructure and to the carbon tax proceeds of the carbon tax. In scenario C, environmental benefits linked to the use of hydrogen are given more importance, but capital investments are always doubled relative to other economic indicators. The case the government prefers to achieve energy security objectives (D) is also considered.

The weights for the 14 indicators under each scenario is listed below:

*Table 2: Weight of Indicators Under Each Scenario*

Indicators	Scenarios			
	A	B	C	D
Capital Investment	2	4	2	2
Production Costs	1	2	1	1
Distribution Costs	1	2	1	1
Dispensing Costs	1	2	1	1
CO2 Disposal Cost (Seq.)	1	2	1	1
Carbon Tax	1	2	1	1
CO2 Emitted	1	1	2	1
Criteria Emissions	1	1	2	1
Overall Energy Efficiency	1	1	2	1
Land Consumption/ Intrusion	1	1	2	1
Construction Time	1	1	1	1
Infrastructure Risk	1	1	1	1
Energy Security	1	1	1	2
Decommissioning	1	1	1	1

Four additional scenarios (Case 2) are created with reference to a higher average oil price case of US\$40 but using the same weights for the indicators. The idea is that if higher oil prices persist for a long period of time, a petroleum-importing country may consider with greater attention the possibility of switching to an alternative fuel that can be obtained from several different sources, such as hydrogen. Case 2 is practically achieved by increasing the production cost of Alternative 0 from \$0.93 (under Case 1) to \$1.24 per kg of hydrogen equivalent, reflecting the 33% increase in price of the feedstock (petroleum) to the process. Moreover, it is assumed that production costs for other fossil fuels (i.e. natural gas) under Case 2 do not change because the country is able to produce or achieve the same price for these feedstocks.

Scenarios:	A	B	C	D
<b>Case 1 (\$30/bbl):</b>	Business as Usual (BAU)	Budget-Sensitive World	Environmentally-Sensitive World	Domestic Energy Priority
<b>Case 2 (\$40/bbl):</b>	Same Attitudes, Higher Oil Price	Budget-Sensitive World	Environmentally-Sensitive World	Domestic Energy Priority

## 4 Results

The outcome of the analysis under each scenario is shown in Table 3 for Case 1 and Table 4 for Case 2. These tables list the ranking of each pathway based on the summed score for all indicators. It can be seen that in the first case (petroleum price at \$30 per barrel), alternative zero is best under all scenarios. Its position is quite robust in scenarios A1 and B1, less so under scenario C1, and nearly equal to Alternative 10 under scenario D1. For the second case (petroleum price at \$40 per barrel), alternative zero is still the best alternative for scenarios A2, B2, and C2. There is a rank reversal, however, under scenario D2 as Alternative 10 becomes best. The next section will describe in detail the sensitivity of these results.

*Table 3: Ranking of Alternatives for Case 1 (\$30/bbl Petroleum Price)*

Rank	Scenario A1		Scenario B1		Scenario C1		Scenario D1	
	Alternative	Total Score	Alternative	Total Score	Alternative	Total Score	Alternative	Total Score
1	ALT0	0.792	ALT0	0.828	ALT0	0.758	ALT0	0.742
2	10-DGFN	0.758	10-DGFN	0.795	10-DGFN	0.734	10-DGFN	0.742
3	2-CGFN	0.721	2-CGFN	0.753	2-CGFN	0.695	2-CGFN	0.707
4	6-MGFN	0.696	6-MGFN	0.715	6-MGFN	0.689	6-MGFN	0.684
5	4-CGFY	0.673	12-CCFN	0.71	4-CGFY	0.655	12-CCFN	0.668
6	9-DGCN	0.664	9-DGCN	0.701	8-MGFY	0.649	4-CGFY	0.662
7	1-CGCN	0.653	4-CGFY	0.696	9-DGCN	0.639	9-DGCN	0.654
8	12-CCFN	0.646	1-CGCN	0.69	1-CGCN	0.626	1-CGCN	0.644

*Table 4: Ranking of Alternatives for Case 2 (\$40/bbl Petroleum Price)*

Rank	Scenario A2		Scenario B2		Scenario C2		Scenario D2	
	Alternative	Total Score	Alternative	Total Score	Alternative	Total Score	Alternative	Total Score
1	ALT0	0.787	ALT0	0.821	ALT0	0.754	10-DGFN	0.742
2	10-DGFN	0.758	10-DGFN	0.795	10-DGFN	0.734	ALT0	0.737
3	2-CGFN	0.721	2-CGFN	0.753	2-CGFN	0.695	2-CGFN	0.707
4	6-MGFN	0.696	6-MGFN	0.715	6-MGFN	0.689	6-MGFN	0.684
5	4-CGFY	0.673	12-CCFN	0.71	4-CGFY	0.655	12-CCFN	0.668
6	9-DGCN	0.664	9-DGCN	0.701	8-MGFY	0.649	4-CGFY	0.662
7	1-CGCN	0.653	4-CGFY	0.696	9-DGCN	0.639	9-DGCN	0.654
8	12-CCFN	0.646	1-CGCN	0.69	1-CGCN	0.626	1-CGCN	0.644

### 4.1 Sensitivity Analysis

A detailed sensitivity analysis was performed on each scenario by altering the weight of each indicator. The following tables summarize the sensitivity of the best alternative to each indicator

based on the relative weights selected. The most competitive alternatives are highlighted by criteria with the relative weight required for a rank reversal. In these tables, “Sensitivity on Right” means increasing weight of indicator, while “Sensitivity on Left” means decreasing weight of indicator. In general, the criteria that are most contestable appear to be potential criteria emissions reductions, energy efficiency and energy security.

*Scenario A1*

<b>Criteria</b>	<b>Weights</b>	<b>Sensitivity on Left</b>	<b>Sensitivity on Right</b>
CAPITAL	0,133	-	-
PRODCOST	0,067	-	2,784 -> 12-CCFN
DISTR COST	0,067	-	0,737 -> 10-DGFN
DISPECOST	0,067	-	0,298 -> 10-DGFN
CO2SEQUEST	0,067	-	-
CARBONTAX	0,067	-	0,24 -> 10-DGFN
CO2EMISS	0,067	-	0,69 -> 19-MBFY
CRITEMISS	0,067	-	0,113 -> 10-DGFN
ENERGYEFF	0,067	-	-
LAND	0,067	-	-
CONSTTIME	0,067	-	-
INFRASTRISK	0,067	-	-
ENERGYSEC	0,067	-	0,134 -> 10-DGFN
DECOMM	0,067	-	-

*Scenario B1*

<b>Criteria</b>	<b>Weights</b>	<b>Sensitivity on Left</b>	<b>Sensitivity on Right</b>
CAPITAL	0.182	-	-
PRODCOST	0.091	-	2.295 -> 12-CCFN
DISTR COST	0.091	-	0.747 -> 10-DGFN
DISPECOST	0.091	-	0.317 -> 10-DGFN
CO2SEQUEST	0.091	-	-
CARBONTAX	0.091	-	0.261 -> 10-DGFN
CO2EMISS	0.045	-	0.777 -> 19-MBFY
CRITEMISS	0.045	-	0.091 -> 10-DGFN
ENERGYEFF	0.045	-	-
LAND	0.045	-	-
CONSTTIME	0.045	-	-
INFRASTRISK	0.045	-	-
ENERGYSEC	0.045	-	0.111 -> 10-DGFN
DECOMM	0.045	-	-

*Scenario C1*

<b>Criteria</b>	<b>Weights</b>	<b>Sensitivity on Left</b>	<b>Sensitivity on Right</b>
CAPITAL	0.105	-	
PRODCOST	0.053	-	3.608 -> 12-CCFN
DISTR COST	0.053	-	0.53 -> 10-DGFN
DISPECOST	0.053	-	0.217 -> 10-DGFN
CO2SEQUEST	0.053	-	-
CARBONTAX	0.053	-	0.176 -> 10-DGFN
CO2EMISS	0.105	-	0.654 -> 19-MBFY
CRITEMISS	0.105	-	0.138 -> 10-DGFN
ENERGYEFF	0.105	0.029 -> 10-DGFN	-
LAND	0.105	0.011 -> 2-CGFN	-
CONSTTIME	0.053	-	
INFRASTRISK	0.053	0.005 -> 10-DGFN	-
ENERGYSEC	0.053	-	0.1 -> 10-DGFN
DECOMM	0.053	-	-

*Scenario D1*

<b>Criteria</b>	<b>Weights</b>	<b>Sensitivity on Left</b>	<b>Sensitivity on Right</b>
CAPITAL	0.125	0.124 -> 10-DGFN	-
PRODCOST	0.063	0.062 -> 10-DGFN	1.442 -> 12-CCFN
DISTR COST	0.063	-	0.066 -> 10-DGFN
DISPECOST	0.063	-	0.064 -> 10-DGFN
CO2SEQUEST	0.063	-	-
CARBONTAX	0.063	-	0.063 -> 10-DGFN
CO2EMISS	0.063	0.062 -> 10-DGFN	0.504 -> 19-MBFY
CRITEMISS	0.063	-	0.063 -> 10-DGFN
ENERGYEFF	0.063	0.062 -> 10-DGFN	-
LAND	0.063	0.061 -> 10-DGFN	-
CONSTTIME	0.063	0.062 -> 10-DGFN	-
INFRASTRISK	0.063	0.062 -> 10-DGFN	-
ENERGYSEC	0.125	-	0.125 -> 10-DGFN
DECOMM	0.063	-	-

*Scenario A2*

<b>Criteria</b>	<b>Weights</b>	<b>Sensitivity on Left</b>	<b>Sensitivity on Right</b>
CAPITAL	0.133	-	-
PRODCOST	0.067	-	0.913 -> 2-CGFN
DISTR COST	0.067	-	0.637 -> 10-DGFN
DISPECOST	0.067	-	0.263 -> 10-DGFN
CO2SEQUEST	0.067	-	-
CARBONTAX	0.067	-	0.214 -> 10-DGFN
CO2EMISS	0.067	-	0.678 -> 19-MBFY
CRITEMISS	0.067	-	0.106 -> 10-DGFN
ENERGYEFF	0.067	-	-
LAND	0.067	-	-
CONSTTIME	0.067	-	-
INFRASTRISK	0.067	0.01 -> 10-DGFN	-
ENERGYSEC	0.067	-	0.124 -> 10-DGFN
DECOMM	0.067	-	-

*Scenario B2*

<b>Criteria</b>	<b>Weights</b>	<b>Sensitivity on Left</b>	<b>Sensitivity on Right</b>
CAPITAL	0.182	-	-
PRODCOST	0.091	-	0.952 -> 12-CCFN
DISTR COST	0.091	-	0.61 -> 10-DGFN
DISPECOST	0.091	-	0.27 -> 10-DGFN
CO2SEQUEST	0.091	-	-
CARBONTAX	0.091	-	0.225 -> 10-DGFN
CO2EMISS	0.045	-	0.761 -> 19-MBFY
CRITEMISS	0.045	-	0.081 -> 10-DGFN
ENERGYEFF	0.045	-	-
LAND	0.045	-	-
CONSTTIME	0.045	-	-
INFRASTRISK	0.045	-	-
ENERGYSEC	0.045	-	0.097 -> 10-DGFN
DECOMM	0.045	-	-

*Scenario C2*

Criteria	Weights	Sensitivity on Left	Sensitivity on Right
CAPITAL	0.105	-	-
PRODCOST	0.053	-	0.81 -> 2-CGFN
DISTR COST	0.053	-	0.45 -> 10-DGFN
DISPECOST	0.053	-	0.19 -> 10-DGFN
CO2SEQUEST	0.053	-	-
CARBONTAX	0.053	-	0.156 -> 10-DGFN
CO2EMISS	0.105	0.003 -> 10-DGFN	0.645 -> 19-MBFY
CRITEMISS	0.105	-	0.133 -> 10-DGFN
ENERGYEFF	0.105	0.041 -> 10-DGFN	-
LAND	0.105	0.017 -> 2-CGFN	-
CONSTTIME	0.053	-	-
INFRASTRISK	0.053	0.013 -> 10-DGFN	-
ENERGYSEC	0.053	-	0.092 -> 10-DGFN
DECOMM	0.053	-	-

*Scenario D2*

Criteria	Weights	Sensitivity on Left	Sensitivity on Right
CAPITAL	0.125	-	0.159 -> ALTO
PRODCOST	0.063	-	0.08 -> ALTO
DISTR COST	0.063	-	-
DISPECOST	0.063	0.031 -> ALTO	-
CO2SEQUEST	0.063	-	-
CARBONTAX	0.063	0.039 -> ALTO	0.529 -> 12-CCFN
CO2EMISS	0.063	-	0.086 -> ALTO
CRITEMISS	0.063	0.056 -> ALTO	2.282 -> 15-CNFN
ENERGYEFF	0.063	-	0.077 -> ALTO
LAND	0.063	-	0.09 -> ALTO
CONSTTIME	0.063	-	0.076 -> ALTO
INFRASTRISK	0.063	-	0.072 -> ALTO
ENERGYSEC	0.125	0.116 -> ALTO	0.272 -> 12-CCFN
DECOMM	0.063	-	-

## 4.2 Limitations

This work was based on numerous assumptions chosen to simplify the problem and render the analysis feasible yet useful. For example, we have dealt only with supply of hydrogen for fuel cell vehicles yielding a given and constant level of demand. In reality, there would be a dynamic balance of supply and demand over time. To that end, the penetration of fuel cell vehicles would need to be modeled. Nonetheless, knowing these limitations is important to understand the significance of the results and suggest possible future areas of improvement and next steps for this work.

Secondly, the indicators chosen represent the best set of available measures in common for all alternatives. For a multi-criteria analysis, the indicators should ideally be exhaustive, non-redundant and mutually independent. However, this is very difficult to achieve in practice. Some indicators are of a qualitative nature, thereby introducing the possibility of unwanted subjectivity. Moreover, the quantitative data is based primarily on a single source (NRC, 2004) and perhaps could be improved with diversification of sources.

Thirdly, the scenarios are intended to cover a realistic range of attitudes and possible conditions, but they are arbitrary. Ideally, the scenarios would be country specific and based on the documented perceptions of the government decision-makers or through public opinion surveys.

As for the analysis, most of the utility functions usually have a simplistic linear shape, whereas in reality they may be quite different. Furthermore, we may not have considered all possible alternatives, nor the combination of the alternatives selected. Many observers see the latter in particular as a likely development situation for hydrogen infrastructure.

Finally, this analysis may not be considering all possible factors affecting a hydrogen-based economy. For instance, public incentives (e.g., government subsidies, funding for R&D, tax breaks) or the timely adoption of codes and standards may have an important impact of the development of the infrastructure.

## **5 Conclusions**

Alternative zero (no project) appears to be a robust best alternative for Scenarios A1 and A2. For Scenarios B1, B2, C1, C2, and D1, Alternative zero is again the best alternative but its position is highly contested by Alternative 10 (Distributed, Natural Gas, Future without Sequestration). A rank reversal is achieved only under Scenario D2, but Alternative 10 is highly contested by Alternative 0. The most sensitive criteria appear to be criteria emissions and energy security.

In summary, it appears to be very difficult to beat the existing energy supply system of gasoline/diesel for vehicles (i.e., Alternative zero) in terms of cost even when considering near future technologies. Increased environmental sensitivity generally favors hydrogen supply alternatives but a rank reversal is most easily accomplished when energy security is highly weighted. Natural gas alternatives (via steam reforming) seem to be most competitive overall, particularly in the near future under Alternatives 10, 2 and 6.

## **6 Reference**

U.S. National Research Council (NRC), National Academy of Engineering. (March 2004). "The Hydrogen Economy: Opportunities, Costs, Barriers and R&D Needs".

## **7 Acknowledgements**

This work was performed while the authors were master's level students at Scuola Enrico Mattei – Eni Corporate University. The authors would like to acknowledge the support received from Scuola Enrico Mattei and particularly from the following individuals:

- Giorgio Ballardin, Researcher, Scuola Enrico Mattei
- Sandro Furlan, Professor, Scuola Enrico Mattei
- Eliot Laniado, Professor, Politecnico di Milano
- Marco Migliavacca, Zincar, AEM
- Budi Permana, Fellow Student, Scuola Enrico Mattei
- Riccardo Nava, SOL Group
- Enzo Rusconi, ENEA

## Appendix: Complete Matrix of Data Used for the Analysis

	<b>Plant Scale</b>	Existing	Centralized	Centralized	Centralized	Centralized	Mid-Size	Mid-Size	Mid-Size	Mid-Size	Distributed
	<b>Energy Source</b>	Petroleum	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Natural Gas
	<b>Technology</b>	Current	Current	Future	Current	Future	Current	Future	Current	Future	Current
	<b>Sequestration</b>	No	No	No	Yes	Yes	No	No	Yes	Yes	No
	<b>Production Process</b>	Gasoline	Reforming	Reforming	Reforming	Reforming	Reforming	Reforming	Reforming	Reforming	Reforming
	<b>Distribution Process</b>	Existing	Pipeline	Pipeline	Pipeline	Pipeline	Truck	Truck	Truck	Truck	On-Site
<b>Indicators</b>	<b>Units</b>	<b>Alt 0</b>	<b>1-CGCN</b>	<b>2-CGFN</b>	<b>3-CGCY</b>	<b>4-CGFY</b>	<b>5-MGCN</b>	<b>6-MGFN</b>	<b>7-MGCY</b>	<b>8-MGFY</b>	<b>9-DGCN</b>
Capital Investment	US\$/kg H2 per day	0	1577	1139	1719	1222	3206	1861	3529	2105	3854
Production Costs	US\$/kg H2 equivalent	0.93	1.03	0.92	1.22	1.02	1.38	1.20	1.67	1.46	3.51
Distribution Costs	US\$/kg H2 equivalent	0.09	0.42	0.31	0.42	0.31	1.80	1.10	1.80	1.10	0.00
Dispensing Costs	US\$/kg H2 equivalent	0.09	0.54	0.39	0.54	0.39	0.62	0.30	0.62	0.30	0.00
CO2 Disposal Cost (Seq.)	US\$/kg H2 equivalent	0	0.00	0.00	0.09	0.08	0.00	0.00	0.09	0.09	0.00
Carbon Tax	US\$/kg H2 equivalent	0.08	0.13	0.12	0.02	0.02	0.13	0.12	0.02	0.02	0.17
CO2 Emitted	kg CO2/kg H2 equivalent	5	9.22	8.75	1.53	1.30	9.83	9.12	1.71	1.53	12.13
Potential Reduction in Criteria Emissions	%	0.00	-83	-83	-83	-83	-83	-83	-83	-83	-83
Overall Energy Efficiency	% (total output/total input)	79.5	72	78	61	68	69	75	63	67	56
Land Consumption/Intrusion	qualitative (0=no additional intrusion, 6=max additional intrusion)	0	5	4	5	4	3	2	3	2	2
Construction Time	qualitative (0=no time, 6=max time)	0	5	4	6	5	5	4	6	5	3
Infrastructure Risk	qualitative (0=no additional risk, 6=highest additional risk)	0	2	1	2	1	3	2	3	2	4
Energy Security	qualitative (0=no additional security, 2=max security)	0	1	1	1	1	1	1	1	1	1
Decommissioning	qualitative (0=no additional, 2=highest impact)	0	0	0	0	0	0	0	0	0	0

	<b>Plant Scale</b>	Distributed	Centralized	Centralized	Centralized	Centralized	Centralized	Centralized	Mid-Size	Mid-Size	Mid-Size	Mid-Size
	<b>Energy Source</b>	Natural Gas	Coal	Coal	Coal	Coal	Coal	Nuclear	Biomass	Biomass	Biomass	Biomass
	<b>Technology</b>	Future	Current	Future	Current	Future	Future	Future	Current	Future	Current	Future
	<b>Sequestration</b>	No	No	No	Yes	Yes	No	No	No	No	Yes	Yes
	<b>Production Process</b>	Reforming	Oxidation	Oxidation	Oxidation	Oxidation	Th. Splitting	Gasification	Gasification	Gasification	Gasification	Gasification
	<b>Distribution Process</b>	On-Site	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Pipeline	Truck	Truck	Truck	Truck
<b>Indicators</b>	<b>Units</b>	<b>10-DGFN</b>	<b>11-CCCN</b>	<b>12-CCFN</b>	<b>13-CCCY</b>	<b>14-CCFY</b>	<b>15-CNFN</b>	<b>16-MBCN</b>	<b>17-MBFN</b>	<b>18-MBCY</b>	<b>19-MBFY</b>	
Capital Investment	US\$/kg H2 per day	2000	2159	1590	2180	1609	2924	7353	3608	7472	3670	
Production Costs	US\$/kg H2 equivalent	2.33	0.96	0.71	1.03	0.77	1.63	4.63	2.21	4.82	2.32	
Distribution Costs	US\$/kg H2 equivalent	0.00	0.42	0.31	0.42	0.31	0.31	1.80	1.10	1.80	1.10	
Dispensing Costs	US\$/kg H2 equivalent	0.00	0.54	0.39	0.54	0.39	0.39	0.62	0.30	0.62	0.30	
CO2 Disposal Cost (Seq.)	US\$/kg H2 equivalent	0.00	0.00	0.00	0.16	0.15	0.00	0.00	0.00	0.26	0.17	
Carbon Tax	US\$/kg H2 equivalent	0.14	0.26	0.23	0.04	0.03	0.00	0.03	0.01	-0.31	-0.21	
CO2 Emitted	kg CO2/kg H2 equivalent	10.34	18.76	16.73	3.00	2.21	0.00	2.06	1.03	-22.91	-15.58	
Potential Reduction in Criteria Emissions	%	-83	15	15	15	15	-100	-9	-9	-9	-9	
Overall Energy Efficiency	% (total output/total input)	65	57	66	54	61	35	33	52	37	49	
Land Consumption/Intrusion	qualitative (0=no additional intrusion, 6=max additional intrusion)	1	5	4	5	4	6	3	2	3	2	
Construction Time	qualitative (0=no time, 6=max time)	2	5	4	6	5	6	5	4	6	5	
Infrastructure Risk	qualitative (0=no additional risk, 6=highest additional risk)	3	2	1	2	1	6	3	2	3	2	
Energy Security	qualitative (0=no additional security, 2=max security)	1	2	2	2	2	0	2	2	2	2	
Decommissioning	qualitative (0=no additional, 2=highest impact)	0	1	1	1	1	2	1	1	1	1	