**Linking micro to macro in sustainability analysis: the case of hydrogen based public bus services [a]**

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**Abstract.** Lessening environmental damage due to transport and energy related economic activities is one of the most challenging topics associated with sustainability. The introduction of environmentally friendly innovations in those sectors are included in the list of priorities of the European Union political agenda. Considering hydrogen as an energy carrier could be part of the solution. This paper investigates economic and environmental consequences of the introduction of hydrogen and fuel cell technology in the european economic system by applying environmental input output analysis and life cycle tools. The results of the analysis are based on the assumptions that hydrogen is produced through the reforming of natural gas and it is indirectly demanded by consumers through the use of transport services provided by fuel cell buses. We have built three scenarios (related to both prototype and mass production cost of fuel cell technology): according to the first, 10% of the current public transport’s demand shifts instantaneously to the new transport service provided by fuel cell buses; the second scenario shows the increase in final demand needed to maintain fixed the yearly transit supply previously offered by conventional diesel buses; the third scenario reproduces the effects of a proportional decrease on each product final demand necessary to

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maintain fixed both the total final demand and the yearly transit supply. Finally we compare the environmental impact and the economic value linked to the previous alternatives through the implementation of eco-efficiency analysis. Structural changes are needed to preserve environmental quality hence efficient alternatives have to be compared and chosen accordingly to priorities. The introduction of green technologies at the micro level does not directly end up with environmental improvements at the macro level.

Key words: Environmental input-output; Life Cycle Assessment; Hydrogen and Fuel cell technology; Eco-efficiency.

## I. Introduction

Our socio-economic system, highly supported by the employment of energy, has resulted in an increase of greenhouse gas emissions along with other pollutants. Among others, road transportations, public electricity and heat production represent the key sources that mostly contribute to the raise of air pollution level (EEA, 2005). In this regards, hydrogen might be a desirable alternative.

Hydrogen can be obtained by numerous primary sources like natural gas and coal via steam methane reforming and via partial oxidation (or gasification) or by renewable sources as water (via electrolysis) or biomass (via gasification). Differences among available production paths depend on the cost of the conversion process and on the environmental impacts of production activities. Among the possibilities previously listed, water and biomass paths are costlier than natural gas and coal processes, with results varying accordingly to the different method of distribution (Simbeck and Chang, 2002).

Hydrogen is an high efficiency energy carrier. It is  also a zero-emissions fuel, but only if obtained by renewable energy sources (or nuclear energy). In this concern, R&D projects are also focused on carbon dioxide capture. Depending on the technological improvements, in the medium term hydrogen may be produced through reforming of natural gas or coal gasification in centralized plants with carbon dioxide sequestration and storage (IEA, 2005).

If we think about hydrogen as energy carrier, fuel cells (FC) have a primary role. The technical applications of FC are intended for both mobile and stationary applications (Pehnt, 2003; Weiss et al., 2003). "Fuel cells have the potential to replace the internal combustion engine in vehicles and to provide power in stationary and mobile applications because they are energy efficient, clean and fuel flexible." (EERE, 2005). The ideal candidate are the proton exchange membrane fuel cells (PEMFCs) for their high efficiency and the possible employment in both stationary and mobile power systems. The European Union envisages hydrogen representing 5% of the transportation fuels by 2020 and a significant penetration of fuel cells for combine heat and power system (IEA, 2005).

What if hydrogen will be introduced in the European Union's economic system? What will the economic and environmental effects be if part of the public transport services currently provided by diesel buses will be replaced by services provided by fuel cell buses?

The present paper make use of detailed information from the project CUTE (2004) and other technical sources on fuel cell technology and hydrogen infrastructure (see for instance Carlson et al., 2005; Simbeck et al., 2002) in order to compare the current system running on diesel buses with an alternative system working with fuel cell (FC) buses supported by large scale production of hydrogen via steam methane reforming (hydrogen-based subsystem).

By applying static environmental input-output analysis (Miller and Blair, 1985) and life cycle assessment tools (Guineè et al., 2002) to the European Union (EU 25) economic system in 2005, we show the yearly economic and environmental effects of the introduction of the new subsystem considering two alternatives related to fuel cell technology: the prototype cost and the mass production cost. We have then built different scenarios for both of the two cases. Concerning the former situation, we developed an analysis that results in the comparison between diesel and FC buses assuming that 10% of the current public transport's demand shifts instantaneously to the new public hydrogen transport services. In the latter case we illustrate three modelling versions: the first one is the same as the prototype case; the second one reproduces the effects of an increase in total final demand expenditure if the yearly transit supply that would be offered by the conventional diesel buses with the same previous amount of expenditure (10% of the traditional Local and Suburban Transit industry) were instead provided by fuel cell buses; the third one simulates a proportional reduction on each product final demand sufficient to cover the same yearly bus transit supply previously computed .

The three modelling versions mentioned before answer respectively to the following questions: what if, in order to make use of FC buses, we will accomplish a reduction of the number of kilometres otherwise offered by diesel buses? What if we will let the total final demand increase in order to maintain the same mileage run by diesel buses? And finally what if we will maintain the same mileage and a fixed total final demand?

We start from the results of the EIPRO (CEDAEU25) model (Tukker et al., 2005) that describes which environmental problems can be attributed to a certain product and what's the contribution of that product in the overall environmental impact of economic activities in the european context.

The next step is concerned with the simulation of the hydrogen-based subsystem. We introduce in the EIPRO model a new interdependent subsystem. The analysis at the industry level shows the economic and environmental effects of the system from a microeconomic perspective, with regards both to the supply chain and the final use. While the results, from the entire economy point of view, describe the consequences at the macroeconomic level: the changes that will occur if the traditional system is replaced by the partly hydrogen-based economic system. As short term proposal, this specific hydrogen-based system might be an option for environmental policies. The EIO analysis gives useful insights in terms of collecting information about direct and indirect effects of demand shifts. The environmental consequences due to the hydrogen sub-system are interpreted according to the life cycle assessment method (LCA): we'll show the results related to three impact categories that are relevant for the study: global warming, photochemical oxidation and acidification.

The last phase is the computation of the Eco-efficiency ratio (Huppes and Ishikawa, 2005) that illustrates the relation between environment and economy in terms of reduction/increase of environmental damage and of deterioration/improvement of economic performances. Structural changes are needed to preserve environmental quality. Win-win situations could be possible but we must recognize that actions will be costly and new alternatives should be compared and chosen accordingly to priorities (Millennium Ecosystem Assessment, 2005).

The rest of the paper is organized as follow. Section II illustrates the EIPRO model along with a brief introduction on input-output methodology. Section III describes the eco-efficiency analysis in the EIO framework. Section IV describes the assumptions and the datasets employed. Section V contains the interpretation of the results and, finally, section VI discusses and concludes.

## II. The model: environmental input-output analysis and life cycle assessment

The input-output analysis was devised by Wassily Leontief (Leontief, 1941). Subsequently it was extended to the analysis of the interregional flows, environment and employment, associated to the industrial production.

The model of input-output is constructed from the data observed in a particular economic area (nation, region etc). Assuming to consider a country, its territory can be thought of as subdivided in a number of productive sectors, for instance manufacturing sector or, more precisely, textile sector, knit fabric mills and so on (Miller and Blair, 1985). The market exchanges among sectors are represented by the sales or the purchases of material and immaterial goods.

Beyond the mutual exchanges, the sectors benefit from the sales to external subjects, like the final consumers and foreign countries, and from the purchases of factors external to the interindustry flows like labour force, capital and imported goods. These variable are represented respectively in the columns and rows external to the transaction matrix and are usually defined as final demand (private and public consumption, gross investment and exports) in the case of the columns, added value (employees compensation, interest payments, profits etc.) and imports in the case of the rows.

In technical terms we have a system of linear equations that represent the equality between the total production of a sector and the sum of its sales to both other sectors and final consumers, and export flows to other countries.

Defining $X_i$ sector *i* total output and $z_{i,j}$ and $Y_i$ respectively the amount of sales to sector *j* and sector *i*'s final demand, it follows that

$$X_i = z_{i1} + z_{i2} + ... + z_{in} + Y_i \text{, for } i = 1,..,n . \qquad [1]$$

The lacked illustration of external rows in eq. [1], previously defined added value and imports, is justified by the implications of the accounting identity that, accompanied by the hypotheses of fixed relation between each input and the output of a sector (constant return to scale) and fixed proportions among inputs, constitutes the formal constrain of the model.

The relations between sectors' inputs and outputs are called technical coefficients. They are shown by the expression:

$$a_{ij} = \frac{z_{ij}}{X_j}, \qquad [2]$$

where the coefficient $a_{ij}$ describes the direct amount of good *i* needed to produce a unit of good *j*.

Through a few substitutions and in matrix form, the system can be rewritten as:

$$(I - A)\, X = Y , \qquad [3]$$

or

$$X = (I - A)^{-1} Y , \qquad [4]$$

where $X$ is the vector of industry outputs, $I$ is the identity matrix, $A$ is the technology matrix containing the technical coefficients $a_{ij}$ and $Y$ is the vector of final demand.

The previous discussion refers to input-output analysis in its classic shape. Leontief, in an article of the 1970, proposed an environmental input-output model (EIO). It studies the effects of the environmental impacts, considered in their various forms, through the construction of direct impact coefficients contained in matrix *B*. Such coefficients translate the relation between the amount of pollutants and the level of production of the sectors.

If we post-multiply the Leontief inverse matrix for the direct impact coefficients matrix *B*, and what results times the vector of final demand *Y*, we will determine the vector of total environmental interventions (direct and indirect) due to the production of goods needed to sustain the final demand of the economy:

$$m = [\, B\,(I - A)^{-1}\,]\, Y \,. \qquad [5]$$

Each element $m_i$ of the vector $m$ denotes the total amount of impact/pollutant $i$ generated by the entire economy.

The EIO methodology has been applied to the EU25 in 2005 with some specifications related to both the technology matrix *A* and what has been called the intervention matrix *B* (see Tukker et al., 2005 for detailed explanations).

The mathematical form of the EIPRO model is the following:

$$m = [B_1\ B_2\ B_3]\left\{ I - \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \right\}^{-1} \begin{bmatrix} k_1 \\ k_2 \\ k_3 \end{bmatrix}. \qquad [6]$$

The technology matrix $A$ is a partitioned matrix. $A_{11}$ is the production technology matrix and it represents the intermediate exchanges between production activities. $A_{22}$ is the technology matrix for final consumption activities. It's an identity matrix, sales from consumers to consumers have been disregarded. $A_{33}$ is the technology matrix for disposal activities. $A_{12}$ is the matrix that links production to consumption activities. In some cases it is needed to link the consumption of specific products to a certain consumption activities (for instance the purchase of water, electricity and washing machines into the consumption activity "washing"). $A_{13}$ is the matrix that relates production to disposal activities. Disposal sectors need energy, heat and more other inputs from production industries. $A_{21}$ and $A_{23}$ are equal to zero under the assumption that there are neither second hands market nor sales from households to disposal sectors. $A_{31}$ and $A_{32}$ are the matrices that link disposal to production and consumption activities (all the disposal services required by production industries or waste disposal services for solid wastes generated by the use of products such as discarded products).

The vector $k$ of final demand is composed by $k_1$ as purchases of products combined into the consumptions activities vector $k_2$. $k_3$ is a vector of zeros.

The intervention matrix $B$ is a partitioned matrix. $B_1$ is the intervention matrix for production activities. It is based partly on European statistics for totals of emissions and partly on US data for the detailed structure of emissions. $B_2$ is the intervention matrix for consumption activities. In the EIPRO model, direct emissions from households have been specified for five consumption activities which have main direct emissions in the use stage: car driving; heating, cooking; washing; and use of pesticides. $B_3$ is the intervention matrix for the disposal activities it refers to environmental interventions produced by waste treatments.

The vector $m$ represents the environmental interventions (resource use and pollutants emitted) in the life cycle of all products in the EU25 economic system in 2005.

What are the different impacts due to those polluting activities? What is the share of each pollutant in the overall environmental impact? In order to answer to the previous questions, some of tools of LCA have been applied to the results provided by the EIO analysis, namely impact assessment and interpretation.

According to Guineé (Guineé, 2002) impact assessment is the phase in which the set of results of the inventory analysis is further processed and interpreted in terms of environmental impacts (classification, characterisation and normalisation phases) and societal preferences (weighting procedure). Indeed the result of EIO analysis in EIPRO is an inventory table ($m$ vector) and the impact assessment procedure allows for instance to translate specific emissions or resource use (environmental interventions) into global warming and resource depletion (impact categories). The impact categories included in the EIPRO model are listed below accompanied by the concomitant category indicator (that defines which property of the environmental intervention will be assessed for each impact):

- abiotic depletion (abiotic depletion potential);
- global warming (global warming potential);
- ozone layer depletion (ozone depletion potential);

- human toxicity (human toxicity potential);
- ecotoxicity (fresh water aquatic, marine aquatic and terrestrial ecotoxicity);
- photochemical oxidation (photochemical ozone creation potential);
- acidification (acidification potential);
- eutrophication (eutrophication potential).

The interpretation phase is the last, concluding phase of the Life Cycle Assessment. This is the stage in which the overall conclusions are drawn and in which data, methods and results are evaluated and analyzed. Environmental scores are finally compared to the system's economic value generated by different modelling versions according to input-output analysis results. The previous arguments are used to compute the eco-efficiency ratio that explains the environmental productivity of the three alternatives as it is explained in the next section.

## III. Eco-efficiency and environmental input-output analysis

The notion of Eco-efficiency stems from the work by Schaltegger and Sturm (Schaltegger and Sturm, 1989) and it was later formally defined by the WBCSD (WBCSD, 1992): it is described as "being achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the Earth's estimated carrying capacity".

Nonetheless there exist several overlapping terminologies depending mostly on the application. Those variants can be grouped under a more general concept accordingly to which eco-efficiency can be defined as a ratio between a measure of economic aspects and related environmental issues. Hence, depending on the choice between values and costs in one hand and on the option between numerator and denominator in the other hand, we find the following possibilities: environmental intensity and environmental productivity in the realm of value creation (*creation of maximum value with minimum environmental impact*); and environmental improvement cost and environmental cost-effectiveness in the realm of environmental improvement measures (*reduction of costs for the environmental improvements investigated*) (Huppes and Ishikawa, 2005a). Table 1 gives a graphical representation.

Eco-efficiency, in all its variants, provides a desired integration between economy and environment. It shows the trade-offs between those two aspects and it compares different products or processes in a microeconomic perspective or, from a macroeconomic point of view, it can also be applied to different economic systems. Thanks to the properties of EIO, this analysis is implemented in the same framework. And, more important, EIO is the missing link in describing the effects of the implementation of environmentally friendly measures at the industrial level on the entire economic system (macro perspective).

Accordingly to the taxonomy depicted by Table 1, in this article we use the notion of environmental productivity, by combining the economic value created (we will refer to it as value added) with impact assessment results (environmental impact).

We show the eco-efficiency ratio for every modeling versions. The traditional case (point x in Figure 1) describes the ratio between the production value of the original Local and Suburban Transit industry and its environmental impact and it is further compared to three modeling versions (see section IV below).The values representing the different three alternatives may belong to quadrant **a**, **b**, **c** or **d**. Quadrant **a** is the set of points in which improvements in economic conditions are accompanied by the reduction of environmental exploitation; in quadrant **b** economic score increase at the expenses of environmental quality; quadrant **c** represents the worst situation and quadrant **d** is the set of costly environmental improvements.

## IV. The hydrogen-based economic subsystem

The case study presented in this paper shows the economic and environmental effects of the introduction of a hydrogen-based subsystem in the EU 25 economic system (in the rest of the paper we will refer to the latter as the traditional system, or A1).

It is based on the results of the EIPRO (CEDAEU25) Project (Tukker et al., 2005) that shows the environmental impacts due to the production and consumption activities, disaggregated by products, of the EU25 internal final expenditure (private and public). Given the lack of data, it has been assumed equality between import and export flows in order to satisfy the fundamental accounting identity.

Depending on the chosen amount of monetary flows and on the total yearly mileage run by the buses, three modelling versions are presented for the consumption activities vector $k_2$ (see equation [6]).

Modelling version A2: 10% of the final demand of the traditional Local and Suburban Transit industry instantaneously shifts to the new transport services provided by the use of fuel cell buses. Thanks to this amount of monetary flows, the New Local and Suburban Transit industry is able to satisfy a yearly transit demand of 704 (881) millions km, in other words about 22 (27) urban areas of 2.000 mq. on average (according to Bento et al., 2005) and about 13.300 (16.600) buses driving in the prototype (mass production) FCPS case.

Modelling version A3: letting the total final demand increase by 10% of the traditional public transport services, this modelling version depicts the economic and environmental effects that would occur if the New Local and Suburban Transit industry will provide the transit supply that would have been satisfied by the conventional diesel buses with the same raise in final demand. The number of buses driving per year is 18.800, the total mileage is 998 millions km, about 31 urban areas covered for both cases and an increase of 0,095% (0,075%) of the total final demand expenditure in the prototype (mass production) case.

Modelling version A4: this last modelling version shows what happens if, driving the same mileage before, we want the total final demand unchanged. The consumption expenditure for the fuel cell bus services is provided by a proportional shift from every industry final demands to the New local and Suburban Transit industry.

The following discussion describes changes in technology and intervention matrices. Five new industries are added to the traditional system in the industrial transactions table and, consequently, in the intervention matrix: Hydrogen Production, Hydrogen Distribution, New Local and Suburban transit, New Truck and Bus Bodies and Fuel Cell Power System industry.

*Hydrogen Production*

Hydrogen production pathway is represented by centralized reforming of natural gas. In order to analyse this process we use data from the cost analysis and emissions estimates of the previously mentioned NREL report (Simbeck and Chang, 2002; see also Figure 10). The plant, the compressor, natural gas and electricity are the steam methane reformer's interindustry inputs. The share of value added contributing in the production of 1 EUR/year of output has been assumed similar to that of the Electrical Services industry.

The new $a_{ij}$ are the technical coefficients referring to the production of 1 EUR/year of hydrogen where $i$ is the Hydrogen Production industry and $j$ respectively General Industry Machinery and Equipment, Pumps and Compressors, Natural Gas Distribution and Electrical Services industries. Technical coefficients for the mass production case are presented in Table 2.

The new columns of the intervention matrix are fulfilled by the information contained in Figure 11. Main environmental impacts are related to the reformer activities, namely emissions of substances to air, mostly carbon dioxide (Spath and Mann, 2001).

*Hydrogen Distribution*

Assuming that hydrogen will be distributed through pipelines currently available for the delivery of natural gas, allow us to think about Hydrogen Distribution industry as a Natural Gas Distribution industry with similar technology and inputs. The main differences are hydrogen instead of natural gas as input and the price level. The distinction is reflected by the $a_{ij}$ technical coefficient where $i$ and $j$ are respectively the Hydrogen Production and Hydrogen Distribution industries. The amount of hydrogen distributed per year equals 62,2 (77,8) millions kg/year in the prototype (mass production) case (note that this is the amount satisfying A2 modelling version).

According to the environmental interventions due to Natural Gas Distribution industry's activities, we have built a new column of the intervention matrix for Hydrogen Distribution industry removing both the methane fugitive emissions from leaking compressor components and those arising from the incomplete combustion in reciprocating engines and turbines used in moving the natural gas through the pipeline (Spath and Mann, 2001).

*New Local and Suburban Transit*

The Hydrogen Distribution industry sells its product to the New Local and Suburban Transit industry (refuelling stations have been taken out of the system). The latter provides consumers with public transport services, in our specific case, fuel cell buses transport services. It is also assumed to be a production process similar to the traditional Local and Suburban Transit industry but for the employment of fuel cell buses and hydrogen as a fuel. Consequently we see that the $a_{ij}$ technical coefficients, where $i$ is the New Local and Suburban Transit industry, have been changed as shown by the following list:

- the value have been replaced by zero for $j$ equal to the traditional Truck and Bus Bodies and Petroleum Refining industries.
- a new value has been added for $j$ representing the New Truck and Bus Bodies (namely, the new assembling industry for the fuel cell bus);
- another new value for $j$ equal to the Hydrogen Distribution industry.

Table 3 illustrates the new technical coefficients for the mass production case.

The environmental interventions linked to the production activities of the New Local and Suburban Transit industry are similar to the traditional service apart from emissions due to combustion of fossil fuels. For this reason emissions like trichloroethylene, methyl chloroform etc. (mostly due to combustion activities) and nitrogen dioxide and particulate matter (tail emissions) have been removed.

*New Truck and Bus Bodies*

A new assembling industry produces fuel cell buses. We have assumed similarity with the traditional Truck and Bus Bodies industry's technology for all the interindustry inputs but for the drive train, electric engine and the storage. The main hypothesis underlying the computations is that we have taken the diesel bus as a baseline for both costs and components. As a result the fuel cell bus is the same of a diesel bus but for the employment of a fuel cell power system (explained later in the next section) instead of the diesel engine, a new electric engine and the storage tank for hydrogen. Consequently, we have removed what before was representing the diesel engine and parts of the motor (like carburetors, pistons and valves). The price of the bus according to our computations is 520.000 (266.000) EUR in the prototype (mass production) case. The cost of the Citaro fuel cell bus has been estimated at 1.254.000 EUR (Karlstrom, 2005) anyway not less than 1.000.000 EUR (IEA, 2005). The differences in the results could be explained by the different data collected and assumptions on the components and, finally, by the share of value added that we have set at the same level of that of the traditional Truck and Bus Bodies industry (for instance more technical skills required for the labour force will increase the price of the bus). Table 4 shows new coefficients for the mass production case.

The environmental interventions have been assumed to be equivalent to the traditional industry: assembling activities are similar (even if more technical labour skills may be required).

*Fuel Cell Power System*

The Fuel Cell Power System industry provides the New Truck and Bus Bodies industry with the drive train. The Citaro fuel cell bus Nominal Motor Power is 250 kW and the Fuel Cell Engine net shaft power is 190 kW (CUTE Technology Brochure, 2004). Thanks to a lot of scientific studies on this item, it has been possible to build a subsystem in which the cost of the fuel cell drive train is relative high (a kind of prototype cost) and another one by depicting the world as if the mass production (500.000 units per year) of fuel cell engines were already an economic reality. In the first case we have taken a cost of 1800 $/kW (IEA, 2005) and in the second case the cost is 108 $/kW (Carlson et al., 2005).

The cost of the fuel cell power system has been mostly computed consistently to the data contained in Figure 12. The components of the fuel cell power system are the stack (membrane, electrodes, bipolar plates and gas diffusion layer) and the auxiliary systems (sensors, water management system, air management system, fuel management system and thermal management system). As first estimate we have found the possible suppliers of all the components in the traditional system as depicted in details in Figure 13.

Two other assumptions are concerned with both the share of economic value generated by the industry (employees compensations and other value added) and the use of electrical services employed in the industry activities. As first estimation, both these values have been set at the same level of that shown by the industry Turbines and Turbine Generators, according to the fact that both the industries activities are related to the production of high technology products. The technical coefficients for the mass production case are shown by Table 5.

Because of the lack of data, it was not possible to elaborate a vector of environmental interventions related directly to the Fuel Cell Power System industry activities. Nevertheless, we show as a first estimate, what is the environmental impact of those activities by assuming that the new industry pollutes similarly to the Electric Industrial Apparatus industry (so far no other option was available).

With the description of the subsystem available, next section illustrates the result of the model.

## V. Results and interpretation

The results of the EIO analysis provide a sort of inventory table according to the LCA terminology. Vector $m$ of equation [6] represents the environmental interventions (resource use and pollutants emitted) in the life cycle of all products in the EU25 economic system in 2005, it now contains information on the hydrogen-based subsystem too. Vector $m$'s elements are then classified, characterised, normalised and weighted in the Impact Assessment and Interpretation phases of LCA.

The Life Cycle Impact Assessment phase is concerned with both the interpretation of the environmental impact of different interventions and the inclusion of society's preferences into the analysis. This is the stage in which all inventory results are further processed into category indicators, subsequently attached to impact categories both in a qualitative and in a quantitative way, then characterised with respect to the magnitude of influence on every environmental impact, normalised with respect to the context of the study, grouped and finally weighted relatively either to a certain method (like stated or revealed collective preference, stated or revealed individual preference, comparative efficiency, Huppes et al., 2005) or economic allocation (Guinée et al., 2004).The reference situation in the normalisation phase is the total EU25 private and public internal expenditure. For the weighting procedure we apply two methods: the equal method that gives to each impact category the same weight and the NOGEPA method that gives the contribution of each impact category to the overall environmental score according to public officials and stakeholders opinions and specific knowledge (Huppes et al., 2004).

Next sections describe and interpret the results through comparative and contribution analysis at different levels for the mass production case. We show the results related to three impact categories that are relevant for the study: global warming, photochemical oxidation and acidification. The lasts subsections deal with the eco-efficiency analysis related to both the mass production and the prototype case.

### *V.I Characterisation level: Comparative and Contribution Analysis - mass production case.*

#### *Global Warming*

Compared to the traditional system, A2 modelling version shows an higher impact in global warming. By investigating the contribution of each process to the total impact, we know that this higher value is mostly due to carbon dioxide emissions by the steam methane reformer: hydrogen production emissions value is the dominant factor (Figure 2). A3 modelling version shows an even higher increase in global warming: the increase in final demand sum up the environmental impact of the traditional system and the interventions due to the subsystem. Global warming score for A4 modelling version is the lowest: the proportional decrease in every industry final demand and the subsequent reduction of environmental interventions compensate for the carbon dioxide emissions from hydrogen production. In particular, both the reduction of electric services final expenditure and the use of vehicles by households mostly contribute to the positive effect.

*Photochemical Oxidation*

The introduction of the hydrogen subsystem increases the photochemical oxidation score, mostly because of the increase in volatile organic compounds. Natural gas purchases by Hydrogen Production industry and the purchases of new buses from the new Local and Suburban Transit industry are the main contributors to the increase of the environmental score, along with pollution stemming from purchases of both plastics materials and resins, and chemicals (linked to the production of the FCPS). The environmental impact raises more if the total demand increase and less in case of proportional final demands decrease version. Final outputs reduction in industries employing solvents and the decrease in the demand for fuels give the main contribution to the improvement in the environmental score (total scores in Figure 3).

*Acidification*

Sulphur dioxide is the pollutant responsible for around 35% of the total acidification score, followed by nitrogen dioxide emissions (15%). In A2, the decrease in the environmental score is originated by the reduction of sulphur dioxide emissions from both petroleum refining and crude petroleum interindustry purchases due to the final demand of diesel bus transport services (as well decreasing by 10% in this modelling version). However, the employment of the new FC bus service is not enough if we want the same mileage of the traditional system: as shown by A3 acidification score, the increase in final demand results in an increase of the environmental impact. The improvement in the environmental performance in A4 is characterised by the overall effects of the proportional final demand reduction version (total scores in Figure 4).

*V.II Normalization level: Comparative Analysis - mass production case*

At the normalised level, the contribution of each impact category is converted in its contribution compared to a reference situation. In this study the share of each impact category refers to the EU25 total final expenditure. This means that the environmental score of every modelling version is compared to the environmental impact of the EU25 total final demand. The normalisation procedure allows also to compare different impact categories. So that it’s possible to see the most contributing impact category to the overall system. Figure 5 shows the results of the comparative analysis.

The comparative analysis at the normalised level for each impact category shows little differences. Compared to the appropriate indicator results related to EU25 in 2005, all of the alternatives show similar share for each impact category result. From another point of view photochemical oxidation has the largest impact with respect to the other categories. According to our results it means that new industries responsible for these emissions represent the weakest elements of our hydrogen subsystem (namely Hydrogen Production and FC power system industries).

*V.III Weighting level: Contribution Analysis- mass production case*

We investigate the contribution of the four relevant impact category in the overall environmental score by applying two weighting methods:

- the equal weighting method, that gives to each impact category an equal weight;
- the NOGEPA weighting method, that gives a weight to each impact category according to public officials and stakeholders opinions and specific knowledge.

Figure 6 and 7 illustrate the results of the analysis applying both methods. According to the equal weighting method the traditional system has the highest contribution in terms of photochemical oxidation. From the comparative analysis at the Characterisation level we know that in terms of kg of ethylene equivalent A1 is actually the best option. This means that, contrary to the normalised level, the weighting level might change the rank. Nothing changes for the rest of the categories.

The NOGEPA weighting method shows better the global warming contribution trend. As before, the rank has changed: from this results global warming is the most contributing impact category, for climate change is considered relatively more relevant to the overall environmental impact.

*V.IV Eco-efficiency results – mass production*

In this paper, the eco-efficiency analysis describes the comparison between the economic value and the environmental impact generated by the system. All modelling versions are compared according to their economic and environmental effects in terms of value added (labour compensations, profits etc.) and environmental weighted score. Figure 8 illustrates the results of the mass production case. With the traditional system as a reference eco-efficiency results characterize A2 and A4 as the best options of the study. With the same economic value created, their environmental impact is lower than the traditional one. A3 has the highest environmental impact while the rise in final demand increase the economic value generated by the system.

If the assumption on the instantaneously increase in total final demand is accepted, one could say that A3 could be an option for instance in the short period along with additional corrective actions in the future (like CO2 capture and storage). The input output framework is especially useful to verify the previous thought: it is true that the model depicts an increase in the total economic value, but that rise has redistributional effects due to indirect transactions. According to the results, the economic value created by Local and Suburban Transport, Petroleum Refining, Electric services and all the industries related to the production of the diesel buses decrease. The production of the Plastics Materials and Resins industry and Primary nonferrous metal (platinum for the membrane) output increase.

If we consider A2 modelling version as the best (for example we weight more the environment then the economy) then we should expect a decrease in the production of the traditional Local and Suburban Transport industry as first, then to the all the industries directly and indirectly linked to it.

### *V.V Summarizing results: prototype case*

The prototype version of the study assumes a cost for the FC bus around 1,2 million EUR. The difference from the mass production case is due the cost of the FC power system (1800 $/kW for the prototype and 108$/kW for the mass production alternative). The number of buses produced is 20% less (5 urban areas less) along with the reduction of the total output of Hydrogen Production industry, Hydrogen Distribution and so on. This implies a decrease in the environmental score with respect to the mass production case and a different amount of economic value created by the system. Figure 9 summarizes the economic and environmental effects of the “prototype” hydrogen subsystem through the eco-efficiency analysis. As before A2 and A4 are preferred in terms of environmental impact, while A3 has the highest economic value.

## VI. Conclusions

The present paper shows the economic and environmental effects of the introduction of a hydrogen-based subsystem in the EU25 economy in 2005 by comparing the current transport system running on diesel buses with an alternative system that works on the use of FC buses supported by large scale production of hydrogen via steam methane reforming (hydrogen-based subsystem). We have analyzed both the mass production and the prototype case by implementing three possible variants: the first is a comparison between diesel and FC buses assuming that 10% of the current public transport demand shifts instantaneously to new public hydrogen transport services (A2); the second one reproduces the effects of an increase in total final demand expenditure if the yearly transit supply that would be offered by conventional diesel buses with the same previous amount of expenditure (10% of the traditional Local and Suburban Transit industry) will be instead provided by fuel cell buses (A3); the third one simulates a proportional reduction on each product final demand sufficient to cover the previous computed yearly bus transit supply (A4).

We have shown the results relative to the three modelling versions for the mass production case and a summary for the prototype case. We have found little improvements in environmental terms in both situations. Eco-efficiency analysis has shown that only A3 modelling version is superior in economic terms while A2 and A4 are better in terms of environmental impact. However all the alternatives have redistributional effects. In A2 and A3 modelling versions all the industries involved in the production of the final transport service provided by diesel bus face losses. While in the case of a proportional decrease in every final good production sufficient to sustain the hydrogen subsystem, all the industries have to cope with losses (a part from those involved in the production of the FC buses and related transport service).

Concerning the environment, we have shown the outcomes of the analysis in terms of three relevant impact categories: global warming, photochemical oxidation and acidification. Albeit the absence of tails emissions from FC buses, the production of hydrogen from the reforming of natural gas increases the level of greenhouse gases because of carbon dioxide emissions from the steam methane reformer. As well as the purchases of natural gas raises the photochemical oxidation score. Instead FC buses are environmentally friendlier than diesel bus in terms of the acidification score. But from an overall point of view the results suggest that the use of hydrogen in FC buses (and similar fuel cell applications) is only relevant if accompanied either by the employment of renewable sources or by carbon dioxide capture, or both. Project like the CUTE are very useful to both the discovery of possible cost/technological impediments and the investigation of public acceptance over a sustainable future. The employment of hydrogen as energy carrier in other applications like vehicles and stationary applications will as well improve the overall environmental impact of the European economic system. In this concern the analysis could gain useful insights from the addition of fuel cell stationary systems.

However much remains to be done to develop a more complete picture about the effects of the use of hydrogen and its impact on sustainable development. Even if static EIO analysis gives useful insights in improving our knowledge on the effects of demand shifts in an integrated way, it still disregards the dynamics of complex systems like economy and environment. Both preference and technological changes are left a part. Like cost and benefit analysis in general, it ignores the possible gains from creative destruction (Hisschemoller et al., 2006). In addition the social aspect is neither modelled nor shown by the analysis, but for employment considerations that can be derived by value added variations. The limitations due to linearity work also in the eco-efficiency context, where LCA approach does not describe the differences between average and marginal unit increase of production (Huppes and Ishikawa, 2005b).

About the availability of data, it must be said that improvements are needed. Investment considerations are not offered by this version of the EIPRO model. Moreover the lack of data on import-export exchanges and on public expenditure detailed information, give to the analysis a partial view.

Concerning the hydrogen-based subsystem, data gaps should be fulfilled: in order to have an encompassing system, economic and environmental aspects of the refuelling stations should be taken into account, as well as the issues related to carbon dioxide sequestration. At a more specific level, the cost analysis of fuel cell buses can be improved by considerations on O&M costs and reliable data on labour costs. Finally it would be very useful to have information on the environmental interventions due to the fuel cell power system industry.

## VII. References


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## VIII. Tables and Figures.

Table 1: source Huppes and Ishikawa, 2005a.

| | *Product or production primary* | *Environmental improvement primary* |
|---|---|---|
| Economy divided by environment | Production value per unit of environmental impact, or *environmental productivity* | Cost per unit of environmental improvement or *environmental improvement cost* |
| Environment divided by economy | Environmental impact per unit of production value, or *environmental intensity* | Environmental improvement per unit of cost, or *environmental cost-effectiveness* |

Table 2. Hydrogen Production technical coefficients

| **Hydrogen Production** | technical coefficients |
|---|---|
| Total Output | |
| Purchases from General Industry Machines and Equipment | 1,82E-01 |
| Purchases from Pumps and Compressors | 2,64E-02 |
| Purchases from Natural Gas Distribution | 7,53E-01 |
| Purchases from Electric Services | 3,89E-02 |

Table 3. New Local and Suburban Transit technical coefficients.

| **NEW Local and suburban transit** | technical coefficients |
|---|---|
| Total Output | |
| Purchases from NEW Truck and Bus Bodies | 2,63E-01 |
| Purchases from Hydrogen Distribution | 1,35E-01 |

Table 4. New Truck and Bus Bodies technical coefficients.

| **NEW Truck and bus bodies** | technical coefficients |
|---|---|
| Total Output | |
| Purchases from Fuel Cell Power System | 6,08E-02 |
| Purchases from Hydrogen Storage (pumps and compressors) | 1,30E-01 |
| Purchases from Motors and Generators | 1,34E-02 |

Table 5. Fuel Cell Power System technical coefficients.

| **Fuel Cell Power System** | technical coefficients |
|---|---|
| Total Output | |
| Purchases from Plastic Materials (Membrane) | 2,31E-02 |
| Purchases from Manmade organic fibres (Bipolar Plate) | 1,92E-02 |
| Purchases from Miscellaneus plastic products (WMS) | 4,27E-02 |
| Purchases from (Gasket, packing etc. (Seal+BOS) | 1,54E-02 |
| Purchases from Primary nonferrous metals (Electrodes) | 2,96E-01 |
| Purchases from Pumps and Compressors (AMS) | 7,93E-02 |
| Purchases from Blowers and Fans (FMS) | 2,44E-02 |
| Purchases from Refrigeration and Heating Equip. (TMS) | 2,44E-02 |
| Purchases from Realys and Industrial Controls (Fin. and Stack Assembly + Sensors and Valves) | 6,65E-02 |
| Purchases from Carbon and Graphite Products (GDL) | 1,92E-02 |
| Electricity | 5,10E-03 |

Figure 1. Eco-efficiency analysis.

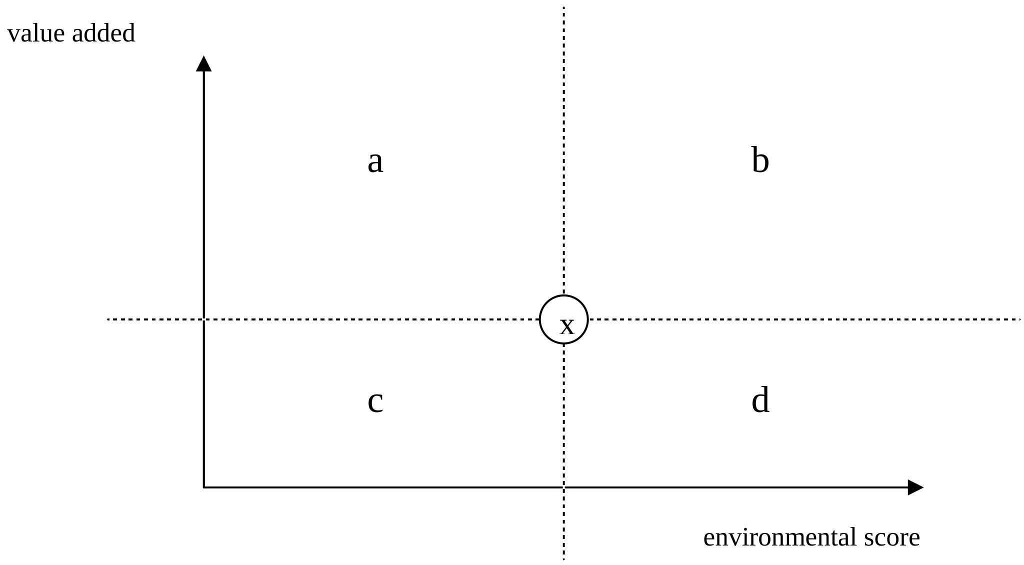

Figure 2. Comparative analysis – Global Warming.

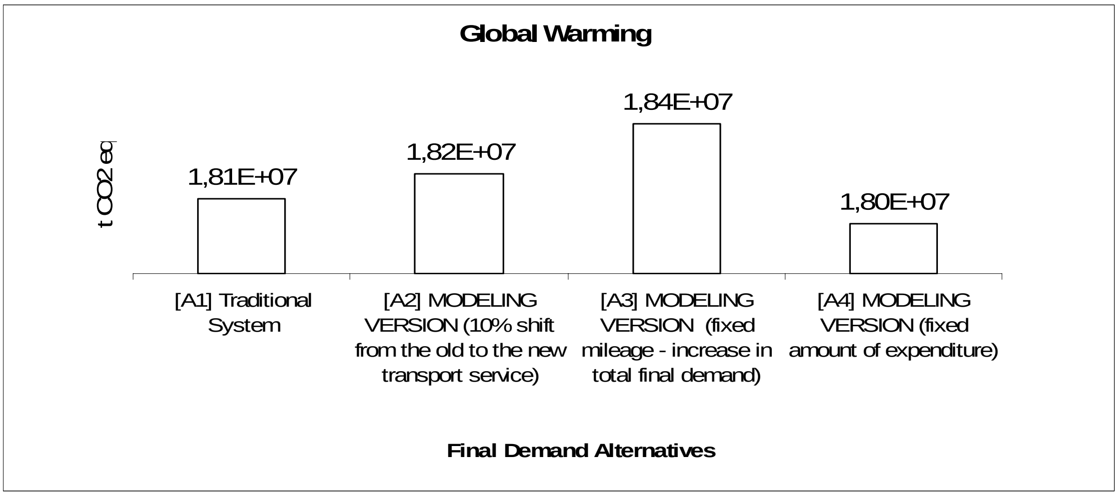


Figure 3. Photochemical Oxidation.

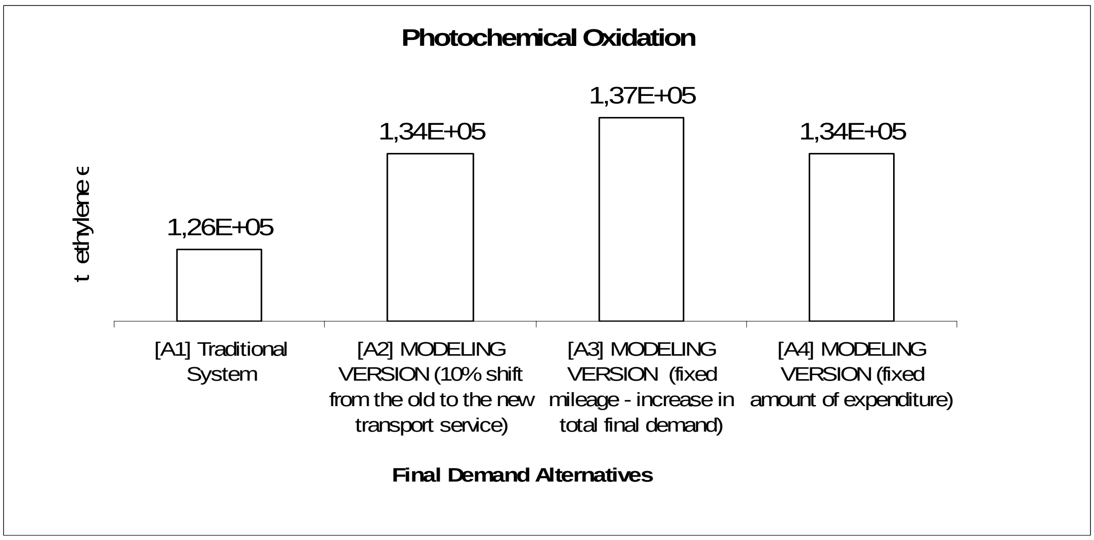

Figure 4. Acidification.

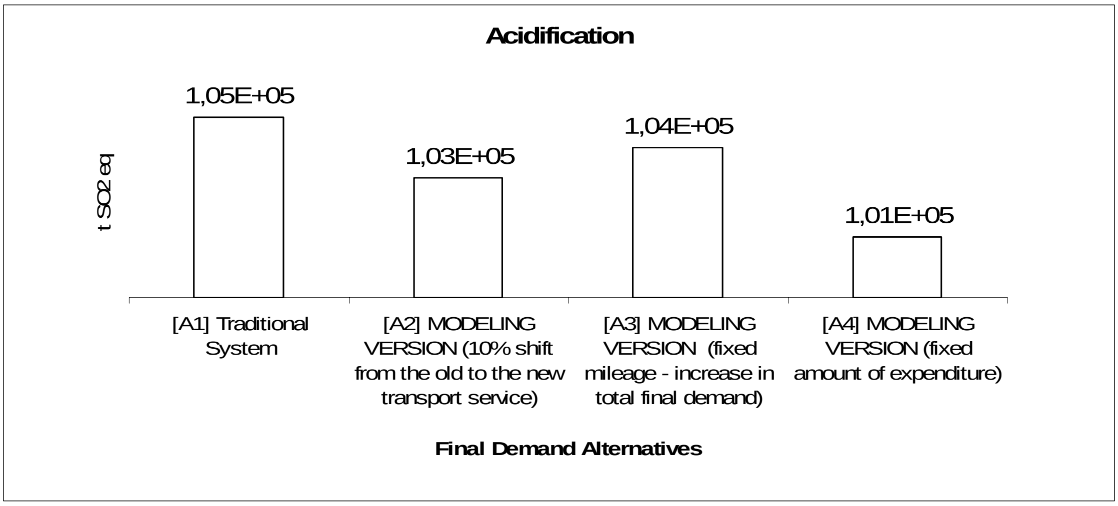


Figure 5. Normalised environmental profile – Comparative Analysis.

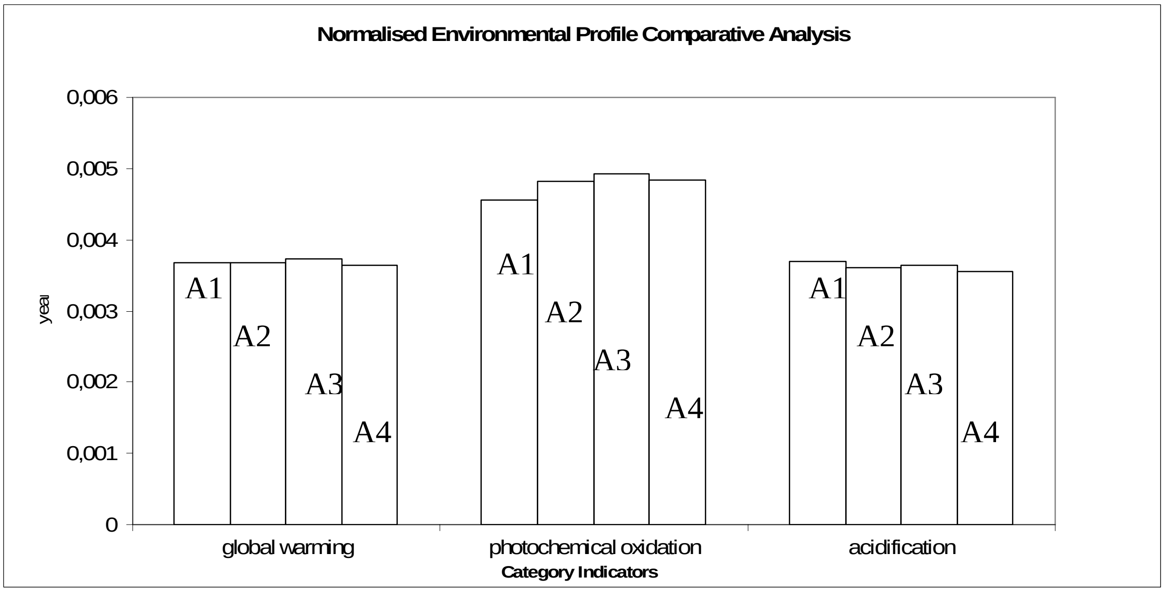

Figure 6. Contribution Analysis – Weighting Level (equal method).

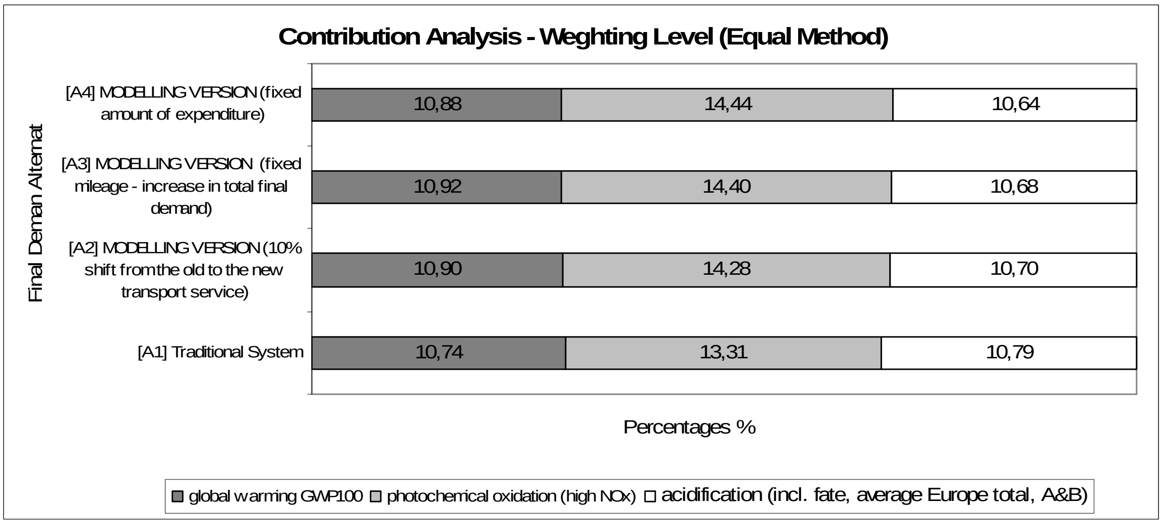


Figure 7. Contribution Analysis – Weighting Level (NOGEPA method).

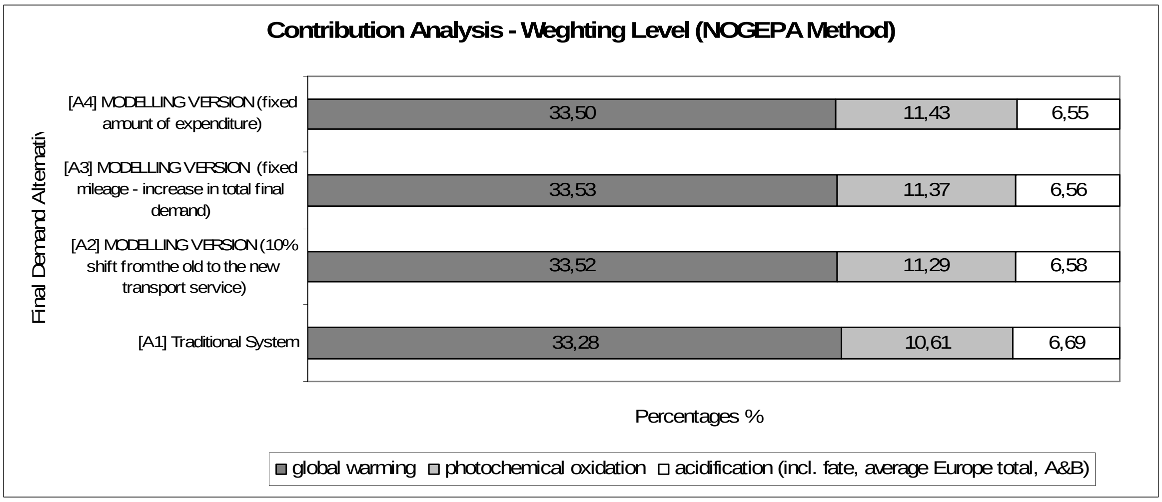

Figure 8. Eco-efficiency results for the mass production case.

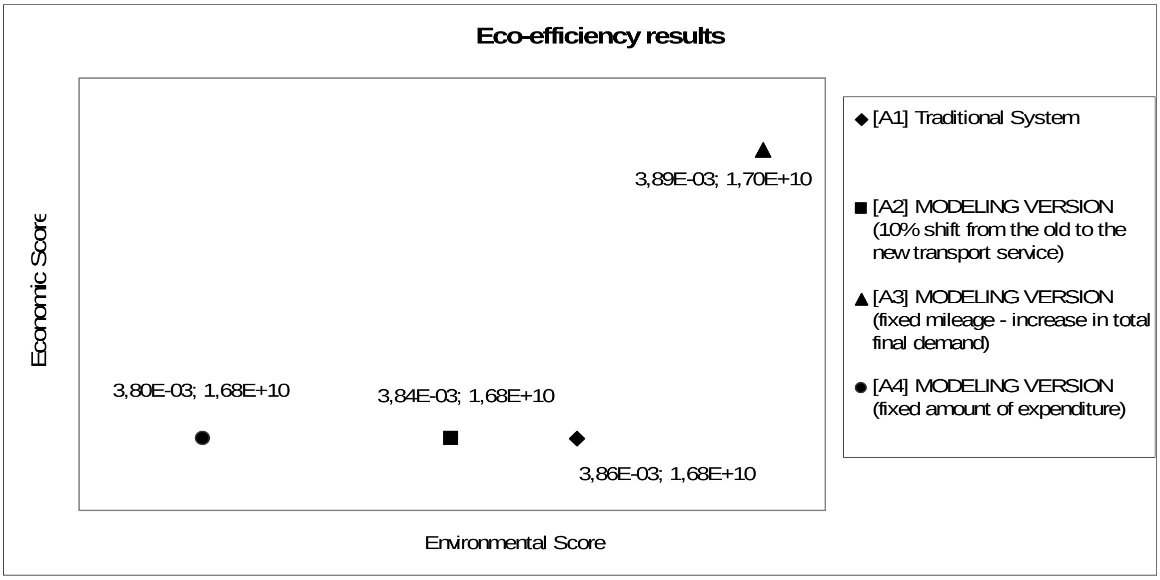


Figure 9. Eco-efficiency for the prototype case.

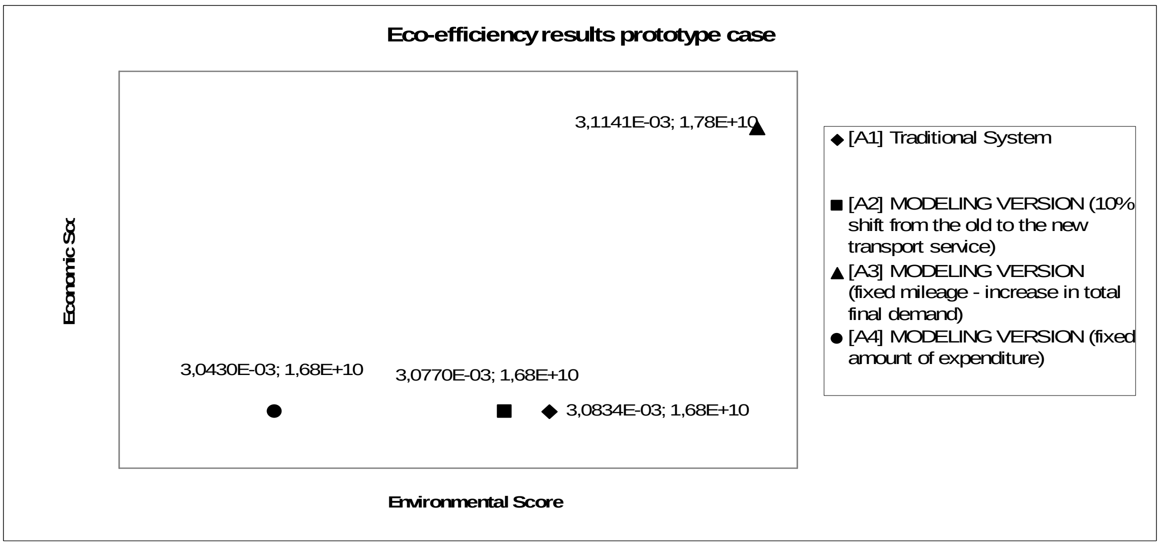

Figure 10. Source Simbeck and Chang, 2002.

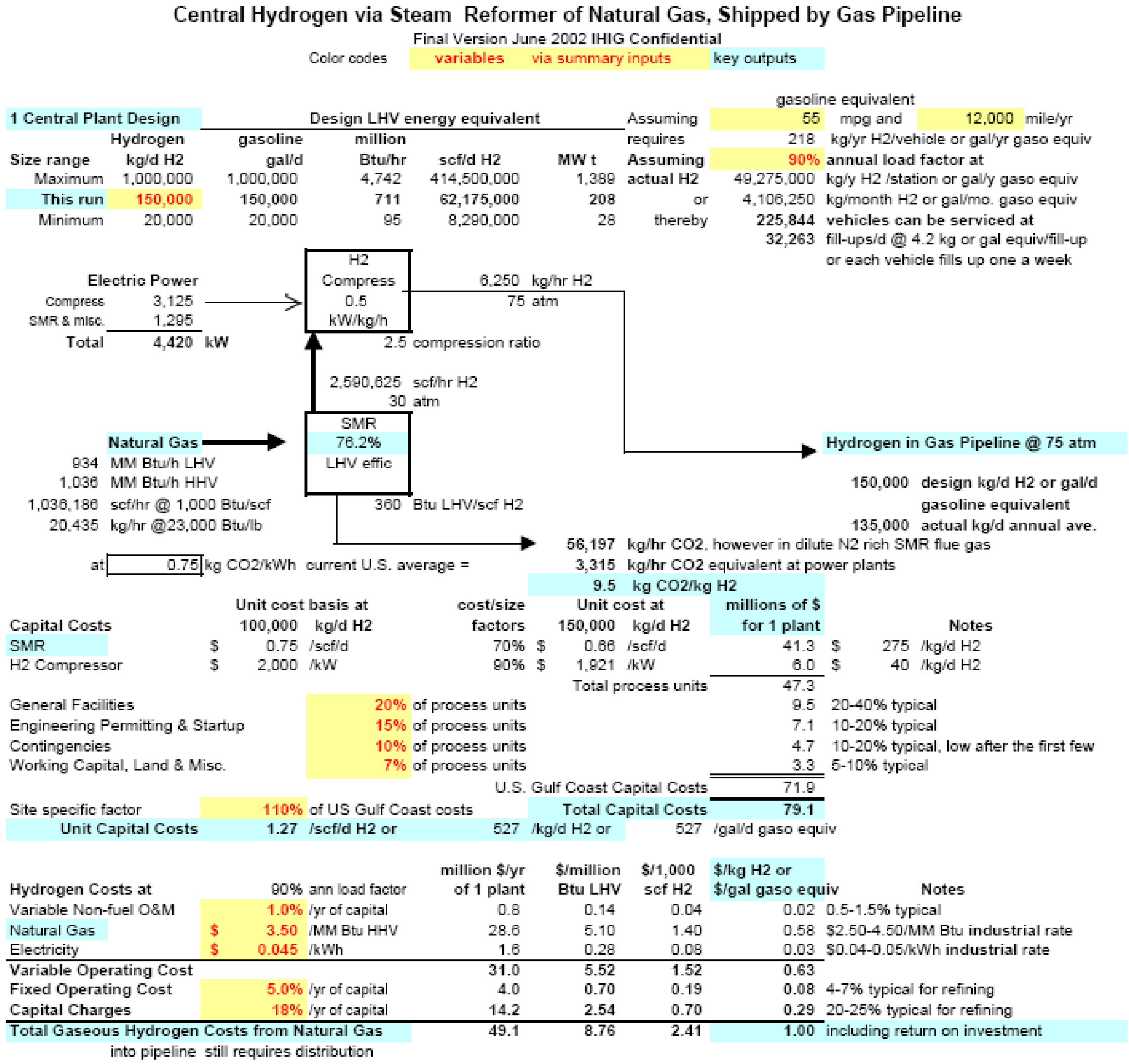


Figure 11. Source Spath and Mann, 2001.

**Table 4: Average Air Emissions**

| Air Emission | System total (g/kg of $H_2$) | % of total in this table | % of total excluding $CO_2$ | % of total from construction & decommissioning | % of total from natural gas production & transport | % of total from electricity generation | % of total from $H_2$ plant operation | % of total from avoided operations |
|---|---|---|---|---|---|---|---|---|
| Benzene ($C_6H_6$) | 1.4 | < 0.0% | 1.3% | 0.0% | 110.9% | 0.0% | 0.0% | -10.9% |
| Carbon Dioxide ($CO_2$) | 10,620.6 | 99.0% | | 0.4% | 14.8% | 2.5% | 83.7% | -1.5% |
| Carbon monoxide (CO) | 5.7 | 0.1% | 5.3% | 2.0% | 106.3% | 0.7% | 1.4% | -10.4% |
| Methane ($CH_4$) | 59.8 | 0.6% | 55.7% | < 0.0% | 110.8% | < 0.0% | 0.0% | -10.9% |
| Nitrogen oxides ($NO_X$ as $NO_2$) | 12.3 | 0.1% | 11.0% | 1.8% | 90.3% | 9.5% | 7.3% | -8.9% |
| Nitrous oxide ($N_2O$) | 0.04 | < 0.0% | < 0.0% | 7.3% | 37.6% | 58.7% | 0.0% | -3.7% |
| Non-methane hydrocarbons (NMHCs) | 16.8 | 0.2% | 15.6% | 1.7% | 89.8% | 14.5% | 0.0% | -6.0% |
| Particulates | 2.0 | < 0.0% | 1.8% | 64.5% | 25.2% | 11.6% | 1.1% | -2.5% |
| Sulfur oxides ($SO_X$ as $SO_2$) | 9.5 | 0.1% | 8.8% | 13.5% | 68.3% | 24.9% | 0.0% | -6.7% |

Note: Construction and decommissioning include plant construction and decommissioning as well as construction of the natural gas pipeline.

Figure 12. Breakdown of the fuel cell power system cost. Source Carlson et al., 2005.

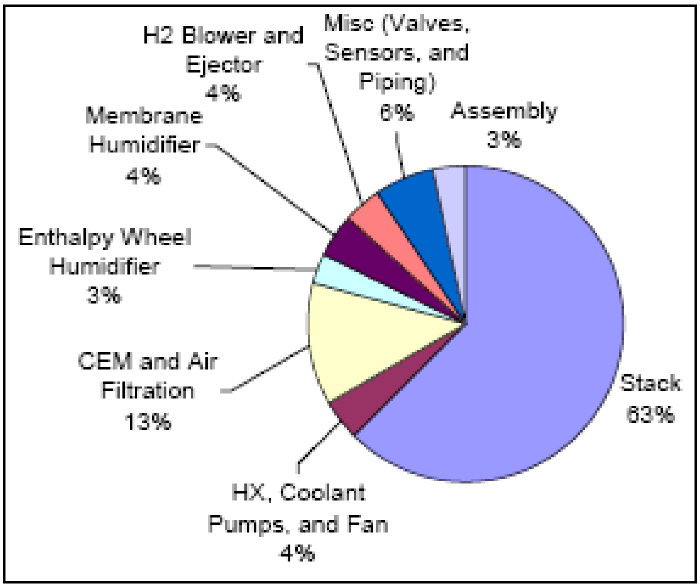


Figure 13. Detailed description of the Fuel Cell Power System by components.