Alternative Fuels for Transportation
- A Sustainability Assessment of Technologies within an International Energy Agency Scenario

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Abstract: Transport sector is an essential driver of economic development and growth, and at the same time, one of the biggest contributors to climate change, responsible for almost a quarter of the global carbon dioxide emissions. The sector is 95 percent dependent on fossil fuels. International Energy Agency (IEA) scenarios present different mixes of fuels to decrease both dependence on fossil fuels and emissions, leading to a more sustainable future. The main alternative fuels proposed in the Blue map scenario, presented in the Energy Technologies Perspective 2008, were hydrogen and second-generation ethanol. An assessment of these fuels was made using the tools SLCA (Sustainability Life Cycle Assessment) and SWOT Analysis. A Framework for Strategic Sustainable Development (FSSD) is the background used to guide the assessment and to help structure the results and conclusions.

The results aim to alert the transport sector stakeholders about the sustainability gaps of the scenario, so decisions can be made to lead society towards a sustainable future.

Keywords: Alternative fuels, second-generation ethanol, hydrogen, life cycle analysis, sustainability

Statement of Contribution

This thesis was the result of the gathering of three engineers that were interested on studying issues that are somehow related to their countries. Brazil and Pakistan are developing countries, and producers of biofuels. The topic emerged from the recommendations for further research proposed by a previous group that has developed a thesis in the challenges of Biofuels industry (França et al. 2006).

Shehzad focused on hydrogen production from natural gas and water, and contributed with an extensive technical research, bringing valuable information for our discussions. Marcos focused on hydrogen production from ethanol, hydrogen distribution and use phases, electricity and biogas research. He also brought great value in reviewing and rephrasing the English in the report. Valeria focused on the second-generation ethanol and in the structuring and formatting of the report. Marcos and Valeria played the facilitating role on the written report by reviewing and compiling the results.

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Executive Summary

Introduction

Transport is an essential driver of economic development and growth, facilitating exchange among countries and fostering relations among people. It is also one of society's major global energy demanding sectors (World Energy Council 2007, 3), being responsible for 60 percent of all oil consumption and 13 percent of all anthropogenic emissions of greenhouse gases (GHG). It plays a major role in the current climate change challenge representing 23 percent of the world's total carbon dioxide (CO_2) emissions (ITF 2008, 5).

In the transport sector, road transport is accountable for 73% of energy consumption. The world's vehicle fleet, which in 2005 stood at 890 million units and which by 2010 should pass the one billion mark, is the primary market for petroleum products. It is therefore the largest source of CO_2 emissions in the transportation industry.

This thesis studies major technologies proposed in a scenario presented in the Energy Technology Perspectives 2008 report issued by the International Energy Agency (IEA), as possible alternatives to displace the use of fossil fuels in the transport sector. By backcasting from the four sustainability principles developed by (Holmberg and Robèrt 2000), it analyzes how the new upcoming fuels, i.e., second-generation ethanol and hydrogen, combined with existing alternative fuels (first generation ethanol, biogas, electricity) might contribute to their systematic violation. Furthermore it assesses the gaps that could hinder us from reaching a future and more sustainable society. Hydrogen and biofuels together account for almost 50 percent of the proposed mix of fuels in the Blue Map Scenario 2050.

The research question developed was "How can the Framework for Strategic Sustainable Development help to guide the assessment of hydrogen and second-generation ethanol as upcoming alternative technologies in the IEA Blue Map scenario, leading to a sustainable society?

Methods

Hydrogen and second-generation biofuels are still under research as alternatives to displace fossil fuels in the transport sector. An extensive literature review had to be carried out in order to have a view of the many perspectives and possibilities that are being studied as solutions for further development.

Interviews with some specialists in the sectors were conducted and questionnaires were sent out in order to provide a practical and updated vision of the perspectives and also a better view of the proposed technological solutions for the transport sector.

A principle-based definition of sustainability has been used in order to assess these technologies, highlighting gaps that could hinder them to help the sector to reach sustainability. The impacts of the use of these technologies are identified, helping to guide decisions towards the vision of success.

A combination of Sustainability Life Cycle Assessment (SLCA) and Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis has been carried out to address in depth issues related to sustainability and technology, identifying the impacts and assessing the challenges and opportunities of each technology.

The Framework for Strategic Sustainable Development (FSSD) was used as a background theory for this study, to organize and guide this assessment in a comprehensive and clear way.

Results

The SLCA combined with the SWOT analysis brought a considerable amount of information about impacts and challenges for hydrogen and second-generation ethanol that have to be addressed in order for both of these upcoming technologies to be considered sustainable.

The following main points are worth considering when examining the proposed mix of fuels in the Blue Map scenario, from a whole-system perspective.

Second-generation ethanol strength resides on the fact that when using waste (forest and agricultural) as feedstock, more ethanol can be produced without a proportional increase in the use of land, water and fertilizers. Energy crops (e.g. switchgrass) can be produced in lands that are not suitable for food crops. This could be a huge advantage and a strong driver to make this technology become one important source of liquid fuel. Nevertheless, caution is recommended due to the drawbacks caused by change in land use, water consumption and issues such as defining what is to be considered a marginal or idle land, since it can vary according to different perspectives.

One important fact to be taken into account is that this technology is dependent on genetically modified yeasts and enzymes, and also new dedicated crops that are under development. This could pose a threat in the future, as the consequences of inserting new species in the biosphere are not yet fully understood.

The clear relation between the change of land use and CO_2 emissions is yet to be determined, but the consensus is that it cannot be neglected anymore. Policies have to be developed to protect the environment from the overuse of the resources.

Hydrogen can be produced from different sources. In this study, hydrogen produced from natural gas and renewables (ethanol and water) have been assessed under the lens of the presented sustainability principles. The former represents 48 percent of the raw material currently used in hydrogen production and the latter represent the foreseen raw materials for hydrogen production in a future, more sustainable society.

Some positive characteristics that make hydrogen a good candidate as an alternative fuel are lack of harmful emissions in the use phase, quiet functioning, increased efficiency of fuel cell vehicles (FCVs) when compared to internal combustion engines (ICEs).

However, other key findings were that, due to the intrinsic chemical and physical properties of hydrogen, technical solutions in order to make it a viable fuel for transportation tend to be very energy and material intensive. The technology is also dependant on rare metals such as platinum and palladium, which may play a role in hindering it from being more democratic even if production of renewable sources of energy and raw materials are to happen in the future. Other issues such as water intensity, possible atmospheric influences and safety conditions may also have a decisive impact in the decision of deploying the technology as a solution for the transport sector.

Discussion and recommendations

Amongst the scenarios presented in the ETP 2008 report, the Blue Map scenario was the most audacious concerning the carbon emissions issue. The scenario included new technologies such as hydrogen and second-generation ethanol as part of the proposed mix for the transport sector in 2050. The report, nevertheless, does not consider a full SLCA of the technologies and does, therefore not include impacts that could affect our biosphere and the ability of people to meet their needs. A chapter/section analyzing these issues is strongly recommended in the ETP report.

Second-generation ethanol can represent a good economical alternative for farmers, as they can sell the agricultural residues to ethanol plants and grow crops in idle lands as an extra activity. In spite of this advantage and others such as use of marginal lands and use of municipal waste as feedstock, great concern exists related to the drawbacks of the use of non-productive lands. These lands, when prepared for production release great amounts of CO_2, and the technology is highly dependent on genetically modified organisms (enzymes, yeasts and crops). Water use is also an issue that has to be taken into account, as the process of ethanol production still is water intensive.

Despite being free of harmful emissions in the use phase, some issues have to be addressed in order to make hydrogen technology more sustainable. The production from hydrocarbons should be linked to a carbon capture and storage system (CCS) in order to reduce emissions. The dependence on rare metals is an issue since the technology is being evaluated as a Large Scale Solution (LSS) for the transport sector. If in any case the technology is deployed in this context, these rare metals will have to have a very rigorous management system in order to be kept in tight closed loops. Due to its energy and material intensity, its utilization in specific areas of transportation would be advisable. More detailed research to understand the influence of the increase of concentration of hydrogen originated from hydrocarbons in the atmosphere is crucial in order to avoid other drawbacks and pitfalls.

Further research on Battery Electric Vehicles (BEVs) and their impacts, specially from the sources of energy of electricity, are also vital since this technology offers a counterpoint to the Fuel Cell Vehicle (FCV) technology.

Biogas availability tends to increase with population growth and can be used as a renewable fuel to displace fossil fuel consumption, which not only lessens CH_4 emissions from manure management but also lowers fossil CO_2 emissions. Infrastructure laid out for natural gas distribution could be easily adapted for biogas utilization avoiding further land disruption.

Conclusions

This study found gaps that can bring serious threats for the hydrogen and second-generation ethanol technologies to become good alternatives to lead society in the right direction, i.e., towards socio-ecological sustainability. Approaching the technologies only by their CO_2 emissions can be misleading. A strategic approach using a Framework for Strategic Sustainable Development (FSSD) and tools such as a sustainability life cycle assessment (SLCA) is necessary in order to provide a whole systems perspective of the impacts of the deployment of each technology.

We recommend, in the ETP bi-annual report, a complementing chapter including a combined analysis using the SLCA and the SWOT showing, respectively the sustainability gaps and strengths, weaknesses, opportunities and threats of each technology in the mix of fuels proposed in the scenarios. A risk assessment table containing all the technologies and their related impacts would help decision and policy makers in their work to facilitate and finance the development of more sustainable technologies. Without a whole-system perspective and a deep assessment of the impacts they can bring to environmental, social and economical fabrics, a sustainable future for the transport sector can be threatened.

When evaluating hydrogen as a technology for the transport sector, there are barriers such as the dependence on rare metals that need to be overcome in order to make it become a large-scale sustainable technology.

Second-generation ethanol has the potential to decrease the impacts caused by the first generation, and barriers such as the development of genetically modified enzymes and definition of marginal land-use have to be overcome in a very strategic way. The competition between food versus fuel can be minimized with this technology, but other issues like water versus fuel and forest versus fuel are likely to happen in a near future..

Other technologies also mentioned in the Blue Map Scenario such as the use of electricity are seen as possible solutions for the transport sector. An overview of the Battery Electric Vehicle technology shows that it faces some similar threats just like hydrogen in order to become viable, that are related to the dependence on rare metals (Råde and Andersson 2001a). Nevertheless, other forms of electricity storage are being studied and evaluated (Tahil 2006).

Biogas represents a great potential of energy to be exploited. With the increase of population that is forecasted, waste and consequently biogas, are naturally going to increase. It would be wise to start planning for the infrastructure necessary to capture this biogas in order to use it as an energy source rather than plainly let those emissions reach the atmosphere.

Glossary

AFC	Alkaline Fuel Cell
Bagasse	Sugarcane plant waste
BEV	Battery Electric Vehicle
BTH	Blekinge Tekniska Högskola (Blekinge Institute of Technology)
CH_4	Methane
CO_2	Carbon dioxide
DMFC	Direct Methanol Fuel Cell
IEA	International Energy Agency
ICE	Internal Combustion Engine
FAO	Food and Agriculture Organization
FCV	Fuel Cell Vehicle
G8	Group of eight industrialized nations (Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, and the United States)
GH_2	Compressed Gaseous Hydrogen
GHG	Greenhouse gases
HE	Hydrogen Embritlement
IPCC	Intergovernmental Panel of Climate Change
LCA	Life Cycle Assessment
LH_2	Liquified Hydrogen
MCFC	Molten Carbonate Fuel Cell

MEA	Monoethanolamine
Mtoe	1 Mtoe amount of energy released when one million tonnes of crude oil is burnt
NG	Natural Gas
NGL	Natural Gas Liquid
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
NREL	National Renewabel Energy Laboratories
OECD	Organization for Economic Co-operation and Development
PAFC	Phosphoric Acid Fuel Cell
PAN	Perxyacetyl nitrate, an eye-irritant, by-product of ethanol combustion
PGM	Platinum Group Metals (ruthenium, rhodium, palladium, osmium, iridium, and platinum0.
PEMFC	Proton Exchange Membrane Fuel Cell
Ppb	Parts per billion
SLCA	Sustainability Life Cycle Assessment
SOFC	Solid Oxide Fuel Cell
Vinasse	The residue liquid from the distillation of ethanol, rich in potassium and organic matter.
VOC	Volatile organic compounds, air pollutants found in engine exhaust
WEC	World Energy Council

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1 Introduction

Transport is an essential driver of economic development and growth, facilitating exchange among countries and fostering relations among peoples. It is also one of society's major global energy demanding sectors (World Energy Council 2007, 3).

The transport sector is 95 percent dependent on oil accounting for 60 percent of all oil consumption. It is also responsible for 13 percent of all anthropogenic emissions of greenhouse gases (GHG) such as CO_2 and NO_x. Transport represents an even greater share of carbon dioxide emissions from fossil fuel combustion at 23 percent of the world total and 30 percent of OECD emissions (ITF 2008, 5) playing a major role in the current climate change challenge. The IPCC 2007 report states that there is very likely a relation between the increase of concentration of GHG in the atmosphere, global warming, the melting of ice capes and the increase of sea levels. Another issue related to the use of fossil fuels is that they might have already reached their peak production (Hirsch 2005, 8) and further exploitation tends to be more costly, inflicting the whole system with increasing cost pressure. One important effect of this trend is that it can affect the whole food distribution undermining people's ability to meet basic needs such as subsistence as defined by Max-Neef (Max-Neef 1991, 32). Along with the trend of population increase, which is expected to reach nine billion people by 2050 (UN 2007) this would cause further and greater environmental and social fabric disruption.

This scenario can be explained with a metaphor of the resource funnel (figure 1.1). It illustrates society moving inside a funnel where the walls represent, the decreasing resources and ecosystem services in the upper side, and the increasing demand for these resources in the lower part. As cited above, the consequences are already being felt by society, as news about global warming, oil peak and high oil costs, new environmental taxes and policies, hunger and increasing population, lack of access to pure water and electricity, and many others are frequently being released in the media.

The challenge nowadays is to develop and implement more sustainable solutions that help society avoid “hitting the walls of the funnel”, i.e., guiding it to a sustainable future.

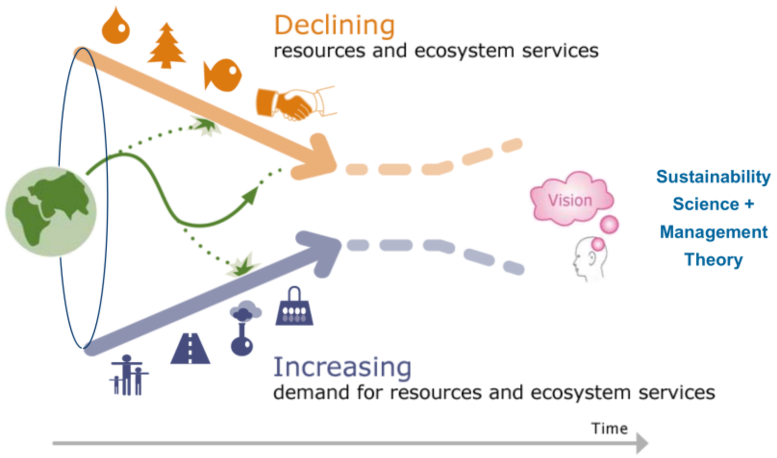


Figure 1.1. Funnel metaphor. (The Natural Step 2008)

In the transport sector, the urge to replace fossil fuels with alternative fuels is therefore of utmost importance. Some renewable fuels are already in the market and are known as the first generation alternative fuels (ethanol, biodiesel). Much attention has been focused on a new way of producing ethanol from lignocellulosic biomass, called second-generation ethanol.

Much effort is also being invested enhancing the efficiencies of current technologies and on developing new ones that have endless renewable potential such as hydrogen from water as a source of fuel for instance. The demands of the transport sector are very likely going to be fulfilled by a mix of different technologies. In this context, scenarios are useful to bring to light the best composition of solutions that can address the sustainability requirements.

Many organizations are producing reports with several possible scenarios that can meet future energy demands taking into account issues such as GHG emissions, progressive fossil fuel substitution and displacement, land use etc. The scenarios do not only take technical issues into consideration but they also make many assumptions on the extent of stakeholders engagement and their importance in facilitating the emergence of alternative fuel technology. The involvement of governments and creation of policies that facilitate research, development and deployment of such technologies in particular play a key role if we expect to avoid further environment disruption.

This thesis will study major technologies in a scenario presented in the Energy Technology Perspectives 2008 report issued by the International Energy Agency (IEA) and, by backcasting from the four sustainability principles (Holmberg and Robèrt 2000), analyze how the new upcoming fuels (second-generation ethanol, hydrogen), combined with existing alternative fuels (first generation ethanol, biogas, electricity) might contribute to their systematic violation. It will then assess the gaps that could hinder us from reaching the future sustainable society.

1.1 Bringing the scenarios to the context

The IEA reports are a response to the request of the G8[1] to provide scenarios and solutions for future energy demands in clean, clever and competitive ways (IEA 2008). They are aimed to be a key-reference for policy-makers and others interested in emerging clean technologies, policies and practices, helping to clarify what are the benefits, challenges and opportunities they are going to face in the future.

The IEA report released in 2008 provides three scenarios (see figure 1.2):

1. Baseline scenario (business as usual), where no action whatsoever is taken to try to reduce CO_2 emissions;
2. ACT Map scenario, which considers that, with technologies that already exist, or are in an advanced state of development, it is feasible to bring global CO_2 emissions back to current levels by 2050;
3. BLUE Map scenario; which considers what has to be done to reduce them by 50 percent in that same timeframe.

The Blue Map Scenario is actually a reaction to the IPCC report of 2007, where it has been stated that in order to have an increase of temperature by 2^oC to 2.4^oC by 2050 we would have to have a decrease of CO_2 emissions between 50 to 85 percent by 2050 (Table 1.1).

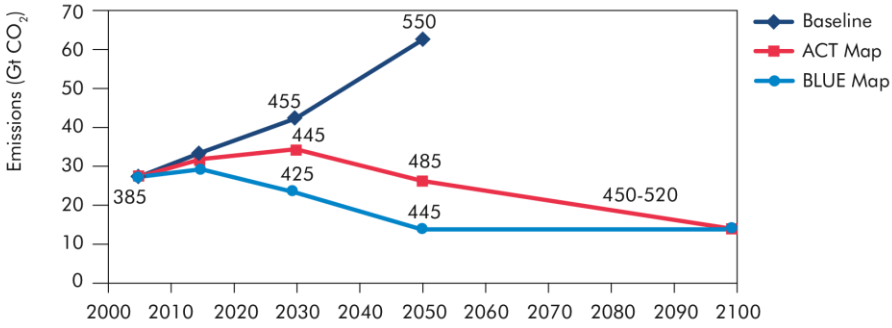
[1] Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, and the United States

Table 1.1. Relation between emissions and climate change according to IPCC 2007.

Temperature increase (°C)	All GHGs (ppm CO_2 eq.)	CO_2 (ppm CO_2)	CO_2 emissions 2050 (% of 2000 emissions) (%)
2.0-2.4	445-490	350-400	–85 to –50
2.4-2.8	490-535	400-440	–60 to –30
2.8-3.2	535-590	440-485	–30 to +5
3.2-4.0	590-710	485-570	+10 to +60

Source: IPCC, 2007.

In order to be able to meet the Blue Map Scenario targets, the report states that "unprecedented technological change and deployment in all aspects of energy production and use" has to take place (IEA 2008, 3).



Note: Figures refer to CO_2 concentrations by volume (ppm CO_2).

Figure 1.2. Energy- related CO_2 emission and CO_2 concentration profiles. (reproduced from IEA 2008, 51)

To assess the impact of CO_2 emissions in the three scenarios, world economic growth is estimated to be approximately four times that of 2005. The Baseline scenario is not desired due to unsustainability caused by impacts on climate change, even though it is feasible because of the availability of fossil fuel reserves. The ACT Map scenario on the other hand, shows that it is possible to make changes in the current energy grid to make it more sustainable in the next half century by using technologies that are already available for commercialization today or are in the midst of becoming available in the market in the next two decades. Finally, in the

Blue Map Scenario, CO_2 emissions are 48 Gt lower in 2050 than in the Baseline scenario.

This thesis will analyze some technologies in the transport sector that could make the Blue Map Scenario viable since, if global warming is to be confined between 2°C and 2,4°C by 2050, it is the only scenario that presents pathways and possible technologies to do so.

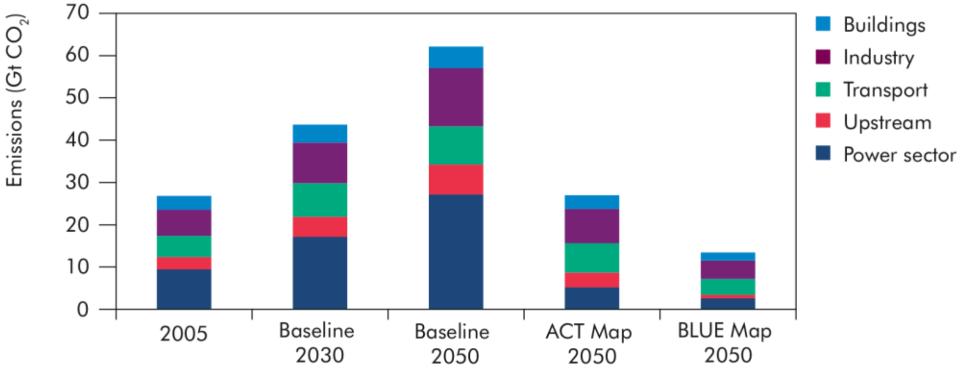


Figure 1.3. Global CO_2 emissions in the scenarios by sector.
(reproduced from IEA 2008, 51)

1.2 Transport sector

In the transport sector, road transport is accountable for 73% of energy consumption, air transport 11 percent, water transport 9 percent and rail only 3 percent. In 2003, 95 percent of transport energy needs were being fulfilled by oil while the remaining 5 percent were being fulfilled by electricity, natural gas, coal and biomass. In the last thirty years the demand and consumption of oil almost doubled in OECD countries while it tripled in non-OECD countries[2].

The world's vehicle fleet, which, in 2005, stood at 890 million units and which, by 2010, should pass the one billion mark, is not only the primary

[2] OECD countries are Austria, Australia, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxemburg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States

market for petroleum products, but also consumes nearly half of all oil produced. It is therefore the largest source of CO2 emissions in the transportation industry, and accounts for some 75 percent of that industry's total. Globally, automotive vehicles are the most rapidly growing source of GHG emissions in the world (MRE 2008, 125).

Considering the IEA scenarios for the transport sector, the expected energy demand for the Baseline scenario is going to increase 120 percent between 2005 and 2050 exceeding 4700 Mtoe by 2050. From this total, oil products provide 75 percent, liquid synthetic fuels (synfuels) produced from gas and coal account for about 22 percent and biofuels, both biodiesel and ethanol contribute with 3 percent. In the ACT Map scenario, in future, the efficiency of current fuel technologies is much higher than the current efficiencies, resulting in 30 percent of reduction in the transportation fuel demand compared to the Baseline scenario in 2050. In this scenario there is a decrease for oil products of 23 percent, synfuels are eliminated and there is an increase of 17 percent of biofuels with equal shares of ethanol and biodiesel, with a clear domination of the second generation when compared to the Baseline scenario. The BLUE Map scenario combines fossil fuels with biofuels, electric vehicles and hydrogen fuel-cell vehicles assuming success in many new emerging technologies (Figure 1.3). In this case fuel consumption is 47 percent lower than in the Baseline Scenario, with oil products being 35 percent lower.

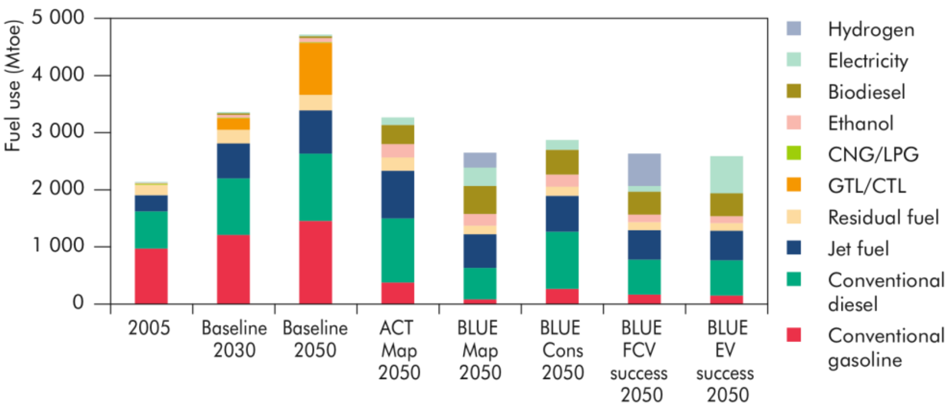


Figure 1.4. Transport energy use in the IEA scenarios. (reproduced from IEA 2008, 92)

In the ACT Map scenario hydrogen does not play a big role but it has relevant importance in the BLUE Map scenario. For the fuel-cell cars to have commercial penetration by 2050 an assumption is being made that the infrastructure is going to start to be laid out by 2020 (IEA 2008, 94).

The enormous use of oil and other fossil fuels in the process of global industrial and economic revolution in the past few decades has its cost in excessive amount of greenhouse gas emissions. Carbon dioxide emissions from the transport sector increased about 30 percent between 1990 and 2003 reaching more than 6 700 Mt globally in 2003.

According to IEA, if current practices of use of oil and other fossil fuels continue there is a risk that global CO_2 emissions in the transport sector would increase about 80 percent between 2002 and 2030 mostly from road transport (IEA 2006).

The mix of fuels proposed by Blue Map scenario seems to be a flexible platform to lead society to a more sustainable future, bringing alternatives that can be developed in a decentralized way, as hydrogen and liquid fuels from biomass.

1.3 Alternative Fuels

Hydrogen and biofuels together account for almost 50 percent of the proposed mix of fuels in the Blue Map Scenario 2050, as shown in figure 1.4. Impacts to the environment and to the social aspects are expected to occur in the envisioned future (2050), on the basis of the increase of 2 to 2.4^{o}C in the global temperature related to the CO_2 emissions (table 1.1).

In order to have a better understanding of what the Blue Map scenario represents in terms of sustainability perspectives, it is of great importance that decision makers and society are clear about how the proposed alternative fuels may affect our lives.

This thesis will assess the sustainability gaps of hydrogen and second-generation ethanol, since they account, to a great extent, for the mix that should meet the demands of the transport sector in the future.

1.3.1 Second-generation biofuels

Unlike fossil fuels, biofuels can be carbon neutral, as the amount of carbon dioxide emitted in its combustion is the same as the amount absorbed by plants through photosynthesis. Because of this factor, environmental policies designed to encourage/develop the biofuels market, are being established in developed countries, since they offer a potentially attractive solution to reduce the carbon intensity of the transport sector. From a strategic point of view, it also addresses security issues by helping to reduce dependence on foreign fossil fuel supplies.

Ethanol and biodiesel are the main biofuels currently being used. Globally, ethanol production more than doubled between 2000 and 2006, and presently accounts for 86 percent of total biofuels production (Worldwatch Institute 2007, 3).

The first generation of ethanol is produced from biomass conversion, mostly from starch and sugar crops, through fermentation process. Brazil and USA are responsible for 89 percent of global supplies deriving their production from sugarcane and corn, respectively (Worldwatch Institute 2008, 6).

Since biofuels originate from plants, ethical questions have been raised about the use of land to produce fuels instead of food, especially when we look at the context of increasing population, putting pressure on natural resources that depend on specific cycles and biodiversity to restore themselves.

Other concerns related to the impacts that the increase of biofuels production can bring to the environment and social fabrics can be listed as: water depletion, water and air pollution, biodiversity loss, soil and forest carbon stock decrease, waste production such as stillage (vinasse), land occupation, exploitation, health issues and social conflict derived from food/energy resource competition (Sims et al, 2008, 78). Latest concern brought about recently by the scientists is that the production of N_2O caused by the use of nitrogen fertilizers can be more dangerous and harmful to climate change than C_2O (Crutzen 2008, 389). These matters bring to light the importance of the development of biofuels produced from non-food biomass.

In response to that, and to increase efficiency, research has been going on to produce ethanol from bulky lignocellulosic material of plants, which is being called second-generation ethanol. The energy yield can increase considerably and the same land is used for production of first and second-generation biofuels. Hence requirements for arable lands would decrease per unit of biofuel output since an important fraction of the biomass needed would come from regenerated and marginal land not currently used for crops or pasture. Other feedstock would include low-cost crops, agricultural and forest residues and the organic fraction of municipal solid wastes (WBCSD 2007; Sims et al 2008, 1).

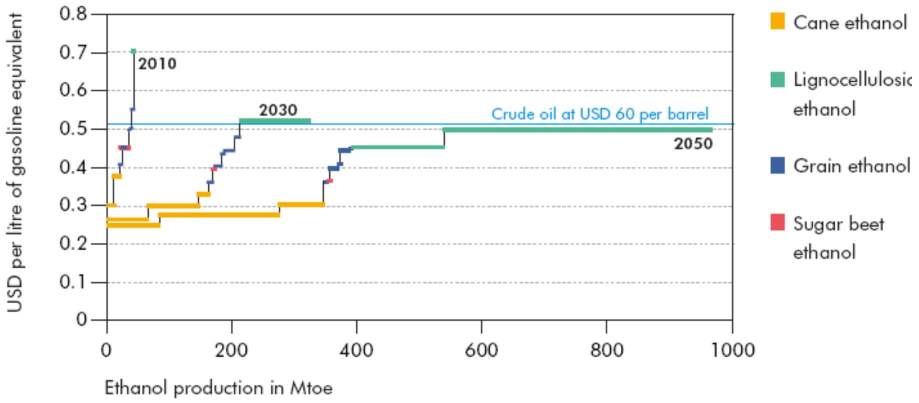


Figure 1.5. Ethanol supply curves. (reproduced from IEA 2006)

As shown in figure 1.5 current costs for first generation ethanol are far lower than the medium cost for the crude oil barrel, while second generation prices are far higher than it. Initially second-generation fuels will remain more expensive per liter, and continued investment in research and government incentives are essential to make it commercially attractive in a near future.

In order to make ethanol a solution for the substitution of fossil fuels in a future society, sustainability assessments are important in order to bring to light the gaps that could lead society into blind alleys.

1.3.2 Hydrogen

Hydrogen is composed of one proton and one electron and is the simplest and most plentiful element in nature. Since on Earth it is only found as linked to other elements, as e.g. in hydrocarbons to carbon and in water to oxygen, it is referred to as secondary form of energy or as an energy carrier, not as an energy source. The hydrocarbons are compounds that make up many of our fuels such as gasoline, natural gas, methane and others.

The energy necessary to isolate hydrogen can be produced by different methods from fossil fuels, water and biofuels that are primary sources while secondary sources like wind and nuclear energy can also be used to produce it. Current world hydrogen production is approximately 50 million tons per year, which is equivalent to only 2 percent of world energy demand. The major consumption of hydrogen these days occurs in petrochemical processes (such as hydrotreating, desulfurization, dealkylation and cracking); in chemical production (e.g. ammonia and methanol); metallurgical processing; electronics industry; and food processing (oil and fat hydrogenation) and not so much for energy production purposes. Hydrogen has been produced from different sources: 48 percent from natural gas, 30 percent from oil, 18 percent from coal, and 4 percent from electrolysis of water (IEA 2006, 291). The hydrogen produced from electrolysis has higher purity but it is a very expensive method. The production from oil, gas and coal on the other hand, is relatively cheaper when compared to electrolysis but it is accompanied by the production of CO_2, CH_4 and other greenhouse gases and therefore, there should be CO_2 capture and storage methods to avoid adverse effects on climate due to emissions.

Hydrogen can, however, also be produced by using less disruptive technologies such as water splitting by electrolysis using electricity produced by wind, hydro and sun and processes based on sustainable production and utilization of biomass.

This thesis proposes to assess technologies that isolate hydrogen from natural gas and renewable sources such as ethanol and water, from well-to-wheel under the lens of sustainability.

1.4 Aim and scope

The main question that guided this research is:

How can the Framework for Strategic Sustainable Development help to guide the assessment of hydrogen and second-generation ethanol as upcoming alternative technologies in the IEA Blue Map scenario, leading to a sustainable society?

The assessment of biofuels or other new fuels like hydrogen to be used in road transport sector is a huge task, and several aspects have to be taken into consideration, such as economical, political, environmental and social issues of each country. Each player in this context has different roles, making the assessment a multi-level task. This thesis has the objective of assessing technologies within the Blue Map scenario, proposed by IEA (International Energy Agency) for 2050, in the report Energy Technologies Perspectives 2008, since it is the only one that more radically addresses the issues related to the greenhouse gases emissions. The second-generation ethanol, hydrogen originated from natural gas and ethanol through the process of steam reforming and through renewable energy will be assessed from a sustainability perspective using backcasting from sustainability principles, and the challenges and opportunities for the deployment of these technologies will be identified.

The chosen method to conduct the assessment is the Sustainability Life Cycle Assessment (SLCA), which is presented in detail in section 2.5.

Political, financial and policy issues related are not included in this assessment due to time constraints.

1.5 Target Audience

This thesis aims to bring into light the impacts of new technologies and put forth some recommendations to ensure that the scenario leads us to a sustainable society. The target audience for these results includes:

- Investors
- Regulatory boards
- Organizations and companies
- Scientific community
- Stakeholders, as international agencies (WEC, IEA, WBCSD and others related to the energy sector)
- Sustainability practitioners
- Industry associations involved with fuels and vehicle technologies.

2 Methods

The thesis aims to assess, from a sustainability point of view, alternative fuels presented in the Blue Map Scenario as options to replace the present technologies based on fossil fuels. The approach will require methods to deal with complex processes, such as technologies for vehicles, efficiencies, environmental and social impacts, future research and developments, global and local policies and many others.

Due to this complexity, and to the fact that hydrogen and second-generation ethanol are still under research, an extensive literature review has been carried out in order to cover as many as possible aspects related to sustainability amongst all the technological approaches that are currently being researched.

Reports from reliable organizations, like IEA, WEC, WBCSD and others were helpful, and gave us important and updated information about the sector and the global demands and scenarios.

Interviews with some specialists in the sectors were conducted and questionnaires were sent in order to provide a practical and updated vision of the perspectives and also a better view of the proposed technological solutions for the transport sector.

2.1 Definition of sustainability

In this thesis, sustainability was defined using the four principles, or systems conditions, that are (Holmberg and Robèrt 2000, Ny et al., 2006):

In the sustainable society, nature is not subject to systematically increasing:
I …concentrations of substances extracted from the Earth’s crust (Fossil carbon or metals),
II …concentrations of substances produced by society (e.g. nitrogen compounds, plastics compounds, CFC’s and endocrine disrupters),
III …degradation by physical means (e.g. heavy deforestation, mining, over-fishing),
and, in that society. . .

IV…people are not subject to conditions that systematically undermine their capacity to meet their needs (e.g. from the abuse of political, structural and economic power).

The first three principles deal with ecological sustainability, while the fourth one is concerned with social sustainability.

The principles have following unique qualities from sustainability perspectives:

- They are based on scientific knowledge
- They are important to achieve sustainability.
- They can be used in every sector and are therefore generic.
- To achieve sustainability compliance with all four is necessary.
- These four SPs together cover all aspects of sustainability.
- They are concrete and guide in solving problems efficiently.

(Holmberg and Robèrt, 2000, Ny et al., 2006).

Having the above combined qualities, the principles make it easier to identify the causes of the problems at their origin, and help to deal with them upstream rather than dealing with consequences as they appear.

When talking about renewable fuels like ethanol and hydrogen these principles make possible an analysis of present activities and the future vision defined by the IEA scenario, from a sustainability perspective. The impacts of the use of these technologies will be identified, guiding the decisions towards the success of the vision.

Translating the sustainability principles to the use of alternative fuels in the transport sector, they become:
I …substitute minerals that are scarce in nature with others that are more abundant, use all mined materials efficiently, and systematically reduce the use of fossil fuels in the processes (e.g. production, transportation, etc.)
II …substitute unnatural compounds with ones that are naturally abundant, or break down more easily, and use substances produced by society more efficiently through dematerialization.
III …use resources from well-managed ecosystems, systematically pursuing the most productive and efficient use of resources and land, use of caution in all kinds of modification of nature like overharvesting and overusing the land causing erosion

IV …check the effect of the solutions adopted in peoples lives, now and in the future, avoiding the restriction of their opportunities to lead a fulfilling life (Robert et al, 2007).

2.2 Framework for Strategic Sustainable Development (FSSD)

The Generic Five Level Framework (Robèrt, et. al. 2007) is a conceptual model designed to enable organizations to plan in complex systems, without incurring in reductionism, i.e., oversimplification of a given system. When used to understand the interrelations between our society and the biosphere, it is known as the Framework for Strategic Sustainable Development (FSSD).

The framework, as already stated, is constituted of five interdependent levels as follows:

Figure 2.1. Five Level Framework

The FSSD is used as a background theory to organize and guide this assessment in a comprehensive and clear way.

The systems level

At this level, the fundamental characteristics of the complex system are identified. To avoid reductionism, all of the major components, interrelationships, and essential aspects of the system must be included.

The transport sector was identified as a part of a complex and dynamic network, where social fabric and ecosystem are directly affected when sustainability is not taken in account in order to guide the developments and policies.

Complexity also increases when considering the vast system boundaries as the whole world, with all countries particularities from geographical location to political and social configuration. The system identified for the scope of this assessment can be defined as:

Society using the transport utilities, within the biosphere, and all the social and environmental impacts caused by the available technologies, policies and society's behaviors.

The success level

At this level, the goals to obtain success in the system are defined. In order to have goals that will guide society towards sustainability, the four sustainability principles have to be considered.

To deal with this complexity and have a clear definition of the boundaries of the scope of this assessment, a scenario where alternative fuels plays major role in substituting fossil fuels on the transport sector was used, and the definition of success can be defined as:

Transport sector, within the society, having its needs mainly being met with the mix of fuels proposed by the IEA Blue Map scenario, in compliance with the four sustainability principles.

The strategy level

Strategic guidelines for planning and acting towards the goal, defined in the success level.

Here, a backcasting perspective has to be set. Backcasting is a planning procedure in which first a successful imagined point in the future is defined and then strategies that lead towards that outcome are defined by asking, "What we need to do today to reach our desired future?"(Dreborg 1996, 813).

Having in mind the complexity explained in the systems level, a scenario has been chosen in order to be set as a future desired goal. IEA scenarios aim to give a picture of the future according to different assumptions related to the use of alternative fuels to meet society's future projected demand for fuels in the transport sector.

To be in accordance to the desired success and guide strategically towards it, the Blue Map scenario will be assessed under the lens of principle-based definition of sustainability. Having the scenario being scrutinized by the basic principles of sustainability, then it can be considered as a stepping-stone towards the sustainable future, as illustrated in the figure below:

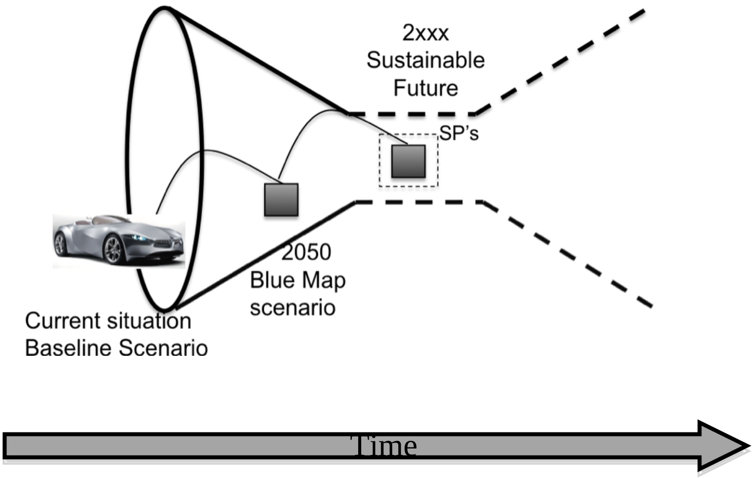


Figure 2.2. IEA scenario as stepping-stone.

The actions level
At this level we can describe what is tangibly necessary to what has been defined in the strategy level to obtain success in the system.
Using the SLCA combined with the SWOT analysis, detailed in the tools level, recommendations to help the sector to make the scenario a sustainable future will be listed.

Tools level
At this level we have the tools that are at our disposal to foster the actions needed to achieve success in the system accordingly to the strategy designed to do so. In the context of this thesis, the tools used are SLCA combined with SWOT analysis, interviews with experts and questionnaires.

2.3 SLCA and SWOT Analysis

2.3.1 SLCA (Sustainability Life Cycle Assessment)

In order to have a strategic approach to this complex issue (i.e., fuels for transportation on a global scale), a Sustainability Life Cycle Assessment was chosen to be used as a tool. A traditional life cycle assessment (LCA) is a long and complex assessment, and its final results are very detailed information, that sometimes distracts decision makers to take the right decision towards a more sustainable solution.

Strategic Life Cycle Assessment (SLCA) is a method that is being developed by BTH researches together with several partners (Guide to BTH tools, 2008) that combines the traditional LCA with the sustainability perspective. The basic concepts came from the SLCM tool (Sustainability Life Cycle Management) (Ny 2006). The SLCA tool has been used already with success in cases like Waterjet Machine (Hallstedt 2008).

The SLCA brings the sustainability "hot spots"/ impacts of the item that is being assessed across each life cycle stage and helps to reach a more strategic view of the real gaps regarding a sustainable future.

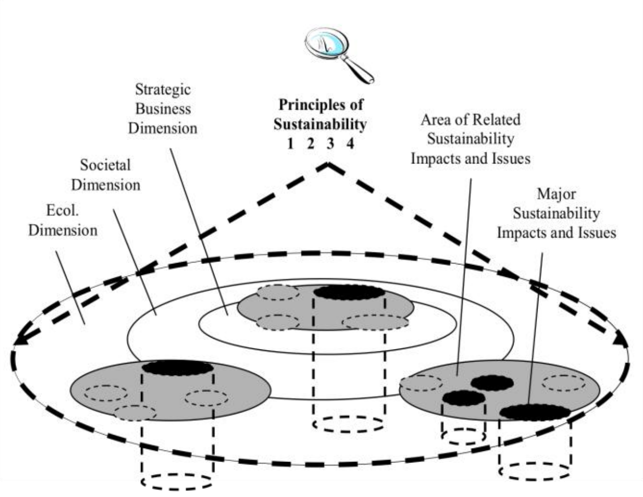


Fig. 2.3. Strategic life-cycle management (SLCM) – sustainability principles as system Boundaries (reproduced from Ny 2006, 45)

This approach is more strategic than the traditional LCA, as it allows the assessment to cross the boundaries of the several dimensions involved in the issue being scrutinized, with an overview of the whole system through the lens of the four Sustainability Principles (SPs).

The SLCA consists in the study of all phases of a given process looking for the possible violations to the four sustainability principles previously presented in section 2.1.

Below, as an example, the SLCA matrix used for the assessment of the hydrogen production from natural gas is presented:

LIFE CYCLE'S PHASES	**SUSTAINABILITY PRINCIPLES**			
	SP1 Materials from earth's crust	SP2 Man-made materials	SP3 Degradation of biosphere	SP4 Undermining capacity to meet their needs
Raw materials (extraction and production of natural gas)				
Production of Hydrogen				
Transporting and storage				
Use phase (combustion or electricity generation)				

2.3.2 SWOT Analysis

The SWOT Analysis is a strategic planning tool used to evaluate the **S**trengths, **W**eaknesses, **O**pportunities, and **T**hreats involved in a project or in a market. This analysis is credited to Albert Humphrey, who led a research project at Stanford University in the 1960s and 1970s.

In this thesis, the SWOT analysis was adapted to the assessment of the technologies, relating the internal aspects to the issues directly connected to the process being accessed, and the external aspects to the consequences and opportunities that this process can bring to other players.

Below is the SWOT analysis template used in this assessment:

INTERNAL	POSITIVE
	STRENGTHS
	NEGATIVE
	WEAKNESSES
EXTERNAL	POSITIVE
	OPPORTUNITIES
	NEGATIVE
	THREATS

2.3.3 Combined SLCA/SWOT Analysis

Combining a SWOT analysis with SLCA approach, not only allow/enable assessing potential issues related to the sustainability principles, but also identifying strengths, weaknesses, opportunities and threats related to each phase of a technology's life cycle.

The combined assessment allows for a complete overview of matters related to a given technology, making it easier to strategically guide the transport sector towards a more sustainable set of technologies for fuels for vehicles. Below is the SLCA/SWOT analysis combined diagram:

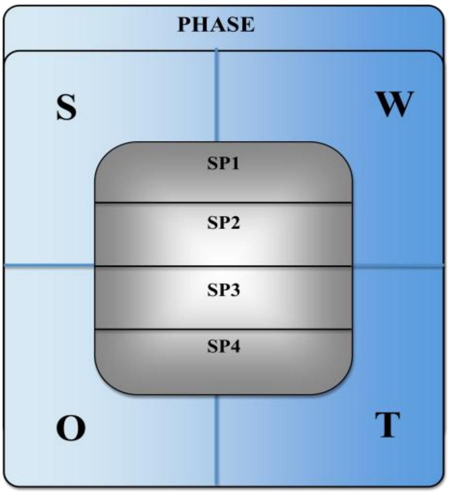


Figure 2.4. SLCA/SWOT combined diagram.

3 Results

In the following sections, second-generation ethanol and hydrogen are assessed in terms of sustainability principles, through the Sustainability Life Cycle Assessment (SLCA). A Strengths, Weaknesses, Opportunities and Threats Analysis (SWOT) is also carried out and the results are presented in tables.

3.1 Sustainability Analysis of Second-generation ethanol

The phases to be considered in the strategic life cycle assessment of the ethanol generation are similar for the first and second generation, despite some new sub-processes related to the harvesting and treatment of the lignocellulosic biomass. When assessing the agricultural phase of the second-generation biofuels isolated from the first generation, considering only new sources of biomass, a much wider variety of feedstocks could be used, beyond the agricultural crops currently used. This could have important implications when addressing agriculture and food security (FAO 2008a). However, in order to make the transition in a more strategic way, the second generation shall be implemented as an evolution of the current production methods. Some examples are the use of the wastes currently being produced by the harvesting and production processes, bringing higher energy yields per hectare of biomass and the need of few additional improvements in the existing production plants to implement pre-treatment processes.

As an evolution of the first generation ethanol, the assessment of the second generation cannot be made without bringing first the current impacts and from them, built the picture of the integrated process. An illustration of the production of ethanol, combining first and second generation is useful to have a better picture of all inputs and outputs of the technology.

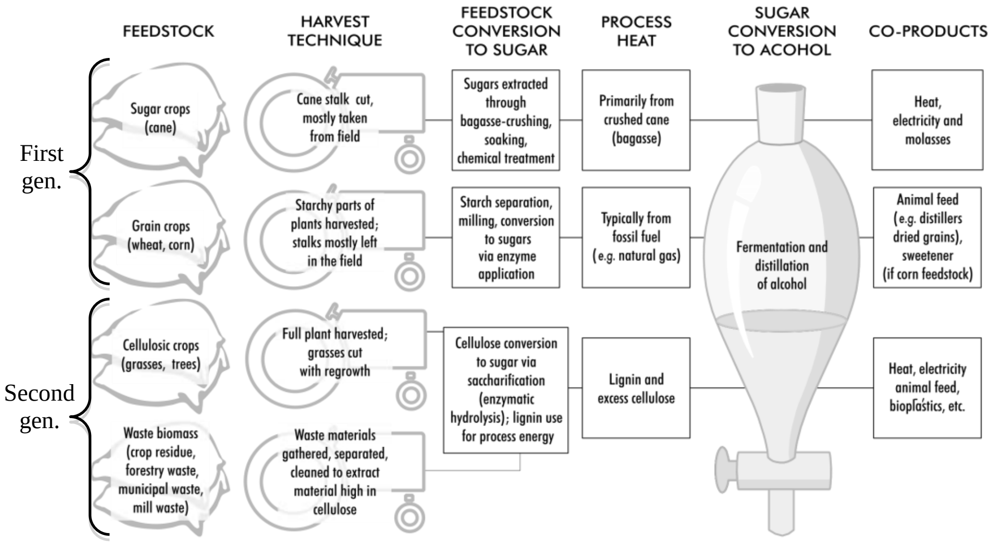


Fig. 3.1 Ethanol production steps by feedstock and conversion technologies. (adapted from IEA 2004, 35)

As cited before, 89 percent of the ethanol produced in the world comes from Brazil (41.1 percent, sugarcane) and USA (47.9 percent, corn). The list of main impacts related to the ethanol from sugarcane production came from the previous thesis denominated Sustainability Opportunities and Challenges of the Biofuels Industry (França et al 2006).

Since 2006, the ethanol production has increased significantly, and its processes have constantly been target of criticism because of impacts related to land use and competition with food production. Even with this current situation, the relevant impacts and challenges caused by the production processes of ethanol from sugarcane are still the same as França et al. listed in 2006. No significant improvements in the traditional production were noticed since then.

Additional relevant impacts have to be considered in this thesis to include the ethanol from corn feedstock, which is mainly produced in the USA. Producing ethanol from grain starches is more land intensive than producing it from sugarcane, because crops from the former have lower yield per hectare. As a consequence, more nitrogen-based fertilizers are needed for the same amount of fuel. N_2O is a by-product of fixed N application in the agriculture. The N_2O is a GHG with a 100-year average

GWP (global warming potential) 296 times greater than the same mass of CO_2 (Prather et al. 2001, 244). The increasing rate of biofuels in the transport sector can further cause enhanced atmospheric N_2O concentrations (Crutzen et al., 2008, 389). Furthermore, an additional process to convert corn into sugars is needed when compared to sugarcane (Worldwatch Institute 2007, 28).

The significant amount of energy needed for the refining processes in the ethanol from corn production is currently being supplied by natural gas and coal in North America and many other regions, increasing the well to wheel GHG emissions. In Brazil (sugarcane) the production plants are self-sufficient as they burn bagasse to produce energy.

Considering all of these points and comparing all options, the production of ethanol from corn is being highly criticized by the scientific community for its high overall emissions.

The life cycle phases considered for this assessment are:

- Phase 1: Agricultural phase (first and second generation), consisting in land preparation, planting, harvesting and transporting to facility site,
- Phase 2: Production phase (first generation), including a new phase for the second generation, consisting on pre-treatment of cellulosic mass (pre-hydrolysis of hemicellulose, delignification and cellulose hydrolysis),
- Phase 3: Use/Combustion phase (similar as the first generation, with additional impacts related to the increase on the ethanol production and consequent use).

3.1.1 Phase 1 - Agricultural phase

Some advantages are crucial for the feasibility of lignocellulosic ethanol technology, such as the lower need for nitrogen fertilizers in the perennial crops growth (SP2) and the capacity of growing in lands that are not appropriate for food crops (SP4). Furthermore, cellulosic crops can be grown as more complex species mixes, including native polycultures grown for additional conservation benefits (SP3). Moreover, the cultivation of cellulosic crops has the potential to promote soil carbon sequestration, reduce nitrous oxide emissions, provide to ecosystems in the surrounding landscape biodiversity-based services such as pollination and pest suppression, and afford much higher rates of energy return than grain-based systems (Robertson et al. 2008).

As energy crops can be grown on agricultural land not used for food, another advantage is that farmers can plant them along the riverbanks, lakeshores, between farms and natural forests, and wetlands, bringing to them flexibility and making the planting a good source of alternative income among all other environmental benefits (Nag 2008, 52).

One important option for the lignocellulosic plant for the second-generation ethanol is switchgrass. Some of the strengths that are important to be listed are (Lal 2008, 755; IEA 2004, 38):

- High yield per hectare
- Can be grown across a wide geographical range
- Great carbon sequestration ratio
- Resistant to many pests or diseases, decreasing needs for pesticides
- The ground will only need to be tilled for replanting every 10-15 years, reducing the need for fossil fuels in the tillage processes
- It requires less chemicals, nutrients and water to grow
- Switchgrass is also very tolerant of poor soils, flooding and drought
- Typically grown in a ten-year crop rotation basis and harvest can begin in year 1, requiring no annual replanting or ploughing.
- They can enrich soil nutrients and provide ground cover, thus reducing erosion

In the future, the main source of lignocellulosic biomass for second-generation biofuels is likely to be from “dedicated biomass feedstocks”, such as certain perennial grass (like switchgrass) and forest tree species. Researchers are investigating genomics, genetic modification and other biotechnological tools to produce plants with desirable characteristics, such as plants that produce less lignin (a compound that cannot be fermented into liquid biofuel), that produce enzymes themselves for cellulose and/or lignin degradation or that produce increased cellulose or overall biomass yields (FAO 2008, 20).

Transforming the biomass into transportable pellets is also a challenge to be addressed by the new developments to make the second generation feasible and accessible to the market.

Life cycle analysis of the ethanol production indicates that GHG emissions can vary widely according to the technologies used. Key sources of emissions are land conversion, mechanization and fertilizer use at the feedstock production stage, and the use of non-renewable energy in processing and transport (FAO 2008).

Currently the vinasse produced is used as fertilizer in a process called in ferti-irrigation. Existing plants produce approximately 10-15 liters of vinasse for each liter of ethanol (Kojima 2005, 25). This is becoming a threat, as using large amounts of vinasse as fertilizers can degrade the soil and contaminate ground water (SP3).

In spite of all the advantages presented above that contribute to the sustainability principles previously presented, caution is recommended due to the drawbacks caused by change in the land use (SP3). Idle lands, such as set-aside, accumulate carbon in the soil and, over a long period of time, may begin to have significant vegetation and above ground carbon stocks. This carbon is generally released when the land is brought back into agricultural production by ploughing (RFA 2008). Another issue that deserves attention in that the definition of what is considered a marginal or idle land can vary, and what is for one an useless land, can be for other of vital importance for the livelihoods of small-scale farmers, pastoralists, women and indigenous peoples (The Gaia Foundation et al. 2008).

Growing wood or energy crops for second-generation ethanol in soil that is not used for food crops can pose a danger, as forests would be cleared. Tropical forests are important players in the carbon sink role and as a source of biodiversity (De Watcher 2008).

No official results of the contribution of the land use change in the CO_2 emissions are available, but the consensus is that it cannot be neglected anymore. Policies have to be developed to protect the environment from the overuse of the resources.

Table 3.1 Results of SLCA (second-generation ethanol) for phase 1

		First-generation (França et al. 2006)	Second-generation
PHASE 1 – Agricultural production	**SP1**	Net increase of mined materials including oil, metals, alloys, and phosphate rocks.	No additional negative impacts
	SP2	Emissions to: **Air**: N_2O, SO_2, (causes acid rain), CO_2, NH3, NOX, CO, particulate ashes, fluorides, organic compounds: HC, CH_4, aldehydes **Water:** solids, oil, phenol, organic matter, N, fluorides. **Water and soil:** Na, K, from excess of vinasse and pesticides, their intermediates, and degradation products, Cd, As, Zn; solid waste.	Additional negative impacts: - Increase of vinasse production, as yield per hectare is increased (nowadays is aprox. 10-15l vinasse per 1 l ethanol)
	SP3	Degradation and loss of soil nutrients, as a consequence of burning and agrochemicals. Loss of water quality and aquatic habitat, salinization from fertilizers. Loss of biological species through deforestation, open mining, and monoculture.	Additional negative impacts: - Degradation and loss of nutrients caused by overharvesting - Increase of vinasse production leading to enhanced use as fertilizers. - Clearance of tropical forests for producing wood or energy crops can reduce the carbon sink and affect biodiversity
	SP4	Chronic and acute health impacts: **E**xposure to agrochemicals, heat, particulate matter from burning, accidents, toxic spills. Social impacts: Use the work of "boias frias" (child labor). Large scale producers pressing small family production to buy land for expansion, unemployment due to mechanization. Contamination of ground water with aldehydes through spillage can cause health problems(eye and respiratory tract irritancy)	Additional negative impacts: - Marginal lands can be of vital importance for local communities that depend on that.

Table 3.2. Results of SWOT analysis (second-generation ethanol) for phase 1

	STRENGTHS
INTERNAL	• Biomass can be from wastes from the first generation production, what increases the yield of the production, decreasing the use of N fertilizers and pesticides per hectare. Also energy crops require less pesticides and fertilizers. • Perennial grasses, such as switch grass and elephant grass, and lingo-cellulosic plants as eucalyptus, poplar and willow can bring more favorable conditions for energy production, concerning to nitrogenous emissions (N_2O) (Crutzen et al 2008) • Agricultural and forestry residues would require no additional cultivation energy

(Worldwatch Institute 2007, 167)

- Some studies suggests that perennial crops encourage increased wildlife populations and diversity of birds, mammals and soil fauna (Worldwatch Institute 2007, 204)
- Cellulosic biomass is easier to store, as it resists deterioration, compared to sugar- based crops (FAO 2008a, 19)
- If well managed, woody crops can regulate water flows and reduce risks of floods and draughts (Worldwatch Institute 2008, 210)
- Marginal lands that cannot support agriculture nowadays can be used for energy crops production (Worldwatch Institute 2007, 201)

WEAKNESSES

- Changes in land use impacts are not accounted nowadays in the calculation of energy balances. According to Gallagher report, carbon is released when idle lands are brought back into production (RFA 2008). For example, switchgrass, a possible second-generation crop, can generate savings of 8.6 tonnes of carbon dioxide per hectare per year, however the conversion of the grassland can release 300 tonnes per hectare and conversion of forest land 600-1000 tonnes per hectare (Fargione et al. 2008)
- Transport of biomass feedstock from fields to bio-refineries nowadays is made by trucks, fueled by fossil fuels (Worldwatch Institute 2007, 176)
- Introduction of energy crops can potentially cause negative impacts in the local hydrology, by interception and use of the rainfall, reducing infiltration (Worldwatch Institute 2007, 210)
- Tropical forests are important players in carbon sink and biodiversity roles, and would be cleared in order to plant wood or energy crops (De Watcher, 2008).

EXTERNAL

OPPORTUNITIES

- Use of marginal lands that cannot support agriculture nowadays can bring extra incomes for farmers (Nag 2008,52)
- More decentralized production of energy, can bring to developing countries great opportunities to become providers in a global scale, as well as supply their internal energy demands, bringing more energy security.
- Development of total fossil free methods of production, using only renewable energy for cultivate, harvest, refine and deliver the biofuels can lower the life cycle GHG emissions and create new technologies and jobs.
- Landfills biomass can be used to produce ethanol, reducing the methane emissions.
- Farmers can improve their economical activities by planting in idle lands the energy crops.
- Selling the agricultural residues to ethanol plants can be a profitable activity for farmers of the food crops.
- Developing countries located at tropical areas have more conditions to produce biofuels
- The development of second-generation ethanol will enhance availability of this fuel for hydrogen production, allowing diversification raw materials for hydrogen production.

THREATS

- Lignin residues account to 1/3 of the plant biomass, and in a near term, it is more effective to use this as fuel to process energy for first generation (Worldwatch Institute 2007, 167)
- Research is needed to determine how much residues from forests can be harvested without affecting soil quality (Worldwatch Institute 2007, 202). Some amount of crop residues has to be left in the field to reduce erosion and recycle nutrients back into the soil.
- Researchers are investigating genomics, genetic modification and other biotechnologies tools to produce plants with desirable characteristics for the second –generation ethanol. It can be a threat for the future, as the consequences of inserting new species are not known (Blue map scenario estimates that from 2020, all ethanol will be produced by second-generation feedstocks).
- Technological developments have to be done convert biomass into transportable pellets,

	when not close to the production plant. • A clear definition of what is a marginal land is necessary. In most cases, lands defined as "marginal", "wasteland" or "idle" are vital for the livelihoods of small-scale farmers, pastoralists, women and indigenous peoples (The Gaia Foundation et al. 2008).

3.1.2 Phase 2 - Production of ethanol

Lignocellulosic feedstocks can be converted into liquid fuels through two main processes (Sims et al. 2008, 7):

- Biochemical – in which specific enzymes and other microorganisms are used to break the cellulose and hemicellulose into sugars. These enzymes for industrial scale use are still under research, and several companies are in the verge of commercializing viable and efficient options.
- Thermo-chemical – where pyrolisis/gasification technologies produce synthesis gas ($CO + H_2$), from which a wide range of biofuels, such as synthetic diesel or aviation fuel, can be reformed. Also hydrogen can be converted from syngas. Thermo-chemical processes are not part of this thesis, and they were cited here to show the relation of the production of hydrogen from biomass.

Production of ethanol from lignocellulosic materials requires additional pre-treatment phases to break the fibers and convert them into sugars in order to start the fermentation phase, as shown in figure 3.2. The aim of the pre-treatment is to expose cellulose and hemicellulose for subsequent enzymatic hydrolysis, and is one of the most critical process steps. In the figure, main stream components are shown as: C, cellulose; H, hemicellulose; L, lignin; G, glucose; P, pentoses; I, inhibitors; EtOH, ethanol.

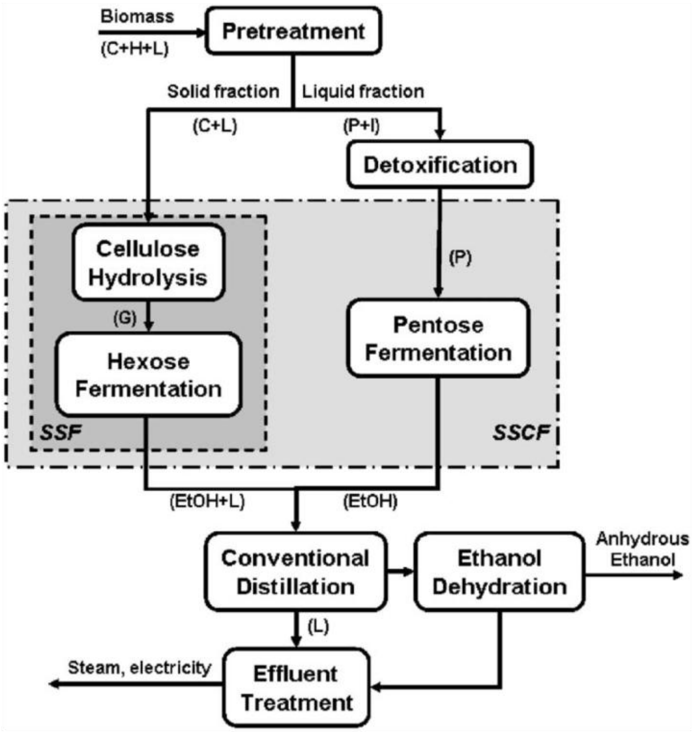


Figure 3.2. Generic block diagram of fuel ethanol production from lignocellulosic biomass. (reproduced from Alzate and Toro 2006, 2449)

Current challenges for this technology are now the development of pre-treatment processes that can be available for industrial scale and in a competitive price. Table 3.3 shows the status of the R&D nowadays:

Table 3.3. Status of each sub-process involved in bio-chemically converting lignocellulose to ethanol. (reproduced from Sims et al. 2008, 46)

Sub-process	Objectives	State of development
Pretreatment	Properly size the material. Produce ideal bulk density. Remove dirt and ash. Rapid depressurisation to explode fibre. Open the fibre structure.	Demonstration/commercial - but needs optimisation for different feedstocks and downstream processing.
Fractionation	Cyclone to separate solids from vapours.	R&D.
Enzyme production	Cost and processing rate are key factors.	Commercial -but needs further cost reductions to reach USD 0.02-0.03 /litre of ethanol.
Enzymatic hydrolysis	Produce C6 and C5 sugars. Reduce viscosity.	Early demonstration.
Hexose fermentation	Standard yeast	Commercial.
Pentose fermentation	Standard yeast is not suitable. New micro-organisms dictate yield and rate. This affects feedstock demand / unit of product and capital expenditure on plant.	Research/pilot plant moving towards commercialisation.
Ethanol recovery	Distillation to obtain 99.5% ethanol.	Commercial.
Lignin recovery and applications	Separate lignin and other solids. Combust for heat and power or to produce biomaterial co-products.	Research/pilot plant -co-products to improve economic performance.
Waste treatment		Research/commercial

A recent study made by researchers in Brazil (Dias et al. 2008), assessed the use of bagasse for fuel and heat producing, in an integrated process. The results was to have better efficiency in the process, the bagasse should first be used for producing heat and energy for the process, and the rest for fuel production. In that case study, the result is that 40 percent of the bagasse was enough to produce all the energy needed for the processes, and 60 percent of the bagasse was available, and increased the ethanol production with 18 percent (Dias et al. 2008). This study brings the concern that evaluation of the energy consumption, when integrating the production of first and second generation, constitutes an obstacle for the technical and economical feasibility of the hydrolysis processes.

Nowadays there are no industrial scale plants available for production of second-generation ethanol. Further research is also being made in order to come up with an efficient chemical process (Worldwatch Institute 2007, 64).

Table 3.4 Results of SLCA (second-generation ethanol) in phase 2

		First-generation (França et al. 2006)	**Second-generation**
PHASE 2 – Production phase	**SP1**	Net increase of mined materials from oil, metals, and alloys used in processing and infrastructure.	Additional negative impacts: - Acid hydrolysis: Greater amount of sulphur used - Increase on energy consumption in the process - Need for expansion of infrastructure for transport and storage of final product
	SP2	SO_2, CO, CaO, Ca $(OH)_2$ hydrated lime, CO, H_2SO_4, aldehydes from processing activities. Na, K from vinasse industrial effluents to water systems. Solids, phenol, organic matter N, P Cleaning products compounds, NH_3, Cl^-, Cu, and Zn. Methane (produced in acid hydrolysis	Additional impacts: - Pre-treatment: Hydrogen peroxide - Acid hydrolysis: Greater amount of sulphuric acid or sodium hydroxide in the hydrolysis - Enzymatic hydrolysis: New man-maid enzymes produced - Increase of vinasse production - New genetically modified yeasts developed to break 5-carbon sugar (NREL 2007)
	SP3	Degradation of water quality and resources from washing processes. Use of equipment and machinery highly dependent on mining materials and processes that contribute to loss of biodiversity due to open mining activities.	No additional negative impacts
	SP4	Chronic and acute health impacts caused by exposure to heat of machinery operations. Accidents and toxic spills caused by use of chemicals and poor workplace safety practices.	New yeasts and enzymes are patented, and can be in hands of few producers

Table 3.5. Results of SWOT analysis (second-generation ethanol) for phase 2

INTERNAL	**STRENGTHS**
	• Same infrastructure is used to produce ethanol from first and second generation, with inclusion of the pre-treatment equipments. • Cellulosic ethanol offers health benefits from PM2.5 (particulate matter < 2.5) reduction (Hill et al. 2009, 2077)
	WEAKNESSES
	• More energy is needed in the production plants to convert lignocellulosic matter into sugars. • Biochemical enzymatic processes have low efficiency (Patzek 2006). • Enzymes for industrial-scale production are not available yet.

	OPPORTUNITIES
EXTERNAL	• Installation of organic treatment systems to treat the waste water produced can significantly reduce the amount of fresh water needed in the process, consequently lower production costs • Methane can be captured in the wastewater treatment process, and used as a fuel, bringing economic incentives. • Use of biofuels fueled trucks when transporting feedstocks from plantation to production plant and final product to the stations can reduce considerably the CO_2 emission in the life cycle. • Developing decentralized energy production can help developing countries to improve energy security.
	THREATS
	• Genetically modified products (yeasts and enzymes) are needed to convert lignocellulosic mass into sugars and ethanol. • Use of the bagasse as a fuel for energy production is more effective that for producing ethanol. Then best ratio shall be used in order to balance the use for both functions. • Enzyme process for a lignocellulosic alcohol can take 5-7 days, while corn fermentation processing time can be maximum 72 hours, to avoid contamination with bacteria. This is a big barrier for the industrial batch production (Patzek 2006). • New genetically modified yeasts to break 5-carbon sugars are patented and can be monopolized by few companies. It can also occur with the enzymes.

3.1.3 Phase 3 - Use / Combustion of ethanol

Ethanol could play an important role in reaching very low GHG emissions levels from the transport sector by 2050, since sustainability impacts are previously addressed. In use phase, several important issues have to be considered, related to vehicles technologies and mixtures used.

Ethanol can be used in different blends, according to the vehicle technologies available in each location. This factor can bring different conclusions related to the reduction of GHG in transport sector.
The most commonly used blends of ethanol/petrol are E5, E10, E85, and E100. The E stands for Ethanol and the number denotes the percentage of ethanol in the blend.

Low ethanol blends (E5 and E10) can increase the volatility of the compound, causing more evaporation in the fueling process. Higher volatility in turn leads to higher evaporative emissions, including emissions of harmful hydrocarbons (such as benzene) and ozone precursors (such as light olefins) (Mojima and Johnson 2005, 21). There is evidence that NO_x level from low ethanol blends range from a 10 percent decrease to a 5 percent increase relative to pure gasoline. Nowadays, in modern engines, very efficient catalyst converters are used to reduce VOC, NO_x and CO emissions to very low levels. Also aldehyde emissions can be reduced with the use of three-way catalysts (Worldwatch Institute 2007, 224-228). There are important drawbacks for this fact that have to be considered in the assessment:

- The catalyst systems are based on rare metals, as platinum or palladium (SP1)
- Most of exhaust gas leaving the engine through a catalytic converter is CO_2 (SP2)

E85 blend tested by NREL researches showed that CO emissions increased and NO_x decreased (NREL, n.d.). As in colder countries the pure ethanol is not considered viable because of its low vapor pressure, attention must be given to the control of these emissions related the high-blends combustion (Worldwatch Institute 2007, 17).

Second-generation ethanol can encourage the increase of the low blend ethanol, where no adaptation in the engines is needed. Advantages related to GHG emission can occur, but also an increase of pollutants that affect human health (SP4). There is concern that aldehydes might be carcinogenic; but the impacts of this are reduced when stated that pollutants that are reduced by blending gasoline with ethanol (as benzene, 1,3-butadiene, toluene and xylene) are comparatively much more dangerous to human health.

Table 3.6. Impacts of the emissions of ethanol blends compared to gasoline

	NO_x emissions	**CO emissions**	**Hydrocarbons**	**Acetaldehyde, formaldehyde, PAN**
E5/E10	Increase in old vehicles (related to the fuel/air ratio)	Decrease in old vehicles	-Decrease in combustion -Increase by evaporation (fueling)	Increase
E85	Decrease	Increase	Increase (related to the fuel/air ratio)	Increase
E100	Decrease	Decrease	Decrease	Increase
Flexfuel vehicles	Increase (related to the fuel/air ratio)	Decrease	Increase (related to the fuel/air ratio)	Increase

Table 3.7 Results of SLCA (second-generation ethanol) in phase 3

		First-generation (França et al. 2006)	Second-generation
PHASE 3– Use / Combustion phase	**SP1**		Additional negative impacts: - More catalyst converters mean more mining of palladium and platinum
	SP2	Exhaust gas emissions: CO, CO_2, HC NO_X , aldehydes and PAN	Additional negative impacts: - Increased rate of ethanol blends can increase NO_x, benzene and light olefins - Increased use of catalyst converters can increase CO_2 emissions - Additional ethanol combustion increases acetaldehydes and PAN emissions
	SP3	Degradation of air quality dependence on open mining or metals and alloys used in automobiles. Use of automobile and engine components highly dependent on mining materials that comes from open mining processes that contributes to loss of biodiversity.	No additional negative impacts
	SP4	Chronic and acute health impacts caused by exposure to combustion emissions. Spills and accidents.	Additional negative impacts: - Increased rate of ethanol blends can increase acetaldehydes and PAN emissions

Table. 3.8. Results of SWOT analysis (second-generation ethanol) for phase 3

INTERNAL	**STRENGTHS**
	• No difference for the second generation strengths, that are lower CO_2, VOC's, NO_x and particulates emissions
	WEAKNESSES
	• Blends of ethanol/petrol can increase emissions of hydrocarbons (such as benzene) and ozone precursors (such as light olefins) (Mojima and Johnson 2005, 21). There is evidence that NO_x level from low ethanol blends (E5 and E10) range from a 10 percent decrease to a 5 percent increase relative to pure gasoline.
EXTERNAL	**OPPORTUNITIES**
	• No opportunity identified for second-generation ethanol in this phase • Development of recycling facilities for the catalyst converters
	THREATS
	• Emissions caused by the combustion of ethanol blends can vary according to different vehicle technologies, and have to be considered when deciding for that. • Increasing use of ethanol directly increases the use of catalyst converters, which are produced with rare metals.

3.2 Sustainability Analysis of Hydrogen

The use of hydrogen as a fuel for the transport sector is a complex issue involving several options, where most of them are under research, and not yet available in the market. The assessments were made with the most updated and reliable available sources, and the most likely processes to be the solution in the future were chosen.

When we talk about a future hydrogen economy, we have to bear in mind that hydrogen could potentially be the fuel source to approximately 1 billion vehicles by 2010. The level of hydrogen that are produced from hydrocarbons released into the atmosphere would be immense and could affect the ozone production at ground level, particularly if we continue emitting organic particulates into the atmosphere (VOCs), creating photochemical pollutants. In the stratosphere on the other hand, it can have the reverse effect, reducing ozone molecules and thus affecting the ozone layer (see Appendix F).

Production of hydrogen can be made from different sources. In this study, the following sources of hydrogen will be assessed under the lens of the presented sustainability principles:

- Natural gas
- Renewables (ethanol, water)

In each one of the sources, several sub-processes are presented due to the significant impacts they bring to the final conclusion of the hydrogen technologies. The life cycle phases considered for this assessment are:

- Phase 1 - Raw material, including all phases of i) natural gas production (extraction, production, transportation and storage, distribution), ii) ethanol (agriculture, production, use) and iii) water
- Phase 2 – Production of hydrogen, including all phases of the processing of i) natural gas (steam methane reforming), ii) ethanol (steam reforming) and iii) water electrolysis using electricity generated from wind and solar.
- Phase 3 – Distribution and storage
- Phase 4 – Use

3.2.1 Phase 1 - Raw material

In this phase, impacts of processes to produce the raw material are assessed, and the results are summarized by each one of the sources. Details of the processes and how the data was collected to fulfill the tables can be found in the Appendix A.

Natural gas

Natural gas is a fossil fuel that is extracted from the Earth crust, and its main composition is methane (CH_4) with a small amount of other components such as low molecular weight hydrocarbons (ethane, propane, and pentane), nitrogen, carbon dioxide and helium.

The processes included in the SLCA assessment were:

- Extraction: onshore and offshore drilling
- Production: processing of natural gas to remove impurities
- Transportation (pipelines) / Storage (vessels, depleted gas reservoirs, aquifers and salt caverns)
- Distribution

Table 3.9 Results of SLCA (production of natural gas)

<table>
<tr><td colspan="4">PROCESS: Production of Natural gas</td></tr>
<tr><td colspan="4">SUB PROCESSES:
- Extraction (Drilling, installing well casing for lifting natural gas to surface, drain hole completion, lifting natural gas)
- Production (Oil and condensate removal, water removal, separation of natural gas liquids, sulfur and carbon dioxide removal.
- Transportation/Storage
- Distribution of Natural gas</td></tr>
<tr><td>Sustainability Principle 1</td><td>Sustainability Principle 2</td><td>Sustainability Principle 3</td><td>Sustainability Principle 4</td></tr>
<tr><td colspan="4">EXTRACTION</td></tr>
<tr><td>- Metal used for casing the well (conductor, surface, intermediate</td><td>- Cement used to fix conductor, surface and intermediate casings in</td><td>- Degradation of soil by drilling and building of</td><td>Working and safety conditions.</td></tr>
</table>

casings), well heads, christmas trees [3] and drills, platforms, ships etc - Oil and fossil fuels used to transport and lubricate parts in the process. - Net increase in concentration of mined fossil fuel. - Loss of natural gas from extraction process due to leakages.	place. - Injection of chloridric acid, CO_2. - NO_x, SO_x, CO_2, CO from burning fossil fuels	infrastructure for production. - Use of explosives to reach wells.	
PRODUCTION			
- Loss of natural gas from production process due to leakages from compressors, dehydrators etc. - Absorption oils to separate NGLs. - Iron sponges to dessulfurize NG.	- NO_x, SO_x, CO_2, CO, particulates from burning fossil fuels. - Use of external refrigerants to separate NGLs (ethane). - Use of di/triethylene glicol to take water out of NG. - Use of mono and diethanolamine in NG dessulfurization process.	- Disruption caused by processing plants and gathering lines. - Mining of iron	- Air pollution, health problems related to air pollution, acid rain. - Health and poisoning risks due to working conditions cause by di/triehtylene glycol Health issues related to exposure to MEA and DEA.
TRANSPORTATION / STORAGE / DISTRIBUTION			
Steel for the pipelines - Loss of natural gas from transmission process due to leakages from compressors, pneumatic devices, storage systems. And purging of transmission systems	- Combustion of NG to power compressors (NO_x, SO_x, CO_2, CO, particulates). - Fusion bond epoxy to avoid corrosion of pipelines. - Pipelines made of plastic are option to steel pipelines	- Drilling for storing NG (salt mines) - Possible degradation of water reserves by NG storing in aquifers - Mining for iron. - Disruption caused by distribution lines	- Health issues related to contamination through leakages - Possible water contamination with NG in aquifers can affect human health and availability.

[3] 'Christmas tree' is the piece of equipment that fits atop the casing and tubing heads, and contains tubes and valves that serve to control the flow of hydrocarbons and other fluids out of the well. It commonly contains branches and is shaped like a tree (Natural Gas 2004a).

Table 3.10 Results of SWOT analysis (production of natural gas)

INTERNAL	**STRENGTHS**
	• Nowadays 48% of hydrogen is being produced from natural gas (SP1) (Gupta 2008, 35). • Natural gas is the cleanest of the fossil fuels when compared to coal and petroleum (EIA 1998).
	WEAKNESSES
	• Leakages from the system are a pollution source. • Large disruption has to occur along pipes to install them (EIA 1998). • Raw natural gas has to go through many processes with different substances to acquire pipeline-quality.
EXTERNAL	**OPPORTUNITIES**
	• Fossil fuels like natural gas can be source for hydrogen production in transition period to a hydrogen fueled future economy (Solli et al. 2006, 1786). • Production may have better prospects in emissions when Carbon Capture and Sequestration Techniques are in place (Solli et al. 2006, 1785). • Natural gas is seen by many as an important fuel in initiatives to address environmental concerns.
	THREATS
	• Price fluctuation due to disruptions in supplies or political interests. • Reserves are finite. Peak production expected to be achieved in the middle of this century (Walsh 2000).

Production of ethanol

For the production of ethanol and its impacts, please refer to section 3, tables 3.1 and 3.4 for SLCA, 3.2 and 3.5 for SWOT.

Use of water

Water is used to produce hydrogen directly from the split of the molecule by electrolysis. Water quality requirements to electrolysis are high, and differ across electrolyzers. Processes as purification, external deionizer and reverse osmosis are needed to treat the water before it goes to the fuel cells. A water storage tank may be included to ensure that the process has adequate water in storage in case the water system is interrupted (Ivy 2004, 5).

For hydrogen to be a future energy source there is going to be an increase in demand of water resources, which can undermine people ability to use water for their needs (SP4) (Stephens-Romero and Samuelsen 2008).

Depending on the source of electricity to produce hydrogen by water electrolysis, more pressure on water consumption is expected (Appendix G).

3.2.2 Phase 2 - Hydrogen production

In this phase, impacts of processes to produce the hydrogen from the several sources are assessed, and showed in one SLCA table for each one of the sources.

Production of hydrogen from natural gas

Hydrogen is produced from natural gas by different processes like catalytic steam reforming, pyrolysis and partial oxidation. This assessment will be based on the steam reforming process, which is the most used nowadays (Gupta 2008, 39).

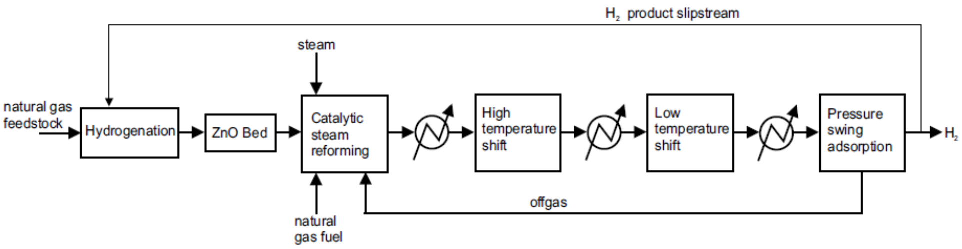


Figure 3.3: Process of hydrogen production from natural gas by steam reforming (reproduced from Spath and Mann 2001, 4).

Before the process of steam reforming begins, natural gas has to go through a pre-treatment using Co-Mo catalysts (Gupta 2008, 39) in order to convert any sulfur compound into H_2S, which is then removed in a ZnO bed (Spath and Mann 2001, 3). Traces of halides such as chlorides may also be present in the natural gas feedstock and they are removed using an alumina guard bed.

The next process occurs in the catalytic reforming reactor, and is very water intensive. Steam reforming hydrogen is produced from methane (SP1) using nickel (Ni) (SP1) as catalyst at 850-900˚C, forming a synthesis gas.

$$CH_4 + H_2O \longrightarrow CO + 3H_2$$

Although nickel is the most common catalyst, other noble metals such as Ru/Rh/Ir/Pt/Pd may also be used. These catalysts are dispersed over supports composed of Al_2O_3, MgO, $MgAl_2O_4$, SiO_2, ZrO_2 and TiO_2.

The gaseous mixture containing H_2, CO, steam and some unconverted CH_4 leaves the reformer, is cooled to about 350˚C and fed to the water-gas shift reactors where CO reacts with steam over a catalyst bed (usually magnetite iron oxide containing chromia) or CuO with ZnO and Al_2O_3, producing H_2 and CO_2. The reaction is the following:

$$CO + H_2O \longrightarrow CO_2 + H_2$$

Older processes used solvents to separate the H_2 from the CO_2, such as monoethanolamine, water, ammonia solutions, potassium carbonate solutions and methanol (Gupta 2008, 41). The remaining CO_2 and CO is removed in a methanation reactor under the presence Ni or Ru as catalysts.

Production of hydrogen from Ethanol

Biomass has relatively low hydrogen content when compared to other sources such as methane coming from natural gas. The processes to convert biomass to hydrogen can be either thermochemical or biochemical, as shown in figure 3.4.

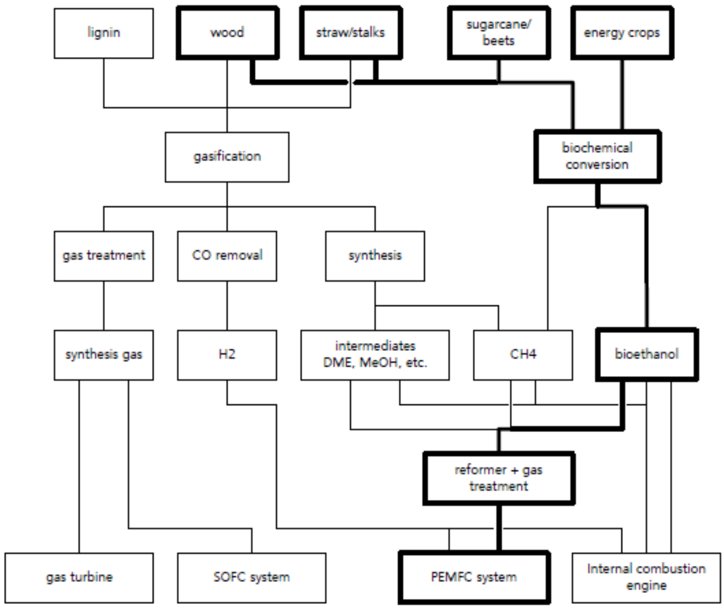


Figure 3.4. Methane and Ethanol Reforming (reproduced from Aicher 2005, 10).

As cited before, ethanol accounts with 86 percent of the biofuels production. This study will assess the production of hydrogen from ethanol through steam reforming conversion.

Steam reforming was introduced to industry during the 1960s and created a basis for more efficient manufacture of synthesis gas and hydrogen in locations where natural gas was not available. The industrial application was a result of development of special catalysts and better methods for desulfurization of the feedstock.

Reforming of renewable liquids is very similar to reforming of natural gas. Since the hydrocarbons of renewable fuels are composed of bigger molecules however, reforming of renewable liquids is more difficult and research on catalysts that may enhance yields and efficiency are needed.

The reaction of the steam with the ethanol is made over a catalyst. Steam reforming requires elevated temperature, and produces primarily hydrogen and carbon dioxide. Some trace quantities of byproducts such as carbon monoxide also result from steam reforming. When using the hydrogen in a

PEMFC (proton exchange membrane fuel cell, presented at section 3.2.4), diluents such as CO_2 and CH_4 are tolerable.

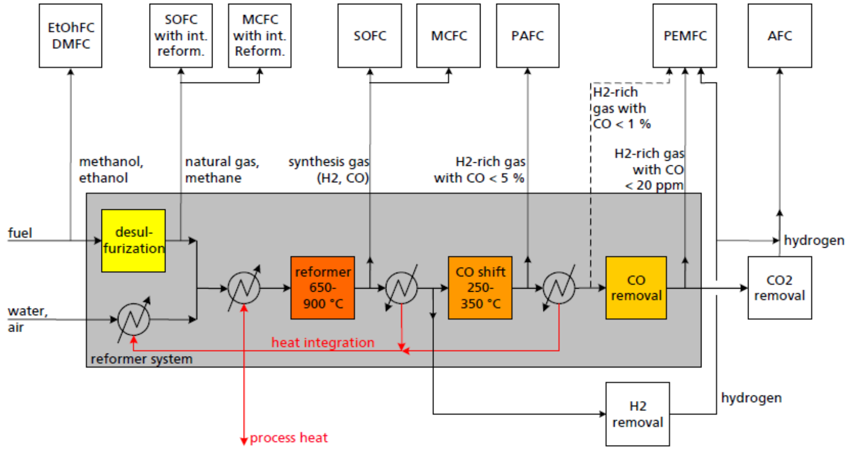


Figure 3.5. Schematic production of hydrogen by steam reforming of ethanol. (reproduced from Aicher 2005, 18)

The reactions that occur in the process of production of hydrogen from ethanol are the following, the first being endothermic and the second exothermic:

$$C_2H_5OH + H_2O \longrightarrow 2CO + 4H_2$$
$$CO + H_2O \longrightarrow CO_2 + H_2$$

The CO that is formed in the first step reaction has to have its concentration lowered to levels beneath 20ppm through a gas cleaning process, since it deactivates the anode catalyst in the PEM fuel cell. This is obtained through a catalytic high and low shift reaction followed by a pressure swing adsorption process (Rampe et al. 2000, 1889).

The production of hydrogen from ethanol through reforming involves the use of catalysts. Much research is currently being done in this area in order to enhance productivity. Catalysts that are currently being tested are nickel (Ni) (Fatsikostas et al. 2001, 851), copper (Cu) (Maia et al. 2007), potassium (K), chromium (Cr), samarium (Sm), strontium (Sr) and cobalt (Co) (Llorca et al. 2002, 306). Noble metals from the Platinum Metal

Group (PGM) such as platinum (Pt), palladium (Pd), rhodium (Rh), and ruthenium (Ru) are also being tested as catalysts (Fierro et al. 2003, 22; Rampe et al. 2000, 1890). Details about current situation of PGM's in the world are in Appendix D and the health problems caused by the metals used as catalysts are in Appendix E.

Hydrogen from water electrolysis

The potential gains associated with a hydrogen infrastructure that relies heavily on renewable energy sources rather than fossil fuel sources are significant regarding criteria pollutant emissions, GHG emissions, efficiency, and water consumption. An aggressive push towards using renewable energy sources to generate hydrogen merits serious consideration.

Hydrogen is produced by electrolysis, where electricity is passed through two electrodes immersed in water. The water molecule splits up into oxygen, which goes to anode and hydrogen, which moves to cathode as shown in the following reaction.

$$2H_2O \longrightarrow 2H_2 + O_2$$

Renewable and clean energy sources like wind and solar can play an important role in production of electricity and hydrogen (Granovskii et al. 2007a and 2007b). In these processes there is no direct use of fossil fuels and hence no emission of greenhouse gases (Granovskii et al. 2006).

Wind power is considered the fastest growing market, and this tendency will continue the coming years. Wind turbines produce electricity by converting the force of the wind into torque, a generator will convert this rotational energy into electricity, and an alternator transforms this energy into alternate (AC) electricity, which is then transmitted to the power grid (Batumbya 2006, 2). The wind energy has good efficiency only in high wind areas, and can reach 67 percent efficiency (Granovskii et al. 2006, 346).

Combining wind power with hydrogen production may contribute to the growth of both technologies, as hydrogen is a good way to store the energy produced by the wind when there is no demand or lower that what is produced (Gupta 2008, 181). For the transport sector, the wind energy will be used as a generator for the power grid, and the electrolysis will be decentralized, inside the vehicles (onboard) through fuel cells, that are being assessed in the use phase, section 3.2.4.

Solar energy is changed to direct current (DC) electricity by photovoltaic systems. This DC electricity is converted into alternate current (AC) electricity by inverter and then supplied to the power grid.

Gallium (Ga) and Arsenic (As) in combination (Gallium arsenide) are the major components of the various types of solar panels available in the market. Since both elements have been identified as carcinogens, risks to human health exist when the solar panels are installed near population centers (Oshita 2007). Propylene Glycol is another chemical compound in solar panels, and tends to evaporate at high heat causing environmental damage (Ardente et al. 2005, 125).

Main impacts of the energy production from wind and solar devices are in their production phase (materials and energy used) and end of life phase (if no recycling policies are implemented).

Results of the assessment of hydrogen production

Table 3.11. Results from SLCA (hydrogen production) in phase 2

PROCESS: Production of hydrogen			
SUB PROCESSES: - From natural gas - Pre-treatment (desulfurization), catalytic steam reforming, water-gas shift, gas separation/H_2 purification. - From ethanol: desulfurization, steam-reforming, water gas shift reaction, CO removal			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
FROM NATURAL GAS			
- Co-Mo / ZnO (DSU) - Ni/Ru/Rh/Ir/ Pt/Pd (SMR) - Fe / Cr_2O_3 / CuO / Al_2O_3	-Monoethanolamine (MEA) to reduce CO_2	- Mining	- Increased consumption of water. - Health issues related to exposure to MEA - Buoyancy and permeability pose safety issues due to flammability. - When burning, H_2

			flames are invisible and are a safety issue (explosion).
FROM ETHANOL			
- Use of catalysts such as Ni, Cu, Cr, K, Zn, Co, La_2O_3, Sm_2O_3, CeO_2. - Palladium alloys with 10-30% wt Ag that compose selective membrane.	- Formation of substances such as H_2, CO, CO_2, CH_4, acetaldehyde, ethylene and ethane.	- Mining of rare metals such as Cu, Cr, Ce, La. - Mining of Ni - Mining of rare metals such as palladium and silver have a very big rucksack.	- Occupational health and safety related to mining and working conditions. - Health problems caused by : Cerium, Lanthanum (Ce, La), Samarium (Sm), Nickel (Ni) - Safety issues related to buoyancy and permeability, and explosion (above)
FROM WATER (ELECTRICITY FROM WIND)			
- Mined materials: iron, copper, steel, fossil fuel	- Concrete, fiber glass, PVC, paints - Use of resins - leakage of oil	- Change of land use (erection bases) - Birds and bats interference	- Obstructing the shipping routes - Decrease value of land - Safety issues - Obstruction of natural or scenic beauty of the sites - Noise - Safety issues related to buoyancy and permeability, and explosion (above)
FROM WATER (ELECTRICITY FROM SOLAR)			
- Steel, Chromium	- Gallium arsenide (GaAs) - Propylene Glycol	- Sand removal to make glass - Landfill (disposal of non recycled panels)	- Ga, As: health - Disposal of panels (hazardous waste) - Safety issues related to buoyancy and permeability, and explosion (above)

Table 3.12. Results of SWOT analysis (hydrogen production) in phase 2

	STRENGTHS
INTERNAL	**Hydrogen from natural gas:** • Large international trade between countries through pipeline network in Canada, USA Russia, Germany, Eastern Europe etc. (Dicks 1996, 114). • It is relatively cleaner when compared to all other fossil fuels. (Dicks 1996, 114). **Hydrogen from ethanol:** • The process of steam reforming of ethanol is considered safer than from methanol. **Hydrogen from water electrolysis:**

- Renewable sources like solar energy and wind energy are clean, and can help to overcome problems like air pollution, global warming, and declining fossil fuel resources (Granovskii et al. 2006, 346).
- When hydrogen is produced via use of wind energy there is GHG decrease of about 12-23 times as compared to the use of currently gasoline fuel (Granovskii et al. 2007b, 470).
- The use of solar energy for hydrogen production and use as fuel instead of gasoline also decrease GHG by about 5-8 times (Granovskii et al. 2007b, 471).
- Air pollution reduces about 38-76 times if hydrogen as a fuel is produced via wind energy and 16-32 times if hydrogen is produced via solar energy (Granovskii et al. 2007b, 470).

WEAKNESSES

Hydrogen from natural gas:

- In hydrogen production plants tones of aluminum, iron, steel and concrete are used (SP1, 2) (Granovskii et al. 2006, 345).
- Emissions of methane from natural gas infrastructure in US pose a threat to environment in future hydrogen economy (SP2) (Stephens-Romero and Samuelsen 2008, 638).

Hydrogen from ethanol:

- The high sensitivity of the PEMFC for CO (50 ppm) puts special requirements on the gas-cleaning system. Selective catalytic oxidation or methanation or the use of a membrane are possible solutions (Rostrup-Nielsen 2000, 287).
- Liquid hydrocarbons require hydrodesulfurisation over Co-Mo catalysts (Rostrup-Nielsen 2000, 284).
- In order to maximize the harvest of purified hydrogen from the reforming process, an expensive, thick and high quality palladium alloy membrane serves as a hydrogen-permeable and selective device (US Patent 1999, 4).

Hydrogen from water electrolysis:

- The production of these energies (from wind and solar) is dependent on geological and weather conditions, e.g. cold places with low intensity of sun or places where wind intensity is low.

EXTERNAL

OPPORTUNITIES

Hydrogen from natural gas:

- Hydrogen from natural gas by steam reforming is the cheapest method of hydrogen production (Dicks 1996, 114).

Hydrogen from ethanol:

- The development of second-generation ethanol will help to enhance availability of this fuel for hydrogen production.
- Crop residues conversion increases the value of agricultural output (Demirbas 2006, 1219).
- Development of methods to produce hydrogen using renewable energy sources such as wind and solar may provide more sustainable processes.

Hydrogen from water electrolysis:

- In these processes there is no direct use of fossil fuels and they are likely to increase with when prices of fossil fuels start to rise.
- Cost of air pollution abatement is ten times lower when hydrogen is produced from renewable like wind and solar energies as compared to its production from fossil fuels (Granovskii et al. 2007a, 1782)

THREATS

Hydrogen from natural gas:

- Decline in fossil fuel resources (Walsh 2000) (Hirsch et al. 2005)

	• Emissions of methane from natural gas infrastructure in US pose a threat to environment in future hydrogen economy (SP2) (Stephens-Romero and Samuelsen 2008). • Massive amount of investment is in research and development required for the hydrogen to be a future energy source (Stephens-Romero and Samuelsen 2008, 638). • For hydrogen to be a future energy source there is going to be an increase in demand of water resources undermining people ability to use water as per their needs (SP4) (Stephens-Romero and Samuelsen 2008). **Hydrogen from ethanol:** • In order to maximize the harvest of purified hydrogen from the reforming process, an expensive, thick and high quality palladium alloy membrane serves as a hydrogen-permeable and selective device (US Patent 1999, 4). • Many catalysts rare in nature may be further explored and increase production costs if production is to scale up. • Ethanol may be produced from biomass, but not without the use of substantial amounts of fossil fuel for fertilizer, distillation, etc. **Hydrogen from water electrolysis:** • Production of hydrogen from renewables like wind is five times expensive as compared to its production from natural gas (Granovskii et al. 2006, 351). • The average cost of wind- and solar-based electricity, respectively, exceeds that of natural gas by about 2.25 and 5.25 times (Newton and Hopewell 2002, 55).

3.2.3 Phase 3 - Distribution and storage of hydrogen

Many papers have been written about the possible ways of distribution and storage of hydrogen and they are mostly considering three primary options for transport. The first one would be through pipelines and tube trailers for gaseous hydrogen or a mixture of hydrogen and natural gas transportation. The second would be transportation of cryogenic tanks containing liquefied hydrogen and the third would be using liquids such as ethanol, methanol or and other liquids derived from biomass to be reformed at the point of use (Gupta 2008, 341).

There are three options for producing hydrogen that have direct impact on the alternatives for the distribution. They are centralized, decentralized and onboard production. The distribution and storage options for these cases are:

Option	Type of production of hydrogen	Description
1	Centralized	Pipelines for gaseous hydrogen
2	Centralized	Trucks (containing vessels for compressed hydrogen)
3	Centralized	Trucks (containing vessels for liquid hydrogen)
4	Centralized	On board storage with metal hydrides

5	Decentralized	Distributed reformers, fed with natural gas or ethanol by the existing infrastructure. In this case no changes in the existent infrastructure is needed.
6	Decentralized (onboard)	No distribution or storage is needed

The same vessels considered in the options 2 and 3 (distribution by trucks) will be used in the on board storage. SLCA results will be based on this assumption.

Option 1 – Pipelines (GH_2)

The density of hydrogen is low and in order to increase it for easy storage and better use as fuel one option is to compress it until probably around 3000psi. This fact makes the need for pipelines that support this high pressure, avoiding the phenomena of hydrogen embrittlement (HE). New materials are being studied to fulfill these requirements, and the high costs are an important barrier for this technology to be available in short-term *(*Gupta 2008, 344, 362).

Although all this technology for leakage detection is being searched, it is good to have in mind that any system failure could have drastic consequences since hydrogen heats up when it expands through a nozzle what can cause it to ignite very easily (Shinnar 2003, 468).

In order to distribute the hydrogen, the velocity in the pipe would have to be tripled compared to natural gas to deliver the same quantity of energy while the compression would have to be nine times greater. Therefore much more powerful compressors would be needed pulling up much more energy from the electric grid (SP1) (Shinnar 2003, 459).

Option 2 – Trucks (GH_2)

Hydrogen is compressed and transported in vessels by trucks. Some issues related to this process have to be presented:

- Volume of hydrogen vessels – In ambient pressure and temperature, one kilogram of hydrogen occupies $11m^3$ of volume and consequently storage requires enormous compression. Five kilograms of hydrogen at 5000psi requires a volume of 212L.

- Energy to compress the hydrogen - during the operation of compression, 8.5 percent of the energy contained in the hydrogen is used (Burke and Gardiner 2005, 8).
- Special materials for vessels - In order to bear this compression, tanks have to be metal lined with a load-bearing composite outer wrap. Another technical option would be a lightweight tank with an internal high-density polymer (SP1, SP2) liner to prevent gas diffusion and load-bearing composite over wrap made of carbon fiber, glass fiber or hybridization of the two with epoxy resin as a binding material (SP2)(Gupta 2008, 374).

Technically, the current challenge for compressed hydrogen is to develop cost effective vessels that optimize space in FCVs. Also, one has to have in mind that high-pressure vessels present a considerable risk with compression being the most dangerous and complicated part (Schlapbach and Züttel 2001, 354).

Serious vehicular accidents can occur since the difference of pressure between the vessel and the atmosphere implies in high potential energy that could give high mechanical impulse in case of rupture and release of hydrogen (SP4)(Wang 2007, 7).

Option 3 – Trucks (LH_2)

Hydrogen can have its energy density doubled as compared to the 10,000psi compressed H_2 to 70g/L by liquefaction to 20K. Five kilogram of hydrogen only requires 71L of volume that is comparable to today’s volume used in cars.

Option 4 – Storage of hydrogen by vessels containing metal hydrides.

Metal hydrides are the most compact way to store hydrogen (more dense than liquid hydrogen). To have a driving range of 500 km, at least 9.1wt% hydrogen metal hydride is needed. Current solutions go to 3.5%wt, what make the application in cars not feasible without research. Some of them, such as MgNi, may reach higher gravimetric densities but also need high temperatures to release hydrogen (600K). Another issue is that metal hydrides have high weight, what is a barrier to use in cars (Gupta 2008, 376).

Option 5 - Storage of hydrogen by Insulated Pressure Vessels.

This alternative considers a combination of the characteristics needed for storage of liquid and compressed hydrogen such as operating in low temperatures (20K) and high pressures (240 atm or higher). In this case hydrogen can be stored in any state or combination of gaseous compressed hydrogen (GH_2)(cryogenic or at ambient temperature) and/or LH_2 (Aceves et al. 2006, 7).

Table 3.13 Results of SLCA (distribution and storage hydrogen) in phase 3

PROCESS: Distribution of hydrogen SUB PROCESSES: - Compression of H2 - Distribution			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
OPTION 1 - PIPELINES (GH_2)			
- More powerful compressors for H_2 distribution (increased use of energy for distribution). - Leakage sensors: V_2O_5, WO_3, NiO_x for chromogenic sensors and Pd for catalyst top layer.	- Stainless Steel or steel (ASME). - FRP (fiber-reinforced polymer), PET, PLS (polymer-layered silicate), is as option to steel pipes.	- Prepare infrastructure to receive H_2. - More land is necessary since tanks be built away from current gasoline tanks for safety reasons (Shinnar 2003, 468) - Mining	- H_2 heats up when it expands through a nozzle what can cause it to ignite. - If there are microscopic cracks, they can grow and pipes/tanks can explode. - Health issues derived from excessive exposure of workers
OPTION 2 - GH_2 in vessels transported by trucks and on board (in the vehicle)			
- Metals for tanks, energy to compress H_2.	- Tanks containing carbon fiber, glass fiber and epoxy resin.	- Mining of metals	- Safety related to working conditions - High pressure vessels impose danger of vehicular accidents
OPTION 3 - LH_2 in vessels transported by trucks and on board (in the vehicle)			
- Metals for tanks, energy to liquefy H_2.	- Bulk: Foam insulators for tanks		- Safety conditions

OPTION 4 - TRUCKS (GH_2), considering solid storage with metal hydrides			
- Metals for tanks, energy to liquefy H_2.	- Onboard: Metal hydrides such as $LaNi_5$, TiFe, $ZrMn_2$, MgNi, - Ti, Zr to revert reaction - Carbon fiber	- Mining of metals.	- Mining working conditions.

Table 3.14 Results of SWOT analysis in phase 3

<table>
<tr><td rowspan="4">INTERNAL</td><td>STRENGTHS</td></tr>
<tr><td>Pipelines:
• Distribution through pipeline network reduces emission as compared to distribution by truck (Stephens-Romero and Samuelsen 2008, 628).
• H_2 has three times the energy content of gasoline on a weight basis.
• H_2 delivery through pipelines offer technical and economic synergies.
Liquefied H_2:
• Volume needed to store 5kg of H_2 is comparable to current storage tanks in vehicles today (71L).
• Will provide longer travel distances without refueling.
• Rapid refueling (3 min) with no evaporative losses (Aceves et al. 2006, 3).
• Insulated pressure vessels are possible solutions for cryo-GH_2 storage and are lighter than hydride vessels.
Storage in metal hydrides:
• Metal hydrides are stable at ambient temperature and are safer than compressed gaseous hydrogen storage.
• Accidental release of hydrogen in metal hydrides is less likely than that of compressed gaseous hydrogen storage (Wang 2007, 8).
Storage in insulated pressure vessels:
• It is very compact when compared with other technologies.
• Insulated pressure vessels also have considerable advantages in reducing evaporative losses during vehicle operation</td></tr>
<tr><td>WEAKNESSES</td></tr>
<tr><td>Pipelines:
• H_2 has four times lower energy content when compared on a volume basis (8 MJ/L for H_2 versus 32 MJ/L for gasoline).
• For H_2 we need to triple the volume to reach the same energy as natural gas.
• Occurrence of pressurized vessels in highly densed areas could be a risk in terms of safety.
• The distribution would probably have to be done with new infrastructure since NG pipes are not specified for transporting H_2.
• Sensors needed to detect leakages
• Special materials and procedures are needed to the H_2 pipelines, related to the H_2 induced cracking, embrittlement and stress corrosion cracking (Gupta 2008, 348).
Compressed H_2:
• H_2 heats up considerably as it is pumped into a storage vessel, reducing the density of storage</td></tr>
</table>

	(Aceves et al. 2006, 4). • H_2 is not an ideal gas, considerably reducing the increase in density that can be obtained by increasing the pressure (Aceves et al. 2006, 4). • Delivery of hydrogen to the fueling station (either by truck or by pipeline) may be difficult and/or expensive (Aceves et al. 2006, 4). • Refueling rate of compressed gaseous hydrogen can be as high as 1 kg H_2 per minute, which yields a total of 5 minutes for filling 5 kg H_2 (Wang 2007, 7). **Liquefied H_2:** • Leakages and evaporative losses occur after a short period of inactivity, high evaporative losses occur during short daily driving distances, danger of being stranded due to fuel evaporation. • There's a period over which H_2 will warm up, expand and convert to gas and energy is needed to vent the vessel. • LH_2 tanks are fueled only 85 to 95% full to prevent spills due to expansion, leaving 5-15% of empty space (ullage) (Aceves et al. 2006, 5). • Less driving results in more time available for evaporation (Aceves et al. 2006, 7). • Insulated pressure vessels are possible solutions for cryo-GH_2 storage but are heavier than GH_2 vessels. • Substantial amount of electricity required for liquefying the H_2 (up to 40% of the lower heating value) (Aceves et al. 2006, 4). **Storage in metal hydrides:** • Hydrides release considerable thermal energy as they absorb hydrogen and therefore require significant thermal energy (10-20% of the H_2 lower heating value) input to release H_2. • Gravimetric storage density of metal hybrids is low, 2 wt%, which does not meet the established weight criterion (9,1%w) (Gupta 2008, 396) • Metal hydrides are currently inefficient in operating a vehicle as they require a significant amount of thermal energy input. • Slow reaction kinetics of the hydrides is a major issue for vehicular applications (Gupta 2008, 376). • The sorption of hydrogen in hydrides does not occur quickly, so the refueling process takes more than 30 minutes (Pool 2005, 19).
EXTERNAL	**OPPORTUNITIES**
	Compressed H_2: • People that are to manipulate the fuel have to be highly trained, what can develop a new field of training and new jobs. **Metal hydrides:** • Advantages over compressed gas storage are legislations like the one of New York that allows only for limited vessel pressure in transportation of gases in tunnels (compressed hydrogen uses pressures from 6000 – 10,000 psi) (Shinnar 2003, 468).
	THREATS
	Compressed H_2: • Legislation like the one of New York that allows only for limited vessel pressure in transportation of gases in tunnels (compressed hydrogen uses pressures from 6000 – 10,000 psi, very high comparing to 300 psi of propane storage) (Shinnar 2003, 468). • People that are to manipulate the fuel have to be highly trained. **Metal hydrides:** • Metals used to store are usually rare and will have to be kept in closed loops.

3.2.4 Phase 4 - Use of hydrogen

There are six different types of fuel cells: (1) alkaline fuel cell (AFC), (2) direct methanol fuel cell (DMFC), (3) molten carbonate fuel cell (MCFC), (4) phosphoric acid fuel cell (PAFC), (5) proton exchange membrane fuel cell (PEMFC) and the solid oxide fuel cell (SOFC).

Considering the transport sector, some features related to the proton exchange membrane fuel cell (PEMFC) make it the most suited for powering automobiles because of features such as low temperature needed to operate it, about 80˚C, high power density, rapid change in power on demand and quick start-up (Gupta 2008, 17). Buses can also be powered by Phosphoric acid fuel cells (PAFC).

The membrane is made of a thin poly (perfluorosulfonic) acid sheet, also known as Nafion, which acts as an electrolyte and allows the passage of hydrogen ions only. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that act as catalysts (Gupta 2008, 18). As already mentioned, the hydrogen fuel used to power the fuel cell has to be very pure since the platinum catalysts are easily contaminated and lose efficiency when hydrogen contains sulfur and carbon monoxide (Dicks 1996, 115).

Table 3.15 Results of SLCA (use of hydrogen) in phase 4

PROCESS: Combustion / Fuel cells			
SUB PROCESSES:			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
OPTION 1 – Hydrogen internal combustion engine (HICE)			
- Steel for storage tanks in cars	- NO_x (function of flame duration and temperature when H_2 is combusted) (INL 2006) & (Momirlan and Verizoglu 2005, 798). - Traces of CO & CO_2 may be present due to oil burning (NHA 2001, 17).	- Mining for iron and metals for alloys.	- The energy necessary to ignite and explode a mixture of hydrogen-oxygen is minimum. Hydrogen cars can be easily modified to become an undetectable bomb for a suicide bomber (Shinnar 2003)

OPTION 2 – Fuel cells			
- Platinum in electrodes (Dunn 2002). - Titanium or stainless steel for plates - Graphite	- Plastic membranes to separate hydrogen from oxygen. - Membranes to separate H_2 from O_2 are composed of Tetrafluoroethylene (TFE)+perfluorinated monomers containing sulfonic acid groups. - TFE is manufactured from chloroform	- Platinum (Mining) - Titanium - Iron and metals for alloys	- Hydrogen can neither be seen nor smelled. Sensors are being developed to detect leaks in cars (Momirlan and Verizoglu 2005, 798). - There is risk of explosion when working with TFE (Mindfully 2009). - TFE is classified as asphixiant and toxic to human health (Cameo 2009). - Chloroform is suspected to be carcinogen. It's a CNS depressant, causes cardiac arrest, liver and kidney damage (Cameo 2009) - Very corrosive and lethal when ingested. Inhalation of HF mist or vapors causes irritation and may be fatal (Cameo 2009).

Table 3.16. Results of SWOT analysis (use of hydrogen) in phase 4

	STRENGTHS
INTERNAL	**General:** • Pure hydrogen can be used as fuel for fuel cells vehicle with no emissions. **ICE** • Hydrogen has good characteristics as a fuel to be used in internal combustion engines of automobiles (Demirbas 2006, 1216) **Fuel Cells** • No harmful emissions, only water vapors. • Fuel cells are quiet and have high efficiencies at partial loads (Gupta 2008, 27). • Higher efficiencies than any other fossil fuel. • A method for recovering and recycling catalyst coated fuel cell membranes includes dissolving the used membranes in water and solvent, heating the dissolved membranes. Active membranes are produced from the recycled materials (Free Patents Online 2009). • Recycling of platinum in fuel cells following best practices make it possible to recover 95% of the metal (DFT 2006, 16).

	WEAKNESSES
	ICE • NO_x (function of flame duration and temperature when H_2 is combusted) **Fuel Cells** • Highly sensitive to fuel contamination. The high sensitivity of the PEMFC for CO (50 ppm) puts special requirements on the gas-cleaning system. Selective catalytic oxidation or methanation or the use of a membrane are possible solutions (Rostrup-Nielsen 2000, 287) • Liquid hydrocarbons require hydrodesulphurization over CoMo catalysts (Rostrup-Nielsen 2000, 284) • Skilled personnel needed for maintenance and overhaul (Gomatom 2003, 2).
EXTERNAL	**OPPORTUNITIES**
	General • Legislation on emissions is likely to be more rigorous in the near future. **Fuel Cells** • GHG emissions are to be increasingly controlled due to their probable relation to climate change effects. • Fossil fuel prices tend to rise with shrinking reserves. This may turn fuel cell technology economically viable.
	THREATS
	Fuel Cells • Highly expensive due to use of catalysts such as platinum that may hinder it's production in large scale. • Platinum ores are located in few countries. This concentration is not good strategically since any political or diplomatic disturbance may disrupt supplies. • Fuel cell technology still has an unproven record although Research and Development is under way in order to come up with cost/effective and reliable solutions.

4 Discussion and recommendations

4.1 Overview

This thesis started with the main goal of assessing new technologies that are not available yet in the market, and build a scenario for the road transport sector with a mix of alternative fuels that would lead society towards a sustainable future. This proposed mix of fuels should meet the demands of the sector, without harming the environment and allowing people to meet their needs. As research was being conducted, the idea of bringing a new scenario showed to be unfeasible, due to the complexity involved to build a generic scenario with the time constraints we had.

In the literature review several scenarios developed by reliable agencies were found, bringing alternative solutions and its related challenges and opportunities to the transport sector. The research was conducted in order to choose a scenario that was updated and significant enough to the road transport sector, and assess it under the sustainability lens. International Energy Agency (IEA) bi-annually releases a document called Energy Technology Perspectives (ETP), with the most updated information related to the current world demand and supply of energy, policies and development status for several energy sources. The Blue Map scenario, included in the ETP 2008, was the most audacious and updated when relating to decrease of carbon emissions, and also included new technologies as hydrogen and second-generation ethanol as part of the propose mix for the sector in 2050. As the ETP 2008 does not include a sustainability assessment of the scenarios, we decided on bringing this contribution to the energy sector, and analyze the impacts that could occur if this scenario becomes reality in 2050.

The complexity of the issues was really high, as i) the hydrogen technologies are under research and development, and many alternatives are likely to occur, and ii) second-generation ethanol can be produced from a diverse list of crops, and the enzymes and yeast for industrial scale are under research. This decision on assessing impacts of non-available technologies required a compilation of extended existing information and also exploration of a fertile land of new developments and possible solutions that the scientific community is working in order to make them possible in a near future for ethanol and mid to long term for hydrogen.

4.2 Research Question

The research question developed was "How can the Framework for Strategic Sustainable Development help to guide the assessment of hydrogen and second-generation ethanol as upcoming alternative technologies in the IEA Blue Map scenario, leading to a sustainable society?

A principle-based definition of sustainability was the key factor for the feasibility of the sustainability aspects assessment that was undertaken for the chosen technologies, despite the complexities previously cited. The Framework for Strategic Sustainable Development was used as a background theory to structure the research and guide the conclusions. The acknowledgement of the system we were dealing with, the definition of success based on the four sustainability principles and the selection of the tools were vital for developing a good flow for research, and consequently to bring the results and recommendations in a clear way.

By using the SLCA, all the phases could be considered in the assessment, not only the use phase, which is more commonly addressed in the papers. A broader picture of the social and ecological impacts on the life cycles phases was essential for a better understanding of the sustainability impacts related to these technologies.

Also of vital importance was the association of the Sustainability Life Cycle Assessment (SLCA) with the SWOT analysis (Strengths, Weaknesses, Opportunities and Threats). This association occurred naturally, as the impacts were being found, and several facts were related to them and could represent strengths or opportunities, weaknesses or threats. Using this method in each of the phases of the life cycles helped us to assess the importance of the role of external stakeholders, associated to the technical challenges associated to the deployment of each technology.

This discussion reviews the main results of our SLCA, and explores the current and future challenges and opportunities of each technology in order to move the road transport sector towards our vision of success, that is: *Transport sector, within the society, having its needs mainly being met with the mix of fuels proposed by the IEA Blue Map scenario, in compliance with the four sustainability principles.*

4.3 Sustainability gaps in hydrogen and second-generation ethanol technologies

Several important points are worth considering when examining the proposed mix of fuels in the Blue Map scenario. The following main points will show that a whole-systems perspective needs to be considered in order to have the actions leading society towards sustainability.

4.3.1 Second-generation ethanol challenges and opportunities

Key sources of emissions in the first-generation ethanol processes are identified as land conversion, mechanization and fertilizer use in the feedstock production stage, and the use of non-renewable energy in processing and transport. Also another threat recently identified is the amount of N_2O produced by the soil, which can be 300 times more harmful to climate change than CO_2. These increasing threats related to the growth of demand for biofuels, are pushing the scientific community to develop a new way of producing the ethanol, without increasing the harms that are already known. Second-generation ethanol is now being strongly considered the future of the biofuels, as it helps in decreasing the threats on the food production and land use change that the first generation currently represents. Energy crops can be produced in lands that are not suitable for food crops. This is a huge advantage and a strong driver to make this technology become one of the most important sources of liquid fuels, if the definition of idle and marginal lands are clear, and the local communities are respected and preserved.

As presented in this thesis, current production of biofuels is strongly based on new crops, developed to increase the efficiency per hectare of the plantation, decreasing the impacts on the use of fertilizers and water in the agricultural phase. Second-generation ethanol also is following the same trend, as new crops are under research in order to have better configuration of lignin amounts to facilitate the pre-treatment and fermentation processes. Also new enzymes and yeasts are being genetically modified to develop the ability to process the lignocellulosic materials. The introduction of genetically modified trees, enzymes and yeasts can bring unknown consequences in the future, and special attention has to be dedicated to these impacts. This can be a threat, as the patents of these developments are concentrated in the hands of few big industries. Further assessments of the social and environmental impacts are necessary.

Finally, in order to make the deployment of this technology in a strategic way, the listed challenges have to be addressed:

- Idle land use can release carbon when the tillage starts. Farming techniques have to be carefully chosen, so the emissions can be minimized. No-till farming is essential to the success of the energy crops plantations, even though it uses the residues to keep one protective layer in the soil.
- Removal of the residues from agriculture can decrease the soil protective layer, increasing the possibility of erosion and decreasing nutrients absorption capacity.
- Definition of marginal land has to be clear, because it can affect life of communities that are settled in that areas, and use the land as subsistence.
- Tropical forests are great carbon sinks, and contribute to biodiversity. The clearance for growth of perennial and energy crops should be avoided.
- Need for development of new enzymes to process the lignocellulosic biomass and new yeasts for fermentation of pentoses. The patent can be centralized with few companies, what is a threat to the autonomy of the producers. Same threat is possible if new dedicated crops are developed to produce more compatible lignocellulosic plants.
- Energy to produce the ethanol from corn (almost 50 percent of world production) is currently being generated by coal, making the carbon balance very unfavorable. If second-generation ethanol in these places is going to follow the same rule, benefits are going to be neutralized.
- Introduction of genetically modified materials can affect agricultural biodiversity.
- Increasing of wastewater proportional to the increased production of ethanol (vinasse and cooling water). Reuse of water has to be a common practice in the production process, and impacts of vinasse in the soils have to be monitored.
- Water needed only for the production phase (excluding the agricultural phase) still is 3-5 gallons for every gallon of ethanol. Even with the second-generation feedstocks needing less water in the agricultural phase, the production of ethanol still is water intensive.

- Use of fossil fuel based energy in the processes, such as machinery for agriculture, transportation of feedstock and final products and production. Renewable energy for theses processes can bring the ethanol closer to the carbon neutrality.
- Feedstock for second-generation ethanol can be far from the production plants. The challenge is to procure it from within a reasonable transport radius of the plant.

Strengths that can lead the deployment of the second-generation ethanol to go in the right direction are:

- Ethanol production from sugar cane, which accounts to almost 50 percent of global production, can be increased up to 20 percent, without any additional impact, if only the lignocellulosic residues of the first generation production is used to produce ethanol and energy to the process (Dias 2008).
- It represents new agricultural activity for the farmers without big investments, bringing fast and secure return of it.
- Wastes of any agricultural activity can be used as feedstock.
- Municipal wastes can be used as feedstock, both decreasing methane emissions from landfills and increasing ethanol productivity.
- Energy security can be achieved by the countries that have better climate conditions and biomass availability.
- Improve biodiversity if well managed and strategically implemented.
- Wastewater from food industry can be used to irrigation processes, instead of freshwater, as crops are not for food production.

4.3.2 Hydrogen - Challenges and opportunities

Hydrogen currently faces many technical challenges in order to make it a viable technology for the transport sector. Although it doesn't emit GHG during the use phase, which happens to be the main driver to justify this technology, its production from hydrocarbons may only be viable if carbon capture and storage (CCS) is possible. Other issues such as storage and distribution also have to be addressed from an environmental point of view. Many special features and materials have to be used in order to turn storage and distribution into a safe reality.

Strengths that can lead the deployment of hydrogen that go in the right direction are:

- no harmful emissions in the use phase, using fuel cell technology.
- efficiency of fuel cells are double of those of internal combustion engines.
- quiet functioning of fuel cell technology.
- if energy needed to produce hydrogen from water electrolysis came from renewable resources, like wind or solar, the whole well to wheel process would have low impact on the environment.

The main challenges related to bring this technology to the market are:

- Technology is dependent on platinum, a rare metal whose mining and processing causes great disruption to the environment. Although hydrogen is viewed as an energy carrier that could democratize access to energy around the world, the dependence of fuel cell technology on platinum or other PGMs is a weak point since the main ores are localized in few countries (Appendix D). If any political disturbances or misunderstandings disrupt the exploration of the ores, fuel cell technology will be held hostage of the situation as occurs today with the fossil fuels. Another issue to take into consideration is the rate which these resources can be extracted. If current mining rates are to be taken into consideration, it would take two hundred years to extract the reserves of PGMs needed for the deployment of hydrogen technology (Råde and Andersson 2001, 32) considering that consumption of platinum would range between 10-30g per vehicle (DFT 2006, 6; Råde and Andersson 2001b, 21).

  Until the present moment, no feasible substitute has been found for the PGMs. Current best practices of recovery from fuel stacks show that about 95% of the platinum can be recycled through the removal of the bipolar plates and electrolyte membranes, incineration, smelting and solvent extraction (DFT 2006, 16). If deployment occurs, tight closed loops have to be kept in order to optimize reutilization.

- Technology is dependant on high quality steel to bear pressures involved in compression. If hydrogen technology is to be deployed in large scale, closed loops will have to be kept in order to minimize disruption caused by extraction and processing of the metals.

- Coatings and sensors in pipelines to avoid hydrogen embrittelment. The installation of pipelines will cause great disruption and resource demand in a full scale deployment. Quantitative studies of resources are required in order to make a recommendation between centralized and decentralized options of production and distribution.

- In a hydrogen economy based on hydrocarbons extracted from the Earth's crust, the concentration of hydrogen is likely to increase in the atmosphere. The increase of concentration of hydrogen in the atmosphere, when coming from hydrocarbons may affect the layer of Ozone in the troposphere (Appendix F). A thorough understanding of the consequences of this increase is of utmost importance in order to have a better picture of these effects and to avoid a blind alley.

- Safety issues related to compression and handling of hydrogen. Special compressors, leak detection systems and a lot of personnel special training will be required to deal with these issues.

- Use of water is likely to increase due to steam reforming and gasification processes.

  Steam reforming from hydrocarbons is a water demanding process and water consumption is expected to rise. As we all know, water is essential for life and using it for steam reforming or as a raw material to produce hydrogen as a fuel could also be debatable. The demand that would be created for water to fuel at least one billion vehicles by 2010, could create another issue similar to the one concerning the use of land to grow crops for fuel instead of food (Appendix G).

In this scenario, the less disruptive way to produce hydrogen would be to do the electrolysis of water from renewable sources of energy such as wind and solar. These solar and wind farms could be decentralized to avoid disruption caused by pipelines and safety issues related to distribution. Still, the issue of using platinum in the fuel cell technology remains.

In order to make hydrogen a sustainable fuel, these issues have to be strategically addressed. In view of the huge challenges stated, and unless a major breakthrough in technology occurs, it would be best to use hydrogen fuel in special applications or specific situations.

4.3.3 Common issue

One important common issue was identified for second-generation ethanol and hydrogen production during this research. Water consumption is likely to increase with the deployment of both technologies. Processes to produce hydrogen from steam reforming, ethanol and using electricity generated by thermalelectrics are water intensive. This could raise ethical issues since water supply is going to be very demanded in a society with predicted 9 billion people by 2050.

A recent statement given by the executive director of the American Biofuels Council (ABC), corroborates this fact.
"In order to produce biofuels sustainably, there are additional issues we are going to face including water use. The industry needs to start preparing for this now." (O'Hanlon 2009).

In order to avoid a similar debate as the land use for fuel versus food, a strategic approach to the water issue is recommended.

4.4 Complementary discussion

During the research some issues were identified, and are very important for the conclusion of this thesis. A brief explanation is in the next sections, in order to bring them to the context and connect to the conclusions and recommendations.

4.4.1 Biogas

Biogas has a great energy potential. Nevertheless waste gases released from raw materials such as those coming from manure handling, municipal and food processing wastewater, residual sludge, food waste, poultry manure, aquaculture wastewater, seafood processing wastewater, yard wastes, and municipal solid wastes are still largely unexploited.

Management of these wastes can attenuate greenhouse gas emissions that will otherwise be released to the atmosphere contributing to the global warming effect (Appendix B). Methane, which is naturally produced from anaerobic decomposition of manure and nitrous oxide, which originates from nitrogen in manure and urine, have a greenhouse warming potential of, respectively 21 and 310 times that of CO_2 (EPA 2009, 7).

Furthermore, biogas can be used as a renewable fuel to displace fossil fuel consumption, which not only lessens CH_4 emissions from manure management but also lowers fossil CO_2 emissions. Another advantage is that it can be distributed using the same pipelines and infrastructure that are already being used for natural gas, avoiding further disruption caused by placing new infrastructure. Some cities such as Växjö, in Sweden, are successfully using it in public transportation helping to address the climate change challenge.

4.4.2 Electricity

According to the Blue Map Scenario, electrical cars can play an important role in the transport sector. For this to be feasible in a sustainable manner, improvements in the electrical grid are necessary, since some forecasts predict an increase in electricity supply of about 50 percent with the demand generated by electric vehicles (Shinnar 2003, 467).

Electricity, just as hydrogen, is not an energy source, but an energy carrier. Therefore the use of electricity is clean, but the impact on the environment depends on the primary energy source used. Like hydrogen, the generation of electricity is flexible concerning the primary energy source.

While electricity by itself has not been a scope of our study, it indirectly affected it since solar and wind power had to be assessed as an energy source to generate hydrogen from water by electrolysis. Many authors criticize the idea of creating a hydrogen economy using electricity to power hydrogen generating plants. They argue that using electricity directly to power vehicles would be much more efficient than trying to convert hydrogen from different sources for the same end (Shinnar 2003; Bossel 2006).

Figure 4.1. below illustrates the efficiency comparison between hydrogen versus electricity for transportation.

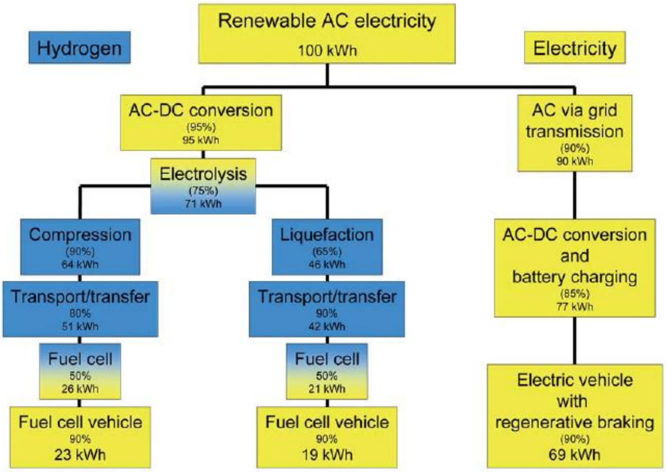


Figure 4.1. - Useful transport energy derived from renewable electricity (reproduced from Bossel 2006, 1835).

As shown in the figure above, using electricity directly to power electric vehicles would be three times more efficient than using it to produce hydrogen and run vehicles with it.

Electricity has one other great advantage. It is available almost anywhere in all developed countries whereas hydrogen infrastructure still has to be built.

An overview of battery technology shows that it also currently relies on rare metals to deliver its function (Råde and Andersson 2001a), i.e., store energy in the form of electricity (Appendix C). The rare metals ores used in the construction of batteries are restrained to certain countries which could play a role in hindering electricity from becoming a democratic form of alternative fuel for the transport sector. However, new technologies and other forms of electricity storage are being studied and evaluated (Tahil 2006).

4.4.3 Behavior

One of the most preoccupying trends is the growing population that should be reaching 9 billion by 2050. As has already been cited, transport is an essential player in economic development and growth. If its demand continues to systematically increase, as the trends are showing, no mix of fuels will be enough to fulfill it in a sustainable way, and social and ecological impacts are going to be magnified proportionally. Concerning this, changing behavior becomes an important issue to be addressed.

The use of cars in our society has many underlying statements. Many years of marketing and media linking ownership of big and powerful cars to subliminal messages such as success, liberty, virility etc. provokes consumption and use behavior patterns that hinder us from achieving a more sustainable society. Instead, mass media could spread the concept of responsible and environmentally friendly consumption and behavior. Spreading and incentivizing ideas such as eco-driving, car pooling, using public transport, biking or walking more could drastically affect the consumption of fuels and of vehicles themselves. Some estimates state that, aside of emissions, producing an average car produces 54 tonnes of waste (Bullock 1996). This figure is important if we take into account that, on average, 60 million vehicles are produced every year.

Change of behavior is not only a matter of marketing and media, but also one concerning education, accessibility and availability of services such as public transport, safe cycling and walking pathways. In order to be able to provide these features, a city has to be planned taking them into account. The involvement of city planners, stakeholders related to public transport, contractors and services linked to city planning have to be involved in order to provide those characteristics.

Environmental education should be a continuous process. To incorporate sustainability issues in formal education will increase awareness and more responsible behavior. It is also common that lessons learned by children transfer to parents, changing their behavior.

5 Conclusion

This study assessed technologies proposed in the IEA Blue Map scenario and found gaps that can bring serious threats for them to become a good alternative to lead society in the right direction, i.e., towards socio-ecological sustainability. Approaching the technologies only by their CO_2 emissions can be misleading. A strategic approach using a Framework for Strategic Sustainable Development (FSSD) and tools such as a sustainability life cycle assessment (SLCA) based on sustainability principles is necessary in order to provide a whole systems perspective of the impacts of the deployment of each technology.

We recommend, in the ETP bi-annual report, a complementing chapter including a combined analysis using the SLCA and the SWOT showing, respectively the sustainability gaps and strengths, weaknesses, opportunities and threats of each technology in the mix of fuels proposed in the scenarios. A risk assessment table containing all the technologies and their related impacts would help decision and policy makers in their work to facilitate and finance the development of more sustainable technologies. Without a whole-systems perspective and a deep assessment of the impacts they can bring to environmental, social and economical fabrics, a sustainable future for the transport sector can be threatened.

In order to make the transition to a sustainable future, not only new technologies and tools have to be developed, but also the decrease on the demand for fuels is of utmost importance. Change of behavior allied with the deployment of new technologies, using different and more environmentally friendly energy resources are important to reach for a more sustainable transport sector.

When evaluating hydrogen as a technology, one must be very careful not to be lead into blind alleys. There are presently many options being studied to deploy it as a fossil fuel substitute for stationary and vehicle applications and some of them may cause great disruption to the environment. For the transport sector, there are huge barriers that need to be overcome in order to make it become a large-scale sustainable technology.

Second-generation ethanol has the potential to decrease the impacts caused by the first generation, and the barriers have to be overcome in a very strategic way. The competition between food versus fuel can be minimized with this technology, but others like water versus fuel and forest versus fuel are likely to happen in a near future. The whole-systems perspective is strongly recommended for the assessment of the processes, in order to make the second-generation ethanol the promised environmental-friendly biofuel.

Other technologies also mentioned in the Blue Map Scenario such as the use of electricity are seen as possible solutions for the transport sector. An overview of the Battery Electric Vehicle technology shows that it faces some similar threats just like hydrogen in order to become viable, that are related to the dependence on rare metals (Råde and Andersson 2001a). Nevertheless, other forms of electricity storage are being studied and evaluated (Tahil 2006).

Biogas represents a great potential of energy to be exploited. With the increase of population that is forecasted, waste and consequently biogas, are naturally going to increase. It would be wise to start planning for the infrastructure necessary to capture this biogas in order to use it as an energy source rather than plainly let those emissions reach the atmosphere.

Several alternatives are already available and others might be in medium to long term. Without a deep assessment of the impacts they can bring to environmental, social and economical fabrics, a sustainable future for the transport sector can be threatened.

5.1 Further research

As scientific community is still developing solutions for hydrogen and second-generation ethanol to become a future basis of the economy, continuous assessments on the upcoming breakthroughs are of utmost importance. During the research for the thesis, the following issues were identified, where a deeper assessment would benefit a broader understanding of the system related to the transport sector.

- Development of a SSD related tool for IEA experts to build the sustainability assessment of the scenarios.

- More detailed sustainability assessment of the use of biogas in the road transport sector.

- Sustainability assessment of impacts related to improvements needed in the electrical grid to support a large-scale penetration of electrical cars.

- Atmospheric impacts of systematic increase of hydrogen from hydrocarbons.

  The following topics can be a good theme to be developed within The Real Change Program[4], where collaborative partnerships with industries and scientists can be made in order to have a deeper assessment of the technologies and hopefully the development of more sustainable alternatives:

- Use of batteries in electric cars
  The assessment of sustainability impacts of materials and technologies, current and under development, used in large scale in batteries.

- Use of water in electrolysis process to produce hydrogen.
  Impacts of the water use in large-scale applications..

- Assessment of social and environmental impacts of GMOs (genetically modified organisms) such as trees, energy grasses, enzymes and yeasts to produce biofuels.

5.2 Final thought

"The world's current energy prospects are – put simply – unsustainable…It is reassuring to know that human ingenuity can rise to this challenge. Existing technology – primarily energy efficiency – is an obvious first step, but it is ultimately new technologies that hold promise of economic opportunity and benefit for all the world's countries – and a strong basis for common action toward common objectives."

Nobuo Tanaka, IEA Executive Director, 2008

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4 An international, trans-disciplinary and cross-sector program connecting scientific theory, methodology and applications for Strategic Sustainable Development (SSD), conducted in BTH – Blekinge Tekniska Hogskola – Sweden.

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APPENDIX A

EXTRACTION, PRODUCTION, STORAGE AND DISTRIBUTION OF NATURAL GAS

The stages of the natural gas production are (NaturalGas.org, n.d.):

- Extraction: drilling, installing well casing for lifting natural gas to surface, drainhole completion, lifting natural gas;
- Production: processing of natural gas to remove impurities,
- Storage, transport and distribution: raw natural gas to pipeline for transportation.

The operations of extracting, processing, transmitting, storing, and distributing natural gas, some gas is lost to the atmosphere through leakages of compressor components, pneumatic control devices, engine exhausts due to incomplete combustion, purging of transmission/storage equipment and others (Spath and Mann 2001, 9).

Extraction

When assessing the impacts of natural gas extraction, there are two kinds of extraction; onshore and offshore drilling. When drilling occurs onshore, two main technologies are available: Cable Tool Drilling and Rotary Drilling.

Cable tool drilling is performed to assess shallow and low pressure wells by systematically raising and dropping a heavy metal bit into the ground with the intent to punch a hole into the Earth. The other technique is rotary drilling. When the well has finally been drilled (SP3), the process of casing it with metal tubes (SP1) to strengthen its walls and fixing it with cement (SP2) takes place. The following step is to do a well treatment using acid (usually chloridric acid) (SP2) in order to dissolve rocks in the formation, or using water or gases (CO_2) to fracturize them (Natural Gas 2004a).

When offshore exploration is the case, some other features have to be taken into account. In this case platforms have to be built and transportation infrastructure has to be layed out in order for raw natural gas to reach the processing plants.

The act of using natural gas for combustion purposes to generate energy on platforms releases substances such as SO_x, NO_x and CO_2 and others into the atmosphere (SP2). Nevertheless, natural gas is still recognized as the cleanest fossil fuel when comparing its emissions to oil and coal.

PROCESS: Extraction of Natural gas.			
SUB PROCESSES: – Drilling, – Installing well casing for lifting natural gas to surface, – Drainhole completion, – Lifting natural gas			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
Metal used for casing the well (conductor, surface, intermediate casings) Metals used in well heads, “christmas trees” and drills, platforms, ships etc. Oil and fossil fuels used to transport and lubricate parts in the process. Net increase in concentration of mined fossil fuel. Loss of natural gas from extraction process due to leakages.	Cement used to fix conductor, surface and intermediate casings in place. Injection of chloridric acid, CO_2. NO_x, SO_x, CO_2, CO from burning fossil fuels	Degradation of soil by drilling and building of infrastructure for production. Use of explosives to reach wells.	Working and safety conditions.

Production: processing of natural gas to remove impurities,

Although raw natural gas is primarily composed of methane, some small amounts of other components such as low molecular weight hydrocarbons (ethane, propane, pentane), nitrogen, carbon dioxide and helium are also present. Natural gas can also have some sulfur compounds in the form of hydrogen sulfide (H_2S) and carbonyl sulfide (COS) (SP2) (Dicks 1996, 114) (Spath and Mann 2001, 8). In order to reach “pipeline quality”, raw natural gas has to be purified (Natural Gas 2004b). It is also worthy of note that it is a common procedure to add components containing sulfur to make it easier to identify and track leaks during distribution.

One processing plant can be linked through gathering lines to hundreds of wells. The gathering lines are made of steel (SP1) tubes with small diameter and low pressure.

The production of natural gas goes through the following processes (Natural Gas 2004b):

a) Oil and condensate removal;

Oil and condensate removal is done in separators where the gas is initially cooled of and, by using pressure differentials the liquid present in the natural gas then condensates. Oil can also be removed by gravimetry.

b) Water removal;

In this step natural gas is dehydrated. Glycol solutions such as diethylene glicol (DEG) and triethylene glicol (TEG) that have great affinity with water are used to react with it in the gas stream.

Another way of dehydrating the natural gas is using solid dissecants such as alumina or silica gel in absorption towers.

c) Separation of natural gas liquids (NGLs);

The separation of NGLs is done by absorption oils (SP1) and by cryogenic cooling of the natural gas by turbo expansion and using external refrigerants (SP2).

d) Sulfur and Carbon dioxide removal.

Sour gas, i.e., gas containing sulfur and carbon dioxide can be extremely harmful and even lethal when breathed and it is also extremely corrosive.

To take sulfur (H_2S) out of the gas ('sweeten the gas') one adds amine solutions such as monoethanolamine (MEA) and diethanolamine (DEA).

When exposed to these substances, people may suffer central nervous system depression and liver and kidney damage (SP4) (Equistar 2006, 2). Another way is to take the sulfur out using iron sponges (SP1, SP3).

PROCESS: Production of Natural gas.			
SUB PROCESSES: – Oil and condensate removal, – Water removal, – Separation of natural gas liquids, sulfur and carbon dioxide removal.			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
Loss of natural gas from production process due to leakages from compressors, dehydrators etc.	NO_x, SO_x, CO_2, CO, particulates from burning fossil fuels. Use of external refrigerants to separate NGLs (ethane).	Disruption caused by processing plants and gathering lines. Mining of iron.	Air pollution, health problems related to air pollution, acid rain. Health and poisoning risks due to working conditions cause by

Absorption oils to separate NGLs. Iron sponges to dessulfurize NG.	Use of di/triethylene glicol to take water out of NG. Use of mono and diethanolamine in NG dessulfurization process.		di/triehtylene glicol. Health issues related to exposure to MEA and DEA.

Storage, Transportation and Distribution

PROCESS: Transportation/Storage of Natural gas.			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
Loss of natural gas from transmission process due to leakages from compressors, pneumatic devices.	Combustion of NG to power compressors (NO_x, SO_x, CO_2, CO, particulates). Fusion bond epoxy to avoid corrosion of pipelines.	Drilling for NG.	Health issues related to pollution.

Storage of natural gas can be done using depleted gas reservoirs, aquifers and salt caverns. In case of using aquifers, there's a risk of water contamination (Natural Gas 2004c).

PROCESS: Storage of Natural gas.			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
Loss of natural gas due to leakages from compressors, pneumatic devices and purging of storage systems.	Combustion of NG to power compressors (NOx, SOx, CO_2, CO, particulates).		Health issues related to pollution. Possible water contamination with NG in aquifers.

PROCESS: Distribution of Natural gas.			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
Pipelines made of steel. Loss of natural gas due to leakages from compressors, pneumatic devices and purging of transmission systems.	Pipelines made of plastic are option to substitute steel pipelines.	Drilling for oil.	

APPENDIX B

PRODUCTION, STORAGE AND DISTRIBUTION OF BIOGAS.

Raw Materials

Biogas is typically a gas mixture containing the following range of gases, as shown in table xx.

Table B.1. Biogas composition in volume (Nogueira 1986, 26).

Gas	Content in volume (%)
Methane (CH_4)	55 - 75
Carbon Dioxide (CO_2)	25 - 45
Nitrogen (N_2)	0 - 3
Hydrogen (H_2)	0 - 2
Oxygen (O_2)	0 – 0,1
Hydrogen sulfide (H_2S)	0 - 1

The raw materials utilized to produce it are considered organic wastes from different processes as manure handling, municipal wastewater, residual sludge, food waste, food processing wastewater, poultry manure, aquaculture wastewater, seafood processing wastewater, yard wastes, and municipal solid wastes (Wilkie 2008a). In order to transport them to the biodigestor one has to use fossil fuels, oil for lubrication and the combination of fuels used to generate the electricity in the power grid (SP1). Their combustion originates emissions (SP2) and their extraction causes physical disruption of the environment (SP3).

PROCESS: Raw Material			
SUB PROCESSES: Transportation			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
- Fossil fuels, oil			- Odors inherent to organic waste.

Production Phase

In the production phase, one has to be aware of the production of hydrogen sulfide gas (H_2S), a very corrosive, poisonous (SP4) and also a gas that reduces the efficiency on burning methane. It is common to employ solvation solutions (solvents) to dissolve CO_2 and H_2S or solutions such as alkanolamines and alkaline salts that alter ionic characteristics through chemical reactions (Nogueira 1986).

There are membrane materials, which are specially formulated to selectively separate CO_2 from CH_4. The permeability of the membrane is a direct function of the chemical solubility of the target compound in the membrane. To separate two compounds such as CO_2 and CH_4, one gas must have a high solubility in the membrane while the other is insoluble. One of the substances used to separate both components is CaOH (Wilkie 2008b) (calcium hydroxide) which, when swallowed can cause severe health issues on workers such as irritation of the skin, breathing difficulties, loss of vision or other symptoms if swallowed such as intestinal hemorrhages, blood pressure decrease etc.(SP4). Monoetanolamines (MEAs) and dimetil ether from poliethilene glicol are also used for the same purpose and are known to be skin and eye irritants (SP4) (Nogueira 1986).

PROCESS: Production			
SUB PROCESSES: Dessulfurization			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
- Iron	- production of steel for biodigestor, valves, pipes etc. - Monoetanolamines (MEAs) - Dimetil ether from poliethilene glicol.	- mining for iron.	- Health issues related to exposure to CaOH and MEAs and dimetil ether.

Distribution and Storage

The use of biogas in mobile engines requires compression to high pressures to achieve minimal storage volume. Biogas is stored in medium-and high-pressure storage vessels that are usually constructed with materials such as mild steel (SP1, SP3). Low pressure storage vessels can be made of steel (SP1, SP3), concrete and plastics such as polyester fabric (SP1, SP2). The delivery pressure required is directly related to the kind of material that is going to be used in the construction of the storage vessel (Wilkie 2008a).

PROCESS: Distribution & Storage			
SUB PROCESSES: Compression			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
- Iron	- production of steel for biodigestor, valves, pipes etc. - Monoetanolamines (MEAs)	- mining for iron.	- Health issues related to exposure to CaOH and MEAs

Use Phase

Biogas, if compressed for use as an alternative transportation fuel in light and heavy duty vehicles, can use the same existing technique for fueling already being used for compressed natural gas vehicles. In many countries, biogas is viewed as an environmentally attractive alternative to diesel and gasoline for operating buses and other local transit vehicles. The sound level generated by methane-powered engines is generally lower than that generated by diesel engines, the exhaust fume emissions are considered lower than the emission from diesel engines, and the emission of nitrogen oxides is very low. Application of biogas in mobile engines requires compression to high pressure gas (>3000 psig) and may be best applied in fleet vehicles. A refueling station may be required to lower fueling time and provide adequate fuel storage (Wilkie 2008a).

PROCESS: Use Phase			
Sustainability Principle 1	*Sustainability Principle 2*	*Sustainability Principle 3*	*Sustainability Principle 4*
- Oil for engine lubrication	- CO, CO_2, NO_x, HC	Mining for Fossil Fuels	

APPENDIX C

BATTERY ELECTRIC VEHICLES (BEVs)

Battery electric vehicles are vehicles propelled by an electric motor (or motors) powered by rechargeable battery packs. They have been considered as a means to meet some of the environmental and resource challenges that road transport faces today. Some of the features of BEVs compared to internal combustion engines (ICEs) are displayed in the table below.

Table C.1. Comparison between BEV and ICE technologies.

	BEV	**ICE**
Energy efficient	75 - 80%	20 - 30%
Emissions	No tailpipe emissions	CO_2, CO, NO_x, SO_x
Energy dependence	Electricity can be generated from many sources	Fossil Fuels
Performance	Quiet & Smooth operation, stronger acceleration	More maintenance
Driving Range	240km / 150 miles	480km / 300 miles
Recharge / Refuel	4 to 8 hours	3 min
Battery Cost	Expensive and must be replaced	Engine is the same through lifespan of vehicle.
Bulk & weight	Heavy & take up considerable vehicle space.	Engines are getting lighter and smaller using new materials.

Of course, when talking about emissions, one has to assess and consider the raw materials used to produce the electricity and the distribution to the whole electricity grid.

Concerning the batteries, many different configurations using different metals are being tested. Lithium-metal, lithium-ion, sodium-beta, nickel-hydroxide and lead-acid battery (Råde and Andersson 2001a, 56).

For lithium-metal technology, batteries are composed of lithium and vanadium (V). The cathode of lithium-ion batteries may be composed of manganese (Mn), nickel (Ni) or cobalt (Co). Sodium-beta batteries are composed of sodium (Na) and nickel (Ni). Nickel-hydroxide batteries may be composed of nickel (Ni) and other different compositions of metals composed of cadmium (Cd), zirconium (Zr), titanium (Ti), vanadium (V) and chromium (Cr). Lead-acid batteries are composed of lead (Pb) (Råde and Andersson 2001a, 58-62). Vehicles production along with available reserves of these metals play a determinant role in which technology could be deployed in a large scale (Andersson and Råde 2000, 23). Amongst those, lithium-ion batteries are rapidly becoming the technology of choice for electric vehicles, plug in hybrid and BEVs (Tahil 2006, 1).

South America currently dominates lithium production with Chile and Argentina contributing with approximately 47 percent of world production. When world reserve-base[5] is taken into consideration, South America responds for about 80 percent of world's ores. Lithium deposits can be of two types: a hard silicate mineral called Spodumene and Brine Lake or Salt Pan deposits. Of those, only the second is economically and energetically viable for Li-ion batteries (Tahil 2006, 4). They would however fulfill only 10 percent of the demand at current production rate which are, by the way, being used for other purposes.

Other technological options for batteries could be ZnAir or NaNiCl with more metal reserves to fulfill upcoming demand for vehicles (Tahil 2006, 9).

[5] According to the U.S. Geological Survey department, the definition of Reserve Base is "that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth". The reserve base is the in place demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub-economic (sub-economic resources)."

APPENDIX D

PGMs[6] AND OTHER METALS CURRENT SITUATION

The PGMs have unique characteristics such as high catalytic activity, refractory properties, oxidation resistance and being chemically inert to a wide variety of elements and compounds at elevated temperatures, which make them very valuable. Furthermore, PGMs are among the rarest of the chemical elements on the Earth's crust. Platinum for instance, accounts for 0.4 ppb and ruthenium 0.1 ppb (Råde and Andersson 2001, 2).

For the PGMs, reserves[7] are estimated to be 71,000,000kg while consumption of platinum has been 200,000kg in 2008, The six metals of the platinum group occur closely associated with nickel and copper and themselves in nature. They have always been a concern in terms of supply specially after they have been started to be used in vehicle catalysts (Loferski 2009, 123).

The major platinum producers in the world are South Africa, holding 70% of total production followed by Russia with 22%. Other minor players in the market are Canada, the US and Zimbabwe.

Platinum production is very enery intensive. In order to withdraw 1kg of Platinum one has to dig 450.000kg of ore. Pollution of water and air are intimately associated with its production. Some of the emissions are sulfur dioxide, ammonia, chlorine and hydrogen chloride gases. A base metal liquor containing iron and zinc is also produced in the process. After precipitation of the metals, it is landfilled and can cause groundwater contamination (DFT 2006).

[6]The PGMs are: ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir) and platinum (Pt).

[7] According to the U.S. Geological Survey department, the definition of reserve is "that part of the reserve base which could be economically extracted or produced at the time of determination". The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials.'

Overview of other metals situation

The annually production of copper is 12 million tonnes a year while exploitable reserves on Earth are believed to be around 300 million tonnes. That would give us a approximate estimation of 25 years of further possible exploitation at the present rate on this metal. Cromium is utilized in many applications around the world and the consumption is around 20.000 tons a year. Lanthanum is rarely found in nature. It is mined in the oxide form and some 12.000 tons are produced per year with current known reserves at about 6 million tons. Samarium production is about 700 tons per year with estimated reserves of about 2 million tons. Strontium forms about 0,034 percent of all igneous rock in the form of celestite ($SrSO_4$) and carbonate strontianite ($SrCO_3$).Cerium makes up about 0,0046 percent of Earth's crust by weight and is consumed at a current rate of about 23.000 tons a year. These catalysts are generally carried or supported by lanthanum oxides (La_2O_3) alumina pellets (Al_2O_3) (Fatsikostas et al. 2001, 851), ceramic (CeO_2) (Yakimova et al. 2008) and zinc (Zn) (Llorca et al. 2002, 306).

APPENDIX E

HEALTH ISSUES RELATED TO METALS.

Some of these metals such as Ni, Zn and K, are common in nature and are even part of our daily dietary. Nevertheless, high exposure to these metals may cause health problems (SP4) such as:
Ni - Lung, nose, larynx and prostate cancer, asthma, chronic bronchitis.
Cu – dizziness, vomiting and diarrhea.
K - Inhalation of dust or mists can irritate the eyes, nose, throat, lungs with sneezing, coughing and sore throat. Higher exposures may cause a build up of fluid in the lungs that can cause death. Skin and eye contact can cause severe burns leading to permanent damage.
Cr – Skin rashes, upset stomach, ulcers, alteration of genetic material, damages to kidneys and liver and a weakened immune system.
Sm - can cause eye and skin irritation.
Co – Cobalt is beneficial for humans since it is part of vitamin B12. However in high concentrations it may damage human health. People who work with cobalt may experience asthma and pneumonia because of its high concentrations in the air.
La, Ce - may cause lung embolism, cancer and are a threat to the liver.
They damage cell membranes in water animals when accumulated in that environment.
Rh – Flammable when mixed with air and in form of powder or grains. It is the least toxic of the PGMs.
Sr – Strontium in general doesn't have any effects on humans. The only way it could become a health risk is if children exceeded strontium uptake, because it can cause problems with bone growth (Lenntech 2008).

APPENDIX F

ATMOSPHERIC IMPACT OF H_2 FROM HYDROCARBONS.

Although hydrogen is being shown as a future solution as an energy resource that is emission free, it can also cause the following effects on environment (DFT 2006).

- ground-level ozone production;
- tropospheric ozone production;
- climate change;
- stratospheric ozone chemistry.

Ground level ozone is a secondary photochemical pollutant formed from the sunlight-initiated oxidation of volatile organic compounds (VOC, for example hydrocarbons) in the presence of nitrogen oxides (NO_x) (DFT 2006).

One of the key factors in assessing episodic ozone production is the rate of reaction of ozone-precursor compounds with OH.

$$OH + H_2 \rightarrow H + H_2O$$

Molecular hydrogen will make an insignificant contribution to ground-level ozone production on a 4-5 day timescale.

The complete oxidation of hydrogen to water in the troposphere leads to the production of ozone (O_3), as shown below:

$$H_2 + 2O_2 + hv \rightarrow H_2O + O_3$$

The tropospheric chemistry of hydrogen is strongly coupled to that of methane as the oxidation of methane produces formaldehyde (HCHO), as an intermediate. One of the photodissociation channels formaldehyde produces molecular hydrogen, which is a major source of atmospheric hydrogen (Simmonds et al. 2000).

$$HCHO + hv \rightarrow H_2 + CO$$

The free radical route is a significant pathway in the formation of ozone and photochemical smog conditions (Simmonds et al. 2000).

$$HCHO + hv \rightarrow H + HCO$$

The lifetime of hydrogen in the atmosphere would be of about two to three years with oxidation by hydroxil radicals happening in the troposphere and sink occurring by deposition in soil (Novelli et al. 1999).

Together with water vapour and methane, molecular hydrogen is a source gas that controls the stratospheric water vapour budget. These molecules act as sources of odd hydrogen (H, OH), which can catalyse ozone destruction in the upper stratosphere through the following reactions:

$H + O_3 \rightarrow HO + O_2$; $OH + O \rightarrow H + O_2$; $O + O_3 \rightarrow 2O_2$

APPENDIX G

THE WATER ISSUE

Water is essential for life on Earth. It participates and plays an essential role in practically every biological life cycle. It also plays an important role in human activity. It is necessary for agriculture, industrial production, power generation and as a way for transporting people and goods. It is estimated that 10% of world water withdrawal is consumed for domestic purposes, 20% in industrial activities and 70% for agriculture irrigation. Nevertheless water is also a scarce resource in many parts of the world. According to figures released by the OECD, about 3.9 billion people could be living in waterstressed areas by 2030, compromising health, sanitation, food production and consequently livelihood. Currently, about four million people die per year due to problems with water quality related to drinking water, sanitation and human health (OECD 2005). These problems are related to infrastructure, institutions and shortfalls in economic capacity. These problems tend to become more acute with the trend of growing population and consequent need for food and resources.

In this scenario, it is important to address water issues in a holistic way. In a fully developed hydrogen economy, water is going to be one of the major feedstocks for hydrogen production and also as a cooling fluid for the thermoelectric generation of electricity that is used in water electrolysis. Nevertheless, energy reports such as IEA's report ETP 2008, the National Research Council report of 2004 and others do not mention the impact that a transitional hydrogen economy can have on water resources.

If electrolysis is to become one of the main paths for production of hydrogen, sources of electricity such as thermoelectric, hydroelectric and irrigated renewable should be avoided in order to take pressure off of water resources. The less water consumption pathway to produce hydrogen would be to use wind or solar energy (Webber 2007, 6).

As stated in the 5th World Water Forum that took place in Istanbul 2009: "The true importance and full value of water is still largely ignored. This vital resource needs to be recognized more strongly by politicians, business people and stakeholders from civil society alike. Much stronger commitment is needed to facing the water challenge now, while it can still be resolved" (WBCSD 2009).