NORGES HANDELSHØYSKOLE

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The Car of Tomorrow

An Assessment of Alternative Fuel Vehicle Technology and the Use of Policy Instruments to Facilitate the Implementation

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MSc Thesis – Major in Strategy and Management

NORGES HANDELSHØYSKOLE

«That the automobile has practically reached the limit of its development is suggested by the fact that during the past year no improvements of a radical nature have been introduced»

Scientific American, Jan. 2 edition, 1909

Preface

A strong shared interest in environmental issues and technological innovation initiated a collaboration between the authors, which resulted in this thesis. The process included a great deal of work collecting data and selecting valid and useful information. At times the amount of data was overwhelming with new discoveries continually affecting our points of view. We are very pleased with our choice of study and satisfied with the outcome.

We hereby thank our supervisor, Associate Professor Tor Fredriksen, for his wise guidance, friendly and professional support, and for his encouragement during more challenging stages of the process.

We also want to thank (in alphabetical order):

Andrew Burnham (Fuel and Vehicle Systems Analyst at Argonne National Laboratory), Tomas Levin (Research fellow at the Foundation for Scientific and Industrial Research (SINTEF)), Lars Jacob T. Pedersen (Research fellow at the Norwegian School of Economics and Business Administration (NHH)), Martin Sjøgård (Norwegian University of Science and Technology (NTNU)). We deeply appreciate their willingness to answer our questions and their valuable contribution to our thesis.

Abstract

This master's thesis assesses different alternative fuels and fuel vehicles in a European context in short and medium term. We apply a contextualised GREET model to determine the energy usage, emissions and technological improvement of eight selected vehicles running on four different fuels. In addition we use a payback analysis to determine the payback period of each alternative. The results show that diesel vehicles outperform petrol vehicles. Plug-in hybrids look promising, but their efficiency improvement from 2010 to 2020 is modest compared to some of the other technologies. The battery electric vehicle and fuel cell vehicle are the cleaner and more efficient technologies in 2020, however the FCV involves a high degree of uncertainty within our timeframe. We therefore select HEV, PHEV and BEV as our preferred alternatives. Using a stakeholder approach, we identify barriers to the implementation of our selected technologies. To overcome these barriers we apply a selection of policy options.

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List of Abbreviations and Acronyms

AC	Alternating Current	
AER	Average Electric Range	
AFV	Alternative Fuel Vehicle	
ANL	Argonne National Laboratory	
B100	100 % Biofuel	
B20	20 % Biofuel	
BEV	Battery Electric Vehicle	
BFV	Bifuel Vehicle	
BG	Biogas	
Btu	British Thermal Unit	1 Btu = 1.055 Kj
BYD	Build Your Dreams	
CARB	California Air Resources Board	
CBG	Compressed Biogas	
CD	Charge Depleting	
CHG	Compressed Hydrogen Gas	
CIDI	Compression Ignition Direct Injection	
CNG	Compressed Natural Gas	
CO2	Carbon Dioxide	
CONCAWE	Conservation of Clean Air and Water in Europe	
CS	Charge Sustaining	
DC	Direct Current	
DI	Direct Injection	
DME	Dimethyl Ether	
DOE	Department of Energy	
E85	Ethanol 85 %	
ETBE	Ethyl TERT-Butyl Ether	
EtOH	Ethanol	
EU	European Union	
EUCAR	European Council for Automotive R&D	
Eur	Euro	
FAEE	Fatty Acid Ethyl Ester	
FCV	Fuel Cell Vehicle	
FFV	Flexi-Fuel Vehicle	
G-C	Grid-Connected	
GHG	Greenhouse Gas	
G-I	Grid-Independent	
GM	General Motors	
GNP	Gross National Product	
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation	
GW	Gigawatt	
H2	Hydrogen	

H2O	Water	
HEV	Hybrid Electric Vehicle	
HHV	Higher Heating Value	
IC	Internal Combustion	
ICE	Internal Combustion Engine	
ICEV	Internal Combustion Engine Vehicle	
IEA	International Energy Agency	
IPCC	The Intergovernmental Panel on Climate Change	
ISO	International Standards Organization	
JET	Joint European Commission	
JRC	Joint Research Centre	
Kj	Kilojoule	
KWH	Kilowatt-hour	
LCA	Life Cycle Assessment	
LHV	Lower Heating Value	
Li	Lithium	
LNG	Liquid Natural Gas	
LPG	Liquid Petroleum Gas	
M&A	Mergers & Acquisitions	
M	Million	
M85	Methanol 85 %	
MDI	Motor Development International	
Mile		1 Mile = 1.609 Km
Mj	Megajoule	
MPG	Miles per Gallon	1 MPG = 0.425 Km/l
MSc	Master of Science	
MT	Megatonnes	
MTBE	Methyl Tert-Butyl Ether	
MTE	Million Tonnes	
NG	Natural Gas	
NHH	Norges Handelshøgskole	
NiCd	Nickel Cadium	
NiMH	Nickel Metal Hybrid	
Nox	Nitrogen Oxide	
O2	Oxygen	
OPEC	Organization of the Petroleum Exporting Countries	
PB	Payback	
PEM	Proton Exchange Membrane	
PHEV	Plug-in Hybrid Electric Vehicle	
PSI	Pounds per Square Inch	1 PSI = 0.069 BAR
PTT	Plant-to-Tank	
PTT	Pump-to-Tank	
PTW	Plan-to-Wheel	

PTW	Pump-to-Wheel
R&D	Research and Development
SA	Strategic Alliances
SCiB	Super Charge Ion Battery
SI	Spark Ignition
SIDI	Spark Ignition Direct Injection
TTW	Tank-to-Wheel
U.K.	United Kingdom
U.S.	United States of America
UN	United Nations
VMT	Vehicle Miles Travelled
VW	Volkswagen
WH	Watt Hour
WTT	Well-to-Tank
WTW	Well-to-Wheel
WWF	World Wide Fund for Nature
ZEV	Zero-Emissions Vehicle

1. Introduction

1.1 Motivation

Transportation has been one of the main drivers of the economic growth of the industrialised world, allowing for more efficient movement of people and goods. The development since the Roman Empire paved roads to allow armies to travel at greater speed to the breakthrough of the T-Ford around 1910[1] has been nothing less than remarkable. The beginning of the 20th century represents a historic crossroads for vehicle technology. Electric powered vehicles became increasingly expensive, cities became interconnected leading to the need of longer-range vehicles[2], and at the same time oil production rose significantly[3]. In 1912 an electric roadster sold at more than 2.5 times the price of a gasoline car[4]. The discovery of Texas crude oil led to a reduction in gasoline prices making it affordable for the average consumer. The rest is history.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that most of the observed increase in global average temperatures since the mid-20th century is *very likely due to the observed increase in anthropogenic greenhouse gas concentrations*.[5] This increase in temperature leads to a rise in sea levels and shortage of freshwater in some of the poorest areas of the world, like Africa. The transportation sector is responsible for a large portion of the global GHG emissions. More than 800 million cars and light trucks[6] account for the majority of the emissions from the transportation sector. The pollution from these cars affects air quality, especially in main metropolitan areas[7].

According to Kendall (2008), 95 % of the primary energy consumed in the transportation sector is fuel derived from crude oil. Crude oil is a finite resource and therefore cannot be extracted indefinitely. The estimated occurrence of peak oil, the point in time when the maximum rate of global petroleum extraction is reached[8], varies among experts and analysts. The creator of the peak oil theory, M. King Hubbert, has designed a bell-shaped production curve which indicates peak oil is upon us[9]. OPEC, on the other hand, has suggested that peak oil might never occur[10]. What is certain, however, is that today's oil consumption cannot be maintained in the long run.

The Hirsch report (Hirsch, 2005) assumes an increase of 50% in world oil demand by 2025 (Hirsch, 2005, p. 12). A summary of the report, published in October 2005 for the Atlantic Council stated that oil production is in decline in 33 of the world's 48 largest oil producing countries[11]. These countries include superpowers U.S. and Russia[12]. Taken into consideration that the U.S., China, Japan, Germany, South Korea, France, India, Italy, and Spain constitute the largest net importing countries of oil[13], it seems clear that there exists a strategic aspect, where reducing one's dependency on a scarce resource is the desirable outcome for the world.

In some ways we find ourselves at a crossroads for vehicle technology yet again. This time, however, the prerequisites are different. The aspects introduced above give notice of a necessary shift in the automobile industry. A just question is *how*?

While crude oil has had a substantial influence on the development of a number of technologies through the rise of the modern world, it might actually have put obstacles in the way of the oil-dependent vehicle technology. It is the authors' opinion that if vehicle technology had developed at the speed of computer processors, we might as well have been flying cars as opposed to driving them years ago. In short- and medium term other technologies are more likely to take up competition with the internal combustion engine vehicle. At this point, opinions as to what is the best alternative technology vary. Battery electric vehicles, plug-in hybrid electric vehicles, hydrogen fuel cell vehicles, and bifuel vehicles are all considered promising. Can either of these outperform the ICEV?

Governments can play a key role in stimulating innovation of new technologies that can reduce the dependency of fossil fuel, as well as arrange for a transition of alternative fuel vehicles by reducing entry barriers. The EU has recently introduced joint efforts to reduce emissions from light-duty vehicles, e.g. through setting emission performance standards[14]. A number of policy options, such as regulatory standards, tax incentives, and fuel pricing measures, are available in the government tool box. There are, however, a number of stakeholders that can affect the process, and governments need to take this into consideration.

1.2 Research Question

This thesis compares different vehicle- and fuel technologies in an attempt to determine which is the most promising as a worthy competitor to the fossil-fuelled ICEV in the European market. The different technologies are compared in four dimensions: economy, efficiency, environment and technology. Secondly the thesis tries to identify stakeholder barriers that may impede a transition of the new technologies, and suggests how governments can make use of policy options to overcome these barriers.

Our research question is: ***Which vehicle and fuel technologies are the best options for the European mass market, and how can European governments use policy instruments to facilitate the implementation of these technologies?***

By *best* we mean a balanced way of trying to identify and optimise certain goals or criteria which from a contextual point of view are regarded as appropriate responses to the serious environmental challenges we face in our time. By *options* we assume that we for the time being have several real choices. We will investigate some of the most relevant choices limiting the alternatives to the most interesting from a practical point of view.

Our research question is twofold: While the first part has a strong technical/economical/environmental orientation, the second part involves a stronger political/sociological dimension. We believe that these two principally different but equally important parts should be dealt with simultaneously. In some sense the part of the problem statement concerning implementation is the most difficult one. However, through the institutions of the European Union we have policy instruments that may be very useful in order to make a difference. In our research we will try to investigate how policy instruments can be used constructively to implement the main results we obtain from the first part in our problem statement. We have a clear focus on the methodological measuring of different alternatives, rather than a thorough theoretical analysis. This is described in more detail in the *Methodology* chapter.

1.3 Introduction to Alternative Fuel Vehicles

An AFV is a vehicle that runs on other fuels than solely petrol or diesel[15]. Since the automobile became popular in the beginning of the 20th century, various versions of AFVs have been introduced to the market. However, no personal AFVs have experienced success over time or in global market shares. The last 10-15 years, public awareness of the environmental issues have once again made AFVs popular. The introduction of the Prius Hybrid in 1997 is probably the best example. New technologies that may make an impact in the future are the Plug-in Hybrid, electric vehicles, or vehicles on biofuels or CNG. Fuel cell technology is also promising in a longer view. Nevertheless, AFVs only constitute a niche market globally today. This is mainly because AFVs usually have some shortcomings compared to petrol vehicles, as for instance higher price, shorter range or weaker performance. If we look to Brazil, we see that active government policies can quickly change the market mix of AFVs. Ethanol gained a larger market share than petrol in 1980 after the Brazilian government launched the *National Fuel Alcohol Program* in the mid 70's[16].

1.4 Introduction to The EU

The European Commission, which acts as the EU's executive arm[17] and *seeks to uphold the interests of the Union as a whole*[18], make use of *Green* and *White* papers to address ideas and proposals which are of interest for the Union. *While green papers set out a range of ideas presented for public discussion and debate, white papers contain an official set of proposals in specific policy areas and are used as vehicles for their development.*[19] The EU has agreed to cut GHG emissions by at least 20 % of 1990 levels by 2020 (30 % if the rest of the world follows up)[20]. Since it will take time to restore the balance in the ecosystem and reduce the increase in temperature, cutting GHG emissions quickly is of utmost importance. Figure 1-1 illustrates costs of different scenarios with regards to rise in sea levels and whether or not actions are taken.

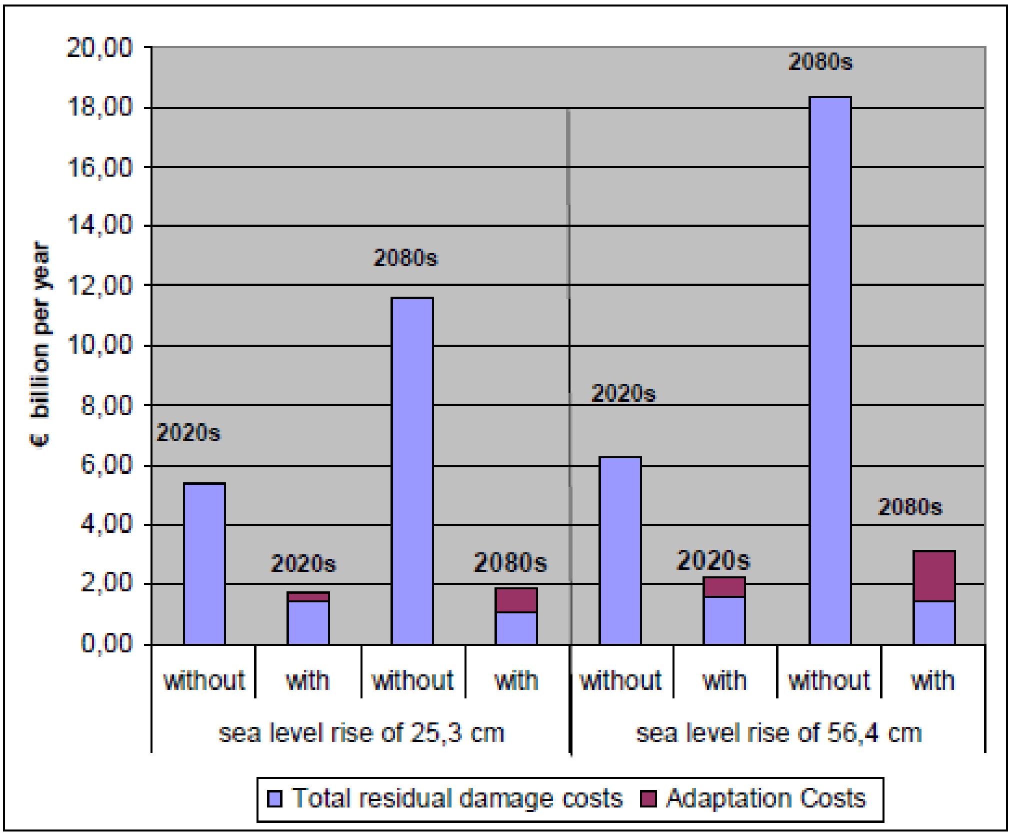


Figure 1-1: Impact of Adaptation Measures on Damage due to Low and High Sea Level Rise. Costs With and Without Adaptation Measures

Source: The EU Commission: Green paper 2007

Today, roughly half of the EU's gas consumption comes from just three countries. This number is expected to increase to 80 % for gas and 90 % for oil within 2030.[21][22] Transportation accounts for 30 % of final energy consumption in the EU-25, making it the largest consumer[23]. Passenger cars constituted 74 % of all passenger transport in 2004 (EU-25)[24]. While GHG emission from energy production, services and industry decline, the emission from transport has increased significantly[25]. Passenger cars hence have a considerable potential for reduction of GHG emissions as well as of oil/gas consumption in the EU. To address this issue the EU has specified a target of 95g/km for light duty vehicles for the year 2020[26].

1.5 Structure

Chapter 1 aims to motivate the thesis, and presents the research question. *Chapter 2* contains a theoretical overview of the pieces from which our frame of reference is derived. In *Chapter 3* the methodology, including the research design of the thesis is presented. A presentation of the construction of our model follows in *Chapter 4*. *Chapter 5* starts out with a presentation of the different fuels, engine and vehicle technologies and moves on to the results and comments on the results. In *Chapter 6* different stakeholders and a selection of the most important stakeholder barriers are presented. This part is meant to give an insight into what governments need to assess when creating policies. The second part of the chapter suggests policy options to reduce the most important barriers for our selected tecnologies. Our conclusions and recommendations are summed up in *Chapter 7*. *Chapter 8* is devoted to our suggestions of further research.

2. Theory

In this chapter, we cover the most important theory that we make use of directly or indirectly in our analysis. First we present the life cycle assessment, focusing on a Well-to-Wheel evaluation. This covers the environmental effects of a product's life, from cradle to grave. Then we take a closer look at innovation and technology, and how it can lead to new technologies or the rebirth of existing ones, and the different phases a technology goes through. Next we link this together with the Porter's Five Forces and discover how new innovations can become or improve substitutes, which can affect the degree of rivalry within the industry and even take over the industry. We also introduce the government, which can also influence the competition, by for instance improving substitutes' chances to enter. This brings us further to how the new and existing companies can use mergers and acquisitions to strengthen or maintain their position, depending on which phase they are in, and how companies not only compete, but also cooperate. Lastly we take a closer look at who the stakeholders may be, which barriers they may need to overcome, and how the government can influence the stakeholders and barriers.

2.1 Life Cycle Assessment

Life Cycle analysis, also known as Life Cycle assessment, has gained more attention the last couple of decades and emerged as a response to an increasing environmental awareness amongst the public, industry and governments[27]. A definition is given by Christiansen et al (1995, p. 12): *A Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product system, or activity by identifying and quantitatively or qualitatively describing the energy and materials used, and wastes released to the environment, and to assess the impacts of those energy and materials uses and releases to the environment. The assessment includes the entire life cycle of the product or activity, encompassing extracting and processing raw materials; manufacturing; distribution; use, reuse, maintenance; recycling and final disposal; and all transportations involved. LCA addresses environmental impacts of the system under study in the areas of ecological systems, human health and resource depletion. It does not address economic or social effects.*

The procedures of the life cycle assessment (LCA) are part of the ISO 14000 environmental management standards, and a life cycle assessment is typically carried out in four different phases: **1.** The goal and scope of the study, **2.** The life cycle inventory with data collection, description and verification, **3.** Life cycle impact assessment and **4.** The interpretation of the LCA. However, an LCA may be difficult to calculate accurately, and social implications are usually not accounted for.[28]

2.1.1 Well-to-Wheel

A variant of LCA is the WTW analysis. It shows the specific LCA of the efficiency of fuels used for road transportation[29]. In this model, the WTW is usually split up in well-to-tank (WTT) and tank to wheel (TTW). For an electric vehicle, it would be split up into well-to-plant (WTP) and plant to wheel (PTW). Through a WTW analysis, the total emissions and energy consumption for a vehicle can for instance be calculated, accounting for the feedstock and fuel production, and not just the emissions and consumption during vehicle operation. The overall efficiency of the fuel can also be calculated, providing a better picture than just checking the TTW efficiency. A graphical representation of a WTW LCA is illustrated below:

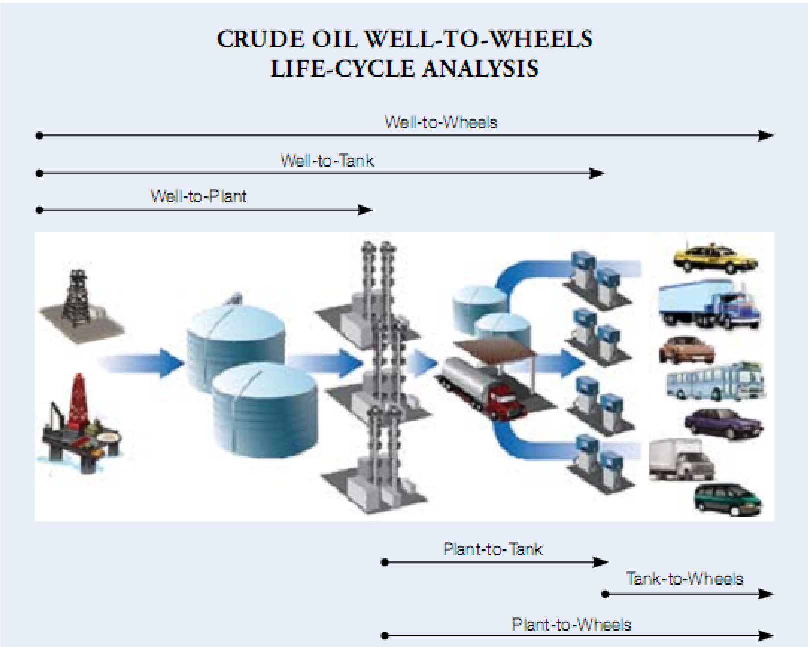


Figure 2-1: Graphical Representation of the Well-to-Wheel Life Cycle Analysis

Source: Kendell, G. 2008: Plugged in- The end of the oil age. WWF-World Wide Fund for Nature

While a life cycle assessment and Well-to-Wheel analysis can be useful in determining the environmental effects and efficiencies of for instance an alternative fuel, it says little about the future potential, which requires a closer look.

2.2 Technology and Innovation

Technology can be defined as all the knowledge, products, processes, tools, methods, and systems employed in the creation of goods or in providing services (Khalil, 2000). One model on how technology might develop is expressed through *Patterns of Dominant Business Model Development*[30]. The four ways are *gradual* development, *continuous* development, *discontinuous* development and *hypercompetitive* development[31].

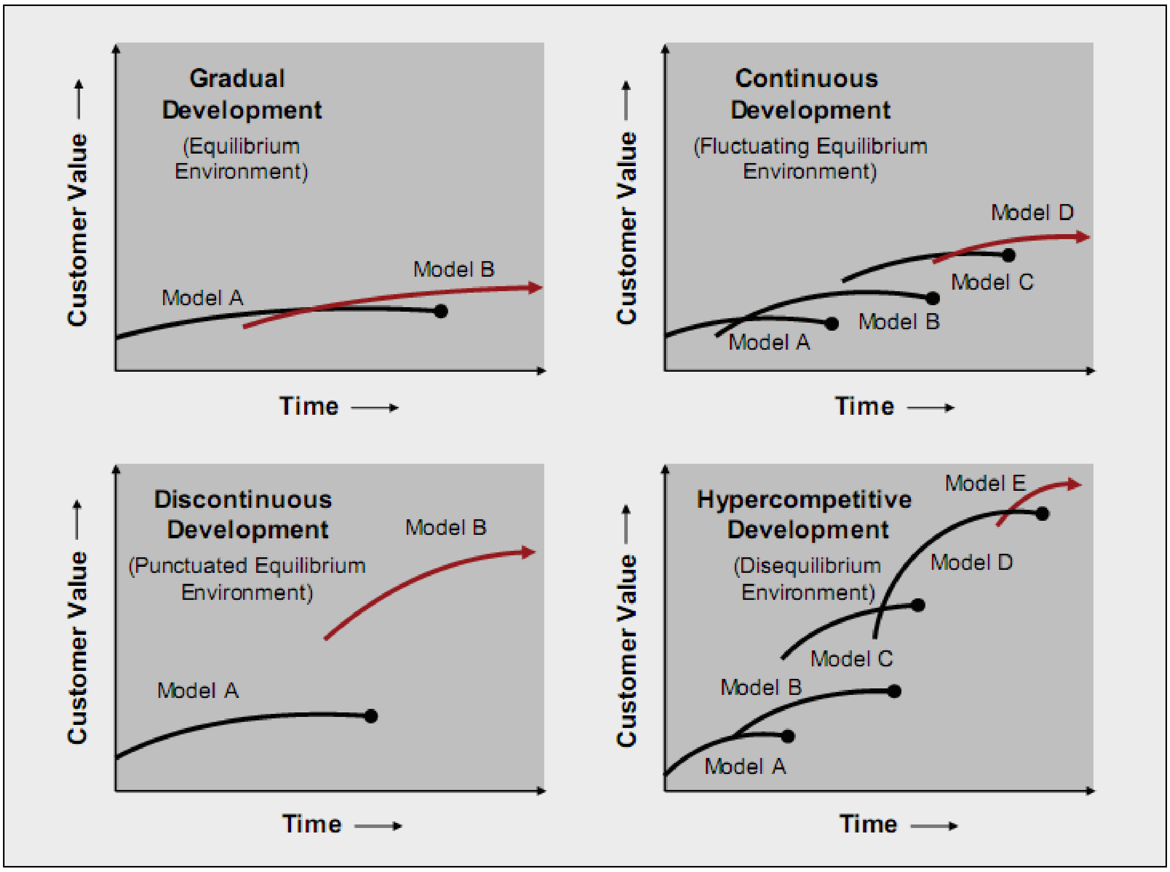


Figure 2-2: Patterns of Dominant Business Model Development

Source: Meyer, R. (2007): Mapping the Mind of the Strategist. A Quantitative Methodology for Measuring the Strategic Beliefs of Executives

A mature industry, such as the car industry, is usually known for gradual development, where the large automakers apparently have been in a stalemate. However, the rise of new competitors from low cost countries (China and India) and small companies with innovative technologies often constitute a threat. In addition, we have new threats like the recent major financial challenges for some of the dominating auto companies, as well as much stricter environmental standards. Those threats may shift the gradual development towards the discontinuous or even hypercompetitive development.

Innovation can be described as *the managed effort of an organization to develop new products or services or new uses for existing products or services* (Griffin, 2001). A definition of *product innovation* is: *a change in the physical characteristics of a product or service or the creation of a new one* (Griffin, 2001). *Process innovation* can be defined as *a change in the way a product or service is manufactured, created, or distributed* (Griffin, 2001). J. Utterback and W. Abernathy have combined these two in their model of *dynamics in industry* (Utterback, 1994). Utterback argues that major innovations for both products and processes share an important relation and follow a general pattern over time, dividing these phases into the *Fluid phase*, where the product innovation is high and process innovation low; the *Transitional phase*, where the product innovation slows down and the process innovation speeds up; before reaching the *Specific phase*, where both innovations slow down.

A third element in this model could be strategic innovation, which can be defined as *the creation of growth strategies, new product categories, services or business models that change the game and generate significant new value for consumers, customers and the corporation (*Palmer, D. & Kaplan, S., 2007). Then we would obtain a model as described by R. Grant (2002). An illustration of a full product life cycle would look like this:

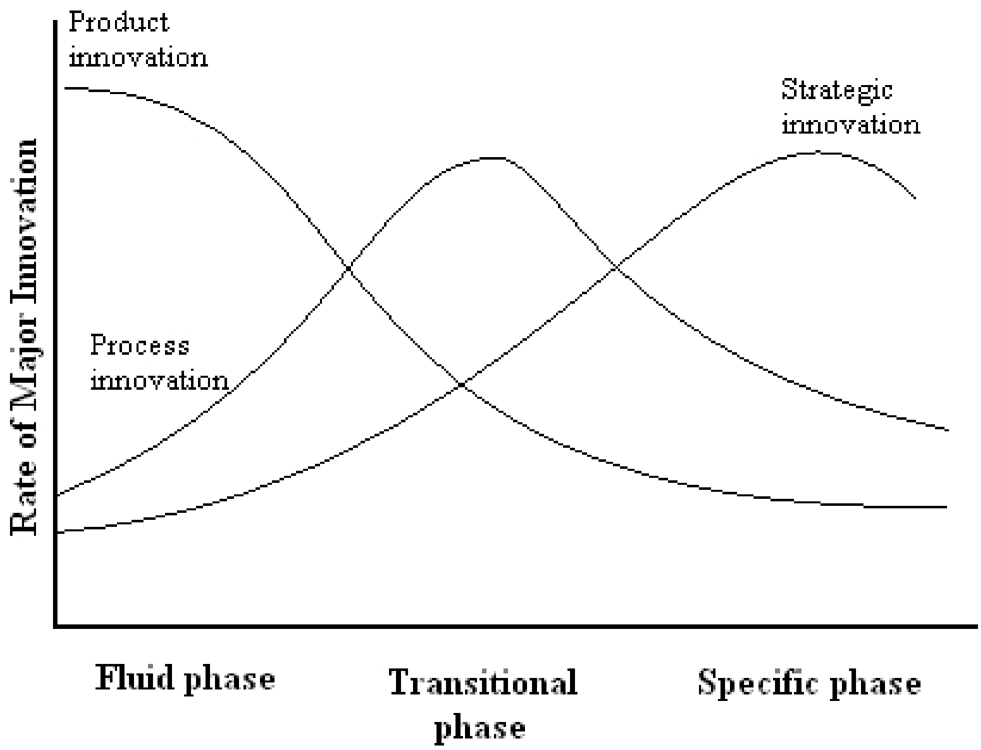


Figure 2-3: Product, Process, and Strategic Innovation over the Life Cycle

Source: Grant, R. (2002) & J. Utterback, (1994)

Here we see how strategic innovation becomes a more important instrument towards the last life cycle phase. Firstly, product innovation has created the competitive technology, and through process innovation the processes have become leaner for large scale production. When the technology or product has become well established, strategic innovation becomes more important where even more of the technologies' potential can be utilised or maintained through strategic key decisions. Now we see how the alternative technologies develop independently, but which forces are influencing it and how do they link together? It is time to take a look at some of the most important forces shaping an industry.

2.3 Porter's Five Forces

To assess the competitive environment within an industry, we can apply Porter's Five Forces. We consider this model to be well known, and will not go into an indepth explanation of the forces. Instead we will present how it can be adapted to suit our area of focus. We will focus on the substitutes, as the AFVs can be considered as substitutes to conventional vehicles running on petrol and diesel. One can argue that AFVs should be categorised as rivals rather than substitutes. However, this depends on how broadly we define the industry boarders in the first step of a Porter analysis. Looking at the vehicle industry through the last 100 years, it seems clear that AFVs have played a minor role in the competitive environment. Although they serve the same purpose, the AFVs make use of different technologies. Further the AFVs have so far struggled to meet the requirements that consumers have had to cars. We therefore choose to look at AFVs as a substitute, and not a rival to the traditional ICEVs. Our focus area is therefore on the substitute's possibility to enter the industry, and how it will affect the rivalry.

The government potentially has great influence over the shaping and reshaping of an industry like the automobile industry. Through the use of incentives, regulative policies, subsidies and taxes they can play a major role facilitating a new technological alternative. By using appropriate policy instruments they can favour the entry of a substitute. If e.g. governments introduce tough regulations that are hard to meet by the industry, they may actually force existing companies to focus on substitute technology, cannibalizing their own market share.

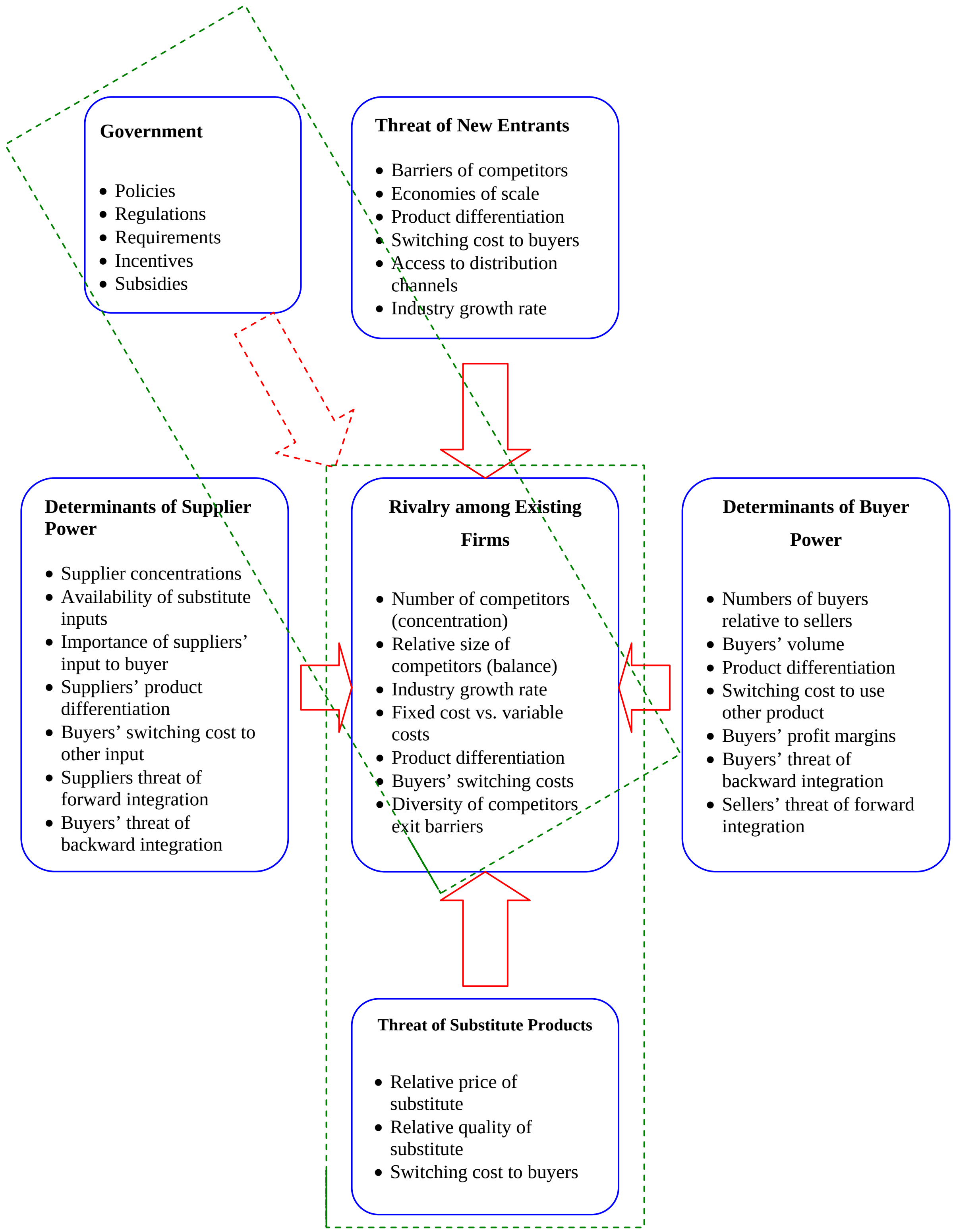


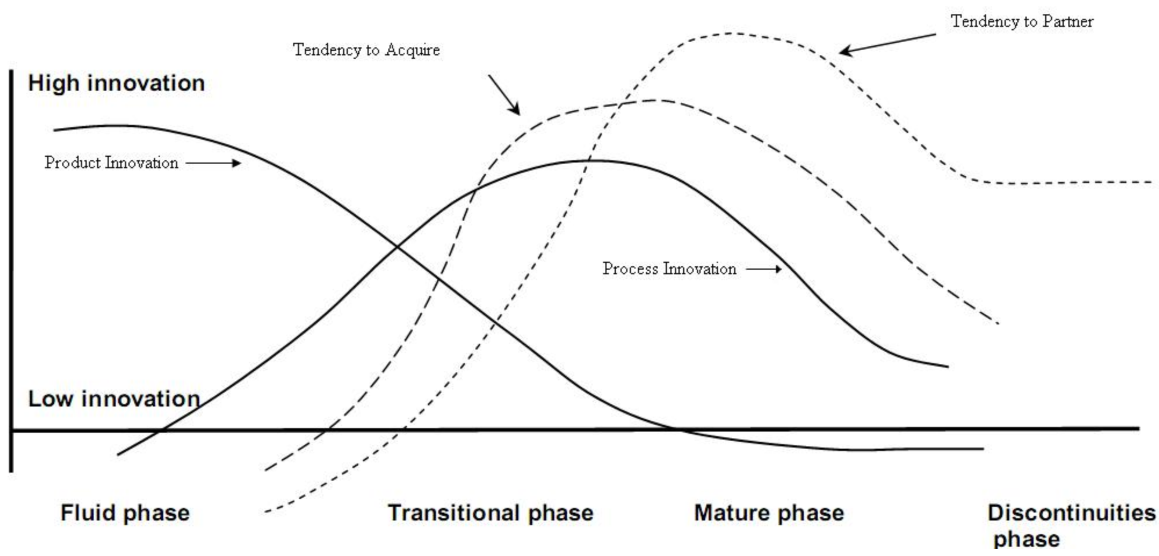
Figure 2-4: Porters Five Forces and the Influence of the Government

Source: Porter, M. E. (1985): *The Five Competitive Forces that Determine Industry Profitability*.

While Porter is mainly focused on competition within an industry, alliances and *co-opetition* are also possible pathways to choose, which we will look closer into.

2.4 Alliances and Acquisitions

Earlier, we presented Utterback's model of dynamics of innovation combined with Grants strategic innovation. Another model that can be considered an evolution of Utterback's model is *the Life Cycle of Alliances and Acquisitions*, developed by Roberts and Liu (2001). This model describes which methods of collaboration are optimal dependent on which phase the technology exists in. In addition to Utterback's three phases, they have added a fourth phase, the *Discontinuities Phase.* This phase is entered when existing technologies are rendered obsolete by the introduction of novel technologies. The barriers in this market are lower, and some markets converge as new technologies emerge (Roberts, Liu, 2001).



SA: Tech Standard	SA: Aggressive Licensing	SA: Join R&D	SA: Market recognition
M&A: Acquisition by established Company	M&A: Acquisition of Competitors	M&A: Horizontal Mergers	M&A : New Markets, Acquire Niche Companies

Figure 2-5: The Life Cycle of Alliances and Acquisitions

Source: Roberts. E. & W. Liu (2001): Ally or Acquire: How Technology Leaders Decide.

Using this model, we see how the tendency to enter into alliances and M&A increases as the technology becomes mature, and that the share of partnerships increases as we move towards the last phase of the cycle. Furthermore we can look at companies that we are not in direct competition with, nor in direct cooperation with, but something in between.

2.5 Co-opetition

The introduced Porter model focuses on competition. With the life cycle model, Roberts and Liu (2001) have shown how the technology phases affect the willingness to merge or form strategic alliances. Looking deeper into this phenomenon, we find an alternative to the five forces model, *the value net*. Brandenburger & Nalebuff (1996) state that in addition to competitors, customers and suppliers, there is a fifth player in the game: the *complementors*. The complementors provide complementary products and services rather than competing ones, and therefore have a positive effect on the value of the company's product or service. In the value net model, we see the players that the company interacts with horizontally, while the players that the company transacts with are positioned vertically. In sum, the value net model as exhibited in Figure 2-6 shows the various roles of the game[32].

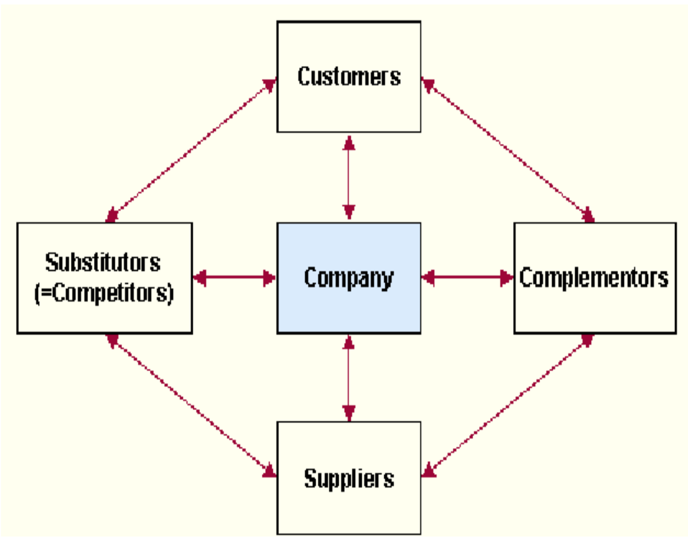


Figure 2-6: The Value net

Source: Brandenburger & Nalebuff (1996) & 12manage.com

In the following chapters we will look further into the role of the government as policy makers, and investigate how they can make use of their policy toolbox to influence the competitive environment.

2.6 Environmental Policy and Industrial Innovation

Environmental regulations have been a source of conflict. They are sometimes associated with costs and burdens, and other times technical progress and innovation. Wallace (1995) argues that the stability of environmental policy and the dialogue between industry and policy-maker are key elements to achieving the desired outcome: *An unstable policy climate causes distrust and pushes industry towards misusing dialogue mechanisms in an attempt to mislead regulators*.

According to Porter (1991), environmental standards do not harm competitiveness. He points out that inducing tough regulations will stimulate innovation and make companies more competitive. Strict environmental standards can, according to Porter, lead to national competitive advantage in two ways.[33]

1. *The first mover strategy*

If a country sets higher environmental standards than other countries, it will force its industry to improve its processes or develop better pollution control equipment. If the other countries subsequently adopt similar tough standards, companies in the country that first applied the standards are likely to dominate the market for the associated technologies, given unrestricted trade.

2. *Stimulating innovation*

Tough environmental standards stimulate industrial innovation. To meet the increased standards companies develop superior technologies and improve corporate performance. These improvements give the companies competitiveness benefits which outweigh the additional costs of adapting to the high standards.

Porter points to the GNP growth in Japan and Germany, where regulations are tough, as proof of this view. There are, however, differences between good and bad regulations. Porter considers regulations that make use of market incentives, take costs into consideration and focus on proactive prevention of pollution, to be good. The bad type entails constraints to technology choice and focus on reactive clean-up measures.

Wallace (1995) argues that environmental policy tends to affect the production process rather than the output and hence that the policy framework influences the competitive environment for the company. This hinders technological innovation: *Uncertainty arising from environmental policy adds to the existing technical and organizational risks of technology development and adaption. Doing more of the same old thing, i.e. not innovating, becomes more attractive* (Wallace, 1995, p. 16). He considers the long term challenges of sustainable development an opportunity for governments to make environmental policy more stable, predictive and less reactive. Cooperation between government and industry that promote flexible, “voluntary” agreements gives firms more responsibility and enhances dialogue, he claims.

We will not go into the companies’ internal dynamics, but rather focus on how government policies can stimulate the automobile industry to invest in environmental innovations. Now we will give a brief overview of which stakeholders the government relates to within the car industry.

2.7 Stakeholders

A stakeholder is defined as a *person, group, organization, or system that affects or can be affected by an organization's actions*. Types of stakeholders include *any organization, governmental entity, or individual that has a stake in or may be impacted by a given approach to environmental regulation, pollution prevention, energy conservation, etc*[34].

The introduction and diffusion of alternative fuel vehicles will have a major impact on society, especially on the transportation sector and its stakeholders. A presentation of each main stakeholder will be given in *chapter 6*. In this section we merely present a figure of the main stakeholders in the automobile industry. We will go further into these issues in *chapter 6* as governments need to be aware of how the stakeholders are affected, and more importantly how they can affect the process of introducing the new technologies. The findings are important when assessing how the interests of the stakeholders should be addressed when developing strategies.

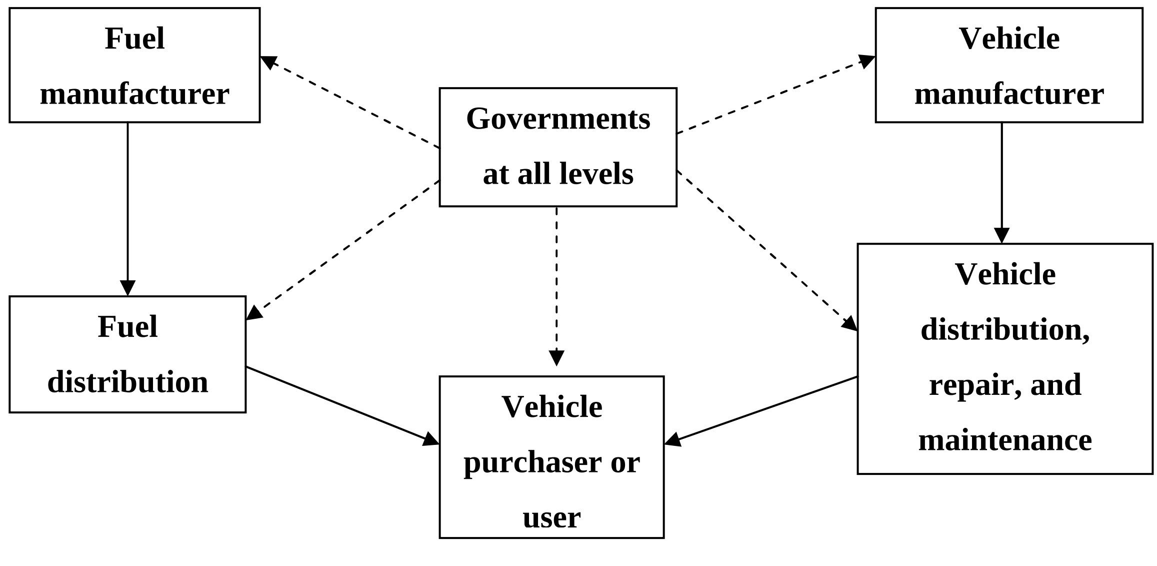


Figure 2-7: Major Stakeholders in the Automobile Industry

Source: Weiss et al (2000)

2.8 Stakeholder Barriers

A *barrier* is defined as *any condition that makes it difficult to make progress or to achieve an objective*[35]. In this case the objective is the market penetration of new technologies and alternative fuels. These alternatives face tough economic, technological and institutional barriers. In this section we will present an overview of barriers for alternative fuel vehicles, AFVs, in relation to the stakeholders introduced in the previous section. We will make use of a selection of these barriers in *chapter 6*. In the following figure, we have taken a closer look into which barriers different stakeholders may experience.

	Stakeholder Barriers		
	Vehicle distribution	**Vehicle purchaser**	**The Government**
Alternative Fuel Vehicles	**New investment (by smaller companies?)** · New service and inspection equipment for new technologies · New fuel facilities for servicing **Component recycling (batteries, Pt group metals, etc.)** **Hiring/training to meet different and higher skill levels for employees** **Distribution cost** **Lack of standards** **Lack of information** **Lack of interest from purchasers**	**Increases in costs and/or decreases in performance/amenities** **Problems with availability and refuelling convenience of new fuels** (especially in early introduction, although first introduction with fleet applications would reduce this problem) **Safety of new vehicle in existing vehicle fleet** **Uncertainty about technology reliability and serviceability** **Interest in pioneering new technology?** **Status** **Fuelling options** **Driving range** **Risk of a low second hand value**	**International and national policy actions on GHG reduction** **Implementation of GHG reduction mandates, if used, by locale, sector, etc.** **Economic impacts/shifts related to new infrastructure investment** · Major investments (offshore FT or methanol production) · Significant investments (debottleneck or expand natural gas or electric infrastructure, build clean methanol infrastructure) **Impacts on competitiveness in global markets** **Safety management** · Highway safety (crashworthiness, fleet size, traffic management) · Fuel safety (new standards for CNG, methanol, H2) · New local safety and zoning requirements for fuelling stations **Environmental stewardship and social equity issues**

Figure 2-8: Overview of Stakeholder Barriers #1

Source: Weiss et al (2000), Romm (2005), Moura et al (2007)

	Stakeholder Barriers		
	Fuel manufacturer	**Fuel distribution**	**Vehicle manufacturer**
Alternative Fuel Vehicles	**Major new offshore investment (FT plants, methanol, LNG?)**	**Significant investments (by smaller companies?)**	**Marketing challenges (cost, performance, amenities)**
	Infrastructure expansion and debottlenecking (CNG, H2, electricity)	· New distribution infrastructure for ultra clean fuels (methanol, FT diesel, etc.)	· Constrained by future government requirements?
	Lack of interest from vehicle manufacturers	· Fuel station storage and transfer facilities for CNG and methanol	**Technological challenges**
	Profit loss	· Reforming, storage and transfer facilities for H2	· Clean diesel technology
	Little support for R&D	**Increased safety concerns**	· Hybrid and Fuel Cell system refinements
	Chicken-and-egg	· H2 facilities including pressure transfer	· Sulfur guards for FC
		· Methanol (corrosion? poisonous? environmental fate?)	· CNG, H2, and battery energy storage improvements
		· CNG pressure transfer	· Advanced control systems to optimise performance
		Longer fuelling times (e.g., CNG, H2)	**Recycling challenges (if driven by government requirements)**
		Loss of fuel business (electricity)	· Alloys, plastics
		Limited fuel stations: chicken and egg problem	· Pt group metals for fuel cells and specialized catalysts in advanced after treatment systems
			New suppliers (more electrical systems, system integrators, fuel cell suppliers, etc.) · Scarce resources i.e. lithium
			On-board fuel storage issues (i.e. limited range)
			Improvements in the competition (better, cleaner gasoline vehicles).
			Incentives and policies implemented have to stable over time
			Critical mass

Figure 2-9: Overview of Stakeholder Barriers #2

Source: Weiss et al (2000), Romm (2005), Moura et al (2007)

Now that we have an overview of the barriers, we will look at how it is possible to overcome these barriers. We will focus on the government and their potential influence.

2.9 Policy Measures

Governments have a variety of policy tools available that can influence the transition of AFVs. We will not elaborate on these policy measures in this chapter, but merely give an overview. Different authors have summed up the possible policy tools and labelled them. The following shows different views on policy options available.

Subvention	**Fiscal Measures**	**Regulation**	**Market stimulation**	**Technology Development**
Investment subsidies	Energy taxation	Technical product standards	Information and counselling	R&D
Tax rebates	Emissions taxation		Product labelling	
Sales subsidies			Public procurement	Demonstration projects

Figure 2-10: Overview of Policy Measures #1

Source: Sandgren (1999)

Conventional Regulatory Approaches	**Economic Instruments**	**Voluntary Agreements**
Emissions standards	Environmental taxes	Industry-based institutions
Performance standards	Tradable emission permits	Maximizing information flow

Figure 2-11: Overview of Policy Measures #2

Source: Wallace (1995)

Market Incentives	**Technology and Vehicle efficiency**	**Overall System Improvement**
Fuel pricing measures	Regulatory standards	Informational measures
Tax incentives and credits for efficient technologies	Voluntary agreements	Investments in R&D
Vehicle taxation		

Figure 2-12: Overview of Policy Measures #3

Source: Steenberghen & Lopez (2006)

This overview of policy measures form a basis, as we go further into detail in *chapter 6* and propose measures that can be used to overcome the stakeholder barriers.

2.10 The Road Ahead

Through the theory presentation above, we have seen how a technology comes to life, which stages it passes through, and how it can be innovated. Furthermore, we have discovered how this technology is part of an industry, with different players involved, and how companies are competing, merging or cooperating together. Lastly we have viewed the stakeholders, which barriers they need to overcome, and especially looked closer into the most influential stakeholder, *the government*, and how it may affect the barriers and rules of the game.

Further, we will apply this theory practically on the case of AFVs and alternative fuels. We will evaluate the technologies separately, but also take into account the existing competition and similarities of the alternative and existing technologies, since the different AFVs may have lower general barriers depending on how large changes an implementation will need. We will look closer into the most important barriers of the best suited technologies, and how the government can use policy options to reduce or overcome them. This will give the answer to our research question: *Which vehicle and fuel technologies are the best options for the European mass market, and how can European governments use policy instruments to facilitate the implementation of these technologies?*

3. Methodology

3.1 Research Design

Saunders (2007) describes research design as *the general plan of how you will go about answering your research question(s). It will contain clear objectives, derived from your research question(s), specify the sources from which you intend to collect data, and consider the constraints that you will inevitably have as well as discussing ethical issues* (Saunders et al, 2007, p.131).

The research approach can be either deductive, in which you develop a hypothesis and design a research strategy to test it, or inductive, in which you will collect data and develop a theory as a result of your analysis (Saunders et al, 2007). We attempt to determine which vehicle technologies are best suited to replace today's ICE, and how policy makers can stimulate the implementation of these technologies. Since part of our research is to develop validate, analyse and use the results of a model we might say that our project uses mixed strategies instead of a completely inductive approach. Based upon a literature review and our own contemplated experiences on the theme, we will develop a model which will be used in order to analyse relevant sets of data. The model will be generated from different partly eclectic sources presented in the literature review. The models fruitfulness will be assessed based upon the conclusions we are able to draw from it. This research strategy has much in common with a generative approach used in grounded theory, where the models are created successively based upon a systematic generation of data (Glaser and Strauss, 1967). A grounded theory approach is, according to Goulding (2002), helpful for research seeking to predict and explain behaviour, emphasizing the development and building of theory. Ghauri and Grønhaug (2005) point out that grounded theory has been criticized as theory-neutral observations are hardly feasible, and what we see when *conducting research is influenced by multiple factors* (Ghauri and Grønhaug, 2005, p. 214). We argue, however, that our research is well-founded in theory, and hence that the criticism to no notable extent applies to our study.

Our study is partly exploratory and partly explanatory. An exploratory study seeks new insights and is particularly useful to clarify your understanding of a problem (Saunders et al, 2007). Brown (2006) claims that *exploratory research tends to tackle new problems on which little or no previous research has been done. This leaves the researcher free to define the scope of research, with the hope that the result will be an extension of existing knowledge* (Brown, 2006, p. 45). The first part of our study invites to an exploratory, comparative approach where we seek to extend the knowledge of different fuel technologies future potential. Ghauri and Grønhaug (2005) identify ability to observe, get information, and construct explanation... as key skill requirements in exploratory research (Ghauri and Grønhaug, 2005, p. 58). We will emphasise that we will see the art of building or corroborating an optimising model as part of an explanatory conceptual scheme. The last part of our study seeks to determine how stakeholder barriers can be overcome, explaining the relationship between lower vehicle emissions and improvement in vehicle technology, and the policies that lead to this. In this process we will make use of the introductory parts on *stakeholders* and *policy measures* from *chapter 2*, as well as the results we are able to acquire from *chapter 5*.

3.2 Data Collection

The model which we will present in part one of the thesis requires a great deal of input data. Within the timeframe of this study it would be difficult to gather sufficient primary data for all the different technologies. Hence we have made use of secondary data. *Secondary data include both raw data and published summaries* (Saunders et al, 2007, p. 246). The main advantage for using secondary data is the saving of resources, in particular time and money (Ghauri and Grønhaug, 2005). In addition, secondary data is more likely to be of higher quality than if you collected it on your own (Stewart and Kamins, 1993). The second part of the thesis is also based on secondary data, merely from published summaries. Considering the potentially higher-quality data and the time frame of our study, we find it advantageous to make use of secondary data. However, when needed we will use primary sources, as we have done to modify parts of the main model used in order to be fit for our European perspective. We have for instance been in contact with the developers of the GREET model in order to calibrate our model.

The data is collected from a variety of sources including books, government publications, dissertations, journal articles, research papers, newspaper articles, encyclopedias, internet articles and a film documentary. We make use of both quantitative and qualitative data.

Quantitative is predominantly used as a synonym for any data collection technique or data analysis procedure that generate or use numerical data. In contrast, qualitative data is used predominantly as a synonym for any data collection technique or data analysis procedure that generate or use non-numerical data (Saunders et al, 2007, p. 145). The use of both qualitative and quantitative techniques is increasingly applied within business and management research (Curran and Blackburn, 2001).

In the first part, quantitative data is collected from different, partly independent sources. The purpose is to get descriptive and objective input data that can help us reduce the threat of biased results. In our study, where we examine competing technologies, there is a chance that data could be biased by stakeholders that benefit from one technology appearing superior to others. Examples could be vehicle manufacturers or environmental protection organizations (NGOs) that might have conflicting interests in the transition of AFVs to the mass market. We seek to present as reliable and objective data as possible in order to make our results valid.

In the last part qualitative data is collected from a variety of articles, research papers and publications. These summaries present different viewpoints on policy making, stakeholder relationships and innovation dynamics, and provide us with theories, findings and lessons from historical viewpoints. The main emphasis of qualitative data is usually on gaining insights and constructing explanations or theory (Ghauri and Grønhaug, 2005).

3.3 Analysis

There are significant distinctions between data produced from qualitative research and data that result from quantitative work. Saunders (2007) highlights three distinct differences. The first states that while quantitative data are based upon meanings derived from numbers, qualitative data are based on meanings expressed through words. Secondly, quantitative data collection results in numerical and standardised data, as opposed to qualitative data that results in non-standardised data requiring classification into categories. The final distinction is related to the analysis, where the quantitative data is analysed through the use of diagrams and statistics, while qualitative data analysis culminates in a conceptualization of a model or theory (Saunders et al, 2007). However, we think that the distinction between data produced from qualitative and quantitative research often is overcommunicated, because many types of quantitative data ultimately are generated from perceptual data

We will make use of our model to generate and analyse quantitative data. Before (and after) running our tests we need to format the data, e.g. converting to metric measurement. We will make use of quantifiable data, which means values are measured numerically as quantities. Quantifiable data are more precise than categorical data and allows a far wider range of statistics (Saunders et al, 2007). To avoid errors and improbable results we have crosschecked the output data. When experiencing surprising results we have tried to find explanations. In the cases where the data has varied from our expectations and we have been unable to account for it, we have made comments in the text. As a safety we have run the test calculations a number of times and continuously improved results as we have gained new insights.

4. Model

To best determine the different technologies' weaknesses, strengths and technological potential, we have developed a four-dimensional model, with five different aspects. For the economical part we have chosen to look at the *payback* period of the different vehicles. This is because we have chosen a consumer perspective regarding the economical part, and payback is an easy way to compare costs for the different models. Regarding efficiency, we have chosen to look at a Well-to-Wheel basis, so that we actually can compare the different technologies over the whole fuel cycle. We have also evaluated the WTW energy consumption, as the production of some types of fuels require a lot of energy, for instance some liquefied gas fuels and biofuels. The WTW greenhouse gas emissions are also examined, covering not only CO_2, but also other GHGs. By comparing the technologies in the near future (2010) and medium term (2020), we can predict the relevant technological improvements. We have chosen a WTW perspective, using an average of the WTW energy and GHG emissions, which are very similar.

4.1 Conseptual Framework

Most of our analysis is based on data and calculations made through use of the *GREET model*. It will calculate the environmental effects, energy usage, technological improvement, and also be an important asset when determining the payback and energy efficiency, for instance when calculating the average mileage and differences between 2010 and 2020.

The GREET model stands for the *Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation*, and was developed by the Argonne National Laboratory in 1999 on behalf of the U.S. Department of Energy[36]. The model we have used is the GREET version 1.8.c.0, which was released on March 23rd, 2009. It looks at the fuel cycle on a WTW basis. GREET version 2.7 would be an option if the vehicle cycle was of importance.

4.2 Presentation of the GREET Model

The GREET model consists of 28 excel sheets, based on the newest data available. 8 sheets cover the inputs, 16 sheets deal with the processing, and 2 sheets handle the graphs. The calculations are easily done with the help of macros, and over 75 vehicles/fuel systems are available[37].

4.3 Presentation of Modifications made

Since the GREET model is developed for the U.S. market, some modifications had to be made. First of all, we decided to replace the U.S. energy mix with the EU energy mix, since the EU energy mix is much cleaner then the U.S. mix (see chapter 5.2.7). We used the 2008 data, illustrated in chapter 5.2.7. One problem that occurred was that hydro power and wind power was not included in the GREET model, but accounted for 24 % of the EU mix. We contacted Andrew Burnham, the *Fuel and Vehicle Systems Analyst* at *Argonne National Laboratory*, who told us that we could put those renewable energies in the “other” section, and that the model would treat it as a renewable energy source. However, this calculation may not be completely correct. While the “plugged in” report by WWF claims that the EU mix is 40 % cleaner than the U.S. mix regarding CO_2 emissions, the difference for BEVs was only 23 % in 2010 and 2020 according to our calculations in the GREET model. However, we have chosen to use the GREET model’s assumptions in this case.

We also had to change the travelled distance in CD (electric) and CS (hybrid) mode. In the model, these numbers were about 45 % in CD, and 55 % in CS. However, with a PHEV distance of 32 km (36 km all-electric range), and an average daily driving distance in Europe of 40-44 km, a 45 % CD share was far too low. We therefore decided that a 75 % electric share would be more accurate. This corresponds well with the PHEV study performed by Argonne, where 79 % could be driven all electric with an average driving distance between 20-30 miles[38]. Either way, the GREET model will make use of a blended CD mode, increasing the vehicle-miles travelled (VMT) and the all-electric range to 36 km. Because of this, the tailpipe emissions will also increase, since the 75 % electric share will be a combination of electricity from the grid and the blended mode, making the tailpipe emissions higher.

Another problem we encountered was that the calculations for fuel efficiency and driving range were based on five year old vehicles, meaning that the 2010 simulation was based on the 2005 model of the car, and the 2020 simulation on the 2015 model. This can be a good estimate if you want to determine the average WTW rates of an entire fleet (due to the average vehicle age of the fleet). We, however, wanted to find out how the 2010 model would compete in 2010 and the 2020 model in 2020. Further we discovered a bug regarding the PHEV. Since the 2005 assumptions of the PHEV was equal to the baseline gasoline vehicle (either due to lack of data or simply an error in the model), it resulted in 2010 numbers far worse than today's PHEVs. Since the macros were password protected, we had to move all data in the CAR_TS sheet one step down for every vehicle, so that 2010 data was moved to 2005, 2015 to 2010 and 2020 to 2015. Also this was done after double-checking with Mr. Burnham at the ANL.

Another change we made in the model was to replace the SI petrol vehicle we used as the baseline of the 2010 calculations with the SIDI petrol vehicle as the 2020 baseline, since we believe that most new cars will have shifted to this technology by then. This makes the technological improvement for the petrol engine appear very good, although it is actually a better model replacing an older technology.

Finally we converted all numbers from American standards to European standards, switching mpg to km/l and btu/mile to Mj/km and g/mile to g/km. However, an aspect to bear in mind is that the vehicles evaluated are based on the American market, meaning that the average vehicle may be larger and less fuel efficient than the predicted European models.

4.4 Explanation and Presentation of the Dimensions

We chose *payback* as the method for covering the **economical** dimension since we wanted to see how the differences in technologies will turn out for the costumers. The reason all vehicles have a positive payback is that they all cost more than the baseline vehicle, and all have lower fuel costs per litre. The payback is calculated on a yearly basis, meaning that a PB of 5 would mean it would take 5 years to get the additional cost back. However, based on independent mileage and years of ownership, vehicles with higher PB then others (e.g. BEV vs. CIDI diesel) may become the best alternative in the long run.

For **efficiency**, we first chose a well-to-wheel *energy efficiency*, which ultimately tells us how much of the energy extracted from the well is left to provide forward thrust. By splitting up the analysis, we see how much is lost during refining and transportation, and how efficient the vehicle itself is. We also looked at the overall *energy usage,* since some energy sources require more energy during production then others, e.g. some biofuels. In addition, it is important not only to have a clean technology, but also an energy efficient technology. As long as we mainly depend on non-renewable energy sources, the total amount of energy we use will decide how much is left for future generations. With regards to the energy efficiency we combined the results from the GREET model with different sources as basis for our calculations. The energy use was solely based on the GREET model. An implication of these choices is that a comparison of the energy efficiency and energy usage may not be completely congruent. Our reason for making this choice is that we, based on multiple sources and our acquired knowledge, consider the GREET numbers in some cases within this dimension to differ too much.

For the **environmental** dimension we chose to look at the total GHG emissions on a WTW basis. The pollution aspect is probably the biggest driving force in the energy and car industry now, and EU has set serious goals for substantial reductions. Since there are green house gases other then CO_2, we chose to look at them as a whole. By performing a WTW, we see how vehicles without tailpipe emissions compare to vehicles with for instance the HEV and BEV.

Lastly we considered **technology improvement** as an important aspect, since the vehicles we compare are in different stages of development and have different potentials. Our comparison based on WTW energy and GHG emission will help to illustrate which technology may improve even after 2020. We chose to look at the whole Well-to-Wheel process, since we believe that a WTW analysis is the most correct comparison of widely different technologies.

5. Different Fuels and Engine Technologies

5.1 Introduction

In this chapter we will present the most relevant fuels and engine technologies for the automobile industry. Based on this evaluation and the results from the GREET model, we will propose some technologies that we will compare using our model. Based on our results, we will present our recommendations. This part will also lay the foundations for the last part of the thesis, where we combine a product mix of the best suited technologies from this part with the suggested policies from the second part in order to recommend a feasible solution.

5.2 Alternative Fuels

5.2.1 Petrol

Petrol has been the main fuel source globally for over 100 years. As with diesel, it is one of the outputs from the distillation of petroleum. The output may vary somewhat according to demand. However, to maintain an efficient process there cannot be too large variations. Because of its high Well-to-Tank efficiency and energy density along with diesel, in addition to generally low oil prices, petrol has been the preferred fuel for personal vehicles. Petrol uses high voltage spark to ignite the engine.

5.2.2 Diesel

The high compression ratio, throttleless operation and easier distillation process makes diesel more efficient than petrol. While diesel car sales today exceed 50 % in Europe[39], its market share in the U.S. is far lower. This is mainly because of stricter particle emission standards in the U.S., different taxation and price differences between petrol and diesel. However, if the U.S. would increase their demand to European levels, synthetic Fischer-Tropsch diesel or biodiesel would have to be produced, since the refining process normally gives higher petrol than diesel output. Already in 2004 the EU exported a surplus of almost 250 000 mte petrol per annum, while importing about the same amount of diesel/gas oil[40]. A disadvantage with diesel, in addition to higher particle emissions (especially NO_x), is its need for additives to avoid becoming too viscose in lower temperatures. Fuel heaters are therefore becoming a standard and short trips during cold weather reduce the diesel engines' advantage over petrol.

5.2.3 Natural Gas

Natural Gas is a mixture of hydrocarbons, mainly methane. It is the most environmental friendly of the fossil fuels. It has a high octane rating, is non-toxic, non-corrosive, and non-carcinogenic, and its properties makes it well suited for an ICE[41]. NG is a non-renewable fossil fuel, extracted from gas wells onshore, offshore or from shales. For the use in cars, it can either be used in compressed form (CNG), or as liquefied natural gas (LNG). The advantage of CNG is that the process is easier than that of transforming NG into LNG, as the main challenge for CNG is pressurising the gas to about 200-220 bar. On the other hand, in order to produce LNG the natural gas must be purified and condensate into liquid, cooled down and stored at about -160 degrees Celsius. This process is more energy intensive and expensive, and makes strict requirements of the vehicle being able to maintain such temperatures. The advantage however, is that more energy can be stored in the same size tanks, since CNG energy density is about 42 % of LNG density[42]. If we emphasise energy usage, emissions and costs, CNG is a better alternative then LNG, although the range of the car will be shorter.

Compared to petrol vehicles, CNG vehicles have lower energy usage and emission rates per km, but the range is also shorter. The infrastructure for CNG vehicles in Europe is also poorly developed. About half of CNG vehicles are located in South America[43].

5.2.4 Liquefied Petroleum Gas

LPG (also known as propane) is synthesised by refining petroleum or wet natural gas. As with NG, it is non-toxic, non-corrosive, free of additives and has a high octane rating. The

Petroleum gas is pressurised at about 22 bars, and in this state the propane becomes liquefied. It has many of the same advantages and disadvantages as natural gas, compared to petrol. It is considered the third most widely used motor fuel in the world[44].

5.2.5 Biomass/Biofuel

General Introduction to Biofuels

Biofuel is defined as *solid, liquid or gaseous fuel obtained from relatively recently lifeless or living biological material and is different from fossil fuels, which are derived from long dead biological material*[45]. The advantage of biofuels is in general that they are considered CO_2 neutral, as they take up and store the same amount of CO_2 during production as they release when combusted. However, the overall climate effect of biofuels may vary immensely among the different types, from negative to positive. Also the cost and area needed may vary widely. Another important issue is that biofuels grown today use space and crops that could have been used for growing food for humans or animals instead.

Biofuels are derived from biomass. In general, it is regarded more economically and environmentally friendly to use biomass directly to generate electricity and heat through large power plants, rather than convert them to biofuels used in cars[46 47 48]. Still the overall net effect of biofuels is controversial, and one study has concluded that the net benefit of 6.9 % biofuel share in EU (before the 10 % share was agreed upon) between 2007 and 2020 would be negative:

	billion €
CO2 benefit	8,6
Employment benefit	1,8
Security of supply benefit	8,0
Total indirect benefit	**18,4**
Production cost difference	**-56,7**
Net benefit	**-38,5**

Figure 5-1: Net Benefit of Biofuels in the EU

Source: [JRC/IPTS 2006] "Cost Benefit Analysis of Selected Biofuels Scenarios", adapted from: Edwards, R. et al. 2008: Biofuels in the European Context: Facts and Uncertainties. European Commission JRC.

First Generation biofuels

First-generation biofuels are biofuels made from sugar, starch, vegetable oil, or animal fats using conventional technology[49] [50]. The fuels we will present in this paper can be produced as first and/or second generation biofuels. The advantage of first generation biofuels is that the technology has come quite far. However, their overall contribution is heavily debated, and the use of potential farmland for food production is the most important issue.

Second Generation Biofuels

Second generation biofuels are produced using non-food crops. Examples are waste biomass, the stalks of wheat, corn, wood, and non-food crops which can be grown in areas unsuited for food crops. Second generation biofuels have the potential of serving a larger part of the vehicle fleet, and with greater environmental effects[51]. The first generation biofuels can also be produced as second generation biofuels, however most of the technologies are at an early stage of development, with issues that need to be dealt with, and it is unlikely that second generation biofuels will be competitive against first generation before 2020[52].

Third Generation Biofuels

Third generation biofuels are made from algae. *Algae are low-input, high-yield feedstock to produce biofuels. It produces 30 times more energy per acre than land crops such as soybeans*[53]. Another advantage is that many of the algae can be grown in salt water instead of taking up land area. Unfortunately, the major problem so far is the high cost, and it is not likely to become a competitive factor in the near future.

Biodiesel

Biodiesel *is produced from oils or fats using transesterification and is a liquid similar in composition to fossil/mineral diesel*[54]. It can be produced by a number of feedstock, both as first and second generation biofuels, and is the most common biofuel in Europe. As car fuel it can either be blended into normal diesel, e.g. B20 (20 % biodiesel) or be used as pure biodiesel, B100. B20 can be used in most diesel cars without problems, while B100 can be used in some diesel cars without modifications. However, B100 may face problems at lower temperatures, and may need fuel line heaters. Biodiesel saves fossil energy and GHG emissions compared to conventional diesel. Biodiesel produced from sunflowers has lower emissions than biodiesel from rape[55].

(Bio)ethanol

Ethanol is the most used biofuel worldwide and has been used for decades in Brazil[56]. In Europe, ethanol has become increasingly popular, for instance in Sweden where many models are capable of running on E85 (85 % ethanol, 15 % petrol). These cars are defined as flexi-fuel vehicles (FFVs). However, most SI cars can use up to 15 % ethanol without modifications. Bioethanol can be produced by *fermentation of sugars derived from wheat, corn, sugar beets, sugar cane, molasses and any sugar or starch that alcoholic beverages can be made from*[57]. Conventional production of ethanol gives small savings in energy and GHG emissions. Second generation ethanol from wood and straw or use of by-products have greater potential. However, in the short term, sugar beet and wheat are the more likely alternatives[58]. The efficiency of ethanol production is also disputed, but several independent sources conclude that ethanol gives approximately 34 % more energy than it takes to produce it[59].

(Bio)methanol

Methanol and biomethanol are alcohols and M85 can be used in FFVs in the same manner as E85. However, it has an energy percentage of only 49 % compared to petrol, worse than ethanol at 64 %[60]. Unfortunately, methanol is extremely corrosive, requiring special materials for delivery and storage, and is considered a worse choice then ethanol[61]. Another disadvantage of methanol compared to ethanol is its toxicity to most organisms. Biomethanol may be produced by organic materials or synthetic gas and is considered an advanced (second generation) biofuel. Methanol may be an alternative source for hydrogen production.

Biogas

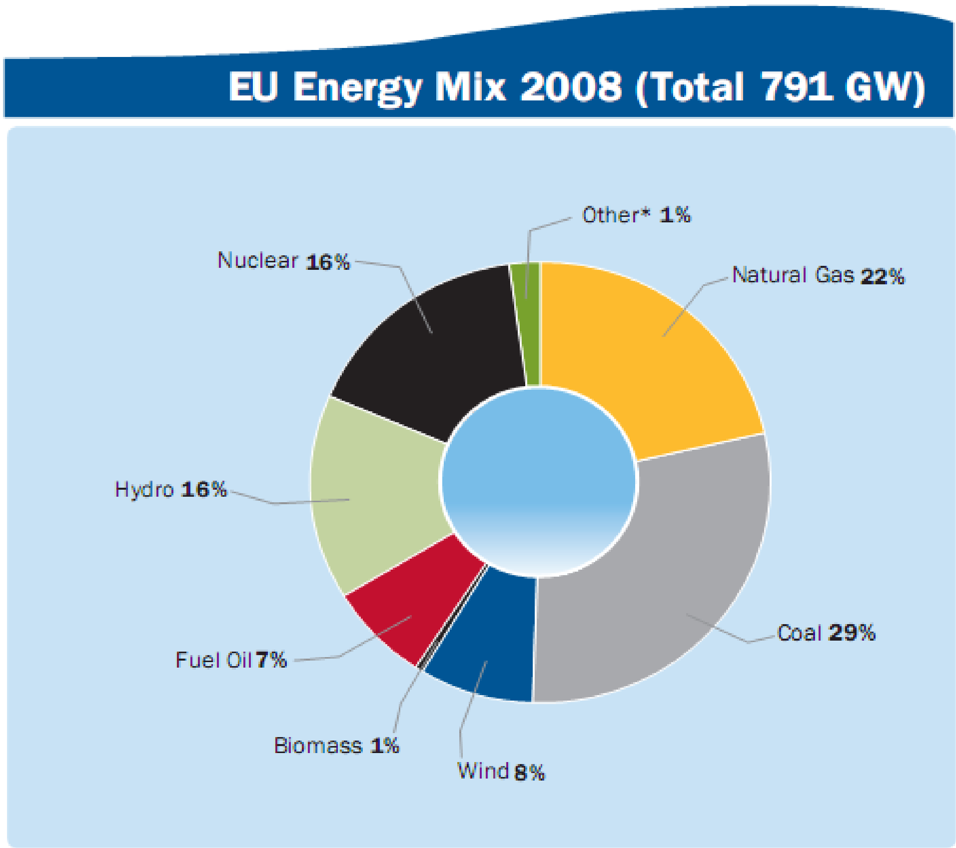
Compressed biogas (CBG) is produced through the process of anaerobic digestion of organic material by anaerobes, or with the biodegradation of waste materials which are fed into anaerobic digesters which yields biogas[62] Biogas has a favourable GHG effect since it makes use of waste materials. Through the use of wet manure it may have an extremely positive effect, potentially reducing WTW GHGs with about 150 g CO_2 equivalents per km since it stops the methane from reaching the atmosphere[63]. However, to be economical, the purification and compression needs large power plants, which would need the equivalent of 8000 cows or 50 000 pigs and 20 % organic waste within a 10-20 km distance, limiting the potential for large scale production[64].

5.2.6 Hydrogen

Hydrogen is the most abundant resource in the universe. However, hydrogen in its natural form is rarely found, so it has to be produced through other energy sources. Converting one form of energy to another always involves a loss of energy, and this is one of the major drawbacks of using hydrogen as a fuel. An advantage of hydrogen is that the only by-product of hydrogen in cars is pure water. Hydrogen can be produced in different ways. These methods include natural gas to synthesis gas reforming, renewable electrolysis, gasification from coal or biomass, renewable liquid reforming, nuclear high-temperature electrolysis, high-temperature thermochemical water-splitting, photobiological or photoelectrochemical[65]. Most of these technologies are young, expensive and with low efficiencies, and in the near future the reformation of NG into synthesis gas will be the dominant source of hydrogen production. Hydrogen can either be stored or used as compressed hydrogen or as liquefied hydrogen. As with CNG and LNG, liquefaction allows for larger amounts to be stored in equally large space, but is less energy efficient and more expensive. Since hydrogen has the lowest volumetric density of all elements, it needs a very large tank even though it is compressed at about 350 bars (5000 psi)[66]. Compression at 700 bars is also an option. Hydrogen can either be used directly in IC engines, or in fuel cells, which is a much more efficient, but currently expensive option. Although hydrogen from NG already is environmentally friendly and fuel efficient, it is unlikely to be competitive on price before earliest in 2020.

5.2.7 Electricity

Electricity from the grid can also be used as a source of fuel. As with hydrogen, use of electricity in cars through batteries, gives no tailpipe emissions. However, electricity from fossil fuels creates emissions, and although electricity in cars is very energy efficient, the Well-to-Plant efficiency is much lower than direct use of fossil fuels in cars. As the electricity grid production becomes cleaner in the future, the emissions will decline. The use of most renewable energy sources today amounts to a very small part of the total energy production, and the production must multiply many times before constituting a substantial amount of the energy mix. A good thing is that the European electricity mix is cleaner than for instance the American electricity mix, releasing 619 g/CO2/kWh compared to 1037 g/C02/kWh in 2004[67]. An overview of the European energy mix in 2008 is given below:



*Geothermal, peat and waste

Figure 5-2: EU Energy Mix 2008

Source: EWEA and Platts PowerVision

5.2.8 Overview of Selected Fuels

A comparison and summarization of the most important fuel types are given below.

	Gasoline	Diesel	Biodiesel	CNG	Electricity	Ethanol	Hydrogen	LNG	LPG	Methanol
Chemical Structure	C_4 to C_{12}	C_8 to C_{25}	Methyl esters of C_{12} to C_{22} fatty acids	CH_4 (83-99%), $_2H_6$ (1-13%)	N/A	CH_3CH_2OH	H_2	CH_4	C_3H_8 (majority) and C_4H_{10} (minority)	CH_3OH
Main Fuel Source	Crude Oil	Crude Oil	Fats and oils from sources such as soy beans, waste cooking oil, animal fats, and rapeseed	Underground reserves	Coal, nuclear, natural gas, hydroelctric, and small percentages of wind and solar.	Corn, grains, or agricultural waste (cellulose)	Natural gas, methanol, and electrolysis of water.	Underground reserves	A by-product of petroleum refining or natural gas processing	Natural gas, coal, or, woody biomass
Energy Content (LHV)	116,090 Btu/gal (g)	128,450 Btu/gal (g)	119,550 Btu/gal for B100 (g)	20,268 Btu/lb (g) [3]	3,414 Btu/kWh	76,330 Btu/gal for E100 (g)	51,585 Btu/lb (g) [3]	74,720 Btu/gal (g)	84,950 Btu/gal (g)	57,250 Btu/gal (g)
Energy Content (HHV)	124,340 Btu/gal (g)	137,380 Btu/gal (g)	127,960 Btu/gal for B100 (g)	22,453 Btu/lb (g) [3]	3,414 Btu/kWh	84,530 Btu/gal for E100 (g)	61,013 Btu/lb (g) [3]	84,820 Btu/gal (g)	91,410 Btu/gal (g)	65,200 Btu/gal (g)
Energy Comparison (percent of gasoline energy) [2]	100%	111%	B100 has 103% the energy of gasoline or 93% of diesel. B20 has 109% of gasoline or 99% of diesel	1 lb CNG has 17.5% the energy of 1 gal gasoline [3].	1 kWh electricity contains 3% of the energy in 1 gal gas	E100 contains 66%, E85 contains 72% to 77% [4]	1lb H2 has 44.4% the energy in 1 gal gasoline [3]	64%	73%	49%
Physical State	Liquid	Liquid	Liquid	Compressed Gas	Electricity	Liquid	Compressed Gas or Liquid	Cryogenic Liquid	Pressurized Liquid	Liquid

Figure 5-3: Summarization of Different Fuel Types

Source: http://www.afdc.energy.gov/afdc/fuels/properties.html Notes and Sources: Sources are denoted by letter and notes are denoted by number. http://www.afdc.energy.gov/afdc/fuels/properties_notes.html

5.3 Engine and Vehicle Technologies

5.3.1 The Internal Combustion Engine

The ICE *is an engine in which the combustion of a fuel occurs with an oxidiser (usually air) in a combustion chamber. In an internal combustion engine the expansion of the high temperature and pressure gases, that are produced by the combustion, directly apply force to a movable component of the engine, such as the pistons or turbine blades and by moving it over a distance, generate useful mechanical energy*[68]. The IC engine can work with a range of different fuel types, like petrol, diesel, LPG, CNG, ethanol, methanol, hydrogen, and dimethyl ether (DME). The principles have basically been unchanged since the end of the 19th century. Although the IC principle remains the same, different types of engines work with different types of fuels. The IC engine has dominated the vehicle fleet due to its reliability, range, horse power, and normally cheap fuel. However, the ICE has potential drawbacks compared to alternative engines, especially its low Tank-to-Wheel energy efficiency (much of the energy is wasted on heat generation rather then moving the wheels), pollution and noise.

Spark Ignition

The SI vehicle is the standard petrol vehicle. It can also run on LPG, CNG, ethanol, methanol and hydrogen. The normal SI vehicle is the four-stroke “Otto cycle” engine. In this engine, the fuel-air mixture initiating the combustion is ignited by a spark, thus the name. In a conventional spark ignition engine, the fuel and air is mixed before compression[69].

Spark Ignition Direct Injection

In the SIDI, *the petrol is highly pressurised, and injected via a common rail fuel line directly into the combustion chamber of each cylinder*[70]. The advantage compared to the SI, is an increased fuel economy and a high power input. This technology is still fairly new, and is expected to take over the market in the future.

Other Fuel Types on Spark Ignition

CNG, LNG and LPG can all run on standard SI IC engines. Normally these cars will be bi-fuel cars, able to run on either petrol or natural gas/propane, since the infrastructure of these gases is far less developed. Hydrogen can run on a slightly modified ICE, uses the same spark ignition as petrol engines and would for practical reasons be a bi-fuel car with independent fuel tanks. However, it also gets the same low Tank-to-Wheels efficiency, and is therefore a poor alternative to hydrogen powered fuel cells, if hydrogen is competitive in the future.

Compression Ignition

The diesel engine operates using the diesel cycle. It *uses the heat of compression to initiate ignition to burn the fuel, which is injected into the combustion chamber during the final stage of compression*[71]. The main advantage with the diesel engine compared to the petrol engine, is the CI IC engine’s higher efficiency, resulting in higher mileage and lower total emissions. The engines also generally last longer and generate more power on lower rational speed, but the acceleration and maximum rotation is less than that of the petrol ICE.

Compression Ignition Direct Injection

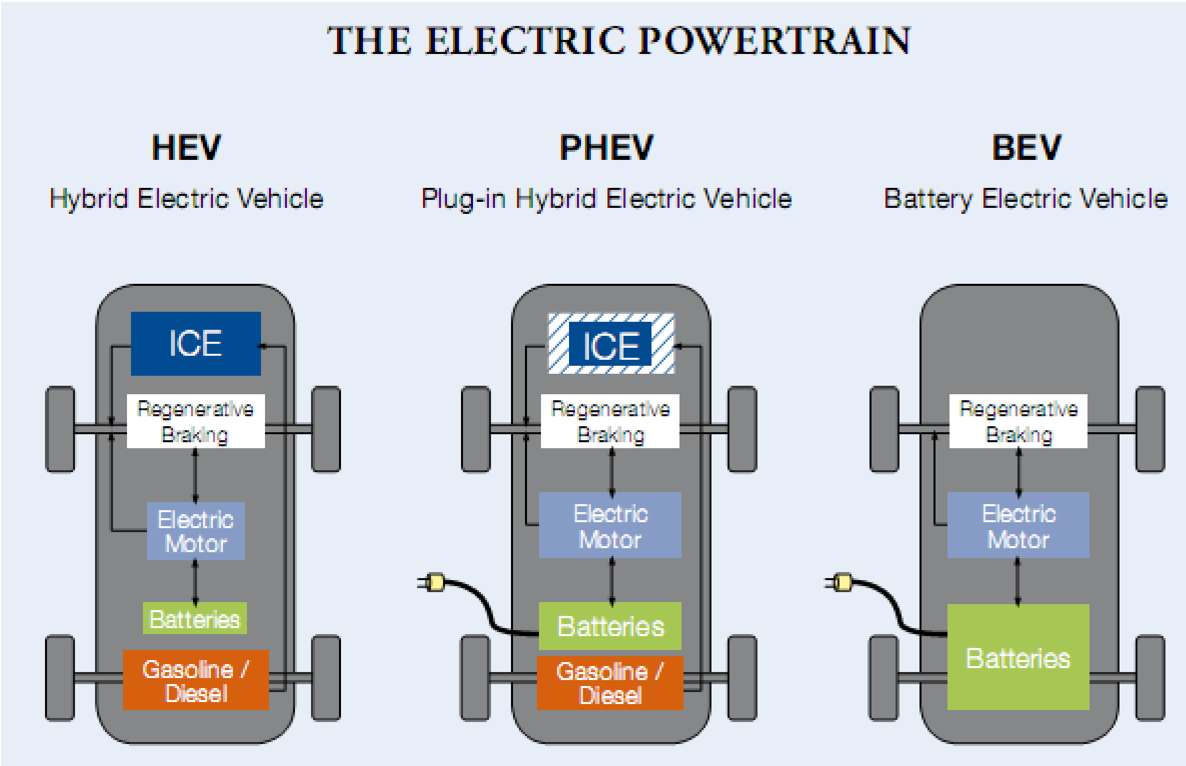
Also the diesel engine makes use of direct injection, like in the SIDI engine, providing an even better fuel efficiency.

5.3.2 Flexible-Fuel Vehicle

A flexible-fuel vehicle is an ICEV with the potential to run on more than one fuel type within the same fuel tank, differencing them from bi-fuel vehicles with separate fuel tanks which run on one fuel at the time. *Flexi-fuel engines are capable of burning any proportion of the resulting blend in the combustion chamber as fuel injection and spark timing are adjusted automatically according to the actual blend detected by electronic sensors*[72]. These engines mostly run on ethanol or petrol, and are most common in the U.S. and Brazil.

5.3.3 The Electric Powertrain

The electric vehicle gets its power from an electric motor where the energy is stored in batteries. We will look at the battery electric vehicle, and a combination between electric and ICE; the Hybrid EV and Plug-in hybrid EV.



The HEV essentially derives all of its motive energy from the combustion of hydrocarbon fuels onboard; regenerative braking offers potentially significant but incremental energy efficiency gains. The alternative PHEV and BEV variants derive up to one hundred percent of their motive energy from batteries, which are charged by connecting to the electricity grid when stationary, and similarly benefit from regenerative braking.

Figure 5-4: Comparison of Different Electric Powertrain Configurations.

Source: Kendall, G. 2008: Plugged in- The end of the oil age. WWF-World Wide Fund for Nature

Variations of the electric powertrains can be classified in different ways; we have adopted the five group classification of Deutsche Bank:

- **Micro hybrid:** Micro hybrid systems only stop the engine during idle (while still running heat, A/C, etc.), and instantly start it when the vehicle is required to move, providing efficiency gains in the 5%-10% range.
- **Mild hybrid:** Mild hybrids stop the engine during idle and provide additional power during vehicle acceleration, providing fuel efficiency gains in the 10%-20% range.
- **Full hybrid:** Full hybrids provide enough power for limited levels of autonomous driving at slow speeds, and they offer efficiency gains ranging from 25%-40%.
- **Plug-In hybrid:** Plug-in hybrids, which will begin rolling out in 2010, will allow for vehicles to store enough electricity (from an overnight charge) for the first tens of miles to be driven solely on electrical power. Beyond this range, they function like full hybrids.
- **Electric vehicle:** Electric vehicles do not have dual mechanical and electrical powertrains. 100% of their propulsion comes from electric motors, energized by electricity stored in batteries.

Figure 4: Hybrid fuel efficiency gains and costs

	Battery Cost	Non Battery Incremental Cost		Total Cost	Fuel Efficiency Gain
Micro Hybrid	$100	$500		$600	5% - 10%
Mild Hybrid	$600	$1,000		$1,600	10% - 20%
Full Hybrid	$1,200	$1,000		$2,200	25% - 40%
PHEV	$6,000	$2,000		$8,000	40% - 65%
Electric Vehicle	$11,000	$0	*	$11,000	100%

* = Incremental costs offset by elimination of ICE and other components

Source: Deutsche Bank

Figure 5-5: Categorisation and Description of Different Electric Powertrains.

Source: Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

In the sections below, we will describe the different technologies.

5.3.4 Hybrid Electric Vehicle

Introduction to the Hybrid Technology

The HEV is about as old as the EV, with models produced already in 1899 and mass produced for a couple of years from 1915[73]. It once again became a factor in the vehicle market after the Toyota Prius introduction in the Japanese market in 1997 and world release in 2001[74]. Modern hybrids switch off the engines during idle, and run only on the electric motor during low speeds, while for instance re-generative braking charges the battery.

Hybrid Variations

In addition to the five group classifications, the technologies inside the HEV may also be different and have different advantages and disadvantages. We can basically distinguish between a series hybrid, a parallel hybrid and a series/parallel hybrid combo[75].

In a *series hybrid,* the petrol engine is not directly connected to the wheels, but used to power the electric generator which powers the wheels (in a series), or charges the battery. The downside is that the performance is low, since only the electric motor powers the wheels.[76] These hybrids will work in *blended mode.*

In a *parallel hybrid*, both the engine and the electric motor can power the wheels, independently or consequently. The power flows to the wheels in parallel. This allows for increased performance, but while the engine is running the batteries cannot be charged, thus reducing energy efficiency. [77]

A *series/parallel hybrid* combines these two systems, maximising fuel efficiency and performance. Both the engine and electric motor can drive the vehicle and the battery can be charged while driving. However, the cost for this combination is higher. [78]

Plug-In Hybrid Electric Vehicle

The PHEV is the newest hybrid technology, allowing for the highest fuel efficiencies while still maintaining the range advantage of a petrol car. They can be charged by the electrical grid using normal wall outlets or higher voltage outlets for faster charging. This means that it can work as an electric vehicle as long as the battery has sufficient power, for instance above 30 per cent, achieving the same high fuel efficiency and economy of a BEV. When a PHEV is operating as a BEV, it is called *charge-depleting mode* (CD-mode). If the battery goes below the threshold of for instance 30 % (will vary according to range potential), it will start working as a normal HEV in a *charge-sustaining mode* (CS-mode), with similar fuel efficiency as a full hybrid. A trip combining these modes would be referred to as running in *mixed mode*.[79] The PHEV may vary on driving ranges. PHEV-20 (or PHEV32km) implies that the vehicle can run 20 miles (32 km) using only the battery, while a PHEV-60 can run 60 miles (96 km) on the battery. With the existing technology there is a trade-off between price, weight and charging time of the vehicle and the range. A short range PHEV may be preferable to a long range PHEV depending on individual driving patterns and future technology improvement. Although the first modern PHEV entered the market in 2003 the technology so far is young compared to normal hybrids. Not until 2010 the PHEV is expected to start gaining noticeable market shares, for instance with the planned introduction of the Chevrolet Volt.

Hybrid/Fuel Combinations

Hybrids can basically be made in any combination of SI, CI or FC vehicles. Hybrids may not be the ultimate solution since two-engine technologies mean more weight and are more expensive than one. Still they offer a good solution as long as the new technologies cannot fulfil all necessary requirements by its own, for instance sufficient range or infrastructure. It is therefore believed that hybrids may get a substantial market share in the coming years. The first mass produced fuel cell vehicles based on for instance hydrogen, may also very well be a hybrid. Developing hydrogen infrastructure will take time and considerable investments before possibly reaching the acceptable penetration rate.

5.3.5 Battery Electric Vehicle

The BEV is about as old as the ICE, and in the early 20th century, electric vehicles competed with the ICE vehicles to become the dominant technology. Because of the cheap, easy accessible oil of the time, the low-cost ICE mass production (T-Ford), the increase in power, and the distance advantage of the ICE as cities became interconnected, the BEV sales peaked in 1912 and rapidly lost ground[80]. An electric powertrain works by bringing the energy from the batteries to the motor with the help of a controller. This can either be a DC or AC controller, where DC is the cheaper one today. An illustration of how it works is shown below:

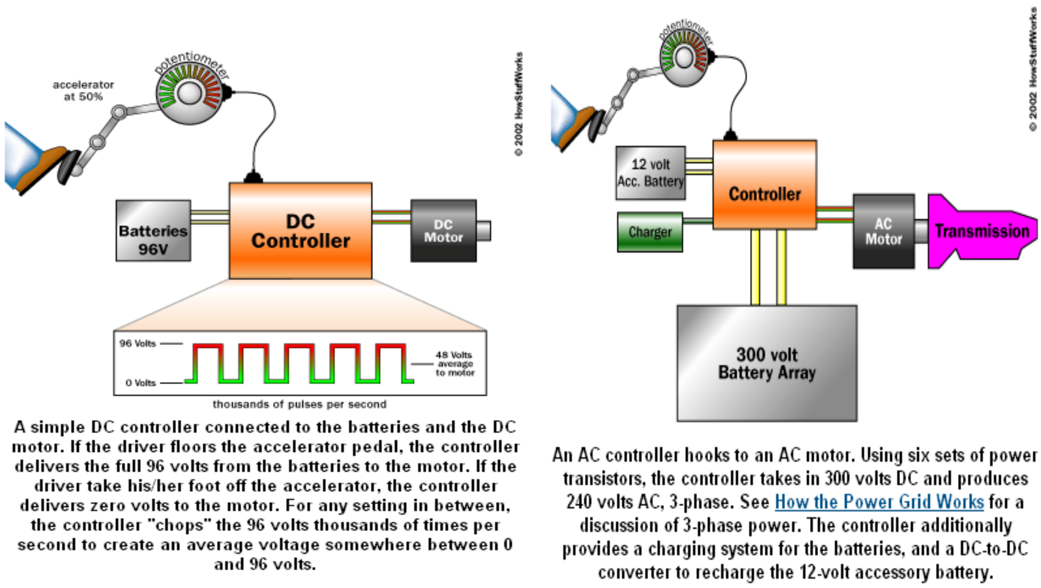


Figure 5-6: Illustration of the AC and DC Controller

Source: How Electric Cars Work, http://auto.howstuffworks.com/fuel-efficiency/vehicles/electric-car2.htm

The main advantage of the electric powertrain compared to the petrol engine, is that it is silent, much more energy efficient on a Battery-to-Wheel basis, without tail-pipe emissions and is much cheaper in use per km. However, the battery packs today are heavy, expensive, have limited range and long charging times, and will probably need to be replaced during the average lifetime of the electric vehicle.

The key for making electric cars competitive is therefore the battery technology. Lead acid batteries have normally been used earlier. However, in the last couple of years, the nickel metal hybrid (NiMH) has become the standard of modern cars, and lithium Ion (the same technology we use in i.e. cell phone and laptop batteries) are by most experts expected to slowly take over the market. A comparison of the battery technologies is shown below:

Figure 14: Battery energy density and cost comparison

Energy Density	Cost	Charge Cycles
Lead Acid 30-40 wh/kg*	Eur/wh 0.15	500-1000
NiCd 40+*	Eur/wh 0.20	1000-2000
NiMH 71 WH/kg*	Eur/wh 0.60	1000-2000
Li Ion 105-170 wh/kg**	Eur/wh 0.3-0.4	7000+

Figure 5-7: Energy Density and Cost Comparison of Battery Technologies

Source: Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

The advantage of the lithium Ion is the superior energy density, higher charge cycles and it being able to recharge half-full batteries. They also have the potential to significantly reduce the charging time. Prototypes of new lithium Ion technology in cell phones can be fully charged in just 10 seconds, allowing for BEV vehicles to be fully charged in just 5 minutes (through high voltage grid), without degrading by repeated charging and discharging[81]. Other fast charging technologies include Toshibas SCiB batteries[82], and a common three-phase 400 Volt adapter (that has the same potential) which major car manufacturers recently agreed upon as a standard[83]. The potential of replacing batteries as fast as refuelling is already shown by the Australian company "Better Place", but building sufficient infrastructure will take time and major investments, as well as causing restrictions for the car layout[84]. The biggest problem with the lithium Ion so far is the costs, however, as the figure illustrates, the costs are rapidly decreasing while the technology is improving, so the outlook is bright.

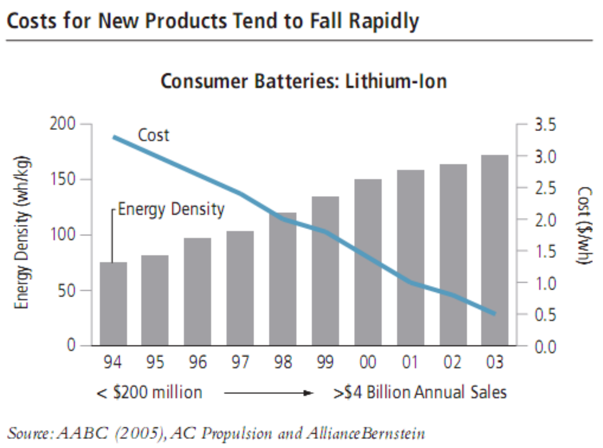


Figure 5-8: Cost and Density Development of the Li Ion Battery

Source: Alliance Bernstein (2006)

Another problem may be the supply side keeping the costs high. Replacing the existing annual production of cars (60 million) with PHEV-20s (20 mile electric range), would require a much larger production as the figure below shows.

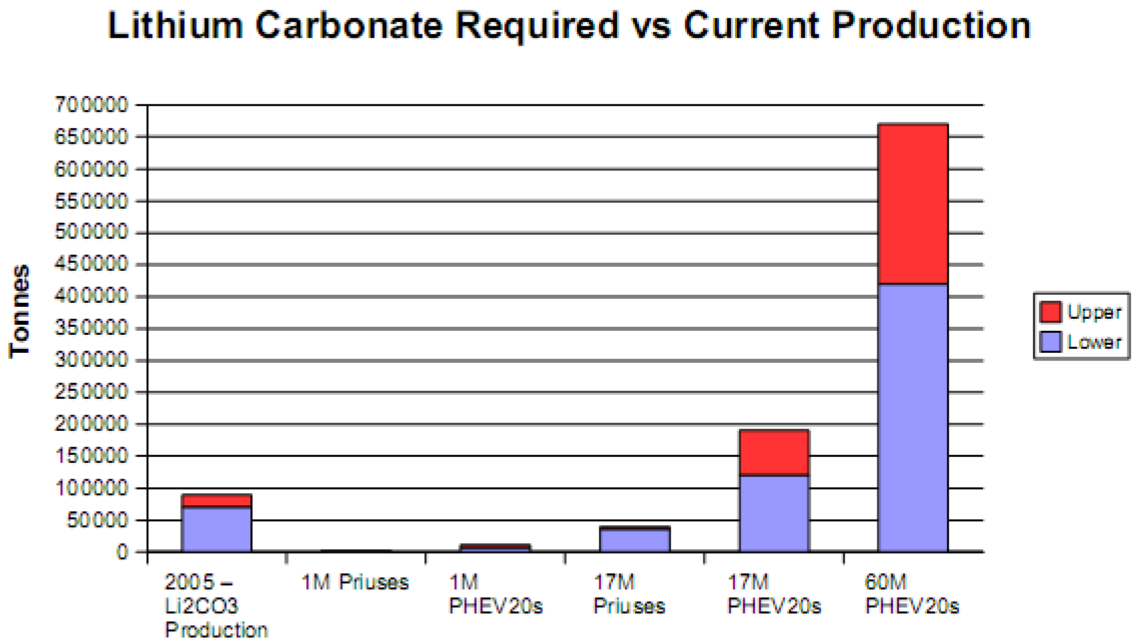


Figure 5-9: Lithium Carbonate Required vs. Current Production

Source: Tahil, W. 2007. The Trouble with Lithium. Implications of Future PHEV Production for Lithium Demand. Meridian International Research

To equip the whole automobile fleet with a 10 KW battery would require 35 % of the known lithium carbonate reserves. A pure EV would require at least a 30 KW[85] battery. However, we expect markets to adapt to such a challenge, and lithium may be outperformed by another technology in the future. Lithium is recyclable, but will still require a large increase in production. In theory, lithium may be possible to extract from sea water in the far future, making it a practically inexhaustible resource. Sea water is estimated to contain 230 billion tonnes of lithium, 4M times more than *Global Lithium Salt Reserve Base estimated at 58MT of* Li_2CO_3[86].

5.3.6 Fuel Cell

The Technology

A fuel cell works much the same way as a battery, and the power running the wheels is electric. The difference is that a fuel cell does not wear down or need recharging, but produces energy as long as new fuel is supplied[87]. If the fuel cell has a *fuel reformer*, it can run on any hydrocarbon fuel. However, because energy usually is more efficient to produce in large power plants, and since pure hydrogen makes the cleanest chemical reaction, hydrogen is the preferred input and hence what we will focus on.

The Hydrogen Fuel Cell

A fuel cell consists of two electrodes sandwiched around electrolyte. Hydrogen is fuelled from the anode side and an oxidant, like oxygen from the air (or as pure oxygen) comes from the cathode side. The hydrogen passes over one electrode and oxygen over the other, generating electricity, water and heat. The chemical process can be expressed as follows: $2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat.

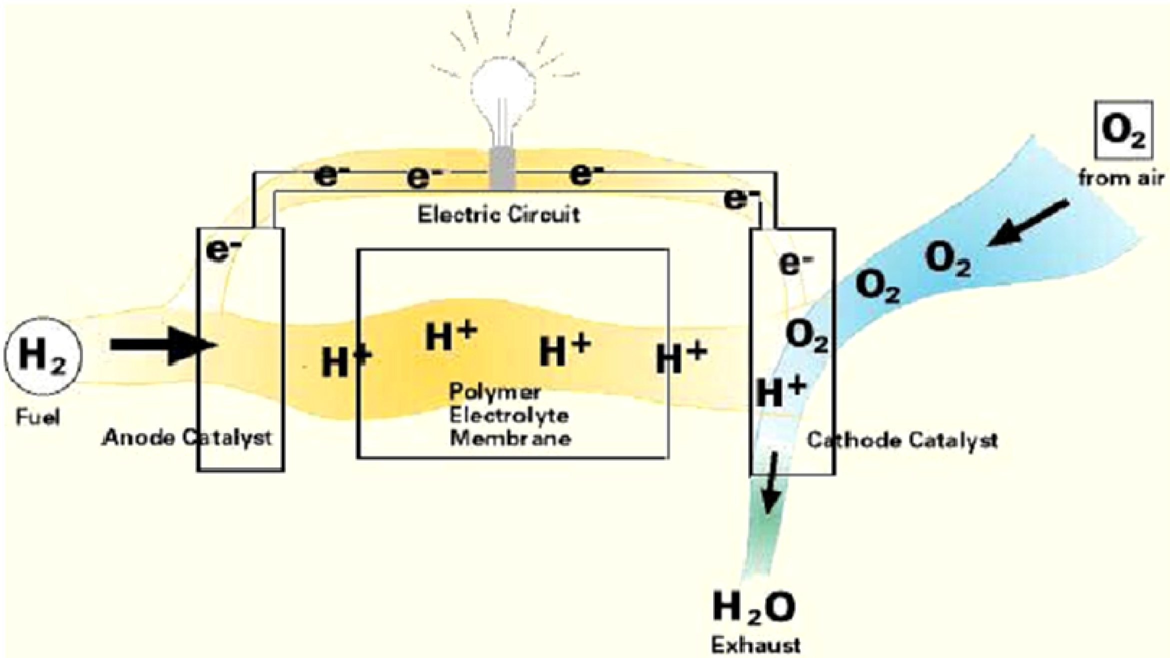


Figure 5-10: The Basics of a Hydrogen Fuel Cell

Source: Fuel cell basics, how they work, http://www.fuelcells.org/basics/how.html

The biggest problem with fuel cells today is the price. It is still a fairly new technology and the prices so far are not competitive. However, car companies believe that mass production of fuel cells and FCV may start in 2015, and start to penetrate the market around 2020. The cost estimates are very difficult to predict and vary widely. The U.S. DOE has earlier set a target cost of $30/kW allowing a 100 kW fuel cell to be produced for $3000[88 89]. One company (Ballard) claimed to have reduced the projected high volume costs to $73/ kW[90] in 2005, another source claims that the actual cost was $4000/kW in 2004[91]. It is difficult to predict when this target will be reached as FC cost and production data are limited and based on predicted mass production. One problem is reducing the need of platinum, an extremely expensive material, in the fuel cells. If fuel cell technologies are to be competitive, further research must be maintained. In the next government budget, the U.S. have announced they will cut subsidies from 168 to 68 million dollar, stating that they doubt that we will become a hydrogen economy within the next 10, 15, 20 years[92].

As for many other new alternative technologies, there is a wide range of competing fuel cell technologies, and it is difficult to pick a potential winner. At the moment it looks as if the proton exchange membrane (PEM) fuel cell may be ahead since it in contrast to some of its rival technologies has the advantage of fairly low operating temperatures, allowing for a quick start[93]. This fuel cell has a theoretical energy efficiency of 64 % according to the IEA[94].

5.3.7 Other Technologies

There are also other future technologies that may be worth mentioning but not going into further details about. Companies like MDI in Luxembourg and Tata in India are working on technologies running on compressed air. Although the technology has a great tailpipe emissions potential, the power and range is a problem and the compression itself needs energy.

Another possibility is liquefied nitrogen fuelled cars. Also here we will have zero tailpipe emission, and the power used to produce liquefied nitrogen can be retrieved from the electric grid. LNFs can also make use of the ICE technology, but is unlikely to be a mass produced alternative in the medium term.

Solar-powered cars is also a possibility, but it creates far too little power, hence solar power will be more effective contributing directly to the electricity grid through large power plants.[95]

5.3.8 Overview Well-to-Wheels Pathways

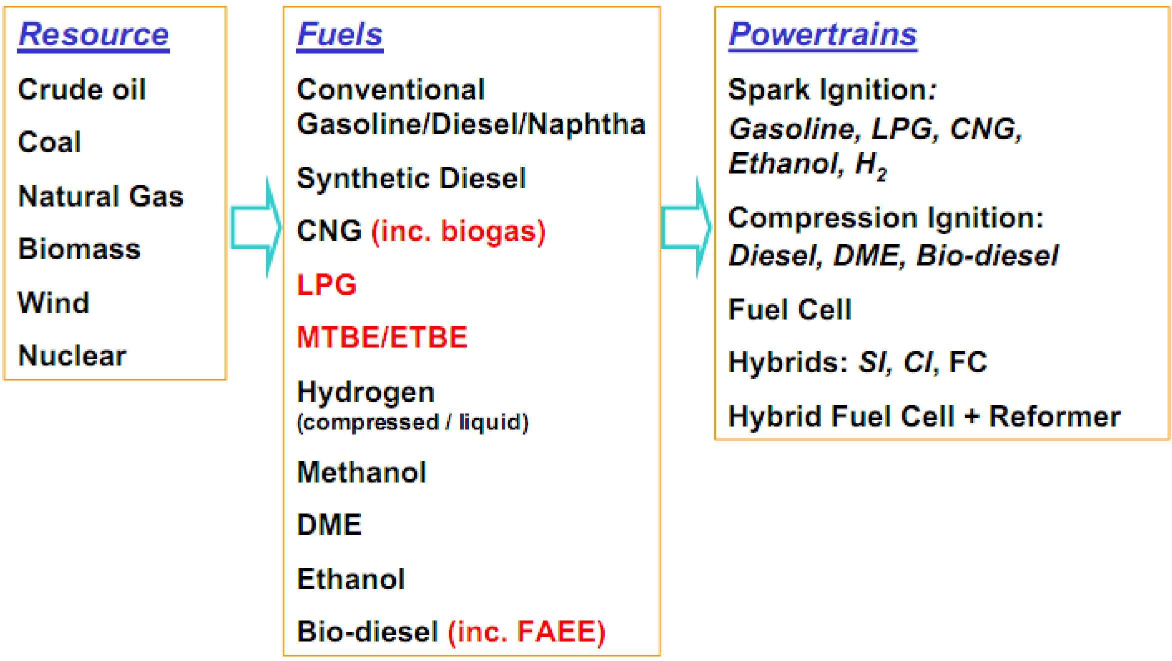


Figure 5-11: Well-to-Wheels Pathways

Source: Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 (http://ies.jrc.ec.europa.eu/WTW)

5.4 Selection Process of the Vehicle Technologies

We first made a simulation of all available technologies and fuels in 2010 and 2020 using GREET 1.8c.0. Based on this data, we narrowed it down to 8 vehicles technologies.

SI 2010/ SIDI 2020: We chose the SI vehicle on petrol as the baseline vehicle, since this still is the most common vehicle worldwide. However, we chose a SI vehicle with direct injection as the baseline for 2020. This is because we expect this technology to take over as the standard by then due to its superiority in efficiency and cost effectiveness and additionally is more environmentally friendly. Starting in 2015 the auto manufactures will be fined if their average CO_2 emissions are too high. A shift to SIDI will therefore probably be necessary for them. This also shows that although the ICEV technology is considered mature, a shift to direct injection can provide huge benefits. However, when comparing the results later it is important to keep in mind that we are talking about two different models.

CIDI Diesel: The GREET model base the CIDI Diesel vehicle calculations on a basic diesel vehicle, with a 20 % better miles per gallon (mpg) performance. Since a standard diesel was not an option, we had to choose the CIDI Diesel vehicle in our study. We chose the CIDI since diesel is a better alternative than petrol, and already has become more popular in Europe then petrol vehicles.

HEV SI Petrol: We naturally wanted to use the performance of the hybrid technology for our comparison, since it is significantly more fuel efficient than the standard SI. The SI petrol was a natural choice, since most hybrid vehicles today run on petrol. In the GREET model, HEV were known as grid-independent vehicles, while PHEV where known as grid-connected vehicles.

HEV CIDI Diesel: Because of the increased efficiency of diesel compared with petrol, we also included the hybrid CIDI diesel vehicle in our study.

PHEV SI EU: The PHEV is by many considered to be the next big thing in the automotive industry, and combines the benefits of a normal hybrid and an electric vehicle. The SI vehicle will probably be launched first. *EU* means that we are using the EU electricity mix as the source of the electricity from the grid. The EU mix is cleaner than the U.S. mix, some sources say 40 % less CO_2 emissions[96], and the GREET model that we used showed a 23 % improvement compared to the US energy mix for electricity from the grid. The PHEV run on *charge depleting mode* while on battery, and *charge sustaining mode* when running as a HEV. As mentioned earlier, we have used a 75 %/25 % share between CD and CS, but also blended CD is included in the CD mode in the GREET model, so the tailpipe emissions will be higher than if the whole 75 % CD use came from the electrical grid.

PHEV CIDI EU: Also here we chose to include the diesel vehicle, to compare its performance with the gasoline vehicle. In general, we assumed the PHEV to run on NIMH in 2010, but to shift to lithium in 2020. This affects the payback analysis, but the other analyses were based on the GREET model.

BEV EU: Naturally, the battery electric vehicle running on the EU mix is included, as the numbers looked very promising. Together with PHEV the BEV has the potential to significantly reduce emissions. It is also silent and with zero tailpipe emissions.

FCV G.H2: The 2010 results for the FCV based on compressed hydrogen produced by natural gas were promising, and we therefore chose to include it. We did not choose any other FCVs since their scores were worse than those of the CHG from natural gas, or they were more expensive. Because of the high costs of the technology, FCVs are not commercially available today, and mass production is predicted to potentially begin between 2015 and 2020. We have therefore chosen not to calculate any payback in 2010. FCV may become the future vehicle, but this is unlikely to happen before 2020. Its success depends on if/when the FCV can be produced economically from preferably renewable energy, as for instance through electrolysis of water.

There were some other models that could be interesting to study that we *did not include*. A bi-fuel vehicle running on *CNG* (compressed natural gas) or even better the *dedicated CNGV,* showed very favourable numbers, and was one of the least energy intensive technologies, and also had very low GHG emissions. However, CNG vehicles are not very common in Europe, and to developing the required infrastructure would be very expensive. In addition, we believe that it is better, cheaper and more efficient to use natural gas in large, stationary power plants to produce electricity, than directly to fuelling cars. In this context we apply the principle of economies of scale. The same reason was also decisive for our choice to not include any *biofuel vehicles* in our study. It is more efficient to use as biomass in stationary power plants than in millions of cars. Even if the EU concludes that biofuels should play an important role in the future, the best choice in our opinion will be to blend biofuels in the ICEV (or (P)HEVs) rather than making dedicated biofuel cars, which would again require a massive investment in infrastructure. As we have mentioned earlier, to blend in for instance 15-20 % biodiesel in diesel pumps for diesel vehicles and 15 % ethanol in petrol pumps for petrol vehicles will usually not be a problem with modern vehicles (without making any modifications). Another reason for not including biofuels is that many are very energy intensive. We were not impressed by what the results showed.

5.5 Presentation of the Results

Below we will present, explain and discuss the results of our study. We have used figures and tables to make it easy for readers to get a quick overview of the technologies. The best technology for each year is highlighted in yellow, so that the best solutions are easy to discover. In the table summing up the results, we have used grey to illustrate the second best option and orange to illustrate the worst candidate.

5.5.1 Economy

For the economical part we used a basic payback analysis. The numbers were based on several sources, but the most important one was Deutsche Bank's *plugged in* report from 2008[97]. However, for some vehicles we needed to use other sources, explained under *assumptions* below. As we can see the fuel costs, especially for the PHEV vehicles and BEV are very low.

	SI 2010/ SIDI 2020	CIDI Diesel	HEV SI Petrol	HEV CIDI Diesel	PHEV SI EU	PHEV CIDI EU	BEV EU	FCV G.H2
Payback Analysis 2010								
Additional costs €	Baseline	700	2870	3570	6440	7140	19880	N/A
Km/l(kwh) (BEV)	10,6	15,3	14,9	20,4	22,7	28,3	8,0	N/A
Fuel Cost €	2088	1450	1491	1088	471	423	303	N/A
Anuel savings €	Baseline	637	596	1000	1616	1664	1785	N/A
Payback (years)	Baseline	1,1	4,8	3,6	4,0	4,3	11,1	N/A
Payback Analysis 2020								
Additional costs €	Baseline	700	1680	2380	3500	4200	7700	7700
Km/l(kWh)[kg] (BEV)[FCV]	16,6	18,4	17,9	24,5	24,1	30,1	10,1	125,5
Fuel Cost €	1339	1209	1243	906	410	364	240	319
Anuel savings €	Baseline	130	96	433	928	975	1099	1020
Payback (years)	Baseline	5,4	17,6	5,5	3,8	4,3	7,0	7,5
Payback 2010	**Baseline**	**1,1**	**4,8**	**3,6**	**4,0**	**4,3**	**11,1**	**N/A**
Payback 2020	**Baseline**	**5,4**	**17,6**	**5,5**	**3,8**	**4,3**	**7,0**	**7,5**

Figure 5-12: Payback Analysis of the Different Vehicle Alternatives.

Source: The authors, Deutsche Bank, GREET, Weiss et al (2000), Wikipedia and wordpress.com

Assumptions (rounded)

Conversion rate 1 US dollar	0.7€
Cost of fuel/l	1.4 €
Cost of electricity/kWh[98 99]	0.15 €
Cost of compressed hydrogen gas[100]	2.5 €
Annual driving range	16000 km
PHEV electric range/actual range	32 km (20 miles)/36 km (22.6 miles)
PHEV electric driving share (CD)	75 %
PHEV hybrid driving share (CS)	25 %
Battery cost NIMH/kWh (2010)[101]	840 €
Battery cost Li Ion/kWh (2020) [102]	350 €
Battery requirement HEV[103]	2 kWh
Battery requirement PHEV[104]	6 kWh
Battery requirement EV[105]	22 kWh
Fuel cell requirement FCV[106]	100 kW

Fuel consumption (mpg) based on GREET values for specific technologies.
Fuel consumption BEV based on Deutsche Bank assumptions[107], increase in 2020 based on technological improvement of 26 %.
Fuel consumption FCV G.H2 based on double distance of baseline vehicle mpg converted[108].
Electricity prices based on EU 27 average prices of 2. semester 2007 & 1. semester 2008
We assume BEV and HEV (and PHEV) to use NIMH batteries in 2010 and Li Ion batteries in 2020.

Additional cost for Hybrids based on Deutsche Bank assumptions, with 700 € price premium for diesel technology[109].
The assumption of 75 %/25 % for PHEV in CD and CS mode based on average daily driving distance and electric range. GREET says that a PHEV20 has an actual range of about 22.6 miles.
The cost of fuel and electricity are fixed at the same level in 2010/2020 making results easy to compare.

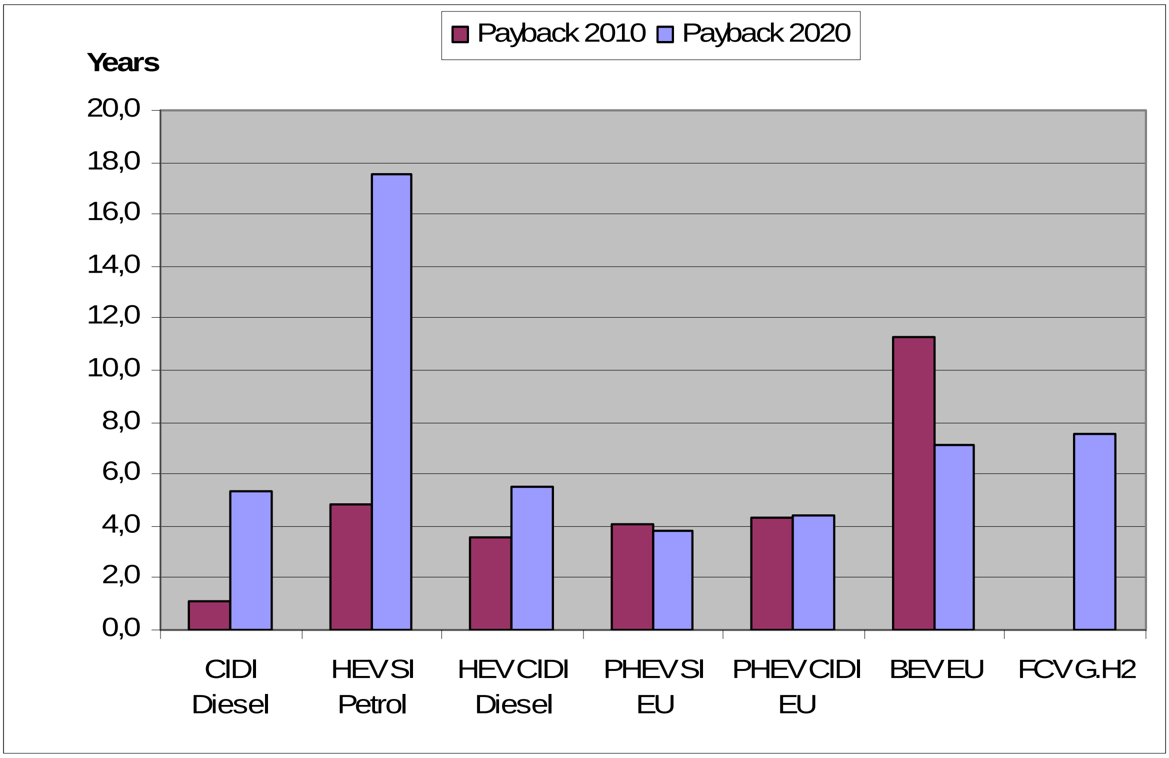


Figure 5-13: Payback comparison of the different vehicle alternatives.

Source: The authors, Deutsche Bank, GREET, Weiss et al (2000), Wikipedia and wordpress.com

As we see from the figures, based on payback the best alternative in 2010 would be the CIDI Diesel, and in 2020 the PHEV would be the best option. However, it is important to keep in mind that based on average driving distance and years intended to own the vehicle, vehicles with longer payback may be preferred over vehicles with shorter payback. The worst option by far in 2020 is the SI HEV. The BEV has a fairly long PB, but also has the highest improvement. The reason why most of the vehicles actually have longer payback periods in 2020 than 2010 is because of the technological shift of the baseline vehicle from SI to SIDI from 2010 to 2020. This is important to remember when analysing the numbers. The most difficult aspect of the payback analysis was predicting the additional costs for some of the vehicles. For instance, we chose to use the same price difference between the SI and CI in

2010 and the SIDI and the CI in 2020. It was also very difficult to predict accurate data for the fuel cell vehicle in 2020. Both the estimated additional costs of the vehicle and of the fuel were difficult to valuate. Many sources were either in favour or disfavour of the hydrogen economy, and we tried to evaluate them critically. In general, there were few sources with future prediction for the fuel cell vehicle, and we consider the data for the FCV to have the highest margin of error.

5.5.2 Efficiency

In this part we analysed the Well-to-Wheel energy efficiency. We used a number of different sources to predict the different values. For the *Well-to-Pump* (WTP), not to be mistaken with Well-to-Plant, which also uses the same abbreviation, we used the values created by the GREET model. Nevertheless, there were some numbers we were a bit uncertain about. First of all, 43 % energy efficiency in WTP for electricity is very high, most numbers range from 32-42 % for Well-to-Plant efficiency, with an additional loss of 8 % when transported through the grid. However, to be consistent, we chose to use the GREET numbers. For the PHEV, we decided to use an average of 75 % electric WTP and 25 % hybrid WTP to find the PHEV WTP efficiency. Since not all the electric power comes from the grid, this number will vary from the GREET model, but fits better with our intention. The PTW and WTW were further based on comparison of many different sources, and through making best assumptions on the basis of the covered literature. To calculate the 2020 WTW numbers, we used the technology improvement percentage from the technology dimension with the 2010 WTW numbers. For WTP we again used the GREET model. Based on those two we calculated the PTW numbers. The results are presented below.

	SI 2010/SIDI 2020	**CIDI Diesel**	**HEV SI Petrol**	**HEV CIDI Diesel**	**PHEV SI EU**	**PHEV CIDI EU**	**BEV EU**	**FCV G.H2**
WTP 2010	80 %	84 %	80 %	84 %	52 %	53 %	43 %	58 %
PTW 2010	20 %	26 %	29 %	32 %	53 %	55 %	70 %	45 %
WTW 2010	**16 %**	**21 %**	**23 %**	**27 %**	**28 %**	**29 %**	**30 %**	**26 %**
WTP 2020	77 %	83 %	77 %	83 %	53 %	54 %	44 %	60 %
PTW 2020	27 %	31 %	35 %	38 %	57 %	58 %	86 %	55 %
WTW 2020	**21 %**	**25 %**	**27 %**	**32 %**	**30 %**	**31 %**	**38 %**	**33 %**

Figure 5-14: Well-to-Wheel Analysis of Energy Efficiency

Source: The authors, Deutsche Bank (2008), GREET, Weiss et al (2000), Kendall (2008), Alliance Bernstein (2006), Future Fuels (2003) and Wikipedia

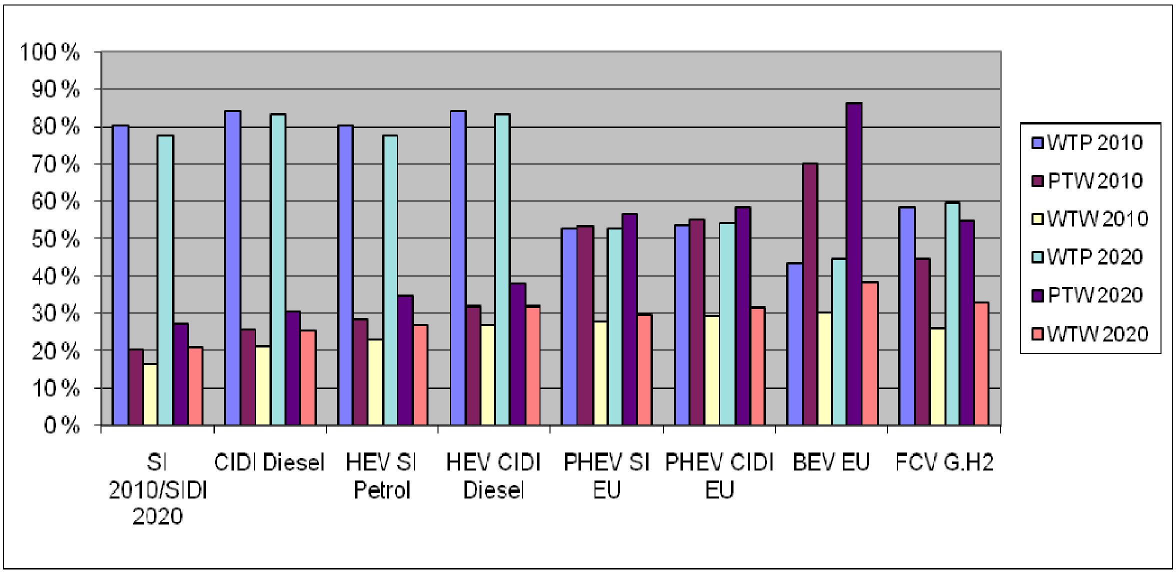


Figure 5-15: Overview over Well-to-Wheel Energy Efficiency

Source: The authors, Deutsche Bank (2008), GREET, Weiss et al (2000), Kendall (2008), Alliance Bernstein (2006), Future Fuels (2003) and Wikipedia

As we see from the table and figure, the battery electric vehicle has the highest overall efficiency for both years (2010/2020). This is not surprising, although as mentioned earlier, the values may be somewhat too high, since the WTP efficiency the GREET model used was higher than other sources. The PTW for 2020 is also very high, possibly too high, but this is due to the predicted technological improvement of 26 %. Not surprisingly the baseline vehicle is the worst alternative, and diesel is performing considerably better than petrol. Still, it is somewhat surprising that the HEV diesel performs better then both PHEV in 2020. An overall efficiency of 32 % is also very high. Nevertheless, these results are consistent with the energy usage showed in the table and figure below. This may be because a diesel hybrid is lighter then the PHEVs and therefore consumes less fuel. Interestingly, it also has a far higher technological improvement than PHEV, possibly illustrating that combining two energy sources might not be as efficient as using a dedicated vehicle. However, the technological improvement for the PHEV seems also to be predicted too low.

The total energy use might be an indicator of the efficiency dimension. By splitting it up, we can see the improvements for each phase and where the energy use is the highest. In light of the above-mentioned findings, the numbers are not very surprising. We get confirmation that the HEV diesel is the most efficient in the making of the fuel, and also scores highly in the other categories. It is interesting to see how well the FCV scores, using about the same energy amount as the BEV. However, it may be that the GREET model is underestimating the energy use of the FCV as it is inconsistent with our predictions of the WTW energy efficiency above.

Fuel and Engine type	Item	Feedstock kj/km	Fuel kj/km	Vehicle operation kj/km
SI 2010	Energy	161	600	3073
SIDI 2020	Energy	139	493	2159
CIDI Diesel 2010	Energy	134	356	2561
CIDI Diesel 2020	Energy	133	288	2069
HEV SI Petrol 2010	Energy	115	429	2195
HEV SI Petrol 2020	Energy	114	405	1773
HEV CIDI Diesel 2010	Energy	100	267	1921
HEV CIDI Diesel 2020	Energy	100	216	1552
PHEV SI EU 2010	Energy	97	667	1542
PHEV SI EU 2020	Energy	101	647	1412
PHEV CIDI EU 2010	Energy	92	600	1448
PHEV CIDI EU 2020	Energy	96	550	1340
BEV EU 2010	Energy	93	1175	964
BEV EU 2020	Energy	68	850	730
FCV G.H2 2010	Energy	100	827	1298
FCV G.H2 2020	Energy	77	594	993

Figure: 5-16 Overview of detailed energy usage

Source: The authors and GREET

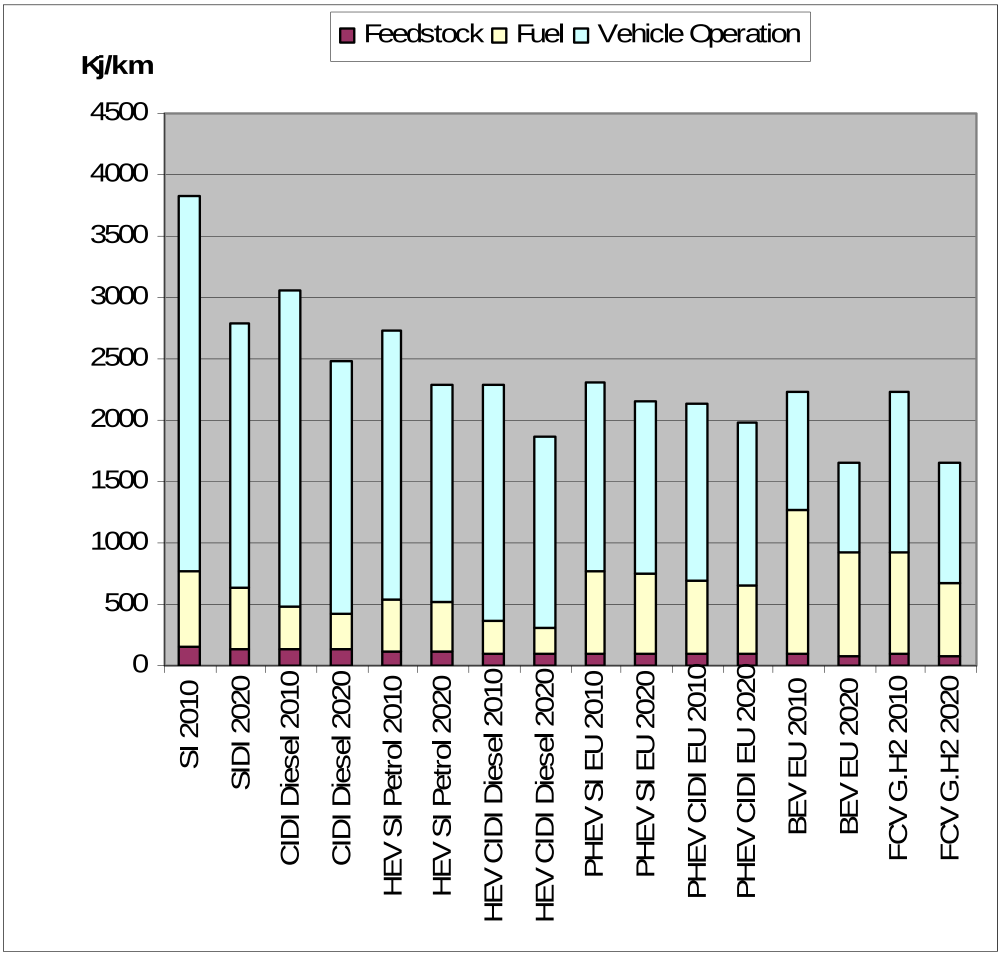


Figure: 5-17 Comparison of energy usage of the vehicles

Source: The authors and GREET

5.5.3 Environment

The third and maybe most important dimension is the GHG emissions. It is important to split up these emissions, since for instance the BEV also discharge GHG through the creation of electricity. The EU and other countries are often focusing on CO_2 emissions. The difference between CO_2 and GHG, however, is minimal, with CO_2 usually representing 90-96 % of the GHG emissions. Compared to the EU target of 120 grams/km (130 g/km required) in 2015, we can see that all the technologies, except CIDI diesel and SIDI petrol, fulfil this requirement by 2020. The only technologies capable of fulfilling the stricter 95 g/km requirement in 2020 are the PHEVs, BEV and CHG FCV. This shows that these technologies will probably have to play an important role if EU and the auto manufacturers are to reach their goals. The petrol and diesel vehicle have very high emissions, higher than the average European vehicle sold today, indicating once again that these numbers probably better describe the US standard vehicle than the European. We would maybe expect the BHEV to release less emissions, but as mentioned earlier, this is due to the 75 % CD range of electricity comes both from the grid an is delivered through blended mode, where it releases GHGs. Interesting to see, the FCV on H_2 actually has the lowest emissions. This may be since it comes from natural gas, which is the cleanest fossil fuel, far cleaner and more effective then e.g. coal, which accounts for 29 % of the EU mix. A calculation in GREET, by replacing all coal production with natural gas, confirms this theory, since the BEV then will use less energy, and have lower GHG emissions than the FCV.

Fuel and Engine type	Item	Feedstock g/km	Fuel g/km	Vehicle Operation g/km
SI 2010	GHGs	16	40	226
SIDI 2020	GHGs	10	31	159
CIDI Diesel 2010	GHGs	17	26	194
CIDI Diesel 2020	GHGs	16	21	157
HEV SI Petrol 2010	GHGs	12	29	162
HEV SI Petrol 2020	GHGs	8	25	131
HEV CIDI Diesel 2010	GHGs	13	19	146
HEV CIDI Diesel 2020	GHGs	12	16	119
PHEV SI EU 2010	GHGs	11	68	89
PHEV SI EU 2020	GHGs	9	65	80
PHEV CIDI EU 2010	GHGs	12	65	84
PHEV CIDI EU 2020	GHGs	12	61	77
BEV EU 2010	GHGs	12	142	0
BEV EU 2020	GHGs	9	105	0
FCV G.H2 2010	GHGs	14	126	0
FCV G.H2 2020	GHGs	11	94	0

Figure 5-18: Greenhouse Gas Emissions WTW Split up

Source: The authors and GREET

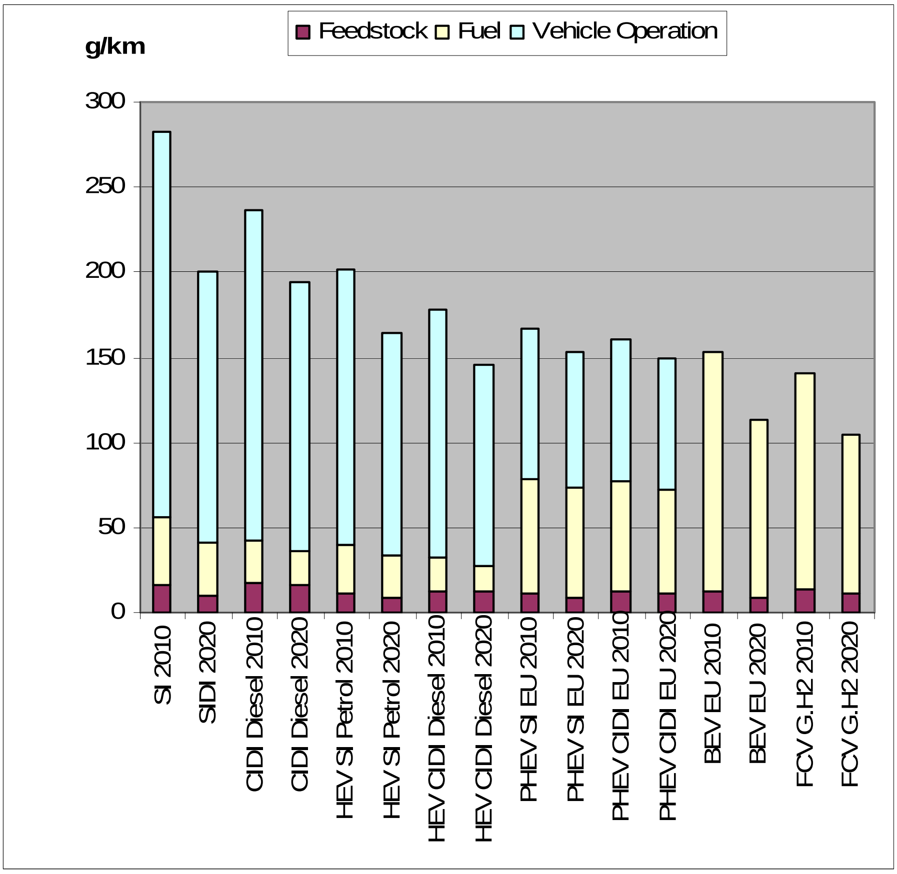


Figure 5-19: Green house gas emissions comparison WTW

Source: The authors and GREET

5.5.4 Technology

The last dimension is the improvement in technology. We here based the calculation on the average of WTW energy and WTW GHGs. Not surprisingly, these numbers where almost identical, varying at only 2 % at the most. We observe with interest that the SI is showing the biggest improvement, due to the shift from SI to SIDI. What is very surprising is that the PHEV is showing the smallest improvement. This may indicate that the PHEV is not the optimal solution over a longer time frame than from now until 2020. As mentioned earlier it is probably caused by the need for two different engine systems which makes the car heavier, more expensive and more complex than a dedicated engine. It also shows the limits as long as petrol is one of the energy sources, setting limits for how clean the technology can become, unless it runs a 100 % on battery. However, it may also mean that the GREET model is predicting the improvement too cautiously. It is for instance surprising to see that the HEV are improving 17-18 % and the BEV 26 %, while the PHEVs combining these two technologies, only improve by 7 %. The potential cost reduction is not accounted for in this comparison, and we refer to the numbers in the economical section for further details. The FCV for instance is likely to obtain the largest cost reduction through further research and mass production, since this is considered the youngest technology.

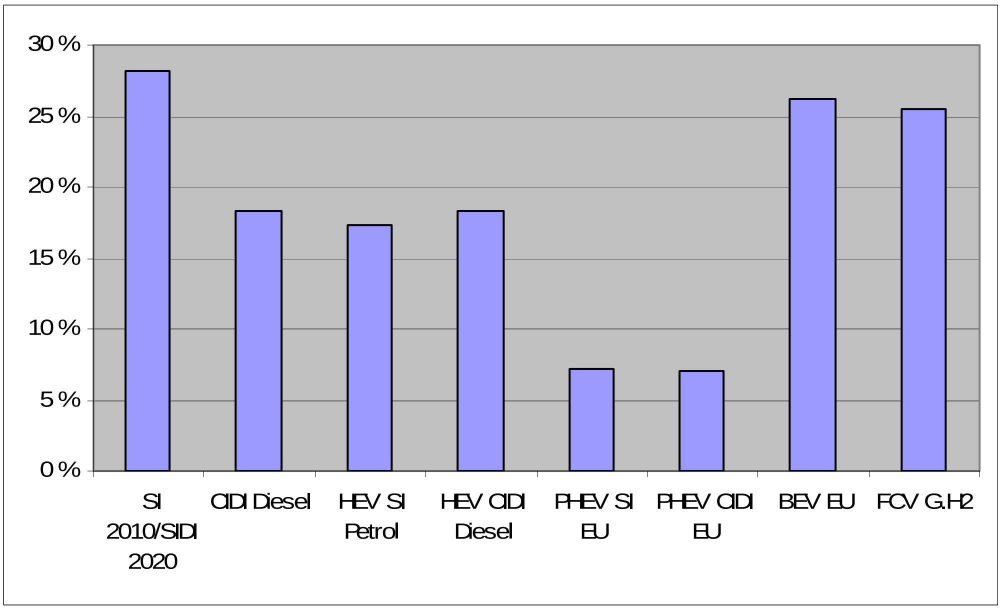


Figure 5-20: Comparison of Technological Improvement

Source: The authors and GREET

5.5.5 Overview of the Results

This section sums up our comparison of the results analysed above. We see that the SI/SIDI is losing on all aspects, although its technology improvement is the greatest. We also see how the diesel technology outperforms petrol. It looks like the best options would be a HEV diesel, a PHEV diesel, a BEV or the FCV. The BEV and FCV may not be competitive on price in 2010 without subsidies, but they are the best alternatives considering most of the dimensions and by far the cleanest technology with the lowest fuel costs. The FCV surprises greatly, and is scoring about as good as the BEV. As we have mentioned earlier, the payback in 2020 might be both higher and lower than our estimate for the FCV. There is also a possibility that the GREET models estimation of the FCV or some of the other technologies, turn out to be inaccurate.

Dimension	Fuel and Engine type	SI 2010/SIDI 2020	CIDI Diesel	HEV SI Petrol	HEV CIDI Diesel	PHEV SI EU	PHEV CIDI EU	BEV EU	FCV G.H2
Economy	Payback 2010	Baseline	1,1	4,8	3,6	4,0	4,3	11,1	N/A
	Payback 2020	Baseline	5,4	17,5	5,5	3,8	4,3	7,0	7,5
Efficiency	Energy efficiency 2010 WtW	16 %	21 %	23 %	27 %	28 %	29 %	30 %	26 %
	Energy efficiency 2020 WTW	21 %	25 %	27 %	32 %	30 %	31 %	38 %	33 %
	WtW energy 2010 Mj/Km	3,83	3,05	2,74	2,29	2,31	2,14	2,23	2,23
	WtW energy 2020 Mj/Km	2,79	2,49	2,29	1,87	2,16	1,99	1,65	1,66
Environment	WTW GHGs 2010 g/Km	282	237	202	178	167	160	153	140
	WTW GHGs 2020 g/km	200	194	165	146	154	149	113	105
Technology	Improvement WTW/PTW	28 %	18 %	17 %	18 %	7 %	7 %	26 %	25 %

Figure 5-21: Overview of the Results

Source: The authors, previous figures

5.5.6 Implications of The Results

It looks as if a combination of PHEV and BEV and also the HEV diesel engine might be the best technologies for the future considering our results. We could also include the FCV here, as potentially the most interesting technology. However, at the current stage, there are so major uncertainties with this technology that we recommend a combination of the other three technologies within our timeframe, of course with the potential to change point of view later on, if the fuel cell technology really starts to improve. This will make it easier as it requires development of infrastructure for only one technology, which also will be possible to use by charging from the grid. However, it is important to remember that we will be dependent of petrol also in the future. As mentioned earlier, the refineries cannot produce only diesel fuels. Petrol will be a major part of the production of fuel from petroleum, normally a larger share than diesel. It will not be possible for everyone to choose diesel. The prices would rise, and the market would adjust. One suggestion could be to mainly use petrol in PHEVs, and diesel in HEVs. It is also important to realise that it would be impossible to only produce BEVs in 2020. Limitations in lithium extraction and battery production are two bottlenecks, although competing technologies may emerge. However, the most important problem will be the increase in the electricity production needed. It will be almost impossible to develop the electric power supply fast enough to support a large BEV market share in 2020. The electricity prices would rise, and more polluting options would look more attractive. Even a sufficient increase in the electricity production would have implications, as it would probably be produced from coal. Coal is the most abundant fossil energy we have and also the least efficient and environmental friendly. Without the use of expensive CO_2-capture technology it would lead to an increase in GHG emissions, making the EU mix, the BEV and PHEV less attractive. The potential for the FCV is difficult to predict. If costs can be decreased further it looks promising, although 2020 will probably be too early considering the price and the infrastructure investments needed. BEV will also need a developed infrastructure, either through battery replacement stations or grids providing high voltage and quick charging. The great advantage is that it can be recharged via the existing wall outlet.

To sum up, we will try to propose a target mix for new vehicles in 2020. We focus on two aspects in our recommendation. Firstly, we will try to keep the petrol/diesel ratio pretty constant. Although we are focusing on the EU, we need to take other parts of the world in consideration too, so they can follow EU's example, without getting a too high petrol/diesel imbalance. Secondly, we will take into consideration that BEV will be best suited in urban areas, but its range limitations and high battery (lithium) consumption, limits its sustainable penetration. Lastly, we will try to minimize the tailpipe emissions with our suggestion. We believe that the BEV may have the potential of gaining 20 % of the new car sales in 2020. To keep the ratio between diesel and petrol, we would propose 60 % of new car sales to be petrol PHEV, and 20 % of new car sales to be diesel HEV in 2020. Since our petrol PHEV runs only about 25 % on petrol, but is less efficient then diesel HEV in CS mode, one PHEV would use about the same petrol amount as three diesel HEVs. This would make the tailpipe emissions from our proposed mix to 71.5 g/km GHGs, or about 70 g/km CO_2, well below the EU target of 95 g/km CO_2 in 2020. In comparison, the tailpipe emissions of a vehicle fleet of half and half petrol and diesel vehicles would emit 158 g/km GHGs, far higher then what is required. A comparison where we also include the other dimensions for our technologies is shown below. We have here included a baseline scenario, our possible suggestion, another proposal if lithium capacity increases higher than expected, and lastly going solely for the best overall alternative according to our model, the BEV.

Scenario	Fuel and Engine Type	Payback	Efficiency	Energy use Mj/km	GHGs g/km	Market share	Tailpipe emissions mix
Baseline	SIDI 2020	Baseline	21 %	2,79	159	50 %	158
	CIDI Diesel 2020	5,4	25 %	2,49	157	50 %	
Possible suggestion	HEV CIDI Diesel 2020	5,5	32 %	1,87	119	20 %	72
	PHEV SI EU 2020	3,8	30 %	2,16	80	60 %	
	BEV EU 2020	7,1	38 %	1,65	0	20 %	
High lithium production	PHEV CIDI 2020	4,4	31 %	1,99	77	45 %	62
	PHEV SI EU 2020	3,8	30 %	2,16	80	35 %	
	BEV EU 2020	7,1	38 %	1,65	0	20 %	
Best alt. without limits	BEV EU 2020	7,1	38 %	1,65	0	100 %	0

Figure 5-22: Summary of Different Target Scenarios

Source: The authors & previous figures

As we see, the BEV scenario would clearly be the best option in most circumstances. However, as argued, this scenario is not plausible. One might argue that none of the scenarios will happen, and that is probably correct, but it is important to have some target scenarios as a foundation, and it should be possible to influence towards a scenario, and even switch scenarios if technologies develop differently than expected. It is also important to mention again, that the numbers for these vehicles might be too high in a European context. It that case, a mix with more petrol and diesel cars and fewer AFV's, could still be within the climate target. An example is the new Toyota Prius 2010 model, which should emit only about 90 g/km CO_2[110], while using our numbers, a standard petrol Hybrid will emit 162 g/km CO2 in 2010 and 131 g/km CO2 in 2020. This is probably since the HEV is an average of different technologies and sizes, and not the market leader and one of few full hybrids on the market today. The fabric data that Toyota use is also usually better then data from actual driving.

6. Introducing AFVs to the European Market

In this part of the thesis we will begin with an introduction of the major stakeholders in the automobile industry and illustrate it with a figure. Relations between the different stakeholders will be discussed briefly. We will, based on *chapter 2*, present some important barriers to the transition of AFVs with regards to the different stakeholders. In combination with the results from *chapter 5* we will suggest policy options that can help to reduce or eliminate these barriers. Our focus lies with the governments' role, and how they can affect the behaviour of the other groups of stakeholders.

6.1 Introduction of Stakeholders

6.1.1 Fuel manufacturer

Oil companies have without comparison been the number one fuel manufacturers and distributors since the breakthrough of the ICEV. These companies played a major part in the process a hundred years ago where the ICEV beat the technologies in electric-and steam engine vehicles to become the reigning technology for a century. The same multibillion dollar industry has contributed to weaken attempts of introducing clean alternatives, perhaps with the failure of the 1990 ZEV mandate in California as the most famous example. Strategy makers and implementers need to take this into consideration when planning efforts to reduce the carbon intensity in fuels.

Alternative fuels face tough competition in the oil industry, where margins are high. The movement in oil prices has been significant lately, peaking at $140 in July 2008[111], collapsing down to $34 in January, and recently passed $65[112]. The change in oil prices has different effects on fuel consumption. When peaking at $140 consumers in the U.S. experienced dramatic increase in fuel prices. As a result oil producers experienced a decrease in demand due to reduced consumption, and a shift to less fuel consuming vehicles occurred. This indicates a potential environmental benefit from high oil prices. On the other hand low oil prices lead to project delays and cancellations within the oil industry, which implies reduced oil production and less pollution.

The oil industry in the U.S. has always had people in the government looking after their interests. Dick Cheney, Condoleezza Rice and Andrew Card from the George W. Bush administration, are all former executives and board members of oil and auto companies[113]. The industry has traditionally had less influence in the EU, where most countries are net importers of oil and hence benefiting from low oil prices. A reduction of oil demand through a shift towards AFVs would make the EU less dependent of oil import.

6.1.2 Fuel distribution

While fuel manufacturers refine raw materials into fuel at the manufacturing site, fuel distributors provide the fuel from manufacturing site to vehicle tank through fuelling stations. These two stakeholder groups are closely related as fuelling stations are owned by the oil companies ensuring their products reaching the market. As mentioned these companies do not appreciate competition – from each other or from alternative fuels. There are many examples of fuel distributors embarking on aggressive price strategies to squeeze out competitors or new entrants. One example is Statoil's response to the entry of Jet to the Norwegian market in 1996. The price competition led to Statoil reducing gasoline prices below variable costs meaning that the company would lose more money as sales increased[114].

Introducing new fuels requires significant investments in distribution infrastructure. An increased number of fuel types mean more fuel pumps and more storage space. In addition some of the new fuels require longer fuelling time, hence more pumps and parking space, and increased safety concerns due to pressure tanks. The companies currently producing these fuels are more likely to invest in distribution infrastructure, as long as it is profitable. However, investment in infrastructure for introducing new fuels requires a sufficient number of vehicles. Herein lies a classic "chicken-and-egg" dilemma. Vehicle producers will be resistant to developing AFVs as long as there is a lack of adequate fuelling infrastructure.

The variety of fuels offered at fuelling stations is likely to be limited in rural areas, where investments in infrastructure and transportation costs are too high to make profit. Vehicle purchasers in those areas will obviously be more reserved to investing in AFVs with the insecurity involved.

Another difficult issue is the charging stations for electric cars and plug-in hybrids. There are clear benefits in customizing and making use of existing infrastructure and distribution systems in order to offer alternative fuels to the market. But what incentives do fuel distributors have to offer and even invest in charging stations that constitute a direct threat to fuel?

6.1.3 Vehicle manufacturer

Vehicle manufacturers have a history of resisting change and have stuck to the internal combustion engine for a century. Examples include withholding technology that can reduce emissions claiming it to be unfit for commercialization due to performance problems and cost, obstructing the research, development, manufacturing, and installation of pollution control devices, and dedicating a minimum of resources to emissions control efforts[115]. The Zero-Emissions Vehicle mandate passed by California Air Resources Board in 1990 led to the development of electric cars such as General Motor’s 1996 introduction of the EV1[116]. The EV1 program was cancelled by GM in 2003 under the statement that they could not sell enough of the cars to make it profitable. The cars, which had only been available under a lease program, were recalled after the end of the leasing period and shredded[117]. The discontinuation was controversial. The ZEV mandate had some positive outcome as Toyota and Honda developed their own EV prototypes to compete with the EV1, and went on to introduce their hybrid electric vehicles, Prius and Insight.

Vehicle manufacturers need to produce and sell a sizable number of each model to cover R&D costs and to reduce production costs sufficiently to make a car profitable, especially when embarking on new technology that excludes the ICE. They face new technical challenges, different recycling challenges and need to find new suppliers. The shift in technology leads to a considerable change in production processes.

The financial crisis has made a huge impact on automobile industry resulting in dismissals, restructuring and bankruptcy. Governments all over the world have given crisis loans to domestic car companies trying to save jobs. Recently the (former) world's largest automobile company, GM, filed for Chapter 11 bankruptcy, the largest industrial bankruptcy in U.S. history[118]. The European companies have not been affected to the same extent, but a few have faced tough challenges, especially the GM owned Swedish manufacturer SAAB.

There seem to be signs of car companies increasing their efforts in reducing emissions and increasing fuel efficiency with VW's Blue Motion technology as a good example. Historically the increases in fuel efficiency have come as a result of oil price shocks. The 1973 and 1979 oil crises led to governments passing fuel economy standards. Due to the phase-in of the fuel economy laws in the U.S. vehicle mileage for passenger cars doubled from 1975 to 1985[119]. The next two decades it decreased. Although European and Japanese vehicle manufacturers traditionally have made smaller, lighter and more efficient vehicles, they too are affected by oil prices rather than lack of technology. The five-door Audi A2, which entered the market in 1999, could run a hundred km on 0.3 litres of diesel or 0.6 litres of petrol[120]. The car would easily pass the 2010 emission standards.

The production of AFV prototypes has increased dramatically the last few years. In the U.S. alone, 13 hybrid electric vehicle models were available in 2007 and at least 75 are expected within 2011[121]. The companies seem to have settled with the fact that a new generation of car production is upon us, and started positioning strategically. VW and Toshiba recently announced their plans to begin working together to develop electric drive units for vehicles[122]. The same company is discussing a possible venture with the Chinese company BYD in an effort to secure battery supplies for HEVs and BPEVs[123]

6.1.4 Vehicle distribution

A transition to AFVs entails distributors to adapt to the change in vehicle demand. As demand for AFVs rises, retailers only offering ICEVs will lose market shares. Picking winners will become increasingly difficult with the growth in new models available. From offering petrol or diesel fuelled cars, distributors will possibly have five to ten different types of technologies to choose between.

The same challenges apply to repair and maintenance of these vehicles. Whilst the differences among engines running on petrol or diesel are limited, the differences in power unit and driveline between the different AFVs are considerable. Depending on the number of new entries the dealers are likely to have to invest in facilities, equipment, and hiring and training to meet different skill levels for their employees. A possible outcome, depending on the scale of each technology, could be company engineers specialized on a limited number of technologies providing maintenance for a number of customers, car dealers or vehicle fleets.

The different AFVs contain a variety of components that require attention. The number of batteries is likely to multiply in a few years causing the need for a substantial effort in recycling and disposal. Fuel cell vehicles will require extra safety measures due to explosion hazard from the hydrogen fuel, as will methanol due to toxicity.

6.1.5 Vehicle purchaser

Vehicle purchasers include private buyers and fleet owners. Constituting the demand side, this group of stakeholders influences the manufacturers and distributors of vehicles and fuels through change in demand due to preferences. The supply side has to satisfy the requirements from vehicle purchasers, or try to affect it, e.g. through marketing campaigns.

There are several aspects that car buyers take into consideration when purchasing a car. The price, design, performance, safety issues, maintenance, insurance, status etc. affects buyers' decisions. Introducing AFVs to the mass market adds a whole new set of considerations for vehicle purchasers. Switching from standard ICEVs to AFVs mean switching from something familiar to something unknown, which many purchasers may perceive as risky. Today production costs of AFVs are higher as for ICEVs and will remain so until they are produced at scale. In addition to possibly more expensive cars there are uncertainties regarding the cost effectiveness (cost of transportation per km) and maintenance costs (reliability). As long as the fuel availability and convenience is inadequate the base for market penetration is limited. Performance of the AFVs regarding range, acceleration, load capacity and comfort style, although improved over the last few years, still do not match the ICEVs. Finally safety is an important issue. Both crashworthiness of vehicles using lighter body materials and safety matters regarding fuels or batteries are possible dilemmas.

Vehicle purchasers will not embrace the new technology if they feel they are paying extra for a second-rate product. Even if technology grows superior to ICEVs there's still quite a challenge gaining consumer acceptance.

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6.1.6 The government

The government is by far the most important stakeholder concerning power and influence over behaviour and decision making of the other stakeholder groups. Using taxes, regulations and incentives they can reduce or remove market barriers and help speed up the development and adoption of AFVs.

The most important reasons for governmental intervention in the automobile industry are on the one hand the environmental aspect as clean air[124] and global warming[125], and on the other the strategic aspect of reducing its dependency on a scarce resource[126]. Nevertheless, these aspects will be weighed against the affect on domestic industry. Germany, France, Spain Italy and the U.K. are among the largest car producers in the world[127] and the industry employs hundreds of thousands. The financial crisis has shown how desperate governments are to keep their automobile industry running, securing the jobs. This implies a gradual transition which focuses on maintaining domestic production as well as keeping up with foreign competition. It’s not unlikely that governments will introduce policies that favour vehicle technology from their domestic companies. Would Norway, which has little history of car production, favour electric cars through tax exceptions, free parking and access to bus lanes had they not been the birth country of Think[128] and Buddy[129]? Would the same benefits be given had the number of electric cars risen to more than a few thousand units?

Although the governments possess powerful tools they are unlikely to succeed without cooperation with other stakeholders. To create a productive collaboration the government needs to communicate a long-term policy that provides predictability for decision-makers. Convincing stakeholders to invest in the new technologies requires governments with a high degree of credibility.

6.1.7 Stakeholder Barriers

Our results from *chapter five* showed that the HEV diesel, PHEVs and the BEV seemed to be the most promising alternatives within our timeframe. Since they all are based on the same battery electric technology, and two of them also share the IC engine, they are somehow affected by the same barriers, although in various degrees. Below we have listed the most important stakeholder barriers

Barriers	**AFVs in General**	**HEV**	**PHEV**	**BEV**
Infrastructure (all stakeholders)	Little or no existing infrastructure, large investments needed	No investments needed.	Investments in charging stations an advantage.	Large investments in charging stations and battery replacement stations needed.
Additional cost for consumer (consumer)	Varying cost premium. Uncertainties regarding fuel and vehicle taxation.	Low cost premium. Cheaper in use than petrol or diesel.	Medium cost premium. Far cheaper if running on electricity.	High cost premium. Very low fuel costs. A battery swap every 5-10 years may be needed.
Additional cost for manufacturer (vehicle/fuel manufacturer)	Most technologies have high R&D costs, and are in early stages and produced in small volumes.	Medium R&D is needed. Technology is proven, and still rapidly improving.	Large investments needed, especially in battery technology. Technology still in a very early phase.	Large investments needed. Battery costs and weight need to be significantly reduced.

Range limitations (vehicle purchaser)	Shorter range than conventional vehicles. Fuel storage requires large space and fuel can be complex to store	No range limitations	No range limitations, but cheaper and cleaner running on battery. Charging is time consuming	Short range, not suited for long distance travel. Charging is very time consuming
Critical mass **(vehicle manufacturer)** **(Chicken and Egg)**	Most vehicles are produced in test- or small volumes. Difficult to gain market share without investments, and little eager in investing without volume.	Still has a small market share, but relatively small adjustments could make the HEV penetrate the market as cost-benefit outperforms conventional vehicles.	Not mass-produced yet, but has the potential to expand faster than the HEV if the technology is working as anticipated.	Small scale production of city cars, family cars not produced yet. Will need improvement in range, and sufficient infrastructure to heavily increase market share.
Consumer attitude (all stakeholders)	Consumers are reluctant to pay higher price for an unproven technology.	Low reluctance. Technology is proven. Few differences from conventional vehicles.	Medium reluctance. Technology is new. Cost premium higher, and charging requires extra efforts.	High reluctance. High cost premium and current limitations in technology.
Uncertainty of technology potential and priority (all stakeholders)	High degree of uncertainty towards which technologies will succeed. Uncertainty concerning which technologies governments and consumers will favour.	Might last only through a transitional phase, until electric vehicles are good enough to replace it. Environmental potential limited by fossil fuel dependency.	Will probably outnumber the HEV pretty quickly once technology is developed. May however be beaten by the BEV when range limitations and infrastructure are in place.	Will probably not become a major competitor before costs are down, and infrastructure and range is improved. Has the potential to reach zero emission WTW if electricity is produced from renewable energy. Has the potential of gaining significant market share in the future.
Limited resources (fuel manufacturer, vehicle manufacturer)	Most fuels are limited, either by production capacity (biofuels), or their dependency of non-renewable energy (NG, electric grid).	Petrol/diesel is a limited resource, but will probably remain a large fuel for decades although prices are expected to rise. Less dependent on new battery technology, but can make use of alternative battery technologies.	Petrol/diesel is limited, and an increase in electricity production will mainly come from non-renewable sources. The most promising battery technology (lithium) also has limited total reserves.	Limited capacity in electricity production which will increase prices. Heavily dependent on an increase in battery production. Unstable government (Bolivia) controls the biggest source of lithium, which can affect production drastically.
Improvements in the competition	Most AFVs are not competitive with the conventional	The HEV is a good alternative to the ICEV	The introduction of the SIDI will improve the ICEVs and reduce	The BEV is expected to experience about the same improvement as the

(vehicle manufacturer, vehicle purchaser)	ICEV today. As they improve, the ICE will also improve from 2010-2020, by 18-28 % according to our data	today, but as we see from our estimates, only the HEV diesel will be completive in 2020.	the advantage of the PHEV. However the PHEV will still go through major improvements and offer shorter payback periods than the ICEV in 2020.	ICEV, but will due to cost reductions, be a better alternative in 2020 than in 2010.
(Battery) Technology (vehicle manufacturer, vehicle purchaser)	Most AFVs are still in early phases of production, where technology is expensive and immature	Battery technology is still rapidly improving, but since the HEV makes use of only a small battery, the size and weight of the battery is not very important	The PHEV relies more on the batteries. Batteries therefore need to have high energy density, be of light weight, and possible to charge quickly and safely. The batteries are not sufficiently developed yet, and the costs are high.	The BEV is fully dependent on the battery, and needs batteries providing long range and quick charge to an affordable price. This has so far been a problem, and the technology needs to improve before the BEV really becomes interesting.
Lack of common standards (all stakeholders)	Many competing firms have their own technologies and standards, making it difficult for the customers to choose the winner	Some implications for the HEV, drivetrains differ widely, and technologies become quickly outdated	Different outlets may cause a problem for charging. Different battery technology and battery platforms.	Same problems as for PHEV, but at a higher level.

Figure 6-1: Overview of the Most Important Stakeholder Barriers

We will make a selection of what we consider the most important barriers, and suggest policy options that can help reduce the barriers. When considering the barriers, there are some that apply to most AFVs. Lack of infrastructure is perhaps the most important one. While all countries are equipped with fuel stations for petrol and diesel, few offer alternative fuels, and none of the European countries at a large scale. The reason for this is two-folded. Due to a limited number of AFVs, the incentives for developing infrastructure are small. In addition, the oil companies, which would have the economic muscles to develop this, would be reluctant to cannibalising their own petrol and diesel sales. Higher cost is another important barrier. Furthermore we have the consumer attitude towards AFVs, few people are willing to be the innovators, and the technologies never grow past this phase. Unless the technology proves to be competitive on all areas against conventional ICEV, the consumers are likely to stay hesitant. The lack of clear, long-term strategies creates uncertainty for investors and hinders large scale investments.

The HEV has the lowest entry barriers in the short term, but also offers the least potential improvement compared to the traditional ICE. General improvement in the competition may actually be the HEV biggest barrier in the medium term, as it is only marginally better than for instance a modern CI diesel, and the PHEV and BEV offer far greater potential.

The PHEV is an intermediate between the HEV and the BEV, both when it comes to technology and barriers. The most important barrier for this AFV is the battery technology. Another problem is the cost premium for purchasers. The final barrier is probably the production capacity and the availability of the raw material for the batteries.

The PHEV barriers apply also to the BEV, though to a greater extent. Relying heavily on batteries as well as a cost premium can prove to be an important problem for the diffusion of the BEV. Last, but not least, the infrastructure will be a major barrier. These barriers will be addressed in the following section.

6.2 Policy options to overcome stakeholder barriers

Let us first recapitulate the reasons for governments to promote AFVs from the *introduction chapter*. The perhaps most important aspect is the *environmental* effects, concerning air quality and the implications of global warming. Further the *strategic* element of reducing one’s dependency on a scarce resource has been mentioned. This dependency constitutes a threat for the EU’s competitiveness. The final reason we have introduced is the need for *technological* innovation. Romer introduced research and cumulative technological development to the neo-classical growth theory as the solution to sustaining permanent economic growth (Norman, 2006, see also Gärtner, 2003, chapter 9&10). Although addressing all these aspects our focus when suggesting policy options is on the environmental effects.

The transition towards new, cleaner technologies will make a substantial impact on emissions given fixed average driving activity. However, if increased transport demand outstrips the improvements of these new technologies, the problem will remain the same. Therefore, policy options directed towards reducing traffic volume are necessary. Such a reduction implies further investments in public transport as well as limiting access for private transportation, thus providing incentives for leaving the car at home. We will, however, not elaborate on these issues, but focus on how to implement our suggested technologies. In our opinion, it is vital to ensure a transition and obtain critical mass, before imposing the same restrictions for environmentally friendly AFVs as experienced by the ICEVs. As long as these remain uncompetitive, other incentives must be provided in order to gain consumer acceptance and will to purchase these alternative vehicles. As they reach a respectable market share, regulations for AFVs can slowly be phased in, but still favour them over less environmentally friendly vehicles. A continual review of environmentally friendly technologies by policy makers should aim at favouring better technologies' market entry. This will create incentives for companies to constantly invest in R&D to improve or invent technology.

Based on our results with regards to vehicle technology, we selected three alternatives which we consider as good options for the European mass market. We will not elaborate on the other alternatives; still a few things are worth mentioning. With regards to use of biofuels we have already argued against developing dedicated vehicles due to high costs, relatively low energy efficiency, social implications of using crops for fuel, and uncertainties concerning the environmental benefits. If the EU wants to make use of biofuels in the vehicle industry, a blend of biodiesel in diesel pumps and ethanol in petrol pumps could be a solution that would be far cheaper than developing new infrastructure. Another alternative is to make use of biomass to produce electricity for electric cars in stationary power plants, an option that is more energy efficient than fuelling millions of cars.

Another alternative which we consider not to be competitive in the medium term is hydrogen produced for fuel cell vehicles. Although the results from the GREET model were promising, we are uncertain about the accuracy of the results. The costs of building sufficient infrastructure as well as the high production costs of fuel cells and uncertainty about fuel costs, makes the alternative unlikely to be competitive within our timeframe of 2020. Steenberghen & Lopez (2007) claim that 20 % of the EUs approximately 100 000 refuelling stations should be equipped with hydrogen dispensers in order for the FCVs to penetrate the mass market. Assuming investments of €1.3 million per station, the total cost sums up to €26 billion. Another implication is that the cheapest and quickest route to hydrogen probably is dependent on natural gas, on which the EU wants to reduce its dependency. Despite of our conclusion we emphasise the need to start acting now to develop future hydrogen fuelling facilities. The European Commission has launched initiatives such as the *European Hydrogen and Fuel Cell Technology Platform* in 2003 for this purpose[130]. We recommend a focus on niche projects and demonstration projects as a preparation to potential future large scale development of infrastructure. This strategy allows the governments to invest in R&D to get confirmation of the potential of hydrogen fuel and develop an environmentally friendly alternative to natural gas in the production. At the same time it sends a signal to actors in the market that as soon as the proper technology is in place, the government is willing to contribute to the transition phase. Examples of these kinds of projects are the EU co-financed CIVITAS-projects (CIVITAS I, II and PLUS), which *helps cities to achieve a more sustainable, clean and energy efficient urban transport system by implementing and evaluating an ambitious, integrated set of technology and policy based measures*[131].

A policy instrument can affect several barriers. Furthermore a variety of policies can contribute to the same objective. Therefore a combination of different policy measures can, if employed appropriately, help to increase the effectiveness of the implementation. Many barriers are highly correlated and the removal of one can affect others. The three main barriers we have identified are: **cost premium**, **battery technology** and **infrastructure**. Infrastructure includes charging stations and battery replacement stations as well as other infrastructural measures that are beneficial for electric cars. In addition infrastructure for recycling of conventional vehicles must be sufficient. Cost premium refers to the cost above normal cost for a vehicle purchase before taxes. By battery technology we mean both the technical aspect of range, charging time, life expectancy, weight and size, as well as the economic and strategic aspects of production costs and access to raw materials.

6.2.1 Cost Premium

Most vehicle purchasers will be reluctant to pay a cost premium for a vehicle technology that is as of yet unproven. Vehicle manufacturers and distributors, as well as fuel manufacturers, are likely to take this into account in their strategies. Without any kind of intervention these stakeholders would go on promoting the vehicles and fuels that maximised their profits. The cost premium therefore constitutes a significant barrier. Our selected technologies come with different cost premiums. According to our calculations the BEV might be twice as expensive in the short run as similar conventional vehicles, not accounting for different tax regimes. The PHEV and the HEV have a cost premium of respectively about one half, and one quarter of the BEV. Although these additional costs are expected to drop massively over time, it requires both technological improvement through investments in R&D, and production of scale to lower production costs. The only way to achieve these requirements is through market penetration and hence governmental intervention during the transition phase.

Looking at the big picture it is desirable that less polluting AFVs, given that all else than price is equal, have lower purchase costs and lower variable costs than ICEVs. This will create a shift towards a larger share of the automobile market for AFVs. However, the purchasing price should only be marginally lower in order to avoid an increase in vehicle demand. Likewise, the variable costs, such as fuelling and variable taxes, should only be marginally lower in order to avoid increased consumption and driving activity. As we have mentioned earlier, improvements in technology reducing emissions has had a tendency to be erased by higher driving activity. When choosing which measures to use and the corresponding dosage, governments need to keep in mind that it is likely to be more difficult to reduce the total number of cars subsequently than to limit the growth in new cars being made. Based on the EU emission target and the predicted environmental and economical benefits of quick reduction showed in figure 1-1, we propose measures that quickly increase the relative growth of our suggested technologies while at the same time limit the absolute growth in the total vehicle fleet.

A possible way to achieve these goals is to subsidise purchasers of AFVs, and increase vehicle scrap deposits (under the condition that vehicle purchasers replace the old ICEV with an AFV) in order to replace old, polluting cars with new, and clean cars. A one-sided focus on increasing the number of AFVs would accordingly lead to a supply surplus of second-hand ICEVs. This again implies a drop in prices in the conventional car segment which leads to higher competitiveness of ICEVs compared to AFVs, and vice versa. The implications from this are on one hand that the old technology suddenly becomes affordable for people who would otherwise not drive their own car, and on the other hand that the decline in price of ICEVs would have to be matched by AFVs somehow. We will not go into specific details about how the scrap deposit system should be developed, but still there are a few things that should be added into the equation. The policy measure, here the increased deposit, must not lead to fully usable cars being scrapped. We assume that sufficient infrastructure for recycling of an increasing number of conventional vehicles is in place. However, one has to consider the total environmental benefits of replacing a high-polluting vehicle with one that is low-polluting in a vehicle life-cycle perspective. A potential solution, if developed further (and costs are reduced) could be to rebuild existing ICE vehicles into BE vehicles simply by replacing the engine with an electric motor and batteries. The process is fairly simple, but so far expensive[132]. However, many European cars share the same platform[133] [134] which, in addition to some of the most sold models, could provide an opportunity to develop standardised solutions that are quick, easy and affordable to implement in vehicles. This could provide a valuable contribution as it helps replacing the ICEV in the fleet with BEV faster and without increasing the total number of vehicles, as well as making use of existing vehicles instead of producing new ones. Several policy options could be considered to make this solution viable. A combination of high taxes on driving activities for polluting cars as well as subsidies for replacing the engine could make it profitable for car owners to make the swap.

There are obviously solutions that are costly for governments. Nevertheless, the alternative cost of not acting taken into account, some of the options appear affordable. There are also possibilities where costs are simply reallocated, from environmentally friendly technologies to polluting technologies. An example is increased taxation of polluting vehicles that counterbalance a tax reduction for zero-emission vehicles. Furthermore, as technologies improve, companies produce at scale and AFVs gain a foothold in the market, governments can phase out the introduced benefits. This is important for several reasons including limiting traffic volume, hindering vehicle/fuel manufacturers and distributors from capturing consumer surplus, and avoiding free rider-effects of subsidising efforts that would be made regardless of the support. A combination of eco-taxes and regulations can provide a requested effect. An emission standard for the average production allows vehicle manufacturers to cut emissions where it is cheaper. Combined with an eco-tax governments can provide incentives to reduce pollution further than the emission standard hence contributing to a dynamic development of cleaner technology.

6.2.2 Battery technology

The battery technology is, besides the cost premium, the highest obstacle today. In 2020 the technology is expected to have improved significantly, and this development should be further promoted by the government through investments in R&D. Today, the NIMH battery technology is the most common in new cars, but in 2020, lithium ion batteries are expected to take over. There are different competing technologies, each with strengths and weaknesses. Deutsche Bank (2008) mentions four major categories, *Lithium Nickel Cobalt Aluminum (NCA), Lithium Manganese Spinel (LMO), Lithium Titanate (LMO/LTO) and Lithium Iron Phosphate (LFP).* Since it is probably too early to pick a winner today, an open approach supporting several alternatives is suitable. Although standardisation towards one technology could be great for the process innovation, other technologies may have higher product innovation potential. We are here talking not only about lithium ion technologies, but also other technologies that may have higher potential and might be extracted in Europe. Therefore, continued diversified R&D should be maintained. The batteries are expected to offer longer range and life expectancy, faster charging; and reduced size, weight and costs compared to today. R&D policies can help to speed up the development making especially PHEVs and BEVs both affordable and technologically superior to conventional vehicles.

Policy options that can help stimulate a diversified and strong research on the battery technology for AFVs is mostly related to whether to consider research by different firms or organisations on different technologies on equal terms or to pick winners. If some technologies stand out positively, the government should allow for increased support to start mass production until the technology is competitive. In the end, fewer technologies allow for economies of scale, but a few competing technologies will be healthy in order to avoid monopoly situations, insufficient markets and reduced investments in R&D by companies.

Regarding R&D subsidies the governments need to state clear goals for what they want to achieve with regards to the electric vehicle and battery technology, and within which time frames. These goals need to be followed up. Without a specific roadmap, it will be difficult to follow the right path. This will also make investors believe in the idea, and be willing to invest in research, in assurance of that they are on the same page as the government.

An element that is connected to the battery technology is the lithium resources. Based on the current production, we have showed in chapter 5.3.5 that the current lithium production is far too low to allow for large scale production of BEV today. Even with a high increase towards 2020, the supply will be limited. In addition to investing in different technologies and innovations as mentioned above, to secure current imports of Lithium will be a key element for European governments. Bolivia has the largest potential for lithium supply today, but mostly for political reasons, they have not been able to start a production[135]. The EU could therefore promote foreign investments in the country, and also offer expertise to Bolivia to try to overcome existing barriers. This may however be difficult, since Bolivia currently are nationalising companies, and may not be willing to let foreigners gain control over their lithium resources. However, a mutually beneficial joint venture with the Bolivian government, where the EU focuses on helping Bolivia develop lithium mining and production, and in return is ensured supply, should be possible. The same strategy can also be used in Russia, who may have large lithium deposits. Lithium is also available within the EU, and the local governments can focus on own production, for instance utilizing the reserves in Finland. One way to help lithium mining would be to consider softening regulations. To get permission for mining is often a complicated and time consuming process. However, a full evaluation must be done, accounting for the positive and negative effects. To map all potential lithium recourses in Europe would be one important initiative to initiate activity.

Another promising alternative would be to try to improve the recycling process of lithium. The governments can do this by developing more recycling stations and improving the recycling processes. Creating public awareness is also important in order to make inhabitants deposit laptops, mobile phones and MP3 players at the recycling stations, instead of throwing them in the garbage or storing them at home. A recycling incentive would be in place, paying the consumers to return their products. Electronic stores should be prohibited to accept return of electronic equipment, and recycle them properly, as is the practice in for instance Norway.

6.2.3 Infrastructure

The need for investments in infrastructure is relatively limited, especially in comparison with some of the other AFVs. As long as there is one common standard for the outlet[136] and the vehicles are equipped with converters, you can charge the PHEV and BEV practically anywhere by the use of an extension cord. Based on the average daily driving distance of Europeans, both the PHEV and the BEV can (despite of limited range and long charging time), provide sufficient range for most people to charge their vehicles at home during the night. Nevertheless, in addition to travelling to and from work many use their cars for weekend trips or holidays where longer range is needed. In these cases there must be available charging posts, parking meters with electrical installations, i.e. at traditional fuelling stations or parking lots. Today these posts are typically found at organised camping sites to provide electricity for light, heating and cooking, and at some private or public parking lots intended for engine block heaters during cold winters. Governments can easily encourage or require fuelling stations and private parking companies to provide this service, although this probably will be unnecessary as it is a low-cost effort that attracts more customers. Local authorities can install charging posts at public parking lots and build dedicated parking bays for plug-ins and electrics. Furthermore governments at all levels can offer charging posts at parking spaces for their employees as well as encourage companies to do the same. In London, posts for on-street-parking, which is much the same as parking meters, have been installed to work safely[137]. This could also be a suitable solution for people that are obstructed from pulling an extension cord from their apartment or house to the parking space.

As for battery replacement stations the investment costs are far higher. The main benefit of this technology is that “refuelling” takes about the same time as refuelling a regular ICEV; the car enters a lane and the depleted battery is replaced by a fully-charged battery, all in an automatic process which takes only a few minutes[138]. This technology is developed by the company *Better Place* and is limited to a few platforms. Whether the governments should support the development of this infrastructure is questionable. Quick-chargers that allow PHEVs and BEVs to regain a large part of their battery capacity in ten minutes provide practically the same service and seem like a better investment that governments should make. Installing quick-chargers may constitute the largest infrastructural investment; however, dedicated parking bays provide the opportunity for a “quantity discount”.

Other infrastructural measures can be used to favour AFVs like the BEV. One example is granting access to public transport lanes. This could typically benefit people driving home from work during rush-hours; a quite common problem in many European cities. Such a measure would provide incentives to either replace the old ICEV with a BEV, or purchase a BEV as a second car meant for city driving. If successful it could effectively contribute to better air quality in urban areas. Other examples are free parking and exemptions from city centre (congestion charge), bridge and tunnel tolls, that impose costs to regular ICEVs. These incentives would naturally, as we have mentioned earlier, have to be phased out gradually as BEVs increase market share. Kendall (2008) claims that combined savings from congestion charge exemptions, parking, and fuel economy can amount to as much as £30 (app. €35) per day for daily commuters to central London.

Structural barriers related to our selected technologies are manageable within reasonable costs and efforts and may be somewhat psychological rather than practical. Policy options need to address both these issues. Governments can create incentives that benefit our solution as we have discussed in the section on *cost premium*.

There are some important, general barriers that need investigation by governments. We will merely comment on some of them briefly. A very important aspect is the flow of information about AFVs, especially to purchasers and investors. In order to gain public acceptance, people need to know about the products and that the vehicles are safe and reliable. Developing European standard measurements of AFVs such as those existing for conventional vehicles can help provide this acceptance. Additionally, in order to set an example, governments at all levels can replace parts of or their entire vehicle fleets with AFVs, as well as make a visible statement showing that these vehicles can meet the requirements of the purchasers. Furthermore, governments can encourage and stimulate large fleet owners like taxi companies, postal services, delivery agencies, leasing companies, rental car companies, etc. to convert, either through setting minimum standards for the AFV share of the fleet, or through providing incentives such as lower vehicle taxes, company car tax deduction and green certificates. Such a measure would make AFVs more visible to the public. Another important general aspect is the need for collaboration between government and the stakeholders to avoid resistance and instead create a mutually beneficial joint venture. A use of voluntary agreements can contribute to more stakeholder ownership of strategies. Again the need for clear, common, long-term goals should be communicated from the governments to ensure predictability for investors. This demands credible policy makers.

To sum up, in this section we have highlighted the need to reduce the cost premium for vehicle purchasers which is directly linked to improvement in vehicle and battery technology. Furthermore we have argued the need for appropriate infrastructure to avoid the chicken-and-egg dilemma. This aspect is especially important with regards to other alternative fuels, such as hydrogen, CNG and biofuels. Finally we have indicated some important general barriers and possible solutions.

7. Conclusions and Recommendations

This master’s thesis has assessed a selection of alternative fuel vehicle technologies for the European mass market based on four dimensions: economy, efficiency, environment and technology. Furthermore, a stakeholder approach attempting to identify transition barriers for the most promising AFVs was used. Finally a selection of appropriate government policy measures that can reduce or eliminate the barriers is suggested.

A GREET model contextualised in a European perspective has been employed to narrow 75 alternatives down to four different fuels in eight different vehicle combinations, and evaluate the appropriateness of these within 2020. Since we believe that biomass is better utilised in power plants for electricity generation rather than as biofuels in cars, and biofuels alternatively can be blended into normal fuel, we did not choose any bioful vehicles. Using a payback analysis we found the plug-in hybrid electric vehicle to have the shortest payback period in 2020. Regarding energy efficiency, the battery electric vehicle was the most promising. The BEV and fuel cell vehicle were tied in both energy consumption and green house gas emissions. The normal petrol engine showed the highest increase in technology improvement thanks to switching to a direct injection fuelling system in 2020, followed by the BEV and FCV.

Based on these performances, we proposed some target scenarios with different vehicle mixes. We chose not to include the FCV due to uncertainties and high infrastructural costs. We proposed mixes between HEVs, PHEVs and BEVs, and showed how these mixes could potentially reduce tailpipe GHGs with over 50 % compared to a fleet running on petrol and diesel in 2020. Although a vehicle fleet consisting solely of BEVs would be the optimal scenario in an environmental perspective, limitations in production and a high cost premium makes it highly unlikely within our timeframe.

Based upon our findings identified potential barriers. The main barriers for our selected technologies were the relatively high vehicle purchase prices, the limited performance of the existing battery technology, and the potentially costly development of sufficient quick-charger infrastructure. Additionally we identified general barriers such as the degree of public acceptance of AFVs and the cooperation between policy makers and stakeholders.

As for the cost premium for AFVs, reduced vehicle purchase tax, subsidies and increased vehicle scrap deposits are suggested policies as well as fuel taxes and emission taxes that favour clean vehicles over polluting. In addition, governments should invest in R&D seeking to reduce production costs. The goal is to replace conventional vehicles with our selected technologies without increasing the total vehicle fleet. As the new technologies gain a foothold in the market the incentives should gradually be phased out.

The battery technology has limitations regarding production costs and performance. We recommend that governments support diversified R&D of several technologies and allow for increased support of those on the tipping-point of becoming competitive and ready for mass production. Further we suggest that European governments, vehicle manufacturers and investors develop strategies for mass production of lithium in Europe, Russia and Bolivia. Finally, improving recycling processes of lithium as well as public awareness campaigns directed towards making people deposit laptops, mp3 players and mobile phones at recycling stations should ensure better utilisation.

Infrastructure is regarded as a relatively manageable barrier as our selected technologies require little more than a wall outlet. However, due to long charging time we expect installing a network of quick-chargers to boost the sale. Additionally we encourage governments to provide incentives such as free, dedicated parking bays, access to public transportation lanes and exemptions from city centre, bridge and tunnel tolls for zero-emission vehicles.

To increase public acceptance, we suggest governments replace parts of their fleet with AFVs and encourage large fleet owners to do the same in order to make AFVs more visible.

Our final recommendation focuses on the need for a broad communicative cooperation between policy makers and stakeholders attempting to find the most suitable solutions. Clear, credible long-term strategies need to be communicated by the governments in order to create a predictable environment for investors.

8. Further research

Throughout our study we have obtained more sophisticated knowledge to answer our initial research questions. However, during the process we have generated more questions. In this chapter we will propose some ideas that could be interesting to investigate in future studies.

One suggestion could be to take our usage of the GREET model further, and to develop a complete model adapted to the European market. Although we made adjustments, we did not change all aspects separating the US and Europe. A sensitivity analysis based on the main variables in GREET could also be interesting to perform, by changing for instance mpg, electricity mixes, and Well-to-Plant efficiencies. The possibility of changing more variables could also be interesting i.e. accounting for different weight and size based on the different vehicles.

Another idea could be to study the effects of biofuels closer. Although there already is thorough research being done in a European context, by e.g. the Joint Research Centre, the opinions about biofuels are divided. It could be especially interesting to investigate the climate effects of biomass used in electricity production compared to the usage of biofuels in vehicles. It could be interesting to establish why the EU has a 10 % target for biofuels by 2020, instead of a 10 % equivalent biomass share, as the EEA (European Environment Agency) is eager to suspend this target[139]. Maybe an action-oriented study on biofuels in Sweden or Brazil could be of interest.

A comparative study of FCVs and BEVs could also be interesting to look closer into. How will the BEV and FCV perform based on different fuel sources? How are they expected to develop in medium to long term? If both technologies make use of 100 % renewable energy sources, how will this affect the comparison?

In our opinion, the environmental issue is the most important aspect considering different technologies. To do a survey study could be fruitful in order to see which dimension the different stakeholder groups would consider as the most important? It would also be interesting to see which barriers the stakeholders see for the different technologies, and if there are important differences between countries.

Moving more directly into the political context we wonder whether a nation's vehicle production influence government tax regimes. Will a nation with a large current automobile production, like Germany, have incentives to propose less environmentally strict laws than as a nation that focuses on BEVs, like Norway? And how will a nation without vehicle production act?

We have emphasised battery technologies, but it is clear that a more thorough research is needed. Which battery technologies have the highest potential in 2010, or in 2020? Assessing lithium Ion, NIMH, Sodium Nickel Chloride battery (NaNiCl) and the Zinc – Air battery (ZnAir) could be one interesting suggestion. And finally, what will be of most importance for the consumers, vehicle range or charging time?

It would also be interesting to explore how price-sensitive the vehicle purchasers are. We have calculated the payback in our analysis, but we do not know how these numbers would affect consumers' decisions. How do they assess a price premium versus a lower fuel cost? How important will the infrastructure be for potential BEV customers? Will it impact the PHEV at all?

Further research into how a sharp decrease in fuel price will influence the average annual driving distance of BEVs would be interesting to undertake. What would be the optimal tax regime for minimising GHG emissions, when customers can chose freely among technologies?

Appendices

2. Well-to-Wheels Energy Consumption and Emissions: per Mile

2010

Gasoline Vehicle: CG and RFG

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	245	916	4 688	5 849	4,2%	15,7%	80,1%
Fossil Fuels	235	815	4 590	5 640	4,2%	14,5%	81,4%
Coal	21	129	0	150	14,2%	85,8%	0,0%
Natural Gas	154	289	0	442	34,7%	65,3%	0,0%
Petroleum	60	398	4 590	5 047	1,2%	7,9%	90,9%
CO2 (w/ C ir	15	61	360	436	3,4%	14,0%	82,6%
CH4	0,436	0,072	0,011	0,519	84,0%	13,9%	2,0%
N2O	0,000	0,005	0,012	0,017	2,3%	28,4%	69,3%
GHGs	26	64	364	454	5,7%	14,2%	80,1%
VOC: Total	0,016	0,112	0,152	0,280	5,9%	39,8%	54,3%
CO: Total	0,031	0,036	3,492	3,558	0,9%	1,0%	98,1%
NOx: Total	0,115	0,106	0,069	0,290	39,6%	36,6%	23,8%
PM10: Total	0,007	0,038	0,029	0,073	9,7%	51,3%	38,9%
PM2.5: Total	0,004	0,014	0,015	0,033	11,7%	43,6%	44,7%
SOx: Total	0,037	0,070	0,006	0,112	32,8%	62,0%	5,2%
VOC: Urban	0,003	0,070	0,095	0,167	1,6%	41,9%	56,5%
CO: Urban	0,001	0,017	2,172	2,190	0,1%	0,8%	99,2%
NOx: Urban	0,005	0,044	0,043	0,092	5,5%	47,8%	46,7%
PM10: Urban	0,000	0,008	0,018	0,026	0,8%	31,8%	67,4%
PM2.5: Urbar	0,000	0,005	0,009	0,014	1,0%	34,3%	64,7%
SOx: Urban	0,003	0,031	0,004	0,038	9,1%	81,3%	9,6%

2. Well-to-Wheels Energy Consumption and Emissions: per Mile

2020

Gasoline Vehicle: CG and RFG

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	243	864	3 787	4 894	5,0%	17,7%	77,4%
Fossil Fuels	234	714	3 627	4 576	5,1%	15,6%	79,3%
Coal	18	116	0	133	13,3%	86,7%	0,0%
Natural Gas	168	272	0	440	38,3%	61,7%	0,0%
Petroleum	48	327	3 627	4 002	1,2%	8,2%	90,6%
CO2 (w/ C ir	10	53	291	353	2,7%	15,0%	82,3%
CH4	0,357	0,066	0,010	0,433	82,3%	15,3%	2,4%
N2O	0,000	0,007	0,012	0,019	1,9%	35,2%	62,9%
GHGs	19	57	294	370	5,0%	15,3%	79,7%
VOC: Total	0,013	0,093	0,150	0,256	5,2%	36,2%	58,6%
CO: Total	0,024	0,030	3,460	3,514	0,7%	0,9%	98,5%
NOx: Total	0,083	0,080	0,069	0,233	35,7%	34,6%	29,7%
PM10: Total	0,006	0,032	0,029	0,067	8,6%	48,4%	43,0%
PM2.5: Total	0,003	0,012	0,015	0,030	10,5%	39,6%	49,9%
SOx: Total	0,028	0,051	0,005	0,084	33,5%	60,8%	5,7%
VOC: Urban	0,002	0,057	0,093	0,152	1,5%	37,2%	61,4%
CO: Urban	0,001	0,013	2,152	2,167	0,0%	0,6%	99,3%
NOx: Urban	0,004	0,031	0,043	0,077	4,9%	39,6%	55,5%
PM10: Urban	0,000	0,006	0,018	0,024	0,6%	24,2%	75,2%
PM2.5: Urbar	0,000	0,003	0,009	0,013	0,8%	26,7%	72,5%
SOx: Urban	0,003	0,020	0,003	0,026	10,0%	78,5%	11,5%

2010

CIDI Vehicle: Conventional and LS Diesel

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	204	543	3 906	4 653	4,4%	11,7%	83,9%
Fossil Fuels	195	532	3 906	4 634	4,2%	11,5%	84,3%
Coal	18	81	0	99	18,0%	82,0%	0,0%
Natural Gas	128	174	0	302	42,4%	57,6%	0,0%
Petroleum	50	278	3 906	4 234	1,2%	6,6%	92,3%
CO2 (w/ C ir	19	40	309	367	5,0%	10,9%	84,1%
CH4	0,363	0,044	0,003	0,410	88,5%	10,8%	0,6%
N2O	0,000	0,001	0,012	0,013	2,6%	4,8%	92,6%
GHGs	28	41	313	382	7,3%	10,8%	81,9%
VOC: Total	0,014	0,017	0,060	0,090	15,2%	18,3%	66,5%
CO: Total	0,026	0,023	0,534	0,583	4,4%	4,0%	91,6%
NOx: Total	0,096	0,070	0,080	0,246	38,9%	28,5%	32,5%
PM10: Total	0,006	0,023	0,030	0,059	10,1%	39,7%	50,2%
PM2.5: Total	0,003	0,009	0,016	0,028	11,5%	32,6%	55,9%
SOx: Total	0,031	0,047	0,002	0,079	38,6%	58,7%	2,7%
VOC: Urban	0,002	0,009	0,037	0,049	4,7%	19,2%	76,1%
CO: Urban	0,001	0,012	0,332	0,346	0,3%	3,6%	96,1%
NOx: Urban	0,004	0,032	0,050	0,086	4,9%	37,2%	57,9%
PM10: Urban	0,000	0,006	0,018	0,025	0,7%	24,7%	74,6%
PM2.5: Urbar	0,000	0,004	0,010	0,013	0,9%	26,3%	72,9%
SOx: Urban	0,003	0,023	0,001	0,027	10,5%	84,7%	4,8%

2020

CIDI Vehicle: Conventional and LS Diesel

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	203	440	3 156	3 798	5,3%	11,6%	83,1%
Fossil Fuels	195	432	3 156	3 783	5,2%	11,4%	83,4%
Coal	15	65	0	80	18,6%	81,4%	0,0%
Natural Gas	140	142	0	283	49,6%	50,4%	0,0%
Petroleum	40	224	3 156	3 420	1,2%	6,6%	92,3%
CO2 (w/ C ir	18	32	250	300	6,0%	10,8%	83,3%
CH4	0,297	0,036	0,003	0,335	88,6%	10,7%	0,8%
N2O	0,000	0,001	0,012	0,013	2,4%	3,9%	93,7%
GHGs	25	33	253	312	8,1%	10,7%	81,2%
VOC: Total	0,011	0,013	0,060	0,084	13,2%	15,8%	71,1%
CO: Total	0,020	0,019	0,534	0,573	3,4%	3,3%	93,3%
NOx: Total	0,069	0,049	0,080	0,199	34,9%	24,9%	40,3%
PM10: Total	0,005	0,018	0,030	0,052	9,2%	33,9%	56,8%
PM2.5: Total	0,003	0,007	0,016	0,025	10,4%	26,9%	62,7%
SOx: Total	0,023	0,032	0,002	0,057	41,2%	55,7%	3,0%
VOC: Urban	0,002	0,008	0,037	0,047	3,9%	16,2%	79,8%
CO: Urban	0,001	0,010	0,332	0,343	0,2%	2,9%	96,9%
NOx: Urban	0,003	0,022	0,050	0,075	4,2%	29,5%	66,3%
PM10: Urban	0,000	0,004	0,018	0,023	0,5%	18,4%	81,1%
PM2.5: Urbar	0,000	0,002	0,010	0,012	0,7%	19,9%	79,4%
SOx: Urban	0,002	0,015	0,001	0,019	11,6%	82,7%	5,7%

2010

Grid-Independent SI HEV: CG and RFG

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	175	654	3 348	4 178	4,2%	15,7%	80,1%
Fossil Fuels	168	582	3 279	4 029	4,2%	14,5%	81,4%
Coal	15	92	0	107	14,2%	85,8%	0,0%
Natural Gas	110	206	0	316	34,7%	65,3%	0,0%
Petroleum	43	284	3 279	3 605	1,2%	7,9%	90,9%
CO2 (w/ C ir	11	44	257	311	3,4%	14,0%	82,6%
CH4	0,311	0,052	0,005	0,368	84,6%	14,0%	1,4%
N2O	0,000	0,004	0,012	0,016	1,8%	22,3%	75,9%
GHGs	19	46	261	325	5,7%	14,1%	80,2%
VOC: Total	0,012	0,080	0,108	0,200	5,9%	39,9%	54,2%
CO: Total	0,022	0,025	3,492	3,539	0,6%	0,7%	98,7%
NOx: Total	0,082	0,076	0,058	0,216	38,0%	35,1%	26,9%
PM10: Total	0,005	0,027	0,029	0,061	8,4%	44,4%	47,2%
PM2.5: Total	0,003	0,010	0,015	0,028	10,0%	37,0%	53,1%
SOx: Total	0,026	0,050	0,004	0,080	32,8%	62,0%	5,2%
VOC: Urban	0,002	0,050	0,067	0,119	1,6%	41,9%	56,4%
CO: Urban	0,001	0,012	2,172	2,185	0,0%	0,5%	99,4%
NOx: Urban	0,004	0,031	0,036	0,071	5,1%	44,1%	50,7%
PM10: Urban	0,000	0,006	0,018	0,024	0,6%	25,1%	74,3%
PM2.5: Urbar	0,000	0,003	0,009	0,013	0,8%	27,2%	72,0%
SOx: Urban	0,002	0,022	0,003	0,027	9,1%	81,3%	9,6%

2020

Grid-Independent SI HEV: CG and RFG

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	174	617	2 705	3 496	5,0%	17,7%	77,4%
Fossil Fuels	167	510	2 591	3 268	5,1%	15,6%	79,3%
Coal	13	83	0	95	13,3%	86,7%	0,0%
Natural Gas	120	194	0	314	38,3%	61,7%	0,0%
Petroleum	34	233	2 591	2 859	1,2%	8,2%	90,6%
CO2 (w/ C ir	7	38	208	252	2,7%	15,0%	82,3%
CH4	0,255	0,047	0,005	0,307	83,0%	15,4%	1,6%
N2O	0,000	0,005	0,012	0,017	1,5%	28,1%	70,3%
GHGs	13	40	211	265	5,0%	15,3%	79,7%
VOC: Total	0,010	0,066	0,107	0,183	5,2%	36,2%	58,6%
CO: Total	0,017	0,022	3,460	3,499	0,5%	0,6%	98,9%
NOx: Total	0,059	0,057	0,058	0,175	34,0%	32,9%	33,2%
PM10: Total	0,004	0,023	0,029	0,056	7,4%	41,3%	51,3%
PM2.5: Total	0,002	0,008	0,015	0,025	8,8%	33,0%	58,2%
SOx: Total	0,020	0,037	0,003	0,060	33,5%	60,8%	5,7%
VOC: Urban	0,002	0,040	0,067	0,109	1,5%	37,2%	61,4%
CO: Urban	0,001	0,010	2,152	2,162	0,0%	0,4%	99,5%
NOx: Urban	0,003	0,022	0,036	0,061	4,4%	36,1%	59,5%
PM10: Urban	0,000	0,004	0,018	0,022	0,5%	18,6%	80,9%
PM2.5: Urbar	0,000	0,002	0,009	0,012	0,6%	20,7%	78,7%
SOx: Urban	0,002	0,015	0,002	0,019	10,0%	78,5%	11,5%

2010

Grid-Independent CIDI HEV: Conventional and LS Diesel

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	153	407	2 930	3 490	4,4%	11,7%	83,9%
Fossil Fuels	147	399	2 930	3 476	4,2%	11,5%	84,3%
Coal	13	61	0	74	18,0%	82,0%	0,0%
Natural Gas	96	130	0	226	42,4%	57,6%	0,0%
Petroleum	37	208	2 930	3 175	1,2%	6,6%	92,3%
CO2 (w/ C ir	14	30	232	276	5,0%	10,9%	84,1%
CH4	0,272	0,033	0,003	0,308	88,3%	10,8%	0,8%
N2O	0,000	0,000	0,012	0,013	2,0%	3,7%	94,4%
GHGs	21	31	235	287	7,2%	10,8%	82,0%
VOC: Total	0,010	0,012	0,047	0,069	14,8%	17,8%	67,4%
CO: Total	0,019	0,018	0,534	0,571	3,4%	3,1%	93,5%
NOx: Total	0,072	0,053	0,070	0,194	37,0%	27,1%	35,9%
PM10: Total	0,004	0,018	0,030	0,051	8,7%	34,0%	57,3%
PM2.5: Total	0,002	0,007	0,016	0,025	9,7%	27,5%	62,8%
SOx: Total	0,023	0,035	0,002	0,060	38,6%	58,7%	2,7%
VOC: Urban	0,002	0,007	0,029	0,038	4,5%	18,6%	76,8%
CO: Urban	0,001	0,009	0,332	0,342	0,2%	2,7%	97,1%
NOx: Urban	0,003	0,024	0,043	0,070	4,5%	34,0%	61,5%
PM10: Urban	0,000	0,005	0,018	0,023	0,5%	19,8%	79,7%
PM2.5: Urbar	0,000	0,003	0,010	0,012	0,7%	21,1%	78,2%
SOx: Urban	0,002	0,017	0,001	0,021	10,5%	84,7%	4,8%

2020

Grid-Independent CIDI HEV: Conventional and LS Diesel

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	152	330	2 367	2 849	5,3%	11,6%	83,1%
Fossil Fuels	146	324	2 367	2 837	5,2%	11,4%	83,4%
Coal	11	49	0	60	18,6%	81,4%	0,0%
Natural Gas	105	107	0	212	49,6%	50,4%	0,0%
Petroleum	30	168	2 367	2 565	1,2%	6,6%	92,3%
CO2 (w/ C ir	13	24	187	225	6,0%	10,8%	83,3%
CH4	0,223	0,027	0,003	0,252	88,3%	10,6%	1,0%
N2O	0,000	0,000	0,012	0,013	1,8%	3,0%	95,2%
GHGs	19	25	191	235	8,1%	10,6%	81,3%
VOC: Total	0,008	0,010	0,047	0,065	12,8%	15,3%	71,9%
CO: Total	0,015	0,014	0,534	0,563	2,6%	2,5%	94,9%
NOx: Total	0,052	0,037	0,070	0,159	32,7%	23,3%	43,9%
PM10: Total	0,004	0,013	0,030	0,046	7,8%	28,5%	63,7%
PM2.5: Total	0,002	0,005	0,016	0,023	8,6%	22,3%	69,1%
SOx: Total	0,018	0,024	0,001	0,043	41,2%	55,7%	3,0%
VOC: Urban	0,001	0,006	0,029	0,036	3,8%	15,7%	80,4%
CO: Urban	0,001	0,007	0,332	0,340	0,2%	2,2%	97,6%
NOx: Urban	0,002	0,017	0,043	0,062	3,8%	26,7%	69,5%
PM10: Urban	0,000	0,003	0,018	0,022	0,4%	14,5%	85,1%
PM2.5: Urbar	0,000	0,002	0,010	0,012	0,5%	15,7%	83,7%
SOx: Urban	0,002	0,012	0,001	0,014	11,6%	82,7%	5,7%

2010

Grid-Connected SI PHEV: CG and RFG

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	147	1 017	2 352	3 516	4,2%	28,9%	66,9%
Fossil Fuels	141	831	2 201	3 173	4,5%	26,2%	69,4%
Coal	13	334	220	567	2,3%	58,9%	38,8%
Natural Gas	89	283	153	525	17,0%	53,9%	29,2%
Petroleum	39	214	1 828	2 081	1,9%	10,3%	87,8%
CO2 (w/ C ir	10	108	139	256	3,8%	42,0%	54,2%
CH4	0,297	0,030	0,005	0,332	89,5%	9,0%	1,5%
N2O	0,000	0,003	0,012	0,015	1,6%	20,4%	78,0%
GHGs	17	109	142	269	6,4%	40,6%	53,0%
VOC: Total	0,013	0,045	0,108	0,166	7,8%	27,0%	65,2%
CO: Total	0,017	0,035	3,492	3,545	0,5%	1,0%	98,5%
NOx: Total	0,064	0,125	0,058	0,247	26,0%	50,5%	23,4%
PM10: Total	0,089	0,019	0,044	0,153	58,5%	12,7%	28,8%
PM2.5: Total	0,023	0,008	0,020	0,052	44,8%	16,1%	39,1%
SOx: Total	0,024	0,238	0,002	0,265	9,2%	89,9%	0,9%
VOC: Urban	0,001	0,028	0,067	0,096	1,4%	28,7%	69,9%
CO: Urban	0,001	0,012	2,172	2,185	0,0%	0,6%	99,4%
NOx: Urban	0,003	0,038	0,036	0,077	4,4%	48,8%	46,7%
PM10: Urban	0,000	0,004	0,027	0,032	0,7%	13,2%	86,1%
PM2.5: Urbar	0,000	0,003	0,013	0,015	0,9%	16,5%	82,6%
SOx: Urban	0,002	0,062	0,001	0,065	3,5%	94,3%	2,2%

2020

Grid-Connected SI PHEV: CG and RFG

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	154	987	2 153	3 293	4,7%	30,0%	65,4%
Fossil Fuels	148	782	1 972	2 902	5,1%	26,9%	68,0%
Coal	12	315	215	542	2,2%	58,2%	39,6%
Natural Gas	101	268	144	513	19,7%	52,3%	28,0%
Petroleum	36	198	1 614	1 847	1,9%	10,7%	87,4%
CO2 (w/ C ir	8	102	125	235	3,3%	43,6%	53,1%
CH4	0,274	0,030	0,005	0,309	88,6%	9,8%	1,6%
N2O	0,000	0,004	0,012	0,016	1,5%	25,1%	73,5%
GHGs	15	104	128	247	5,9%	42,2%	51,9%
VOC: Total	0,012	0,041	0,107	0,161	7,4%	25,8%	66,8%
CO: Total	0,015	0,034	3,460	3,509	0,4%	1,0%	98,6%
NOx: Total	0,051	0,108	0,058	0,217	23,5%	49,8%	26,7%
PM10: Total	0,085	0,018	0,044	0,147	57,6%	12,5%	29,9%
PM2.5: Total	0,022	0,008	0,020	0,050	44,0%	15,4%	40,6%
SOx: Total	0,021	0,197	0,002	0,220	9,6%	89,5%	0,9%
VOC: Urban	0,001	0,025	0,067	0,093	1,4%	26,7%	71,9%
CO: Urban	0,001	0,011	2,152	2,164	0,0%	0,5%	99,4%
NOx: Urban	0,003	0,032	0,036	0,071	3,9%	45,1%	51,0%
PM10: Urban	0,000	0,003	0,027	0,031	0,6%	10,9%	88,5%
PM2.5: Urbar	0,000	0,002	0,013	0,015	0,8%	14,0%	85,2%
SOx: Urban	0,002	0,052	0,001	0,055	3,4%	94,2%	2,3%

2010

Grid-Connected CIDI PHEV: Conventional and LS Diesel

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	141	915	2 209	3 264	4,3%	28,0%	67,7%
Fossil Fuels	135	758	2 091	2 984	4,5%	25,4%	70,1%
Coal	13	328	227	567	2,2%	57,7%	40,0%
Natural Gas	85	251	158	494	17,2%	50,8%	32,1%
Petroleum	37	180	1 706	1 923	1,9%	9,4%	88,7%
CO2 (w/ C ir	12	104	131	246	4,8%	42,1%	53,1%
CH4	0,287	0,021	0,001	0,308	92,9%	6,7%	0,4%
N2O	0,000	0,002	0,012	0,014	1,7%	11,2%	87,1%
GHGs	19	105	134	258	7,4%	40,5%	52,1%
VOC: Total	0,013	0,009	0,047	0,068	18,4%	13,1%	68,5%
CO: Total	0,016	0,032	0,534	0,582	2,8%	5,5%	91,7%
NOx: Total	0,061	0,117	0,070	0,247	24,7%	47,1%	28,1%
PM10: Total	0,092	0,015	0,045	0,152	60,6%	9,8%	29,6%
PM2.5: Total	0,024	0,007	0,021	0,052	46,1%	13,0%	40,9%
SOx: Total	0,023	0,238	0,001	0,263	8,9%	90,7%	0,3%
VOC: Urban	0,001	0,005	0,029	0,035	3,7%	13,2%	83,1%
CO: Urban	0,001	0,011	0,332	0,344	0,3%	3,3%	96,5%
NOx: Urban	0,003	0,035	0,043	0,081	4,0%	42,8%	53,1%
PM10: Urban	0,000	0,004	0,028	0,032	0,7%	11,2%	88,1%
PM2.5: Urbar	0,000	0,002	0,013	0,015	0,9%	13,9%	85,2%
SOx: Urban	0,002	0,061	0,001	0,064	3,5%	95,6%	0,9%

2020

Grid-Connected CIDI PHEV: Conventional and LS Diesel

	Btu/mile or grams/mile				Percentage of each stage		
Item	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	147	839	2 044	3 031	4,9%	27,7%	67,5%
Fossil Fuels	142	692	1 929	2 763	5,1%	25,0%	69,8%
Coal	11	303	219	533	2,1%	56,7%	41,1%
Natural Gas	96	223	147	466	20,6%	47,9%	31,5%
Petroleum	35	166	1 563	1 763	2,0%	9,4%	88,6%
CO2 (w/ C ir	12	97	120	229	5,4%	42,3%	52,3%
CH4	0,265	0,019	0,001	0,286	92,9%	6,6%	0,4%
N2O	0,000	0,001	0,012	0,014	1,7%	10,8%	87,6%
GHGs	19	98	123	240	7,9%	40,7%	51,4%
VOC: Total	0,012	0,008	0,047	0,066	17,4%	12,1%	70,5%
CO: Total	0,014	0,030	0,534	0,578	2,5%	5,2%	92,3%
NOx: Total	0,049	0,099	0,070	0,217	22,4%	45,5%	32,1%
PM10: Total	0,086	0,013	0,045	0,144	59,8%	9,1%	31,1%
PM2.5: Total	0,022	0,006	0,021	0,049	45,1%	12,0%	42,8%
SOx: Total	0,020	0,194	0,001	0,216	9,5%	90,1%	0,4%
VOC: Urban	0,001	0,004	0,029	0,035	3,5%	12,1%	84,4%
CO: Urban	0,001	0,011	0,332	0,344	0,2%	3,1%	96,7%
NOx: Urban	0,003	0,030	0,043	0,076	3,5%	39,2%	57,2%
PM10: Urban	0,000	0,003	0,028	0,031	0,6%	9,4%	90,0%
PM2.5: Urbar	0,000	0,002	0,013	0,015	0,8%	11,9%	87,3%
SOx: Urban	0,002	0,052	0,001	0,054	3,4%	95,7%	0,9%

2010
Electric Vehicle

Item	Btu/mile or grams/mile				Percentage of each stage		
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	142	1 792	1 471	3 405	4,2%	52,6%	43,2%
Fossil Fuels	137	1 394	1 164	2 695	5,1%	51,7%	43,2%
Coal	14	766	593	1 373	1,0%	55,8%	43,2%
Natural Gas	81	463	413	957	8,4%	48,4%	43,2%
Petroleum	43	164	157	364	11,8%	45,0%	43,2%
CO2 (w/ C in	11	227	0	237	4,4%	95,6%	0,0%
CH4	0,349	0,005	0,000	0,354	98,5%	1,5%	0,0%
N2O	0,000	0,003	0,000	0,004	6,5%	93,5%	0,0%
GHGs	19	228	0	247	7,8%	92,2%	0,0%
VOC: Total	0,018	0,005	0,000	0,023	77,1%	22,9%	0,0%
CO: Total	0,015	0,058	0,000	0,073	20,3%	79,7%	0,0%
NOx: Total	0,054	0,227	0,000	0,282	19,3%	80,7%	0,0%
PM10: Total	0,233	0,013	0,021	0,267	87,5%	4,9%	7,7%
PM2.5: Total	0,059	0,007	0,007	0,073	79,9%	10,2%	9,9%
SOx: Total	0,028	0,571	0,000	0,598	4,6%	95,4%	0,0%
VOC: Urban	0,001	0,002	0,000	0,003	34,0%	66,0%	0,0%
CO: Urban	0,001	0,016	0,000	0,017	6,8%	93,2%	0,0%
NOx: Urban	0,004	0,056	0,000	0,060	6,5%	93,5%	0,0%
PM10: Urban	0,000	0,003	0,013	0,016	2,4%	16,5%	81,1%
PM2.5: Urban	0,000	0,002	0,005	0,006	3,6%	26,5%	70,0%
SOx: Urban	0,003	0,134	0,000	0,136	1,9%	98,1%	0,0%

2020
Electric Vehicle

Item	Btu/mile or grams/mile				Percentage of each stage		
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	104	1 296	1 114	2 514	4,1%	51,6%	44,3%
Fossil Fuels	101	1 001	876	1 978	5,1%	50,6%	44,3%
Coal	9	559	452	1 020	0,9%	54,8%	44,3%
Natural Gas	60	320	302	683	8,8%	46,9%	44,3%
Petroleum	32	122	122	275	11,5%	44,2%	44,3%
CO2 (w/ C in	8	167	0	175	4,4%	95,6%	0,0%
CH4	0,255	0,004	0,000	0,259	98,5%	1,5%	0,0%
N2O	0,000	0,003	0,000	0,003	6,3%	93,7%	0,0%
GHGs	14	168	0	182	7,7%	92,3%	0,0%
VOC: Total	0,013	0,004	0,000	0,016	78,3%	21,7%	0,0%
CO: Total	0,010	0,043	0,000	0,053	18,4%	81,6%	0,0%
NOx: Total	0,032	0,155	0,000	0,187	17,3%	82,7%	0,0%
PM10: Total	0,173	0,010	0,021	0,203	85,1%	4,8%	10,1%
PM2.5: Total	0,043	0,006	0,007	0,056	77,0%	10,0%	13,0%
SOx: Total	0,019	0,369	0,000	0,388	4,9%	95,1%	0,0%
VOC: Urban	0,001	0,001	0,000	0,002	36,0%	64,0%	0,0%
CO: Urban	0,001	0,012	0,000	0,013	6,6%	93,4%	0,0%
NOx: Urban	0,002	0,039	0,000	0,042	5,7%	94,3%	0,0%
PM10: Urban	0,000	0,002	0,013	0,015	1,6%	13,1%	85,3%
PM2.5: Urban	0,000	0,001	0,005	0,006	2,5%	21,7%	75,8%
SOx: Urban	0,002	0,091	0,000	0,093	1,8%	98,2%	0,0%

2010
FCV: G.H2

Item	Btu/mile or grams/mile				Percentage of each stage		
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	153	1 261	1 981	3 395	4,5%	37,1%	58,3%
Fossil Fuels	151	1 179	1 981	3 311	4,6%	35,6%	59,8%
Coal	3	159	0	162	1,9%	98,1%	0,0%
Natural Gas	139	974	1 981	3 094	4,5%	31,5%	64,0%
Petroleum	9	46	0	55	16,4%	83,6%	0,0%
CO2 (w/ C in	11	197	0	208	5,1%	94,9%	0,0%
CH4	0,472	0,233	0,000	0,705	67,0%	33,0%	0,0%
N2O	0,000	0,001	0,000	0,001	20,0%	80,0%	0,0%
GHGs	23	203	0	226	10,0%	90,0%	0,0%
VOC: Total	0,012	0,012	0,000	0,024	50,5%	49,5%	0,0%
CO: Total	0,017	0,040	0,000	0,057	29,6%	70,4%	0,0%
NOx: Total	0,048	0,088	0,000	0,136	35,1%	64,9%	0,0%
PM10: Total	0,001	0,053	0,021	0,075	2,0%	70,7%	27,3%
PM2.5: Total	0,001	0,032	0,007	0,040	2,5%	79,4%	18,1%
SOx: Total	0,023	0,078	0,000	0,101	22,7%	77,3%	0,0%
VOC: Urban	0,000	0,003	0,000	0,004	8,5%	91,5%	0,0%
CO: Urban	0,001	0,020	0,000	0,020	3,0%	97,0%	0,0%
NOx: Urban	0,002	0,033	0,000	0,035	4,8%	95,2%	0,0%
PM10: Urban	0,000	0,017	0,013	0,030	0,2%	57,3%	42,5%
PM2.5: Urban	0,000	0,017	0,005	0,022	0,2%	78,8%	21,0%
SOx: Urban	0,001	0,016	0,000	0,016	3,4%	96,6%	0,0%

2020
FCV: G.H2

Item	Btu/mile or grams/mile				Percentage of each stage		
	Feedstock	Fuel	Vehicle Operation	Total	Feedstock	Fuel	Vehicle Operation
Total Energy	117	905	1 515	2 537	4,6%	35,7%	59,7%
Fossil Fuels	116	844	1 515	2 474	4,7%	34,1%	61,2%
Coal	2	117	0	120	2,0%	98,0%	0,0%
Natural Gas	106	692	1 515	2 313	4,6%	29,9%	65,5%
Petroleum	7	34	0	41	16,8%	83,2%	0,0%
CO2 (w/ C in	8	147	0	155	5,3%	94,7%	0,0%
CH4	0,361	0,166	0,000	0,528	68,5%	31,5%	0,0%
N2O	0,000	0,001	0,000	0,001	20,3%	79,7%	0,0%
GHGs	17	151	0	169	10,2%	89,8%	0,0%
VOC: Total	0,009	0,009	0,000	0,018	51,5%	48,5%	0,0%
CO: Total	0,012	0,030	0,000	0,042	29,2%	70,8%	0,0%
NOx: Total	0,031	0,060	0,000	0,091	34,4%	65,6%	0,0%
PM10: Total	0,001	0,040	0,021	0,061	1,7%	64,8%	33,5%
PM2.5: Total	0,001	0,024	0,007	0,032	2,1%	75,2%	22,7%
SOx: Total	0,017	0,051	0,000	0,068	25,4%	74,6%	0,0%
VOC: Urban	0,000	0,003	0,000	0,003	8,5%	91,5%	0,0%
CO: Urban	0,000	0,015	0,000	0,015	3,0%	97,0%	0,0%
NOx: Urban	0,001	0,024	0,000	0,025	4,8%	95,2%	0,0%
PM10: Urban	0,000	0,013	0,013	0,026	0,1%	50,7%	49,2%
PM2.5: Urban	0,000	0,013	0,005	0,018	0,2%	74,0%	25,8%
SOx: Urban	0,000	0,011	0,000	0,011	3,6%	96,4%	0,0%

Endnotes

[1] The History of the Automobile < http://inventors.about.com/library/weekly/aacarsassemblya.htm > (10 June 2009)

[2] The History of Electric Vehicles < http://inventors.about.com/library/weekly/aacarselectrica.htm > (10 June 2009)

[3] Petroleum < http://en.wikipedia.org/wiki/Petroleum#History > (10 June 2009)

[4] The History of Electric Vehicles < http://inventors.about.com/library/weekly/aacarselectrica.htm > (10 June 2009)

[5] IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 10

< http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_SPM.pdf > (10 June 2009)

[6] Cars < http://en.wikipedia.org/wiki/Cars > (10 June 2009)

[7] Zero-emissions vehicle < http://en.wikipedia.org/wiki/Zero-emissions_vehicle > (10 June 2009)

[8] Peak oil < http://en.wikipedia.org/wiki/Peak_oil > (10 June 2009)

[9] Hubbert Peak Oil Plot < http://en.wikipedia.org/wiki/File:Hubbert_peak_oil_plot.svg > (10 June 2009)

[10] Hirsch report < http://en.wikipedia.org/wiki/Hirsch_report > (10 June 2009)

[11] The Inevitable Peaking of Oil Production p. 5

< http://www.acus.org/docs/051007-Hirsch_World_Oil_Production.pdf > (10 June 2009)

[12] Oil producing countries < http://en.wikipedia.org/wiki/Oil_producing_countries#Production > (10 June 2009)

[13] Oil producing countries < http://en.wikipedia.org/wiki/Oil_producing_countries#Production > (10 June 2009)

[14] Position of the European Parliament adopted at dirst reading on 17 December 2008 with a view to the adoption of Regulation (EC) No ..//2009 of the European Parliament and of the Council setting emission

performance standards for new passenger cars as part of the Community's integrated approach to reduce C=2 emissions from light-duty vehicles

<http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P6-TA-2008-0609+0+DOC+XML+V0//EN > (07 May 2009)

[15]Alternative fuel vehicle < http://en.wikipedia.org/wiki/Alternative_fuel_vehicle > (11 June 2009)

[16] Promoting alternative fuel vehicles . (2005), APEIS & RISPO
< http://www.iges.or.jp/APEIS/RISPO/spo/pdf/sp5304.pdf >

[17] EU Institutions < http://en.wikipedia.org/wiki/Eu#Institutions > (16 June 2009)

[18] EU institutions and other bodies < http://europa.eu/institutions/index_en.htm > (16 June 2009)

[19] Green papers and white papers < http://europa.eu/documents/comm/index_en.htm > (16 June 2009)

[20] European Commission. Green paper 2007

[21] European Commission. Green paper 2006

[22] European Commission. Green paper 2005

[23] European Environment Agency. Energy and environment in the European Union. Tracking progress towards integration. EEA Report No 8/2006.

[24] European Environment Agency. Climate for a transport change. TERM 2007: indicators tracking transport and environment in the European Union. EEA Report No 1/2008

[25] European Environment Agency. Energy and environment in the European Union. Tracking progress towards integration. EEA Report No 8/2006.

[26] Reducing CO2 emission from light-duty vehicles. European Comission

< http://ec.europa.eu/environment/air/transport/co2/co2_home.htm > (16 June 2009)

[27] Life cycle analysis and assessment < http://www.gdrc.org/uem/lca/life-cycle.html > (05 May 2009)

[28] Life cycle assessment < http://en.wikipedia.org/wiki/Life_cycle_assessment > (05 May 2009)

[29] Life cycle assessment < http://en.wikipedia.org/wiki/Well_to_wheel#Well-to-wheel > (05 May 2009)

[30] Meyer, R. (2007): Mapping the Mind of the Strategist A Quantitative Methodology for Measuring the Strategic Beliefs of Executives. p. 162. ERASMUS RESEARCH INSTITUTE OF MANAGEMENT (ERIM). < http://repub.eur.nl/publications/index/523081633/ > (08 May 2009)

[31] Meyer, R. (2007): Mapping the Mind of the Strategist A Quantitative Methodology for Measuring the Strategic Beliefs of Executives. p. 162. ERASMUS RESEARCH INSTITUTE OF MANAGEMENT (ERIM). http://repub.eur.nl/publications/index/523081633/ (08 May 2009)

[32] The Value Net, < http://www.12manage.com/methods_brandenburger_value_net.html > (17 June 2009)

[33] Porter, Michael E. (1991): Americas green strategy. Scientific American, April 1991, p. 96

[34] Stakeholder < http://en.wikipedia.org/wiki/Stakeholder_(corporate) > (25 May 2009)

[35] The Free Dictionary by Farlex < http://www.thefreedictionary.com/barrier > (16 June 2009)

[36] The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model,

< http://www.transportation.anl.gov/modeling_simulation/GREET/index.html > (08 May 2009)

[37] Introduction to GREET1.8 Excel Model (2008) (08 May 2009)

[38] Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles, (2009) Energy system division, Argonne national laboratory (17 June 2009)

[39] The Dieselization of Europe < http://www.platts.com/Oil/Resources/News%20Features/eurodiesel/index.xml > (12 May 2009)

[40] Watson. M & Nick Vandervell (2004): The future of UK oil refining (12 May 2009)

[41] What is Natural Gas? < http://www.afdc.energy.gov/afdc/fuels/natural_gas_what_is.html > (12 May 2009)

[42] Liquefied Petroleum Gas (LPG), Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG)

< http://www.envocare.co.uk/lpg_lng_cng.htm > (08 May 2009)

[43] Compressed Natural Gas < http://en.wikipedia.org/wiki/Compressed_natural_gas > (08 May 2009)

[44] Liquefied Petroleum Gas < http://en.wikipedia.org/wiki/Liquefied_petroleum_gas > (08 May 2009)

[45] Biofuel < http://en.wikipedia.org/wiki/Biofuels > (08 May 2009)

[46] Howarth, R.W. et al (2009): Rapid assessment on biofuels and environment: overview and key findings. Pages 1-13 in R.W. Howarth and S. Bringezu (eds), Biofuels: Environmental Consequences and Interactions

with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA. < http://cip.cornell.edu/biofuels/ > (08 May 2009)

[47] Edwards, R. et al (2008): Biofuels in the European Context: Facts and Uncertainties. European Commission Joint Research Centre < http://www.jrc.ec.europa.eu/ > (08 May 2009)

[48] Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 < http://ies.jrc.ec.europa.eu/WTW > (08 May 2009)

[49] Biofuel < http://en.wikipedia.org/wiki/Biofuels > (09 May 2009)

[50] Sustainable Bioenergy: A framework for decion Makers. 2007. United nations < http://esa.un.org/un-energy/pdf/susdev.Biofuels.FAO.pdf > (09 May 2009)

[51] Second generation biofuels < http://en.wikipedia.org/wiki/Second_generation_biofuels > (09 May 2009)

[52] Edwards, R. et al (2008): Biofuels in the European Context: Facts and Uncertainties. European Commission Joint Research Centre < http://www.jrc.ec.europa.eu/ > (09 May 2009)

[53] Biofuel < http://en.wikipedia.org/wiki/Biofuels > (09 May 2009)

[54] Biofuel < http://en.wikipedia.org/wiki/Biofuels > (09 May 2009)

[55] Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 < http://ies.jrc.ec.europa.eu/WTW > (09 May 2009)

[56] Biofuel < http://en.wikipedia.org/wiki/Biofuels > (15 May 2009)

[57] Biofuel < http://en.wikipedia.org/wiki/Biofuels > (15 May 2009)

[58] Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 < http://ies.jrc.ec.europa.eu/WTW > (15 May 2009)

[59] Ethanol energy < http://www.journeytoforever.org/ethanol_energy.html > (15 May 2009)

[60] Fuel Properties Comparison Chart < http://www.afdc.energy.gov/afdc/fuels/properties.html > (15 May 2009)

[61] Crunching the Numbers on Alternative Fuels

< http://www.popularmechanics.com/science/earth/2690341.html > (15 May 2009)

[62] First generation biofuels < http://biofuel.org.uk/first-generation-biofuels.html > (15 May 2009)

[63] Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 < http://ies.jrc.ec.europa.eu/WTW > (15 May 2009)

[64] Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 < http://ies.jrc.ec.europa.eu/WTW > (15 May 2009)

[65] Hydrogen Production < http://www.afdc.energy.gov/afdc/fuels/hydrogen_production.html > (19 May 2009)

[66] Hydrogen Alternative < http://www.afdc.energy.gov/afdc/fuels/hydrogen_alternative.html > (19 May 2009)

[67] Kendall, G. 2008: Plugged in- The end of the oil age. WWF-World Wide Fund for Nature

[68] Internal combustion engine < http://en.wikipedia.org/wiki/Internal_combustion_engine > (19 May 2009)

[69] Gasoline engine < http://en.wikipedia.org/wiki/Gasoline_engine > (19 May 2009)

[70] Gasoline direct injection < http://en.wikipedia.org/wiki/Gasoline_direct_injection > (19 May 2009)

[71] Diesel engine < http://en.wikipedia.org/wiki/Compression_ignition > (19 May 2009)

[72] Flexible fuel vehicle < http://en.wikipedia.org/wiki/Flexible-fuel_vehicle > (19 May 2009)

[73] Hybrid electric vehicle < http://en.wikipedia.org/wiki/Hybrid_electric_vehicle >(19 May 2009)

[74] Toyota Prius < http://en.wikipedia.org/wiki/Toyota_Prius > (19 May 2009)

[75] AllianceBernstein (2006): The Emergence of Hybrid Vehicles - Ending Oil's Stranglehold on Transportation and the Economy, p. 15

[76] AllianceBernstein (2006): The Emergence of Hybrid Vehicles - Ending Oil's Stranglehold on Transportation and the Economy, p. 15

[77] AllianceBernstein (2006): The Emergence of Hybrid Vehicles - Ending Oil's Stranglehold on Transportation and the Economy, p. 15

[78] AllianceBernstein (2006): The Emergence of Hybrid Vehicles - Ending Oil's Stranglehold on Transportation and the Economy, p. 15

[79] Plug-In hybrid < http://en.wikipedia.org/wiki/Plug-in_hybrid > (19 May 2009)

[80] The history of electric vehicles, < http://inventors.about.com/library/weekly/aacarselectrica.htm > (20 May 2009)

[81] Scientists develop mobile phone battery that can be charged in just 10 seconds, Daily Mail

< http://www.dailymail.co.uk/sciencetech/article-1161274/Scientists-develop-mobile-phone-battery-charged-just-10-seconds.html > (20 May 2009)

[82] Lader bilen på 90 sekunder, VG Nett < http://www.vg.no/bil-og-motor/artikkel.php?artid=562075 > (20 May 2009)

[83] Elbilene får felles ladeløsning, VG Nett < http://www.vg.no/bil-og-motor/artikkel.php?artid=571763 > (20 May 2009)

[84] Kan gi elbilene ubegrenset rekkevidde- Slik virker batteribyttestasjonen, VG Nett < http://www.vg.no/bil-og-motor/artikkel.php?artid=572892 > (20 May 2009)

[85] Tahil, W. (2007): The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand. Meridian International Research, p. 8

[86] Tahil, W. (2007): The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand. Meridian International Research, p. 8

[87] Fuel cell basics, how they work < http://www.fuelcells.org/basics/how.html > (20 May 2009)

[88] Hydrogen vehicle < http://en.wikipedia.org/wiki/Hydrogen_vehicle > (20 May 2009)

[89] Testimony before the House Committee on Resources,

< http://republicans.resourcescommittee.house.gov/archives/ii00/archives/109/testimony/2006/chrisguzy.htm > (20 May 2009)

[90] Testimony before the House Committee on Resources,

< http://republicans.resourcescommittee.house.gov/archives/ii00/archives/109/testimony/2006/chrisguzy.htm > (20 May 2009)

[91] Wald, M., 2004. Questions about a hydrogen economy. Scientific American May, pp. 66–73

[92] Teknisk Ukeblad, nr 21/4, June 2009, p 42

[93] Kendall, G. (2008): Plugged in- The end of the oil age. WWF-World Wide Fund for Nature, p. 143

[94] Kendall, G. (2008): Plugged in- The end of the oil age. WWF-World Wide Fund for Nature, p. 143

[95] Alternative fuel vehicle < http://en.wikipedia.org/wiki/Alternative_fuel_vehicle > (20 May 2009)

[96] Kendell, G. 2008: Plugged in- The end of the oil age. WWF-World Wide Fund for Nature

[97] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[98] Electricity prices for first semester 2008, Eurostat, data in focus 45/2008

[99] Electricity prices for second semester 2007, Eurostat,

[100] Rose, R. (2004): Questions and Answers about Hydrogen and Fuel Cells

[101] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[102] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[103] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[104] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[105] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[106] Hydrogen vehicle, http://en.wikipedia.org/wiki/Hydrogen_vehicle

[107] Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

[108] Hydrogen Fact #6 – Hydrogen fuel cells are twice as efficient as gasoline-powered internal combustion engines, http://hydrogendiscoveries.wordpress.com/2008/04/09/hydrogen-fact-6-hydrogen-fuel-cells-are-twice-as-efficient-as-internal-combustion-engines/

[109] Weiss, M. et al (2000): ON THE ROAD IN 2020 A life-cycle analysis of new automobile technologies, MIT Energy Laboratory

[110] Større, sterkere - og litt grønnere, Tv2 < http://www.tv2underholdning.no/broom/article2769532.ece > (17 June 2009)

[111] Financial crisis of 2007-2009 < http://en.wikipedia.org/wiki/Financial_crisis_of_2007%E2%80%932009 > (25 May 2009)

[112] Energy Information Administration, Petroleum Navigator

< http://tonto.eia.doe.gov/dnav/pet/hist/wtotworldw.htm > (07 June 2009)

[113] Who Killed the Electric Car < http://en.wikipedia.org/wiki/Who_Killed_the_Electric_Car%3F > (25 May 2009)

[114] Lien, Lasse B. (2008)

[115] Cahill, E. C. (2002), p. 142

[116]Zero-emission vehicle

< http://en.wikipedia.org/wiki/Zero-emissions_vehicle#California_zero-emissions_vehicle > (25 May 2009)

[117] EV1 < http://en.wikipedia.org/wiki/EV1 > (25 May 2009)

[118] GM files for Chapter 11 bankruptcy, Dayton Business Journal

< http://www.bizjournals.com/dayton/stories/2009/06/01/daily1.html > (03 June 2009)

[119] History of Fuel Economy: One Decade of Innovation, Two Decades of Inaction

< http://www.pewfuelefficiency.org/docs/cafe_history.pdf > (25 May 2009)

[120] Audi A2 < http://en.wikipedia.org/wiki/Audi_A2 > (25 May 2009)

[121] Electric cars – plugged in < http://www.westernlithium.com/_resources/electric_cars.pdf > (25 May 2009)

[122] Toshiba and Volkswagen to Develop Electric Cars

< http://www.alternative-energy-news.info/toshiba-volkswagen-electric-cars/ > (25 May 2009)

[123] Volkswagen Eyes China Venture. The Wall Street Journal

< http://online.wsj.com/article/SB124331239762553635.html?mod=googlenews_wsj > (29 May 2009)

[124] United States Clean Air Act < http://en.wikipedia.org/wiki/United_States_Clean_Air_Act > (29 May 2009)

[125] Global warming < http://en.wikipedia.org/wiki/Global_warming > (29 May 2009)

[126] AllianceBernstein. ”The Emergence of Hybrid Vehicles”, p. 22

[127] Automotive Industry < http://en.wikipedia.org/wiki/Automotive_industry > (01 June 2009)

[128] Think Car < http://en.wikipedia.org/wiki/Think_Car > (01 June 2009)

[129] Buddy Electric Car < http://en.wikipedia.org/wiki/Buddy_(electric_car) > (01 June 2009)

[130] European Hydrogen and Fuel Cell Technology Platform homepage < https://www.hfpeurope.org/ > (04 June 2009)

[131] CIVITAS homepage < http://www.civitas-initiative.org/main.phtml?lan=en > (25 May 2009)

[132] Fiat 500 – stille som en mus < http://www.vg.no/bil-og-motor/artikkel.php?artid=543044 > (14 June 2009)

[133] Peugeot, Citroen and Toyota share knowledge for new car platform

< http://www.fleetnews.co.uk/news/story/?nID=36586 > (16 June 2009)

[134] … men inni er de like < http://www.nettavisen.no/motor/article1456507.ece > (16 June 2009)

[135] Tahil, W. (2007): The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand. Meridian International Research

[136] Elbilene får felles ladeløsning, VG Nett < http://www.vg.no/bil-og-motor/artikkel.php?artid=571763 > (20 May 2009)

[137] Kendall, G. (2008): Plugged in- The end of the oil age. WWF-World Wide Fund for Nature

[138] Better Place – charging < http://www.betterplace.com/solution/charging/ > (16 June 2009)

[139]Suspend 10 percent biofuels target, says EEA's scientific advisory body < http://www.eea.europa.eu/highlights/suspend-10-percent-biofuels-target-says-eeas-scientific-advisory-body > (20 June 2009)

References

A Promising Oil Alternative: Algae Energy, Washington post <http://www.washingtonpost.com/wp-dyn/content/article/2008/01/03/AR2008010303907.html >

About.com:Inventors < http://inventors.about.com >

AllianceBernstein (2006): The Emergence of Hybrid Vehicles - Ending Oil’s Stranglehold on Transportation and the Economy.

Better Place – charging < http://www.betterplace.com/solution/charging/ >

Bipper Communication (2009): Business Plan, CEMS business Project

Brown, R.B. (2006): Doing your dissertation in business and management: the reality of researching and writing. London: Sage.

Cahill, E. C. (2002): Strategies for the Introduction of Advanced Fuel/Vehicle Systems to the Mass Market. Thesis (S.M.). System Design and Management Program. Massachusetts Institute of Technology. Cambridge, MA. 187.

Christiansen, K. et al: Nordic Guidelines to Life Cycle Assessment. The Nordic Council, 1995

Crunching the Numbers on Alternative Fuels

Curran, J. and R.A. Blackburn (2001): Researching the small enterprise. London, Sage

Deutsche Bank (2008) “Electric cars: Plugged in”, <http://www.westernlithium.com/_resources/electric_cars.pdf >

Edwards, R. et al (2008): Biofuels in the European Context: Facts and Uncertainties. European Commission Joint Research Centre < http://www.jrc.ec.europa.eu/ >

Electric cars – plugged in < http://www.westernlithium.com/_resources/electric_cars.pdf >

Electricity prices for first semester 2008, Eurostat, data in focus 45/2008

Energy Information Administration, Petroleum Navigator

Ethanol energy < http://www.journeytoforever.org/ethanol_energy.html >

EU institutions and other bodies < http://europa.eu/institutions/index_en.htm >

EU on track for climate goal, despite Spain, Italy. Scientific American

European Hydrogen and Fuel Cell Technology Platform homepage < https://www.hfpeurope.org/ >

Eurostat < ec.europa.eu/eurostat >

First generation biofuels < http://biofuel.org.uk/first-generation-biofuels.html >

Fuel cell basics, how they work < http://www.fuelcells.org/basics/how.html >

Green papers and white papers < http://europa.eu/documents/comm/index_en.htm

Ghauri, P. and K. Grønhaug (2002): Research methods in business studies: A practical guide. 3rd ed. Harlow, Financial Times, Prentice Hall.

Glaser, B. and A. Strauss (1967): The discovery of grounded theory. Chicago, IL, Aldine.

GM files for Chapter 11 bankruptcy, Dayton Business Journal

Goulding, C. (2002): Grounded theory: A practical guide for management, business and market researchers. London, Sage.

Grant, R. (2002): Contemporary Strategy Analysis. Blackwell Publishing

Griffin, R. (2001): Management, 7th edition. Texas A&M University

Hirsch, R. et al (2005): Peaking of world oil production: impacts, mitigation, & risk management. <http://www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf >

History of Fuel Economy: One Decade of Innovation, Two Decades of Inaction < http://www.pewfuelefficiency.org/docs/cafe_history.pdf >

Howarth, R.W. et al (2009): Rapid assessment on biofuels and environment: overview and key findings. Pages 1-13 in R.W. Howarth and S. Bringezu (eds), Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the Scientific Committee on Problems of the Environment (SCOPE) International Biofuels Project Rapid Assessment, 22-25 September 2008, Gummersbach Germany. Cornell University, Ithaca NY, USA. < http://cip.cornell.edu/biofuels/ >

Hydrogen Fact #6 – Hydrogen fuel cells are twice as efficient as gasoline-powered internal combustion engines, <http://hydrogendiscoveries.wordpress.com/2008/04/09/hydrogen-fact-6-hydrogen-fuel-cells-are-twice-as-efficient-as-internal-combustion-engines/>

IPCC, 2007: Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kan gi elbilene ubegrenset rekkevidde- Slik virker batteribyttestasjonen, VG Nett < http://www.vg.no/bil-og-motor/artikkel.php?artid=572892 >

Kendall, G. 2008: Plugged in- The end of the oil age. WWF-World Wide Fund for Nature

Khalil, T. (2000): Management of Technology: The Key to Competitiveness and Wealth Creation, McGraw – Hill Book Co., Singapore

Lache, R. et al. 2008: Electric Cars: Plugged In, Deutsche Bank

Lien, Lasse B. (2008), lecture: Etableringsbarrierer. STR402 – Strategic Analysis, Norwegian School of Economics and Business Administration, NHH

Life cycle analysis and assessment < http://www.gdrc.org/uem/lca/life-cycle.html >

Liquefied Petroleum Gas (LPG), Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) < http://www.envocare.co.uk/lpg_lng_cng.htm >

Meyer, R. (2007): Mapping the Mind of the Strategist A Quantitative Methodology for Measuring the Strategic Beliefs of Executives. p. 162. ERASMUS RESEARCH INSTITUTE OF MANAGEMENT (ERIM). < http://repub.eur.nl/publications/index/523081633/ >

Moura, Lara et al (2007): Market Barriers for Large-Scale Alternative Fuel Vehicles Procurement. Alternative Fuel Vehicles – the PROCURA project, Technical University of Lisbon

Nalebuff B. and A. Brandenburger (1996): Co-opetition, HarperCollinsBusiness, London.

Nalebuff B. and A. Brandenburger, (1995): The Right Game: Use Game Theory to Shape Strategy. Harvard Business Review, July-August, pp 57-71

Palmer, D. & S. Kaplan (2007): A framework for Strategic Innovation. InnovationPoint LLC

Peugeot, Citroen and Toyota share knowledge for new car platform < http://www.fleetnews.co.uk/news/story/?nID=36586 >

Porter, M. E. (1985): The Five Competitive Forces that Determine Industry Profitability.New York, USA: The Free Press

Porter, Michael E. (1991): Americas green strategy. Scientific American, April 1991.

Position of the European Parliament adopted at dirst reading on 17 December 2008 with a view to the adoption of Regulation (EC) No ..//2009 of the European Parliament and of the Council setting emission performance standards for new passenger cars as part of the Community’s integrated approach to reduce CO2 emissions from light-duty vehicles <http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P6-TA-2008-0609+0+DOC+XML+V0//EN >

Promoting Alternative Fuel Vehicles. (2005), APEIS & RISPO

Reducing CO2 emission from light-duty vehicles. European Comission

Roberts. E. & W. Liu (2001): Ally or Acquire: How Technology Leaders Decide.

Romm, Joseph (2005): The Car and Fuel of the Future. Center for Energy and Climate Solutions, Energy Policy 34 (2006) 2609-2614

Rose, R. (2004): Questions and Answers about Hydrogen and Fuel Cells

Sandgren, J. (1999): Energy efficiency and business development – Making it happen. Renewable Energy, vol. 16, nr. 1. Elsevier Ltd.

Saunders, M. et al (2007): Research Methods for business students. 4th ed. Financial Times, Prentice Hall.

Scientists develop mobile phone battery that can be charged in just 10 seconds, Daily Mail < http://www.dailymail.co.uk/sciencetech/article-1161274/Scientists-develop-mobile-phone-battery-charged-just-10-seconds.html >

Steenberghen, Therese & Elena Lopez (2007): Overcoming barriers to the implementation of alternative fuels for road transport in Europe. Elsevier Ltd.

Stewart, D.W. and M.A. Kamins (1993): Secondary research: Information sources and methods. 2nd ed. Newbury Park, CA, Sage.

Større, sterkere - og litt grønnere, Tv2 < http://www.tv2underholdning.no/broom/article2769532.ece >

Suspend 10 percent biofuels target, says EEA's scientific advisory body < http://www.eea.europa.eu/highlights/suspend-10-percent-biofuels-target-says-eeas-scientific-advisory-body

Sustainable Bioenergy: A framework for decion Makers. 2007. United nations < http://esa.un.org/un-energy/pdf/susdev.Biofuels.FAO.pdf >

Tahil, W. (2007): The Trouble with Lithium: Implications of Future PHEV Production for Lithium Demand. Meridian International Research.

Teknisk Ukeblad, nr 21/4, June 2009

Testimony before the House Committee on Resources, <http://republicans.resourcescommittee.house.gov/archives/ii00/archives/109/testimony/2006/chrisguzy.htm >

The Alternative Fuels and Advanced Vehicles Data Center < http://www.afdc.energy.gov/afdc/ >

The Dieselization of Europe
<http://www.platts.com/Oil/Resources/News%20Features/eurodiesel/index.xml >

The Free Dictionary by Farlex < http://www.thefreedictionary.com/barrier >

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, < http://www.transportation.anl.gov/modeling_simulation/GREET/index.html >

The Inevitable Peaking of Oil Production.

The Value Net < http://www.12manage.com/methods_brandenburger_value_net.html >

Toshiba and Volkswagen to Develop Electric Cars < http://www.alternative-energy-news.info/toshiba-volkswagen-electric-cars/ >

Utterback. J. (1994): Mastering the Dynamics of Innovation. Harvard business school press.

VG Nett < http://www.vg.no >

Volkswagen Eyes China Venture. The Wall Street Journal <
http://online.wsj.com/article/SB124331239762553635.html?mod=googlenews_wsj >

Wald, M., (2004). Questions about a hydrogen economy. Scientific American

Wallace, David (1995): Environmental policy and industrial innovation – Strategies in Europe, the US and Japan. Royal Institute of International Affairs. Earthscan Publications Ltd, London.

Watson. M & Nick Vandervell (2004): The future of UK oil refining (12 May 2009)

Weiss, M. et al (2000): ON THE ROAD IN 2020 A life-cycle analysis of new automobile technologies, MIT Energy Laboratory

Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. A joint study by EUCAR / JRC / CONCAWE. JEC WTW study version 2c 03/2007 <
http://ies.jrc.ec.europa.eu/WTW >

Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles, (2009) Energy system division, Argonne national laboratory

Wikipedia.com < http://en.wikipedia.org >