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Economic and technical assessment of hydrogen and fuel cells opportunities in the Norwegian transport sector

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Foreword

Thanks to this thesis I have been able to find answers to some important questions I had about fuel cells technology and I was able to complete my technologic background with economic skills. It has also allowed me to study a project that will be directly related to my job next year at Symbio FCell and I hope this work will be used for further projects as well.

That is why I would like to thanks Eirin Ryeng and Kjell Arne both from the Department of Civil and Transport engineering and Tor Nicolaisen from Jernbaneverket for giving me the opportunity to sign this master thesis project in a first place.

I would like to address a special thanks to Anders Ødegård from SINTEF for having joined my project as co-supervisor. Thanks to his support and advices this thesis has evolved around real projects and I have been able to participate to the Hydrogen Workshop where I have met really interesting professionals. I sincerely hope our collaboration will continue in the professional world.

My thanks also go to the companies Posten and Symbio FCell for the data they have provided without which this thesis would have been less relevant.

Finally as I have completed this year at the NTNU as an Erasmus student I really would like to thanks my French professors from the Master Génie des Procédés, the international relation department of the Joseph Fourier University and of course the Erasmus + program for this amazing experience they have allowed me to leave in a first place.

Trondheim, Thursday 4th June 2015

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Abstract
Because of the environmental pressure concerning both global and local pollution new ways of using energy are under study. Given that the Norwegian transport sector is a significant contributor to those pollutions at the national scale, the hydrogen and fuel cells technology is a potential solution thanks to its eco-friendly properties. This technology that allows transforming hydrogen and oxygen into electricity has many advantages but has also a cost, some drawbacks and has to be introduced properly in the transport market to insure the success of the energetic transition. By collecting information about existing projects and competitive fuels (diesel, battery, hydrogen and associated technologies) and by using the total cost of ownership as a comparative tool, the most relevant market segments to introduce fuel cells and hydrogen have been determined. This fuel comparison has been completed on a ferry, a light truck, a heavy truck and a car while other sectors have been covered more briefly. It appears that hydrogen has a significant advantage over batteries for medium and long distance trips as well as high energy consumption vehicles like heavy trucks. This advantage can even compete with diesel cars or light diesel trucks thanks to the Norwegian road tax exemption. However those applications are currently limited to captive fleet operation because of the lack of refueling infrastructure network. It has also been determined that, in the maritime sector, fuel cells are competitive with battery ferries for distances longer than 11.5 km. A simplified life cycle assessment also allows us to state that in addition to bring an undisputable CO_2 emission reduction the replacement of diesel vehicle by a fuel cell vehicle also generates significant energy saving whatever the value chain used.

Keywords:

1. Hydrogen
2. Fuel cells
3. Transport
4. Economy

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LIST OF ABBREVIATIONS

FC: Fuel cells

FC-REV: Fuel cells Range Extender Vehicle

LH2: Liquefied Hydrogen

BEV: Battery Electric Vehicle

CV: Conventional Vehicle

ICE: Internal Combustion Engine

NG: Natural Gas

LNG: Liquefied Natural Gas

NPV: Net Present Value

TCO: Total Cost of Ownership

OPEX: Operational Expenditure

CAPEX: Capital Expenditure

FCB: Fuel Cell Bus

LDV: Light Duty Vehicle

MDV: Medium Duty Vehicle

HDV: Heavy Duty Vehicle

Nm^3: Normal cubic meter

HRS: Hydrogen Refueling Station

SMR: Steam Methane Reforming

LCA: Life Cycle Assessment

TTW: Tank-To-Wheel

WTT: Well-To-Tank

WTW: Well-To-Wheel

NOx : Nitrogen oxide

SOx : Sulfur oxide

kWhPE : kilowatt-hour of Primary Energy

1

INTRODUCTION

1.1 BACKGROUND & MOTIVATION

Our century is facing two main challenges in term of energy use and supply. The first one is related to global warming as the IPCC is warning the international community about the necessity to stay below a 2°C temperature increase. This first issue is highly correlated to human activities through greenhouse gases and our transport sector is responsible for one third of those emissions. The second challenge is related to energy supply itself due to the fossil fuel resource depletion. One by one the different gas and oil platforms are reaching their production peak and start to have a declining production. As our economies' growth relies on energy consumption, this resource factor will put an increasing pressure to find alternative energy sources and energy carriers. In this situation hydrogen and fuel cells technology look like a potential answer to those challenges. Indeed hydrogen could become the next energy carrier for the transport sector if used in combination with fuel cells to power electric motors. The interest of this option lays in the high energy content of hydrogen, the interesting efficiency of fuel cells and the properties of this system to release only water. However hydrogen acts as an energy carrier and it has to be produced somehow while fuel cells technology is quite expensive at the moment. Furthermore, it has to compete with other low emission technologies like biofuels and batteries while fulfilling the same requirement as fossil fuels. Therefore, finding the correct balance between economical competitiveness, environmental benefit and operational requirements for hydrogen and fuel cells technology is a real challenge directly related to the main ones we are facing in our century.

1.2 FOCUS & OBJECTIVES

Norway has favorable policies for the adoption of environmental friendly technologies and also has natural resources and economic wealth that support those policies. That is why this master's thesis will focus on the Norwegian transport market and its several sectors. Therefore the objective of this thesis is to determine what are the most relevant sectors for the introduction of hydrogen and fuel cells technology in Norway. This question will be answered thanks to a basic technical assessment as well as an economic approach using the total cost of ownership as reference unit.

1.3 STRUCTURE

Given that our study frame is large and applies to several sectors, the thesis will be split in different chapters each representing one segment of the market. First of all a chapter will be dedicated to the presentation of hydrogen and fuel cells technology to provide the background theory and input data for the rest of the studies. After the introduction chapter we will first cover the maritime sector while the second focus will be a presentation of the road sector including some common information used in the studies to come. Thanks to this introduction to the road sector the chapters five and six will cover the truck segment and the car segment respectively. The chapter seven will provide a lighter assessment of other sectors including the bus, the railway and the aviation segments. Finally, an environmental study using a simplified Life Cycle Assessment will be performed in chapter eight based on Trondheim's Posten fleet. A final conclusion will sum-up the previous results and will answer to the original question enounced in this introduction chapter.

2

HYDROGEN AND FUEL CELLS

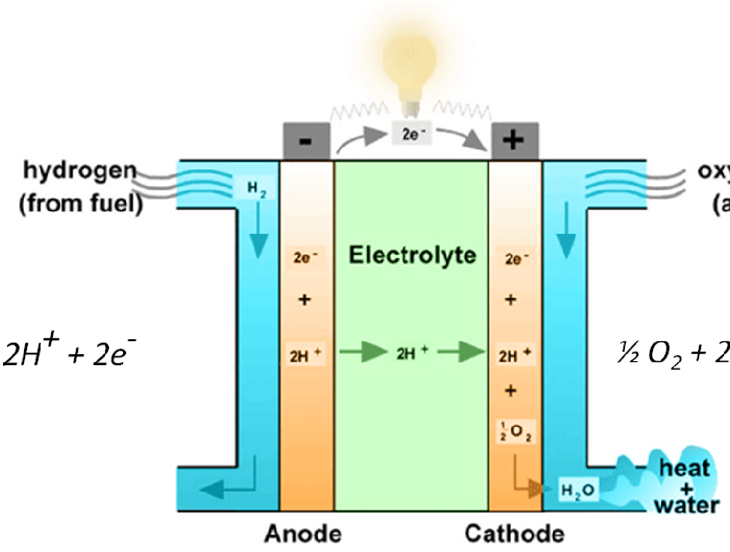
2.1 INTRODUCTION

The topic of this thesis is large as it aims to cover both technologic and economic feasibility of fuel cells and hydrogen. Therefore this first chapter aims to provide enough information to understand the value chain of hydrogen, the technical limits of fuel cells and the economic values related to both. This introduction chapter of the thesis does not include any calculation but gathers a lot of information that will be used in further computation. In the first sections the fuel cells technology will be presented from the technological side (type of fuel cells, different components) but also from the economical side (cost, lifetime, price expectation). Then along the next sections the hydrogen will be detailed. Its properties and risk will be presented as well as the entire value chain from the different production processes to the different transport and storage options. In order to cover some relevant questions a small section will be dedicated to the environmental aspect of hydrogen and its social acceptance. To finish with hydrogen an entire section will be dedicated to the potential of hydrogen in Norway by covering the different production sources, the potential markets and the current and expected policies. Finally, the last section will cover briefly the competitive fuels for the transport market like oil derivates, natural gas, battery or biofuels. As this chapter is a descriptive chapter being used principally as an information source for the following parts of the thesis, there will not be any conclusion for this one.

2.2 FUEL CELLS THEORY

2.2.1 BASICS

A fuel cell is a device that consumes dihydrogen (H2) and dioxygen (O2) to produce electricity, heat and water. The key component of this device is the electrolyte which separate the two reactants (O2 and H2) but which allows the protons (H+) to pass. There are different types of fuel cell operating with different fuels, different electrolytes or range of temperature but the basic principle is the same for all of them. Those differences will be presented further in the report. The diagram below illustrates this reaction for one type of fuel cell called PEM (Proton exchange membrane). This figure allows understanding the electrochemical reactions and the different fuel cell's components.



$$H_2 = 2H^+ + 2e^-$$

$$½\, O_2 + 2H^+ + 2\, e^- = 2H_2O$$

Source : [82]

FIGURE 2-1 - BASIC FUNCTIONING OF A PEMFC

In order to obtain enough power several cells are compressed together, this assembly is called a stack. As the output power is proportional to the number of cells, the power range is very wide and varies depending of the final use. As an example a stack made of 70 cells (PEM) delivers a power of 5kW [2] like in the HyKangoo vehicle [3].

FIGURE 2-2 - A 5 KW PEM FUEL CELL FROM SYMBIO FCELL

2.2.2 DIFFERENT TYPE OF FC

As mentioned before, different types of fuel cell exists. They are differentiated by their application, their fuel, their electrolyte or even their operating temperature. The following table aims to synthesize those differences in order to partly understand the choice of PEMFC for the transport sector.

TABLE 2-1 - DIFFERENT TYPES OF FUEL CELL AND ASSOCIATED PROPERTIES

Fuel cell Type	*Full name*	*Fuel*	*Electrolyte*	*Temperature range (°C)*	*Start-up time*	*Field of application*
AFC	Alkaline fuel cells	Pure H_2 and O_2	30%-50% KOH	60-90	Immediate	Space, transport, submarines
PEMFC	Proton exchange membrane fuel cells	Pure H_2 O_2 (air)	Proton conducting membrane	50-80	Immediate	Transport, Stationary cogeneration, submarines, space
DMFC	Direct methanol fuel cells	MeOH ; O_2 (air)	Proton conducting membrane	80-100	Immediate	Portable, mobile
PAFC	Phosphoric acid fuel cells	H_2 ; O_2 (air)	Concentrated phosphoric acid	160-220	30 minutes	Stationary cogeneration, transport
MCFC	Molten carbonate fuel cells	H_2/ CO/ CH_4/ Coal/ Biogas ; O_2 (air)	Molten carbonate	620-660	Several hours	Stationary cogeneration
SOFC	Solid oxide fuel cells	H_2/ CO/ CH_4/ Coal/ Biogas ; O_2 (air)	Ion conducting ceramic	800-1000	Several hours	Stationary cogeneration

[4]

2.3 FUEL CELLS COMPOSITION AND COST

Given this simple table one can see that several fuel cells can be used in the transport sector. However the PEMFC is preferred to the other because of its low operating temperature (50-80°C), its fuel requirement (Pure H2 and simple air) and its wide power range (up to 300kW) and its specific weight (2 kW/kg) [5]. Furthermore a lot of resources are currently invested in R&D for this fuel cell type because of its potential to reach better performance soon (lifetime and cost) [6] [7]. In this part the surrounding system is studied more precisely in order to understand the different technical requirements of a fuel cell system.

2.3.1 COMPOSITION

To operate correctly, the fuel cell needs to be linked to other components. Those elements can be divided into the hydrogen circuit, the air circuit, the cooling circuit and the electrical circuit. [2]

The hydrogen circuit

The hydrogen can be stored in different ways but at the moment, in the transport sector, the pressurized tank is the most common choice. This high pressure tank made of carbon fiber can be filled at a pressure of 350bar or 700bar [4] and is linked to supply the fuel cell with the needed hydrogen.

The air circuit

As the membrane is very sensitive to any impurity the air has to be as clean as possible. Other gases than oxygen naturally present in the air (nitrogen principally) do not react with the membrane but an efficient air filter is required to increase the performance of the stack anyway (dust, acids). The higher the pressure the better the efficiency. That is why a air compressor is needed to compress the air and make it circulate with a small overpressure (vary from one design to the other). As the membrane efficiency is function, inter alia, of the air temperature and humidity rate a heat exchanger and a humidifier are required before the air enters the stack. The water generated by the reaction is used to humidify the inlet air through the humidifier.

The cooling circuit

Given that the fuel cells generate a lot of heat (proportional to power) the natural air convection is not sufficient and a cooling circuit has to be installed. Most of the time water or glysantin are chosen for their chemical-neutral properties and their good calorific capacity. In addition a heat exchanger has to be designed to allow the water to dissipate enough thermal energy. Like in almost every water circuit an expansion vessel has to be installed to compensate the water's density and pressure variations.

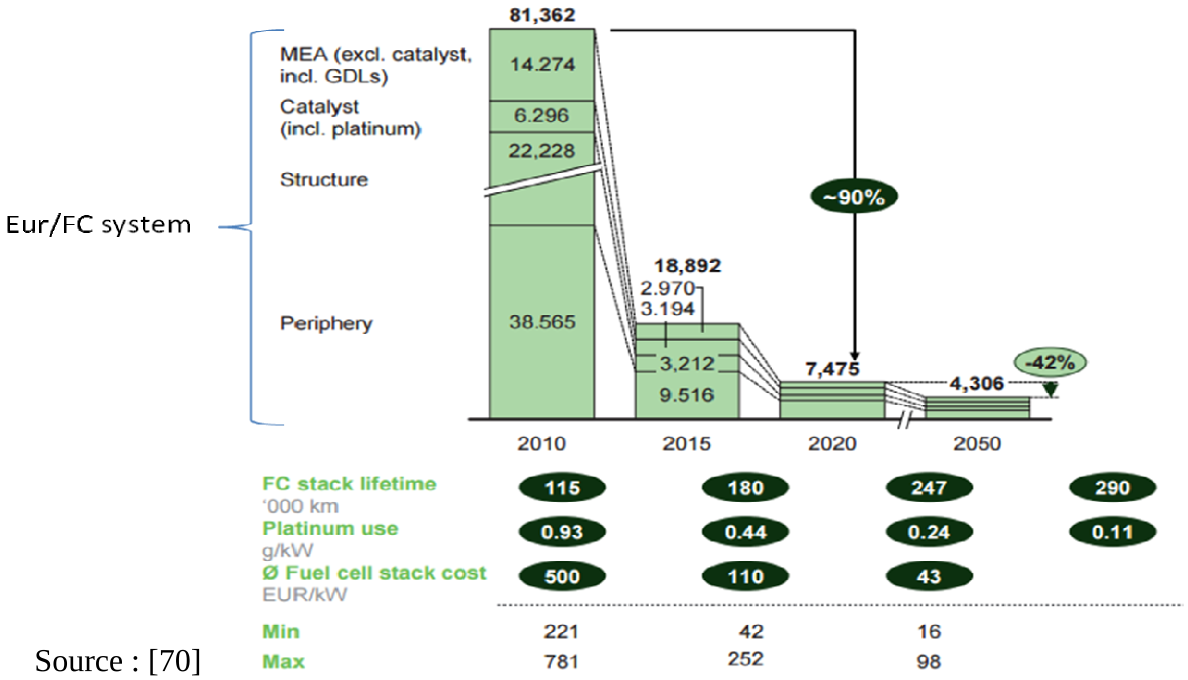
The electrical circuit

In the case of a range extender the fuel cell is connected to the main battery that provides the power to the electrical motor. Therefore the output DC voltage has to be converted to the correct DC voltage to suit the battery voltage requirement. In most cases a DC/DC boost converter has to be designed.

2.3.2 COST & LIFETIME

After this review of the technical aspects of the PEMFC it is important to assess the cost of such a system. Different DOE (Department Of Energy) and some private companies [9] [10] [11] have published their cost analysis (cost breakdown, mass production estimations) for an 80kW electrical output system.

According to the study from McKinsey [70] the cost of the fuel cell systems is about to decrease significantly thanks to a lesser cost of all the different components.



Source : [70]

FIGURE 2-3 - PEMFC COST BREAKDOWN FOR A MEDIUM SIZED CAR

One of the reasons of the high fuel cells price is the low volume of production itself induced by a low penetration of the market. Therefore the price of a PEMFC system can be lowered by considering an economy of scale equivalent to the production of thousands of products. If we assume a mass production of 500,000 units/year, the graph below gives us the expected price as a function of the fuel cells power ([60] and [82]). Those values will be used in the economic studies of this report.

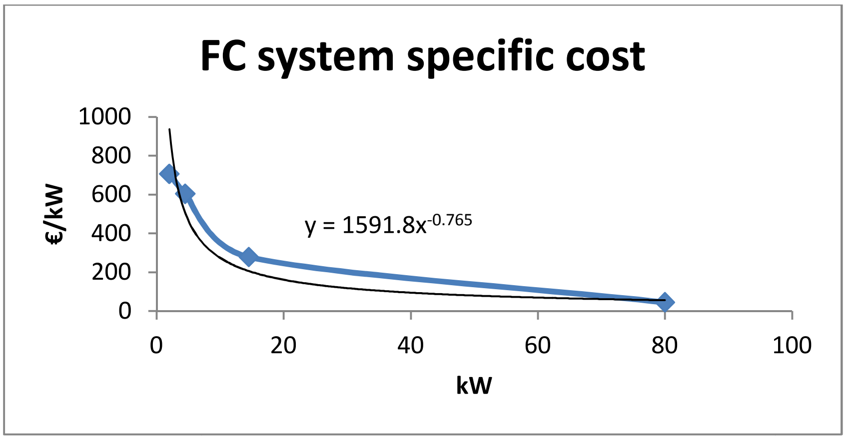
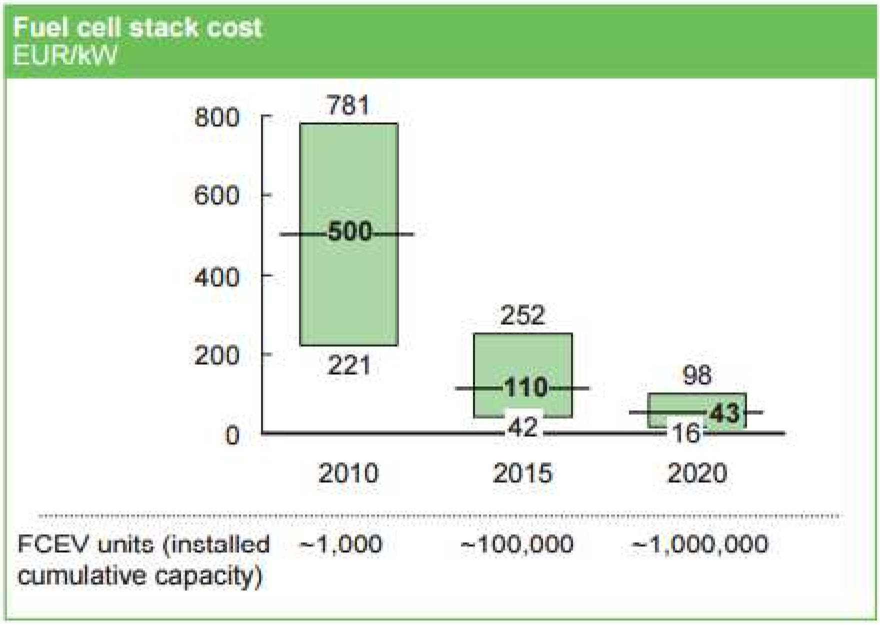


FIGURE 2-4 - PRODUCTION COST PER KW AGAINST FC POWER

Given that a fuel cell is a stack of several cells it has to comply with some mechanical issues. For instance it is necessary that the compression is homogeneous to avoid the bending of the stack and the bigger the stack the more difficult this task. As the fluids (water, hydrogen and air) circulate into the stack it is also necessary to avoid too long channel that will generate too important head losses. In case of too important head losses the cooling would not be efficient and the fuel would not reach the last cells of the stack. For those reasons it is recommended to design 200 kW at the maximum [2]. Therefore a motor with higher power than 200 kW will be supplied by several fuel cells in parallel.

The cost of prototype PEMFC stacks may currently exceed $1,800-$2,000/kW, but producers are confident that mass-scale production for vehicles could reduce the cost below $100/kW. In order to compete with combustion engines, however, the cost of PEMFC should be lower than $50/kW [12]. Considering the expected improvement in the different components manufacturing costs, the McKinsey study ([70]) seems to give a range of fuel cell price from €16/kW to €98/kW for a production of 500, 000 systems per year (in 2017).



Source : [70]

FIGURE 2-5 - EXPECTED PRICE EVOLUTION FOR A MEDIUM SIZED CAR PEMFC (ASSUMMED 500,000 UNITS PRODUCTION/YEAR)

One of the important characteristic of a PEMFC is the lifetime. Usually this parameter is measured by the number of functioning hours. That of PEMFC depends on operating conditions (start-up, temperature, humidification, fuel purity). Under operating conditions occurring in vehicles (cyclic loads, many starts-stops), the typical lifetime of PEMFC is around 5,000 hours (150,000 km). Target lifetimes are up to 20,000 hours for buses. Concerning the MCFC and SOFC the current price varies from $12,000 to $15,000/kW and their lifetime is around 5 years.

2.4 HYDROGEN PROPERTIES AND RISKS

2.4.1 HYDROGEN PROPERTIES

The hydrogen atom (H) is the lightest element of the periodic table and it is the most abundant chemical substance in the universe. However, on earth it mostly occurs naturally in form of chemical compounds, most frequently water and hydrocarbons. As a gas in its free state, hydrogen is very rare (1 ppm by volume in the earth's atmosphere) and it can only be found in natural gas and some volcanic gases. At standard temperature and pressure, hydrogen is a colorless, tasteless, odorless and easily flammable gas. Atomic hydrogen is formed as a result of different chemical reactions, but its lifetime is extremely short, as the atoms join each other to form a hydrogen molecule (H2). The table below presents the main characteristics of the hydrogen molecule and compares them to the methane (CH4) characteristics.

TABLE 2-2 - GENERAL PROPERTIES OF HYDROGEN

Property	Unit	**H2**	**CH4**
Molar Weight	g/mol	2.016	16.043
Heating value	kJ/g	120	50
Standard properties (273K, 1bar)			
Gas density	g/l	0.090	0.718
Gas viscosity	µPa.s	8.9	10.9
Diffusivity	(m²/s *10^5)	6.11	1.60
Cp	KJ/kg.K	14.2	2.22
Explosion limits in air	Vol%	4.0-77.0	4.4-17.0
Detonation limits in air	Vol%	18.3-59.0	6.3-17.0
Minimum ignition energy	mJ	0.017	0.29
Spontaneous combustion temperature	K	833	868
Joule-Thomson coefficient	K/Pa	Negative	positive

[4]

Those characteristics impose technical barriers to the hydrogen storage and have to be considered for safety issues due to the low explosion limits and the minimum ignition energy.

2.4.2 BASIC HYDROGEN SAFETY

First of all it seems important to mention that hydrogen has been used at the industrial scale for decades and we now have the knowledge and the skills to handle this gas safely. Due to its chemical properties the hydrogen, when stored in a vessel, can react with most of the metals to form some metal hydride. This reaction makes the metal weaker due to ductility loss, fractures and cracks and ends up with a hydrogen blistering. To avoid this reaction it is necessary to use some special steels like the Austenitic Chromium-Nickel-Manganese steels (A 302-B, Cr18Ni10, A 212-B or A 372-B). Whatever the storage method it is relevant to proceed to a helium leak test on the device. The small size of the helium atom allows detecting the potential leakages better than air or other gases. However if a leakage occurs the important leak rate of hydrogen empties the vessel very fast. If the design is done correctly then the gas should easily find the shortest way to the open air. To support this design the space containing the hydrogen vessel should be over pressurized to avoid any leakage in the wrong direction. As an illustration of the hydrogen diffusion rate we can observe that a spill on the ground of 1900 liters of liquid hydrogen will have diffused to a non-explosive mixture after about one minute. As a second safety barer it is required to avoid any potential ignition source. Those ignition sources can be a friction spark, impact spark, electrical spark, hot object, flame or smoking. Therefore all equipment and connections shall be grounded, some spark proof tools should be used, some lightning protection installed and wool and synthetic clothes should be avoided. All of the component and design related to the hydrogen use are certified by some international standards. Those components and design are the hydrogen pipelines and piping for pipe sizing procedures, pressure relief devices for hydrogen storage containers, hydrogen containers, hydrogen cylinders, hydrogen vent systems,...

2.4.3 HYDROGEN VEHICLE SAFETY

More specifically to the road transport sector the fuel cell vehicle has some drawbacks and some advantages compared to the conventional one. As mentioned before, hydrogen has a lower ignition point than methane or gasoline, therefore it will initiate with a lower amount of energy in case of an accident. Furthermore it is odorless and both gas and flame are colorless so it is almost impossible to detect it without specific instruments. Hydrogen is very light, which means that the gas will rise very quickly into the air and therefore away from any ignition source. This is not the case of methane or even gasoline which are fuels that will stay close to the accident area. The tank containing hydrogen might be an issue due to the high pressure in it but it is designed to release its content when a given temperature or pressure is reached. Therefore there is no risk of explosion of the tank. The vessels used for compressed hydrogen or liquid hydrogen are designed to resist any choc related to a road accident and are also designed to release their content when an important acceleration change occurs (car accident typically).

2.4.4 REGULATIONS & STANDARDS

Given that hydrogen has been in use in the industry since a long time there are some existing standards. Those codes cover most of the value chain (hydrogen qualities, safety requirements, measurement issues…) however they do not cover all of the news technologies (e.g. very high pressure storage or refueling stations). Concerning the fuel cells, some standards exist concerning performance measurements or the safety. It is important to note that a standard or a code (e.g. ISO) is different from a regulation (e.g. law enforcement). Many organizations provide codes and standard but the most important ones (for Europe) are DNV-GL (private company), ISO (International Standard Organization) and the European commission.

2.5 HYDROGEN PRODUCTION

This general description of the hydrogen and fuel cells technologies would not be complete without a presentation of the hydrogen production. This part is highly relevant from an environmental point of view because of the plurality of the production processes which can have important impact on the environment. The hydrogen can be produced from various energy sources through several processes but the following part aims to briefly describe only the most developed processes. This review uses a techno-economic approach like the one completed for the fuel cells in the previous part. A summary table will provide the corresponding data for each production process

2.5.1 REFERENCE PRODUCTION PROCESSES FOR THE STUDY

2.5.1.1 Steam methane reforming (SMR)

Today the steam methane reforming is the most widely used method with 95% of the world production of hydrogen achieved thanks to this process [13]. Basically the methane is mixed with steam at high temperature through two different processes to make the following reactions occur: $CH4 + H2O\ (+heat) \rightarrow CO + 3H2$

2.5.1.2 Water electrolysis

One of the most promising processes for the years to come is the water electrolysis. This well known process uses an electrical DC current to split the water molecule into hydrogen and oxygen. This process is particularly interesting for the storage of energy from intermittent source (renewable). This reaction takes place in an electrolyser which reproduces the reverse process of a fuel cell: $2\ H2O(l) \rightarrow 2\ H2(g) + O2(g)$

Like the fuel cells it is possible to use different electrolyser types. The two most widely used are the alkaline electrolysis and the PEM (Polymer electrolyte membrane) electrolysis. The main difference lay in the electrolyte which is liquid for the Alkaline electrolyser but solid (membrane) for the PEM electrolyser.

2.5.1.3 Hydrogen refueling station (HRS)

To provide a "ready to use" hydrogen some additional expenses have to be considered. Those costs are related to the compressor, the buffer, the onsite storage, the cooler, the dispenser, the installation and the manufacturer margin. The prices shown in the summary table (1.4.3) include those expenses.

2.5.2 OTHER PROCESSES AND COST PREDICTION

The following processes are not all commercially available and it is hard to estimate a production cost for each of them. However they all have the potential of promising processes in the near future for the hydrogen production.

2.5.2.1 Biomass gasification

The direct production of hydrogen from the biomass is very interesting from a climate change perspective because of the CO_2 neutral cycle of the fuel. The advantage of this process is the use of local fuel like farming wastes or by-products from the wood industry. However it is important to note that the use of biomass for the hydrogen production is very new and therefore not well developed. The characteristics of this process are illustrated in the table below (centralized option) [4]

2.5.2.2 Microwave Plasma Method

Several technics use plasma to split natural gas into hydrogen and carbon powder but they differ by their temperature and their pressure of operation. One of those processes is called the Kværner process (from the Norwegian company Kværner) and is described below.

A plasma arc is produced at 1500°C to split methane into pure hydrogen and pure carbon powder (also called carbon black which is a valuable product. With a ratio of 24 kWh/kgH2 this method is less efficient than the SMR method (3 kWh/kgH2) but has the considerable advantage not to emit any CO_2 in the production process. However it is still more efficient than an electrolysis system (0.41 kWhel/kWhH2 = 1/3 of electrolysis efficiency) [17]. This process is already operational and will be used for commercial hydrogen production in the coming year according to one of the companies (GasPlas)

2.5.2.3 Thermo chemical process

This process uses the property of water that breaks down into H2 and O2 at 2200°C. Such a temperature can be obtained thanks to a solar concentration plant for instance. The difficulty remains in separating the H2 and O2 at such temperature, though. A recent experiment has apparently solved this problem but the industrialization is not quite close yet[18].

2.5.2.4 Hydrogen as a by-product

Hydrogen can also be formed as a by-product in the chemistry industry (chlorine, ethylene and acetylene). Another way to collect hydrogen as a secondary product is during the cracking and catalytic reforming in refineries. However the hydrogen produced in refineries is often used on-site to supply the process. One of the disadvantage of hydrogen as a byproduct is that the gas has either to be consumed close to the site or to be transported.

2.5.2.5 Hydrogen production cost prediction

Based on several assumptions concerning the European energy mix (see Roadmap 2050 from European climate foundation) a study from the European Fuel cells and Hydrogen Joint Undertaking has established a prediction for the hydrogen cost evolution. The figure 2-6 details the composition of the cost (Retail, distribution and production). The abbreviations IGCC and CG in the graph respectively stand for Integrated Gasification Combined Cycle and Coal Gasification.[70]

The graph below shows us that in the next ten years the distribution and retail price will decrease and will impact the hydrogen cost at the pump significantly. As the production cost is highly dependent of the electricity price we can see that its cost will decrease progressively from 2020 as the electricity will be cheaper and cheaper to produce.

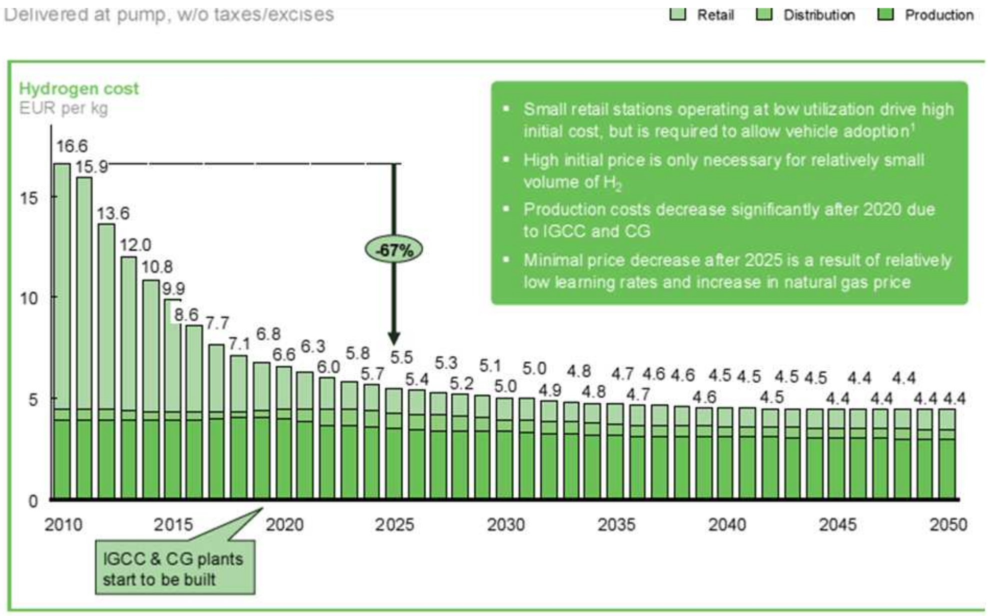


FIGURE 2-6 - HYDROGEN PRODUCTION COST PREDICTION

2.5.3 SUMMARY TABLE

TABLE 2-3 - PRODUCTION METHODS SUMMARY

Technical data	Unit	**SMR**	**Electrolysis (PEM)**	**Biomass**	**Microwave plasma**	**Thermo-chemical**
Capacity	kgH2/day	400	400	3,740	N/A	100,000
Energy efficiency	kWhH2/kWh (%)	75	60	46	58	10
Specific investment [68]	€/kgH2/day	4819 (c)	4875 (c)	1700	N/A	3800 (1020) (a)
Hydrogen cost [68]	€/kgH2	0.77	5.52	2.05	N/A	14.8 (2)
CO_2 *emissions [86]*	$kgCO_2/kgH2$	13.7	0.82 (b)	None	0.38 (b)	None

(a) The target value are written in brackets

(b) Norwegian electricity mix ($0.016kgCO_2/kWh$)

(c) Correspond to the price of the entire refueling station

2.6 HYDROGEN STORAGE AND TRANSPORTATION

If hydrogen has the highest gravimetric energy density (33 kWh/kg) it also has the lowest volumetric energy density at standard conditions (0.64 kWh/l). Due to these physical properties the hydrogen is very difficult to store and it is nowadays one of the most critical issues to solve in the transport sector. However small quantities of hydrogen need to be stored given that an average lightweight car can perform 80 to 125 km with one kilogram of hydrogen. The following section aims to briefly cover the existing storage methods, their cost and respective advantages in order to have a better understanding of the hydrogen challenge in transportation.

2.6.1 REFERENCE STORAGE SYSTEMS FOR THE STUDY

2.6.1.1 Pressurized storage

Given that under the standard conditions (1atm, 293K), the hydrogen is in its gaseous form, and the easiest way to store it is to compress it. The process uses a succession of compressors to reach a pressure of 350bar or 700bar. Then the gas is stored in a tank with appropriate thickness and robustness. The energy use to compress 1kg of hydrogen is equal to 10-17 MJ depending of the final pressure which correspond to 9 to 15% of its lower heating value (LHV). Like in many technologies the specific cost of a component depend on its size. The following graph shows the price evolution against the hydrogen quantity stored. It is used in this thesis for the cost calculation.([60],[82])

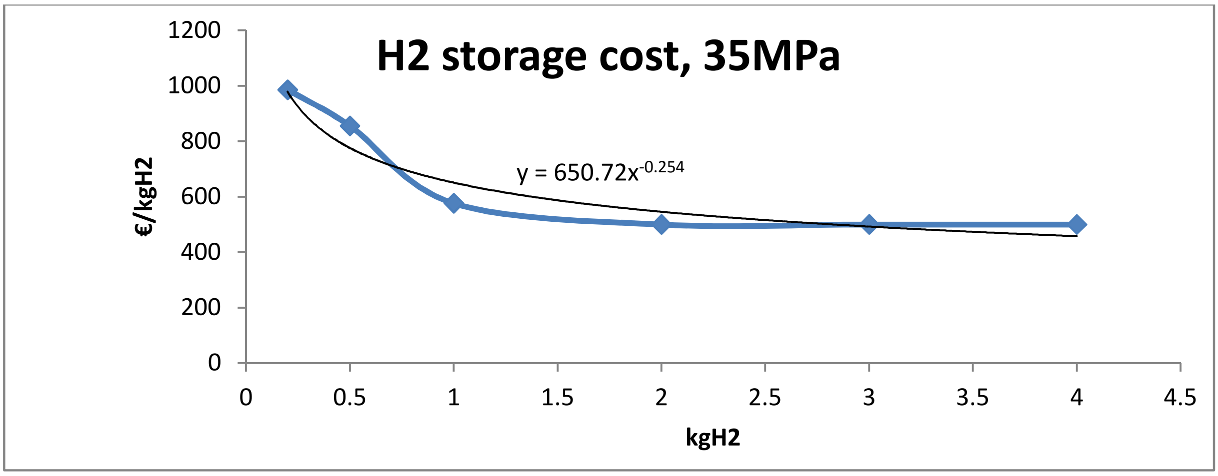


FIGURE 2-7 - PRESSURISED HYDROGEN STORAGE SPECIFIC COST

FIGURE 2-8 - PRESSURISED HYDROGEN TANK
SOURCE: FUELCELLSETC.COM

2.6.1.2 Liquefied storage

By using a series of processes (low temperature and Joules-Thomson valve) it is possible to liquefy the hydrogen gas. The density of this liquid is 70.8 gH2/l which is 796 times more than 1l of gaseous hydrogen under standard condition. However around 30% of the LHV is spent to cool down the gas to 21 Kelvin. Another aspect of this storage technic is the evaporation issue (like any other cryogenic liquids).[4]

2.6.2 OTHER STORAGE METHODS

2.6.2.1 Metal hydride

The method consists of integrating the hydrogen atom in the lattice of a metal, an alloy or a chemical compound (adsorption). This method allows a high volumetric density (80 to 150 gH2/l) but requires a heat management (heat is needed to release Hydrogen atoms, heat is released when storing them).

2.6.2.2 Geological storage

The concept is to inject hydrogen into its gaseous form into a geological formation and to release it when needed. This technic is already employed for the storage of natural gas and can be used for the hydrogen with lesser pressure storage due to the hydrogen specificities. The pressure can vary between 50 and 100 bar for a total amount of 10^6 to 10^8 Nm3* stored. Because of their good sealing, salt mines and empty aquifers are preferred for this technology.

*Normal cubic meter (Nm^3): Corresponds to the quantity of gas contained in 1m3 under the specific conditions (Temperature= 0 °C, Pressure= 1.01325 bar).

2.6.3 STORAGE METHODS SUMMARY

TABLE 2-4 - STORAGE METHODS SUMMARY TABLE

Storage type	*kWh/kgsystem*	*Wt% (0.01kgH2/kg system)*	*Vol% (0.01kgH2/lsystem)*	*Cost (€/kgH2)*
Compressed H2 35MPa	1.8	5.4	1.8	495
Compressed H2 70MPa	1.7	5.1	2.7	588
Liquid H2	1.9	5.7	4.2	372
Metal hydride	0.4	1.2	1.2	N/A

Source: [90]

2.6.4 HYDROGEN TRANSPORTATION

Like in most cases, it is more efficient to produce hydrogen in one large plant than in several small ones. Therefore, the aspect of the transportation has to be covered. This last section aims to provide the different alternatives for the transportation of hydrogen from its production point to its consumption point.

2.6.4.1 Pipeline transportation

The pipeline technology is already well developed and some hydrogen pipelines already exist in Europe to supply some specific industries with hydrogen. One of the main particularities of the hydrogen pipeline is that it has to be made of a non porous metal (i.e. stainless steel) which increases the investment cost by 1.4 or 2. It is also possible to transport up to 30 vol% of hydrogen in a conventional natural gas pipeline (CH_4).

The following table gives the corresponding distance and cost of this transportation option. The "transport" refers to transportation from the production site to the dispatching point while the "distribution" refers to the transportation from the dispatching point to the final location.

TABLE 2-5 - PIPELINE COST

Technical data	Unit	**Transport**	**Distribution**
Investment	k€/km	560	250
Average distance	km	300	50

2.6.4.2 Road and maritime transport

For road transport the most efficient way is to convoy liquid hydrogen even if it can also be done with compressed hydrogen. This is done thanks to cylindrical super insulated cryogenic vessels in semitrailers. Maritime hydrogen transportation can be achieved but is relatively new (Kawasaki Heavy Industries Ltd.). It is possible to convoy up to 100 000 Nm3 during maximum 60 days. This maximum time limit for transportation is related to the evaporation issue.

TABLE 2-6 - HYDROGEN TRUCK DELIVERY COST

	Capacity (kgH2/day)	**Truck GH2**	**Truck LH2**
Specific cost (€/kgH2/day)	100	12935	8393
O&M (€/kgH2)*		18.7	9.4
Specific cost (€/kgH2/day)	400	4753	4004
O&M (€/kgH2)		18.7	9.4
Specific cost (€/kgH2/day)	1000	3793	3195
O&M (€/kgH2)		18.7	9.4

Source : NREL, 2013, *Hydrogen Station Cost Estimates* [68]

* O&M : Operation and maintenance, corresponds to all the regular expenses.

2.7 ENVIRONMENT AND SOCIAL ASPECTS

2.7.1 ENVIRONMENT

Many LCA reports [40] point out that the origin of hydrogen affects strongly the overall impact of a fuel cell system. It is calculated that if the hydrogen is based on natural gas reforming the impact for 1MJ of hydrogen is slightly higher than for 1MJ of gasoline (around 80 gCO_2/MJ). Therefore, in order to keep the environmental interest of a fuel cell system based on hydrogen (PEMFC) it is advised to use either a Carbone Capture storage (CCS) for the SMR or to produce the hydrogen by electrolysis thanks to renewable electricity. The use of renewable electricity (lean CO2 value chain) is crucial as demonstrated in the following example.

In the case where the electricity mix is based on coal (984 $gCO_2eq/kWhe$) and electrolysis efficiency is equal to 70% we can determine that the production of hydrogen emits 47 $kgCO_2/kgH2$ (1.4 $kgCO_2/kWhH2$). As a comparison the SMR process emits 13.7 kgCO2/kgH2 (0.27 $kgCO_2/kWhH2$). The use of electricity based on coal generate three times more CO2 than the SMR process.

As mentioned earlier different types of fuel cell can be used on board. This choice impacts considerably the emissions associated with the operation because of different fuel composition. A PEMFC does not use any hydrocarbon fuel, just hydrogen, so the direct emissions are inexistent while a MCFC or a SOFC uses natural gas so carbonate emissions occur. However, given that the nature of the reaction is different from a conventional stroke engine (lower temperature) some CO_2 is released but there is no NOx or PM formation.

2.7.2 SOCIAL ASPECTS

As a new technology for the public, hydrogen is confronted to some reluctance concerning its safety. However, the few demonstration projects and the normalization processes are working in the favor of a solution for this issue. Better information of the public and a strict safety regulations are the main lines of the EU commission concerning this topic (H2trust Project).

The use of electrical trusters for the propulsion of boats makes an important difference in the comfort of operation. Consequently, the public is satisfied with the operation of boats and the operators (sailors, fishermen, technicians) can work in better conditions which is not negligible. Also the direct positive impact on the local environment empowers this social acceptance.

The low penetration of hydrogen and fuel cells in the market leads to a lack of qualified workers for the maintenance of those systems. In order to achieve a sustainable insertion of hydrogen and fuel cells technology in the maritime sector, the different manufacturing companies will have to train a sufficient number of workers. The operators will also have to be aware of the risk and to ensure safe behavior to avoid any accidents that would be highly damageable for the reputation of hydrogen.

2.8 HYDROGEN IN NORWAY

Ranked as the 11th and the 3rd most exporting country for oil and gas, respectively, Norway is a major key player in the international energy market [20]. Those energy intensive industries, combined with a low population density, lead this Nordic country to have one of the most energy intensive population in the world (6.39 tones oil equivalent per head in 2010, compared to the OECD average of 4.40)[21]. However, because of an important hydropower resource the TPES of Norway (Total primary energy supply) is strongly based on renewable electricity.

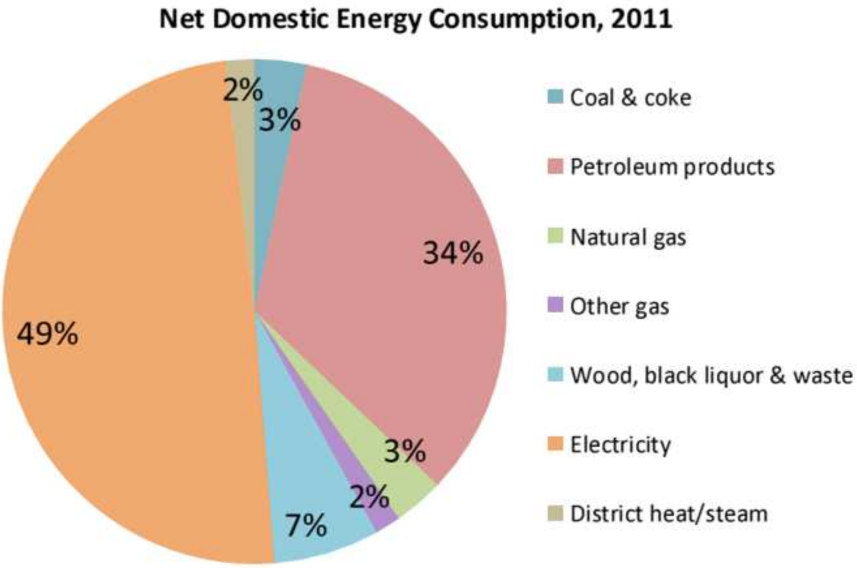


FIGURE 2-9 - ENERGY CONSUMPTION BREAKDOWN FOR NORWAY

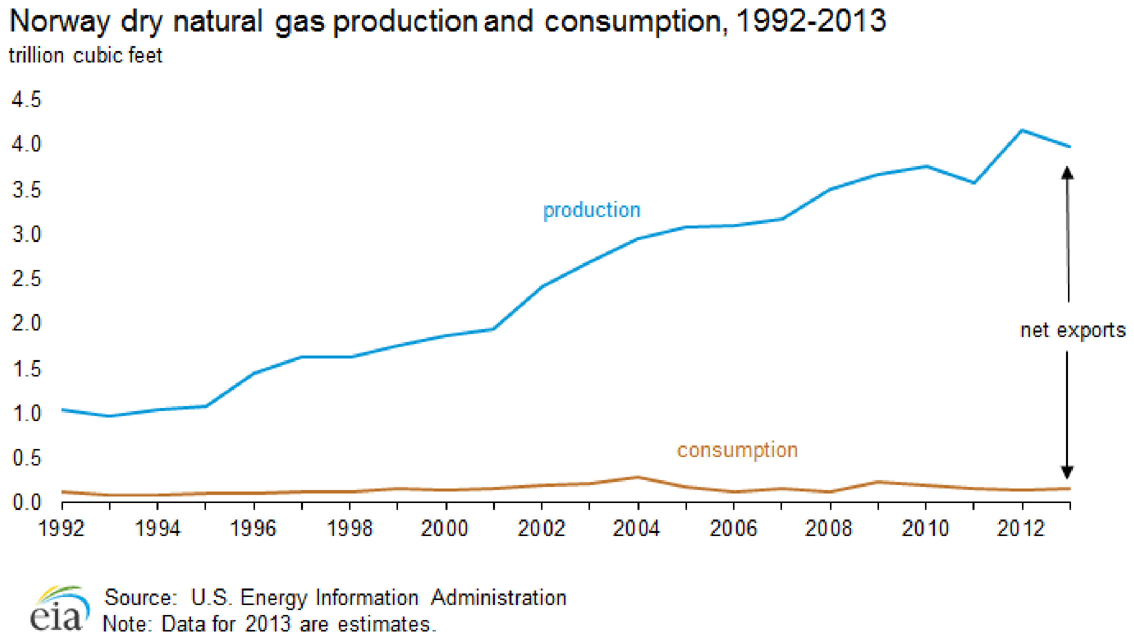
Source: Fuel Cell Today, 2012, *Fuel Cells and Hydrogen in Norway* [17]

After this snapshot the last part of this chapter aims to provide a state-of-the-art of the hydrogen and fuel cells potential in this Norwegian energy market. First, a global assessment is performed about the different resources available for the hydrogen production. The second part consists of establishing the existing network of companies and institutions as well as a review of the governmental position and policies about fuel cells and hydrogen technology.

2.8.1 RESOURCES AND PREDICTIONS

2.8.1.1 Potential for H2 production from Steam Methane reforming

As mentioned previously in this first chapter, the most commonly used method to produce hydrogen is currently the SMR (Steam methane reforming). It is then relevant to estimate and locate the current natural gas resources in order to anticipate the coming hydrogen production. Norway had 74 trillion cubic feet (Tcf) of proven natural gas reserves as of January 1, 2014 [22]. The graph below shows that Norway's domestic consumption of natural gas is very small compared to the annual production (less than 3%). It means that the Norwegian economy has a comfortable leeway to reorientate its natural gas exportation toward its future inner market of hydrogen production and consumption.



Norway dry natural gas production and consumption, 1992-2013

Source: U.S. Energy Information Administration
Note: Data for 2013 are estimates.

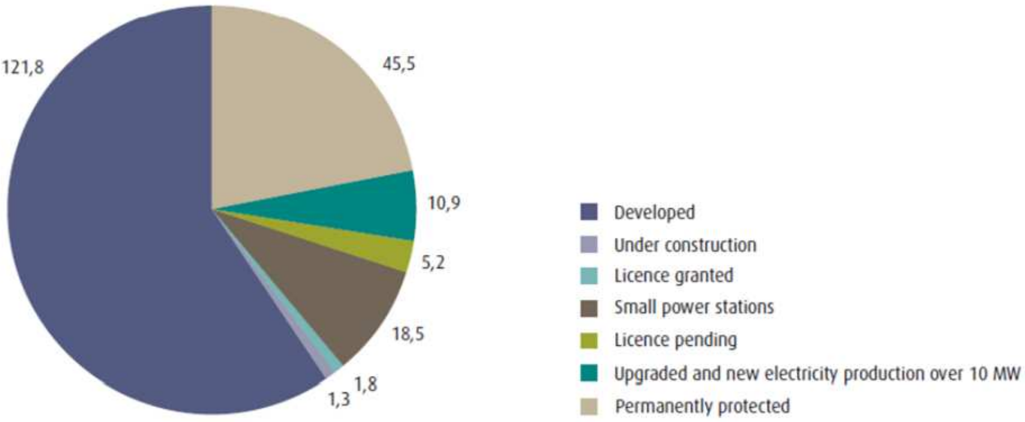
FIGURE 2-10 - NORWAY NATURAL GAS RESSOURCE

The use of both steam methane reforming and microwave plasma reforming has a good potential to achieve the massive scale conversion of methane into hydrogen. Even though the microwave plasma method has to be implemented at small scale (refueling station) this technology has the strong interest of being CO_2 lean and to have an interesting by-product (carbon powder)

2.8.1.2 Potential for H2 production from water electrolysis

However, the different renewable energies have also a serious potential to produce hydrogen thanks to electrolysis or biomass gasification. The interest of those combinations (hydrogen from renewables) would be the production of a CO_2 lean hydrogen very beneficial for the decarbonisation of the Norwegian economy.

If we look at the hydropower potential we can see that an additional potential can be installed for the small power stations. Despite the increasing energy consumption the national policy about energy saving could significantly decrease the use of hydropower. This energy saved can be considered to produce hydrogen thanks to water electrolysis. [92]



Source: Ministry of Petroleum and Energy. (2008). *Fact 2008 – Energy and Water Resources in Norway*. (Internet)

FIGURE 2-11 - NORWAY'S HYDROPOWER POTENTIAL, JANUARY 2008, TWH/YEAR

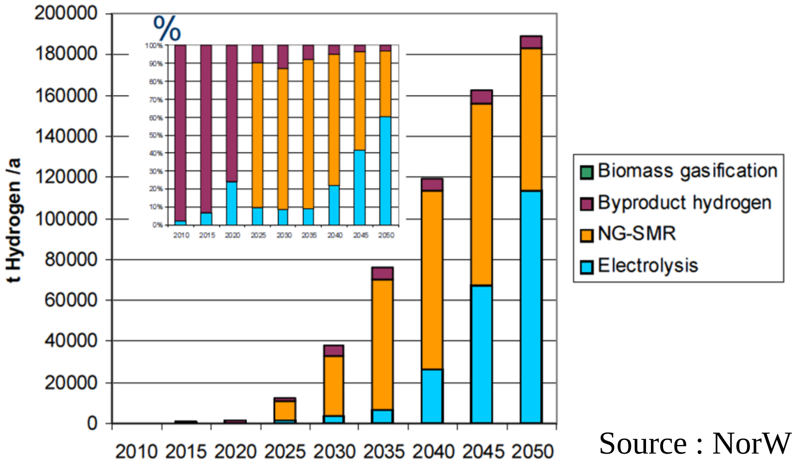
The potential of wind, tide and wave power could also be exploited to develop a CO_2 lean hydrogen production. However, those renewable energy sources represent only 0.06% of the total energy production for the year 2012 [24]. There is a serious wind potential in Northern Norway and this production could supply the additional electricity needed for the production of hydrogen by water electrolysis. However the grid in this region (Finnmark) is weak and the capacity of the power lines does not comply with the power needed. If this hydrogen is dedicated to a domestic use either investment in the grid infrastructure or the use of LH2 carrier like ships (see 2.8.2) are needed. Even if the accumulation of the hydropower and the renewable energy has a limited potential to produce hydrogen by electrolysis, it is still possible to use electricity from thermal plants fuelled by oil, natural gas or coal with a carbon capture storage process.

Biomass is also an important resource in Norway but at the moment it is more interesting to use this biomass for direct district heating or CHP (Combined Heat and Power). Even though a large exploitation of biomass for hydrogen production is not planned, a demonstration project of hydrogen refueling station based on biomass gasification is under study in Drammen. [17]

The available hydrogen in the Norwegian chemistry industry is equal to 0.9 Gm3 H2/year [23]. It can be an important resource especially for the southern Norway where the main hydrogen consumption will occur. As it is a by-product of another process, the production of this by-product hydrogen is a matter of price. If the hydrogen price is high then larger quantities will be available.

2.8.1.3 Prevision of the H2 production

According to the NorWays report [23] the hydrogen production in Norway should follow the evolution shown below.



Source : NorWays report

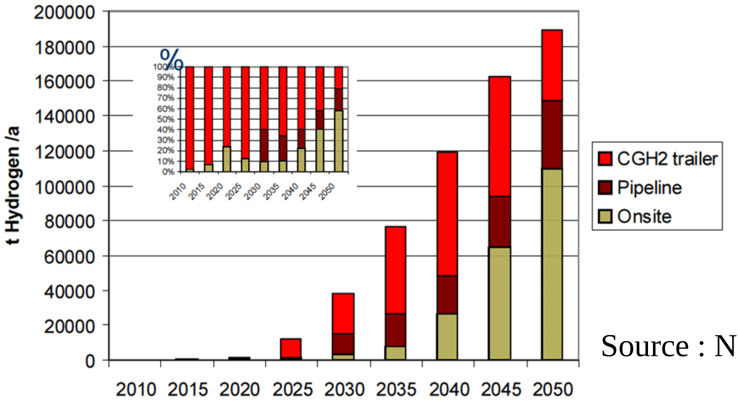
FIGURE 2-12 - PREDICTED HYDROGEN PRODUCTION IN NORWAY BY SOURCE

This estimation has been based on the following assumptions:

- From 2020, Hydrogen central NG SMR (without CCS (€25/ton)) and onsite electrolysis.
- From 2035, more electrolysis (sparsely populated areas deployed; increasing NG prices).
- By-product hydrogen used, biomass gasification and SMR with CCS do not appear economic under current assumptions.

2.8.1.4 Predictions of transport of hydrogen

Except the refineries that use their own hydrogen there is currently no significant hydrogen consumption in Norway. Therefore we can foresee a significant increase in the hydrogen demand due to its use in transportation. It is then relevant to determine where the main consumption centers will be located and how they will evolve (See Chapter 4, Road). In the NorWays scenario the distribution to the southern center of consumption is first done by trailer and is progressively replaced by pipeline, the northern region is supplied by onsite electrolysis. The figure 2-13 illustrates this evolution and allows us to see the increasing share of onsite electrolysis.



Source : NorWays report

FIGURE 2-13 - HYDRYGEN TRANSPORTATION PREDICTION FOR NORWAY

2.8.2 POLICIES

Norway has a strong incentives policy about Zero emission vehicles (ZEV) concerning both Electric vehicle (EV) and Fuel cells electric vehicle (FCEV). Originally this was motivated by the objective of having 50,000 ZEV on the road by 2018 but this goal has been reached in 2014 and this incentive policy has been extended. Biofuels, biogas, CNG and hydrogen are all subject to lower, or exempt from, fuel and CO 2 taxes. All-electric cars, including fuel cell electric vehicles (FCEV), are exempt from purchase tax and VAT, receive a 90% discount on annual road tax, pay no toll or municipal parking fees, are qualified for free ferry passage, and have access to bus lanes and thousands of public charging points. There is also a grant available for establishing private charging points and a financial support has been suggested by the Norwegian Hydrogen council to facilitate the construction of new hydrogen refueling stations. [25] [92]

The road map for hydrogen and fuel cells technology in Norway is principally advised by the Norwegian Hydrogen Council and an action plan has been published for the period 2012-2015. However the development of the Norwegian hydrogen economy is closely linked to the European plans and programs which allow the collaboration in the research field, in the infrastructure network and in the financing of projects.

The NorWays report published in 2008, which was a part of the HyWays project, is probably the most detailed study related to the hydrogen and fuel cells economy in Norway. This report has evaluated the road transport sector as the best market to insert this technology. Thanks to a complete road map this report has drawn the main lines for the development of the hydrogen production, infrastructure and use in Norway. Through different scenarios it has assessed the potential combinations between biofuel, BEV (Battery electric vehicle) and FCEV with the reduction of CO_2 emissions as a baseline. As this report will be used in the chapter 4 of this master's thesis it will not be developed further in this chapter 2. However we can say that this report and its content had an important influence on the hydrogen policy in Norway.

It is important to note that the switch to a hydrogen economy is a common EU policy. Beside the use of hydrogen for transport, it is frequently mentioned that Norway will have enough resources to export hydrogen to the rest of Europe and especially to Germany because of the high energy consumption combined with the lack of natural energy resource of this industrialized country. This option would be interesting for both Germany and Norway as the hydrogen produced will be CO_2 lean. In this configuration Germany would be able to reach its CO_2 quota and Norway to rely on an interesting export business.

The map below establishes the network of pipelines around the Norwegian coast. One can see that the existing gas pipelines reach the continental shore of Europe or even the U.K. Those existing facilities can be used to export the hydrogen by mixing it with natural gas [94]

FIGURE 2-14 - NATURAL GAS PIPELINE NETWORK BETWEEN NORWAY AND GERMANY

Source: The Norwegian Petroleum Directorate

Concerning the hydrogen exportation, Japan is also interested by importing CO_2 lean hydrogen by ship from Norway. This project is understudy between SINTEF, the Ministry of Economy Trade and Industry (METI) and Kawasaki Heavy Industries (KHI). More precisely the hydrogen would be produced in the Finnmark region (as mentioned before) and shipped through the Arctic sea to Japan thanks to special LH2 carrier manufactured by KHI. [93]

FIGURE 2-15 - LH2 CARRIER SHIP OF KAWASAKI HEAVY INDUSTRIES

Source: motorship.com

2.9 OTHER FUELS

In order to determine the hydrogen and fuel cells opportunities we need to compare it to other fuels and technologies. Therefore this section aims to provide a review of the main characteristics for the different energy systems competing with hydrogen. As those descriptions are common to all the transport sectors some specific details will be provided later if needed in each corresponding sections.

2.9.1 MARINE DIESEL OIL, DIESEL, GASOLINE AND INTERNAL COMBUSTION ENGINE

2.9.1.1 Operation

Those three fuels are direct derivates from crude oil with more or less refining. The marine diesel oil (MDO) is the least refined followed by diesel and then gasoline. The internal combustion engine (ICE) has a very interesting power density (0.65 kW/kg), it is also easy to refuel and the infrastructure already exists. As the fuel is liquid under standard conditions, it is easy to store. However, the ICE requires a lot of maintenance due to the rotating parts (change some pieces, corrosion) and it generates a lot of vibration. It is possible to use a hybrid system to generate electricity based on oil derivates and to use electrical propulsion (electric boat, hybrid vehicle).

2.9.1.2 Environment

Given their nature, those oil derivates are carbon intensive, and therefore they generate important direct emissions from their combustion (see table below). Due to the toxicity of MDO and diesel some catalystic treatment are required for the exhaust gases from the boats, trucks and certain cars. In a larger approach the impacts of the fuel extraction and transportation have to be taken into account. In Norway this transportation has a limited effect given that the consumption is local but its extraction still requires a lot of energy. The oil and gas industry is responsible for 29% of GHG emissions in Norway and the environmental damage also includes the risk of spill in the case of an accident. Due to the fact that an ICE is driven by explosions, a lot of noise and vibrations are also generated.

2.9.1.3 Economy

Those fuels are currently cheap, but despite a recent price collapse they are doomed to become more and more expansive due to their depletion. One of the main drawbacks with those fuels is the price volatility. Concerning their prices we can refer to the table 2-7.

2.9.1.4 Safety & social

As internal combustion engine is a well-known technology, and the different safety issues are no longer a problem. However, there are some concerns, like for any other energy storage device. The main one is the case of a road accident where a fire is ignited. In this case the main issue about diesel, gasoline and other oil derivates is the risk to see the fuel spreading itself around the accident area and catching fire. There is currently no way to keep the fuel away from fire efficiently. One of the options is to make the fuel tank more resistant, but if the tank is surrounded by fire the pressure will rise and this will increase the risk of an explosion. As diesel is used widely since many decades, the industry and the different professional sectors are skilled to operate and produce all the components needed for this technology.

2.9.2 BIOFUEL

2.9.2.1 Operation

Biodiesel is produced thanks to the extraction and esterification of vegetable oils, used cooking oils and animal fats using alcohols. It is also possible to use a more advanced process by hydrogenation, gasification and then liquefaction of oil and fat. This advanced process is called BTL (biomass to liquid) and produce synthetical diesel. The biodiesel is ten time more viscous than the conventional diesel and is highly corrosive which increase the maintenance cost. It can either be mixed between 5% (B5) and 10% (B10) with conventional diesel or can also be used as pure biodiesel but then the engine requires special joints. Its use generates some corrosion issues and microbial development due to the nature of the fuel.

2.9.2.2 Environment

Even though the carbon cycle of biodiesel is neutral, it still requires external energy inputs (farming and processing) that emit CO_2. Therefore we can say, according to the IEA, that biodiesel provides a 40-60% reduction in CO_2 emissions compared to the conventional diesel. Compared to conventional diesel fuel, use of biodiesel is generally found to reduce emissions of hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) but to increase oxides of nitrogen (NOx) emissions. Due the important land resources it takes to grow biofuels there is an increasing indirect impact of the biofuel production.

2.9.2.3 Safety and social aspects

Biodiesel has a higher ignition point than hydrogen and benefits of a good image because of its environmental friendly characteristics. However, as mentioned before, its use can lead to some corrosion issues in the strokes and tank.

2.9.2.4 Economy

Before taxes the biodiesel from animal fat costs \$0.4-\$0.5/lde (liter of diesel equivalent), biodiesel from vegetable oil costs \$0.6-\$0.8/lde and biodiesel from BTL is superior to \$0.9/lde (depending of the biomass source). In Norway the B5 is well established and currently follows the price of the Norwegian diesel (Diesel 1.64€/l in average)[55]

2.9.3 NATURAL GAS (CNG AND LNG)

2.9.3.1 Operation

CNG (compressed natural gas) is a compressed methane under the pressure of 200 bar and stored in cylinders while LNG (liquefied natural gas) has been liquefied by being cooled below its boiling point of -163 °C and stored into specific tanks. Those two gas forms can be easily implemented on an existing diesel engine or can even run with a dual fuel engine using diesel and natural gas for the same performance. In any case the storage has to be handled with a special design by considering the inherent leaks common to any cryogenic storage (in the case of LNG).

2.9.3.2 Environment

The combustion of LNG releases almost 30% less CO_2 than diesel (50gCO_2/MJ and 69gCO_2/MJ respectively) [22] and emissions of NOx is reduced by 85%. The natural gas can either come from a conventional extraction or by a biogas production process. This biogas can greatly improve the overall CO_2 emission because it comes from biomass. It is important to note that one kilogram of natural gas has a global warming potential 72 times higher than one kilogram of CO_2. It means that any leak of LNG or CNG in the environment would be highly damageable concerning the global warming.

2.9.3.3 Economy

The cost estimated for a LNG stations is 101€/kg of gas output per hour for a CNG station and 1 100€/kg of gas output per hour for a LNG station. This excludes land purchase and permit costs. Natural gas has the advantage of having a relatively more stable price than diesel but it is still dependent of the oil price fluctuation.

2.9.3.4 Safety and social aspects

Like hydrogen the LNG suffers from a lack of regulation about its use as a propulsion fuel. The safety issues principally concern the storage tank and the associated system (what use of the boil off methane). Given it is a cryogenic liquid not widely used for propulsion yet, it is a challenge to train the operators to manipulate this fuel with all the necessary precaution.

2.9.4 LPG (LIQUEFIED PETROL GAS)

2.9.4.1 Operational

LPG is produced by refining petroleum or natural gas, and is almost entirely derived from fossil fuel sources, being manufactured during the refining process. The engine is converted with minimal changes into a spark ignition engine with equivalent power and torque of the diesel. LPG has a higher specific calorific value of 46.1 MJ/kg compared with 42.5 MJ/kg for fuel oil. However its energy density per volume unit of 26 MJ/l is lower than that of petrol (35.8 MJ/l), therefore it need to be stored into a pressurized tank.[63] At the moment there are 155 LPG refueling stations in Norway covering all the road network.[64]

2.9.4.2 Environmental apsects

To use LPG can have some environmental benefits as a truck conversion to LPG allows reaching the Euro 4 level without catalyzer, achieves CO_2 levels 10% better than diesel and makes the particulate matter almost inexistent.

2.9.4.3 Safety

LPG is heavier than air, unlike natural gas, and thus will flow along floors and tend to settle in low spots, such as basements. There are two main dangers from this. The first is a possible explosion if the mixture of LPG and air is within the explosive limits and there is an ignition source. The second is suffocation due to LPG displacing air, causing a decrease in oxygen concentration. Therefore some places are restricted for LPG vehicles.

2.9.5 BATTERY

2.9.5.1 Operational

In this section we will consider the last commercialized battery technology which is the Lithium-ion battery as it provides the best energy and power density (100-265 Wh/kg) [44]. These battery types can be recharged more quickly, have lower self discharge rates and are free of a memory effect. Due to the combination of the batteries' great energy efficiency (85%) and their considerable weight they are complementary of other energy sources for small and medium energy storage. Batteries offer the operational advantage to have a very low need of maintenance. One of their main disadvantages remains their lifetime (around 1500 cycles per lifetime for the most advanced) and their progressive performance degradation even though some significant improvement has been achieved[44]. We can also note the relatively long recharging time compare to hydrogen or diesel (few hours against few minutes) even though it is possible to use fast recharging station at the expense of the battery lifetime.

2.9.5.2 Environmental aspects

Batteries offer the considerable advantage of zero direct emissions during their operation. However the origin of the electricity stored and used can lead to an even worse climate change potential than diesel (from coal without CCS for instance). In Norway the energy mix is based on 95% CO_2-lean production, so this is not an issue. Although it is relevant to point out that the fabrication of the battery pack is energy intensive, so again, the impact depends on the origin of electricity. Concerning the lithium-ion technology, the raw material supply (lithium) can also be an issue as most of the world resources are located in Chile.

2.9.5.3 Economical aspects

Currently the price of investment for a li-ion battery is high (500€/kWh) [44] compare to the other options, but in the other hand the energy consumption is generally lowered by 40% in average [44] with the cheap electricity in Norway (10c€/kWh) [45]. In addition the governmenent provides a lot of incentives to close this gap between the technologies. All-electric cars are exempt from purchase tax and VAT, receive a 90% discount on annual road tax, pay no toll or municipal parking fees, qualify for free ferry passage, and have access to bus lanes and thousands of public charging points.

2.9.5.4 Safety

Lithium-ion battery, like any other energy storage device, represents a risk at high temperatures (fire accident for example). If the battery is exposed to high temperatures for a significant time, or to a manufacturing default, then the inner temperature can quickly reach 500°C. At this point the cell catches fire or it explodes and releases toxic gases. Some safety requirements for the manufacturers have been established like TBU-207 Safety Concerns with Li-ion or UL1642. Moreover, the basics electrical protections are needed especially in a hybrid configuration where every electrical component (sparkle) should be isolated from any potential explosive mixture (air and hydrogen or air and LNG). As batteries are widely integrated in our economy there is no specific reluctance, we can even say they have a good reputation thanks to their zero direct emissions. Nevertheless, we can notice a common range anxiety which can explain some reluctant attitudes.

2.9.6 OTHER FUELS SUMMARY

TABLE 2-7 - OTHER FUELS CHARACTERISTIC SUMMARY [55]

Fuel	*LHV (kWh/kg)*	*System energy efficiency (%)*	*Carbon intensity* (gCO_2/kg)	NO_2 *emission* (gNO_2/kg)	*Price (€/l)/(€/kWhoutput)*
Hydrogen	33.3	44	0	0	€9.9/kg / 0.17
MDO/ Diesel/ Gasoline	11.3/ 12.1/ 12.3	30/ 25/ 25	3.2	0.014	0.8 / 0.24 1.64 / 0.66 1.86 / 0.83
Biodiesel	11.6	25	3.4	0.004	1.64 / 0.66
CNG LNG	12.7	44 (FC) 25 (ICE)	2.6		0.01 €/kWh / 0.003 0.4€/kg / 0.13
LPG	12.9	25	2.9	0.014	0.7 / 0.40
Battery	-	85	16 $gCO_2/kWhe$	0	Electricity: 10c€/kWhe

3

MARITIME SECTOR

3.1 INTRODUCTION AND ENVIRONMENTAL CONTEXT

3.1.1 INTRODUCTION

This chapter is dedicated to the opportunity of hydrogen and fuel cells technology in the maritime sector. The Norwegian economy is mostly oriented toward the petroleum activity and the shipping of goods, which generate a lot of maritime traffic. All of those sub-sectors are mainly powered by a conventional internal combustion engine (ICE) fuelled by the marine diesel oil (MDO) which is very polluting. Consequently the maritime sector represents 28% of the GHG emission in the transport sector for 2012 [23].

First, the environmental aspect of the maritime sector will be covered in order to understand the related challenges. Then the different applications and aspects of the hydrogen technology will be qualitatively assessed and a non-exhaustive list of some maritime project related to fuel cells technology will be established. After that the specific information related to the other fuels will be also provided. Thanks to this information an economical comparison will be performed through a study case of the Sognefjord ferry. Then we will discuss about the information and the results to finally conclude on the opportunities of hydrogen and fuel cells in the maritime sector. A SWOT matrix will be presented at the end to summarize the content of this chapter.

3.1.2 ENVIRONMENTAL CONTEXT

Ship emissions can impact air quality in coastal regions and further inland. Ships commonly use heavy oil based fuels with high sulphur contents and hence have a tendency to emit sulphur dioxide (SO2) along with other pollutants such as nitrous oxides (NOX), particulate matter (PM), carbon dioxide (CO_2) and other greenhouse gases (GHGs). Ships emit considerable amounts of pollutants, not only when sailing, but also during their stay at berth. This is of particular importance for harbor cities because ship emissions can contribute a lot to regional air pollution and result in some of the EU standards (for PM and NO2) not being met. That was the case for PM limits in Oslo, Bergen and two other cities in 2013. [28]

Based on the previous information it is clear that fuel cells and hydrogen can play a key role in the reduction of emissions. It is even truer that the international regulation put more and more pressure on this issue. The Emission Control Areas (ECA) illustrate the will from various countries to limit efficiently by the means of the law of the environmental impact of shipping. Therefore we can see through those ECAs a real opportunity and a growing interest from the maritime industry for the fuel cells and hydrogen technology. According to the International Maritime Organization the ECA for the North Sea is very likely to be extended to the Norwegian sea in 2015. This extension would result in a larger benefit of adopting low emission technologies.

The map below shows the existing and the possible ECA in the world. As we can see Norway is in a good way to adopt this stricter regulation

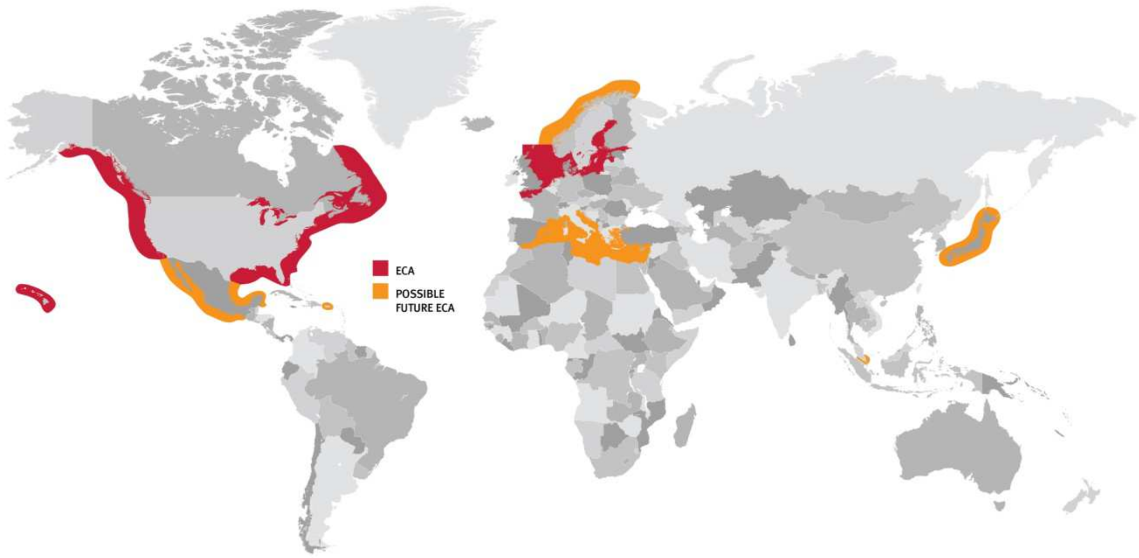


FIGURE 3-1 - WORLD MAP OF THE EXISTING AND POTENTIAL EMISSION CONTROL AREAS

Source: IMO MARPOL Annex VI

3.2 HYDROGEN AND FUEL CELLS

3.2.1.1 Operation

When we speak about fuel cells we have to remember that some of them can work with natural gas and in different conditions than a PEMFC does (cf. chapter 2). As it changes radically the operational aspect of the system, it is relevant to consider the different options in this study. In the maritime sector the fuel and the size are important but there is a better flexibility concerning the response time and the operating temperature (compare to road transportation). Therefore the choice is not only open to the PEMFC but also to the MCFC and the SOFC (even the DMFC can be interesting).

The maritime application also allows the introduction of the high temperature PEMFC (HTPEMFC) which is less sensitive to the purity of hydrogen and can therefore be used more easily with reformed fuel on board. Those different fuel cells have their own characteristics (fuel, size, operating temperature,…) as mentioned in the chapter 2.

Technically speaking it is possible to use the fuel cells technology in three different configurations on a boat:

- As an auxiliary power unit (APU)

Given the increasing electrical consumption on board, the fuel cell can produce the needed quantity of electricity without interfering with the propulsion of the vessel. This configuration leads to beneficial fuel economy.

- Hybrid propulsion (Fuel cells and ICE)

This configuration can be parametered to operate as a base load (providing continuously a percentage of the power) or as a peak load to avoid transient regime for the ICE. This system can also be combined with a battery. The presence of a battery can be useful in the case of a regenerative breaking vessel.

- Full power propulsion

It is also possible to equip the system only with a fuel cell and a battery. The fuel cell provides all the power needed and the battery enable the system to act with regenerative breaking.

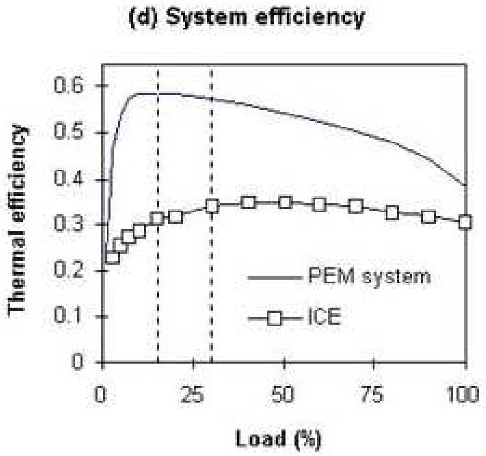


FIGURE 3-2 - DIFFERENT POWER SYSTEM EFFICIENCIES VERSUS BOAT LOAD PERCENTAGE

Sources: Kartha and Grimes, Physics Today 11, p. 54, Fig. 3)

This diagram shows that it is relevant to use fuel cells at low load level like when FC is combined with another stroke engine to act as a base load. It is then technically more interesting to use a high share of the power coming from the fuel cell when the vessel is entering the port and has a small load. The share will diminish when the boat increases its speed/load to move over longer distances. In the case of an engine only based on fuel cell there are two design philosophies: The first one consists of designing one large fuel cell where the operating point corresponds to the highest efficiency. This configuration requires a higher FC power than the electric motor actually needs to be sure to operate at low load level. The second option consists in having several fuel cells to share the load and therefore operate at their maximum efficiency point. The advantage of having one big FC is to optimize the investment cost while having several fuel cells allows having a back-up solution and gives the possibility to have a decentralized powertrain (mass repartition, design flexibility).

3.2.1.2 Design

The different configurations mentioned above lead to different designs but all those configurations will take more space than a single stroke engine. A fuel cell system is more bulky due to the hydrogen storage, but in the other hand the modules can be placed in several different locations around the ship. Together with lower vibrations and noise, modularity makes the engine room location less critical. Even though the safety constraints and the regulation affect the design, if they are handled appropriately, this modularity provides a high degree of design flexibility. None the less the frequent shocks on the hull of the vessel have to be considered in the design to avoid important vibration that might disturb temporarily the operation of the fuel cell (and its lifetime in the long run).

3.2.1.3 Range/Storage

The storage method will depend of the quantity of hydrogen stored. For large amounts of hydrogen the liquid hydrogen is the best option because of the volume gain while small to medium quantities will be stored under pressure (35MPa or 70 MPa). In case of a liquid storage it is very likely that the production will be centralized and the supply achieved by trucks as it is the most economic solution for liquid hydrogen. Of course the range depends directly on the quantity of hydrogen stored but also upon the speed of the boat, its weight and the size of the battery. Contrarily to the road transport it is difficult to provide a common formula (like 1kg of H2/100km) as the characteristics vary a lot from one boat to another. However, by referring to the section "Projects" (cf later in this section) we can have an idea of the range for different projects. As mentioned before, the fuel cells can also use natural gas and operate as a base load but in this configuration it is difficult to attribute a specific range to the fuel cell itself.

3.2.1.4 Refueling

Refueling facilities for hydrogen are not developed in the maritime sector. For each project a refueling station has to be built (see the NemoH2 project in table 3-1) or the fuel has to be supplied frequently by trucks. Depending of the size of the ship's tank the refueling can take few minutes for the smallest or a couple of hours for the biggest [32]. However, it is not excluded in a close future to use the refueling station for different modes of transport simultaneously (e.g. maritime and road transport). The hydrogen can be produced onsite either by electrolysis or by steam reforming.

3.2.1.5 Maintenance

Contrarily to a conventional stroke engine, a fuel cell system has no rotating parts and needs consequently less maintenance (lubrication, corrosion, vibration). However, due to the lifetime of the existing membrane technology, the fuel cell's stack has to be replaced regularly (every 10,000 hours) to maintain the level of performance needed. Fuel cells stacks have not reached yet the goal of 40000 operating hours without having a significant performance degradation. As a comparison the conventional plant has a 20 year lifetime. The comparison of this maintenance will be achieved later in this section[35]. Depending of the type of fuel cells installed, the membranes can be very sensitive to the air composition. A PEMFC will be more vulnerable to the salinity of water or the humidity rate while a MCFC will operate all the same.

3.2.1.6 Environment

In the frame of the European project FC SHIP, a life cycle analysis (LCA) has been performed in 2004 by the companies L-B-Systemtechnik and MTU Friedrichshafen [38]. This LCA includes fuel production, supply and use, fuel cells manufacturing and end-of-life as well as ship operation, and this LCA is compared to a conventional ship operation. Here is a part of the executive summary:

"The analysis comes to the conclusion that fuel cells offer the potential for significant environmental improvements both in terms of air quality and climate protection. Local pollutant emissions and greenhouse gas emissions can be eliminated almost entirely over the full life cycle using renewable primary energies. The direct use of natural gas in high temperature fuel cells employed in large ships and the use of natural gas derived hydrogen in PEM fuel cells installed in small ships allows for a greenhouse gas emission reduction of 20%-40%. Fuel cells have the potential for further efficiency improvements over the values assumed here, which would translate into further reductions of greenhouse gas emissions for fossil based fuels."

Except the air pollution and its consequences the noise induced by conventional vessel propulsion systems is also a favorable point with the fuel cells system. Whatever the fuel cells selected (PEMFC, MCFC, SOFC, DMFC) they all provide an electric supply for the propulsion. This electrification has the effect of lowering considerably the noise level for both the equipage on board and the surrounding environment. Of course this improvement only occurs if the power chain does not include any stroke engine. For instance, it is not the case for an APU systems where a fuel cells is only used for the auxiliary system but where the propulsion is provided by a stroke engine. This silent operation is also of utmost importance for certain applications like scientific studies of sea animals.

3.2.1.7 Regulations

At the moment the maritime industry suffers a real lack of regulation concerning the hydrogen and fuel cells technology on board. The IMO who is in charge of the international maritime regulation has published a draft about this topic in 2013 [29] but no official publication has been released so far. However, the IMO is not the only one to work on the topic, and the company DNV had published its recommendation in 2008 about design and safety for fuel cells ships [32]. Even if this study concluded that safe fuel cells systems are technically feasible it is still the role of the IMO to provide an approval process for the construction of those new ships. None the less the DNV work suggests that two different class notations for fuel cells vessels should be used: "FC-SAFETY" which is mandatory for all fuel cells installations and "FC-POWER" if the fuel cells unit is used for main or auxiliary power.

Source : shipsandoil.com

FIGURE 3-3 - THE VIKING LADY, (SEE PROJECTS)

3.2.1.8 Projects

In order to give a snapshot of the current activity for the integration of fuel cells and hydrogen in the maritime sector a non-exhaustive list of the existing projects has been established. This list covers principally different sizes of projects and different technologies around the world.

TABLE 3-1 - NON EXHAUSTIVE LIST OF FUEL CELLS BOAT PROJECTS

Project name	*Description*	*Power*	*Hydrogen storage*	*Fuel cells*	*Battery*	*Range*
Nemo H2, Amsterdam [34]	87 passengers	90 kW	24kg, 35MPa, 6 cylinders	70 kW, PEMFC	50 kW	9 hours, 9 knots
The Viking Lady [30] DNV-GL	Merchant vessel, ICE+FC+Battery (NG)		Natural gas	330 kW MCFC	500 kWh 5 MW	
Scandlines FC ship (design) [37]	1,500 passengers and 2,200 lane meters for vehicles 18.5km transport corridor		3.1 tons	8.3 MW PEMFC		48 hours, 17 knots
FILHyPyNE project, France (design)	12 meter long ship that can take three fishermen	200 kW	120 kg, 35 MPa	210 kW	124 kWh	3 days of fishing
La Compagnie des Bateaux-Mouches, France	Tourism passenger boat of 250 tons can transport 1000 passengers		600 kgH2	400 kW		

Sognefjord, Norway, Siemens electric boat (study case)

A ferry boat with a capacity for 360 passengers and 120 vehicles that will travel across the fjord 34 times per day, with each trip requiring around 20 minutes to make the six-kilometers crossing. The ferry, which is 80 meters long, is driven by two electric motors, each with an output of 450 kilowatts. The batteries have a combined capacity of 1,000 kilowatt-hours (kWh), which is enough to make a few trips between the two fjord communities. After that the batteries will need to be recharged. At each stop an onshore battery of 260 kWh will supply electricity to the ferry while it waits. Afterward, the battery will slowly recoup all of this energy from the grid until the ship comes back again to drop off passengers and recharge. This method avoids a sudden demand of power from the weak grid. According to Siemens, this type of electric ferries could serve around 50 routes in Norway. [47]

3.3 OTHER FUELS

The general properties of the different fuels and technologies competing with hydrogen and fuel cells are described in Chapter 2. Therefore the specific aspects of those fuels and technologies regarding the maritime sector are covered in this section.

3.3.1 MARINE DIESEL OIL (MDO)

3.3.1.1 Environment

The combustion of MDO impact strongly both local environment (air, water, noise) and global climate (CO_2 emissions). In the case of a tank leakage the consequences are highly damageable for the environment (oil spill). In order to comply with the coming international requirement (Tier 3, MARPOL, Annexe VI, 1 January 2016) the newly built ships will have to be equipped with a selective catalytic reduction system. [35]

3.3.1.2 Economy

Currently the cost of the fuel MDO is cheaper than fuel hydrogen (874 USD/ton) [22], the investment cost is also cheaper. However, the maintenance costs more by using a propulsion system based on MDO than one based on electricity. The stocks of oil are limited and its price is rising progressively. The TCO (total cost of ownership) is currently cheaper for a MDO system. As MDO is a direct derivate from the oil industry, Norway can rely on a national resource but it is important to remind that oil can suffer an important volatility of its price. [35]

3.3.2 LNG (LIQUEFIED NATURAL GAS)

3.3.2.1 Operation

The most common mode is to use it in a stroke engine but it can also feed a generator and produce electricity (hybrid). Another way is the use of a fuel cell as an energy converter (MCFC or SOFC). Those two types of FC having a low inertia can be combined as a base load to any other electric propulsion. LNG carriers move natural gas from liquefaction terminals to re-gasification terminals all over the world, and LNG is available at all these shore-based facilities. As mentioned in Ch. 1 the dual fuel technology allows the ship to run on MDO when travelling and on LNG when operating in ECAs or in port.

3.3.2.2 Environment

The combustion of LNG releases almost one half less CO_2 than MDO ($50gCO_2/MJ$ and $69gCO_2/MJ$ respectively) [22]. In addition to this, the emission of NOx is reduced by 85% and the emission of SOx is almost inexistent. Those characteristics allow the ship to comply with the coming regulation about emissions.

3.3.2.3 Economy

The LNG is cheaper than MDO (0.83c€/MJ against 4.6c€/MJ) [22]. However the refueling facilities are not as well established as for the MDO's and LNG has a more important investment cost due to the design requirement (cryogenic liquid).

3.3.3 BATTERY

At the moment the battery technology can only be self sufficient on some small boats and small ferries. If a battery is used as the main source of energy the grid has also to be designed to sustain the power flow without failure during the recharging period (see Sognefjord project). We mentioned earlier the use of hybrid engine or the combination with a fuel cells. In those configurations the battery is very unlikely to be recharged but is rather used as an energy buffer to manage the fluctuation of power consumption.

3.4 ECONOMIC STUDY CASE: SOGNEFJORD FERRY

For this study case in the maritime sector we have chosen a ferry operating across the Sognefjord. This fjord is located between Bergen and Ålesund and is crossed by several ferries. The line we are interested in circulates between Lavik and Oppedal and is currently operated by the electric ferry named MF boat. This boat is an electric ferry designed by Siemens and has started to operate on January 1st 2015. The description of its operation and infrastructure is given above in the section "Projects".

This study aims to compare the Total cost of ownership* (TCO) of different powertrains over 10 years of operation. Those options are the battery ferry (currently operating), a fuel cells ferry powered by a PEMFC and a diesel ferry. Thanks to the calculations a TCO will be expressed for each option and will allow determining the most relevant option from the economical perspective. First, the comparison will be done with the current technology costs, and secondly the impact of each technology cost will be assessed (Diesel price, hydrogen price and battery price) on the different options. In a second study the TCO of each powertrain will be assess for several trip distances. This second perspective will allow us to generalize our calculations to different operating conditions.

*TCO: The total cost of ownership defines the total expenses of owning an asset. In our case the asset is the powertrain of the boat and the cost is composed of the infrastructure, the powertrain itself and the fuel cost.

3.4.1 METHOD, ASSUMPTIONS AND INPUT DATA

In order to complete the calculations we have used several technology costs as well as component lifetime and efficiencies. The references that have not been given previously will be provided all along the different studies and the values that had been assumed will be notified. The most important values and assumptions are given in this section. Only the graphs will be displayed, therefore the calculation details will be provided in the appendix C. The different calculation steps will be detailed when needed.

First we can find below the relevant information for each powertrain technology

Table 3-2 - Ferry study case, Powertrain specifications

	Electric Ferry	**FC Ferry**	**Diesel Ferry**
Lifetime	10 years (a)	10 000 hours (b)	> 10 years (c)
Powertrain cost (g)	500€/kWh	See Ch1	28 €/kW
Fuel cost	0.1 €/kWhe	5.5 €/kgH2 (d)	0.8 €/l (f)
Technology efficiency	85%	58% (e)	25%
Infrastructure cost	2.15 M€ (a)	4 875€/kgH2/day	(f)

The different assumptions that have been made are listed and explained below:

(a) The infrastructure cost consists of the recharging infrastructure on both shores. The battery lifetime and the infrastructure cost have been provided by the operator Norled

(b) The fuel cells lifetime is based on a stationary operation (few starts and stops)

(c) The renewal rate for the combustion engine was considered as inexistent.

(d) The electrolysis process has been selected given that it is likely to be the favorite one in Norway (CO_2 lean H2).

(e) We assume a full hydrogen recirculation so only the electrochemical efficiency is accounted for.

(f) The diesel infrastructure is considered as already existent. Therefore the price of diesel reflects the infrastructure cost.

(g) The powertrain cost is given without margin. In the calculation a 50% margin has been added to simulate the final customer price.

Then, ine order to determine the TCO of a powertrain we consider the CAPEX and the OPEX where:
CAPEX = Infrastructure + Powertrain (battery, hydrogen storage, fuel cells, ICE)
OPEX = Maintenance cost (battery and fuel cells renewal) + Fuel cost

The OPEX is calculated by considering the time value of the future expenses. Therefore a depreciation rate of 4.1%/year has been applied to all the cost occurring after the first year of operation (principally fuel cost). This total cost over ten years with annual depreciation will be represented by the Net Present Value (NPV-10yr) and is calculated thanks to the following formula:

$$NPV = C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i}$$

C_0 = Initial investment (CAPEX) ; C = Annual expense (OPEX) ; r = Discount rate
Here T = Study time frame = 10 years so the NPV will be expressed as “NPV-10yr”.

Given that T = 10 yr and r = 0.041 we can simplify the NPV as:

$$\text{NPV-10yr}\ (C_0, C_i) = 8.0707 * C_i - 2 * 10^{-13} + C_0$$

Then the TCO is obtained by a simple division:

$$TCO\ (€/km) = \frac{NPV\text{-}10yr}{Lifetime\ distance}$$

3.4.1.1 First study: Price variation

The first study aims to assess the impact of the different technologies price variations. The parameters under study are the hydrogen price, the MDO price, the battery price and the electricity price. This first case uses the Sognefjord ferry and the real life operation distance as a reference. The calculations' most important values are given in the table below:

TABLE 3-3 - FERRY STUDY CASE, GENERAL INFORMATIONS

Annual Distance	74 460 km/year
Number of day of operation	365 days/year
Trip per day	34 trips/day
Distance per trip	6 km/trip
Average energy consumption	26.4 kWhoutput/km or 8.8 Ldiesel/km or 1.37 kgH2/km
Motor power	800 kW
Autonomy requirement (a)	1 day
Study timeframe	10 years
Discount rate	4.1 %

(a) Only for fuel cells ferry.

FIGURE 3-4 - MF AMPERE, ELECTIC FERRY

Source: norled.no

3.4.1.2 Second study: Impact of distance trip

For this second study the changing parameter is the distance of the trip. The interest is to determine what distance range is the best for each technology. For each trip distance, while keeping all the other ferry characteristics, the size of the battery and the quantity of hydrogen onboard has been redesign. Concerning the battery electric ferry, the same operation mode has been assumed with one important battery onboard (5.3 times the energy required for one trip) and two smaller ones onshore at each end of the trip (1.4 times the energy required for one trip). The infrastructure cost for the battery ferry is considered as constant while the refueling station cost for the fuel cell ferry is proportional to the daily hydrogen consumption. Some additional information are gathered on the table 3-4

TABLE 3-4 - INPUT DATA FOR THE FERRY DISTANCE STUDY

Cruising speed	18.2 km/h
Operating time per day	11 hours
Number of day of operation	365 days/year
Energy consumption	26.35 kWhoutput/km

3.4.2 RESULTS FIRST STUDY

This section display the different results obtained after the calculations mentioned above. Short comments will be provided for each graph but a longer interpretation will be written in the next section dedicated to the analysis of those results.

TABLE 3-5 - FERRY STUDY CASE, MAIN RESULTS

	TCO (€/km)	*Energy system weight (tons)*
Diesel ferry	7.1	1.2
Electric ferry	6.9	10
Fuel cells ferry	8.4	7.5

Comments

Those values are obtained with the current technology cost mentioned above. The TCO allows us to compare the results with a common unit to the transport sector (see other chapters).

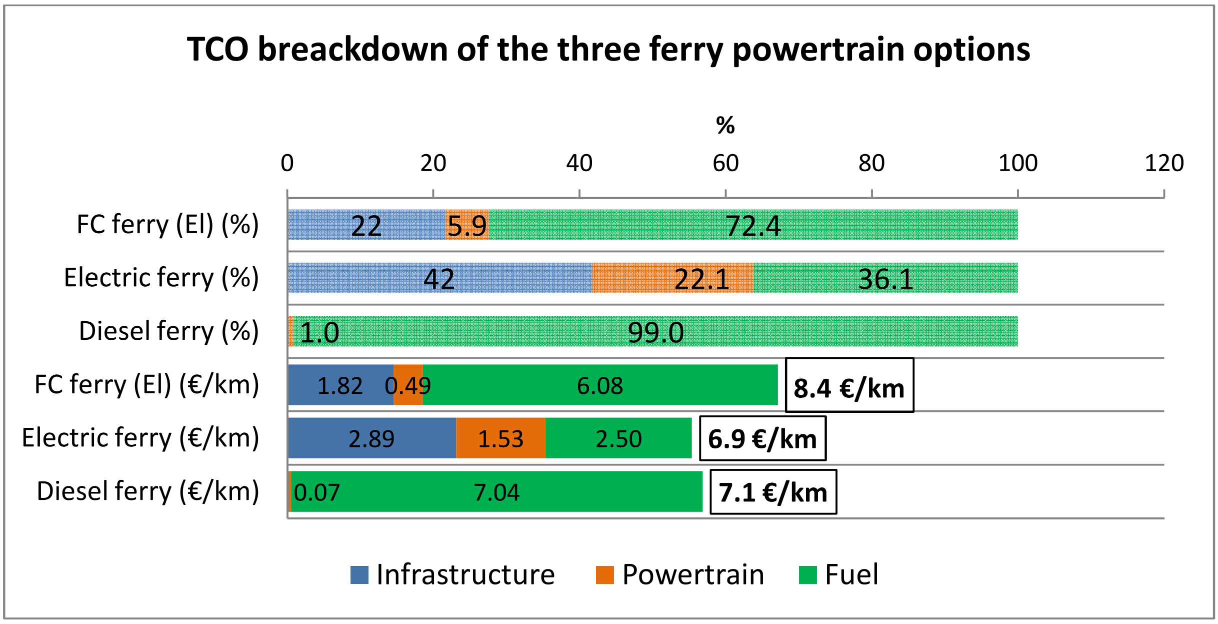


FIGURE 3-5 - FERRY STUDY CASE, TCO BREAKDOWN

Comments

This bar chart allows us to see the repartition of the costs for each TCO. The breakdown is made between the infrastructure cost, the powertrain cost and the fuel cost. As mentioned before the diesel ferry is assumed to have no infrastructure expenses, therefore its breakdown only includes the powertrain and the fuel cost.

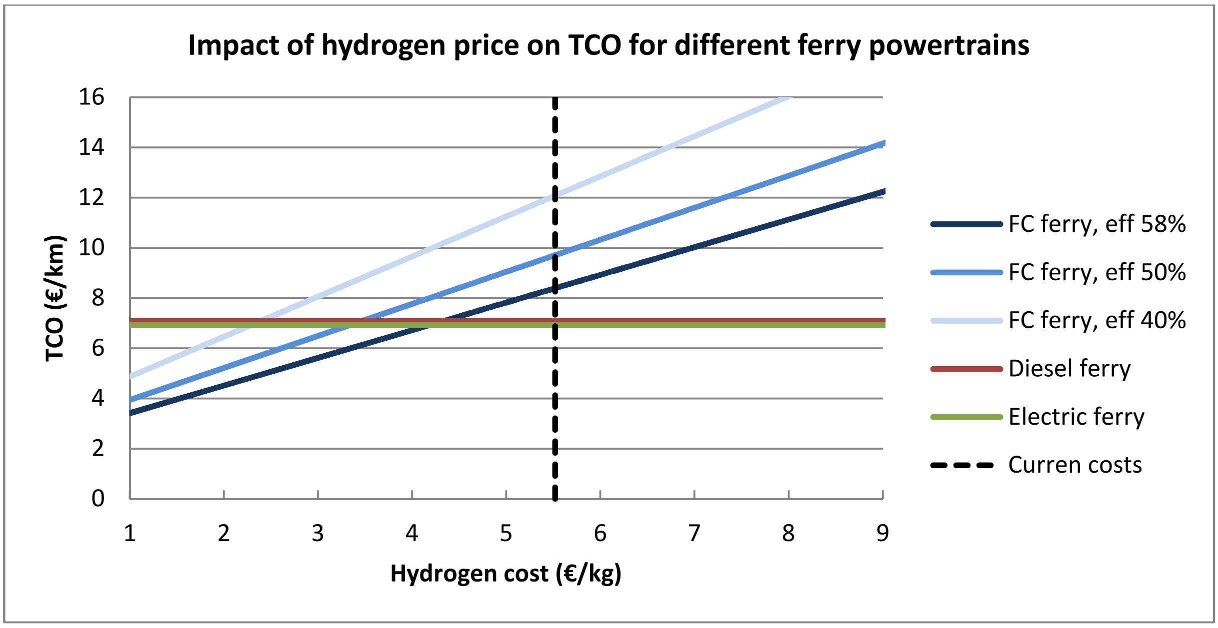


FIGURE 3-6 - FERRY STUDY CASE, IMPACT OF HYDROGEN PRICE

Comments

Here, the variable is the hydrogen cost and as expected only the FC ferry is function of this parameter. Different fuel cells efficiencies are displayed to simulate the effect on the TCO. The FC efficiency can be influenced by the load as shown in fig2-2. The hydrogen cost can be influenced by the electricity price, the manufacturing cost of the electrolyzer or by the size of the plant. For instance the electricity cost can be close to 0 c€/kWhe in case of a wind turbine overproduction. The evolution of hydrogen price is detailed in 2.5.2.5.

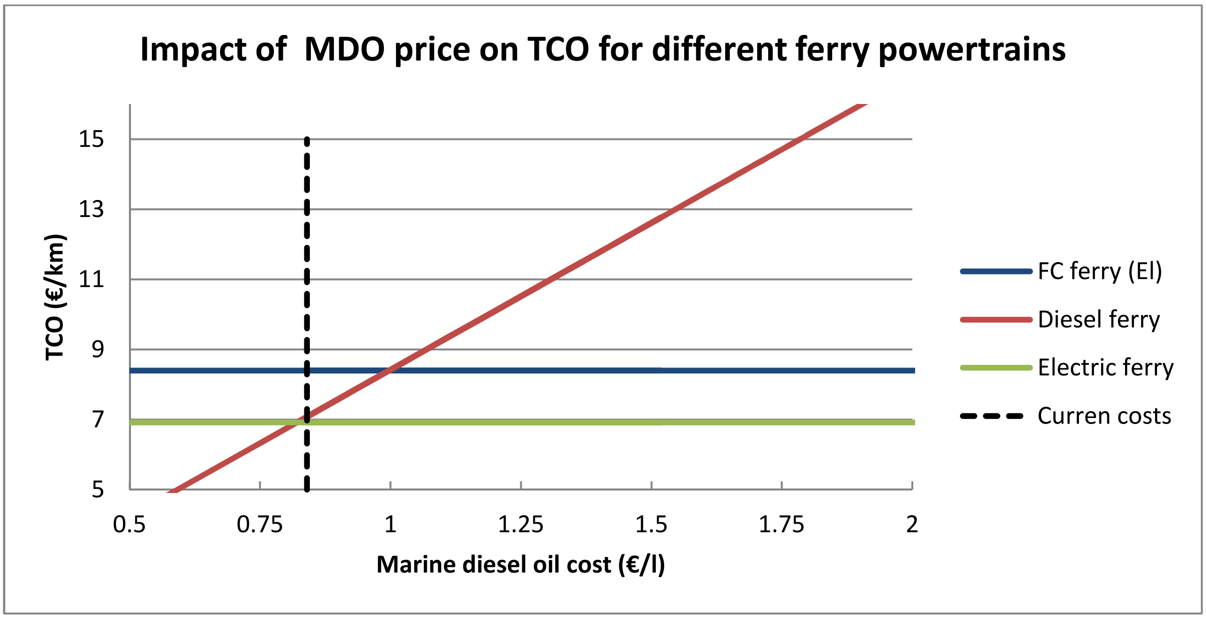


FIGURE 3-7 - FERRY STUDY CASE, IMPACT OF DIESEL PRICE

Comments

Here the variable is the diesel price therefore only the diesel ferry is function of this parameter while the FC ferry's and electric ferry's TCOs stay the same at 8.4€/km and 6.9€/km respectively. The diesel price is very volatile and is dependent of the international market rules. However an increasing number of oil fields reach their production peak and given the increasing world energy demand a simple deduction leads to the conclusion that oil prices will increase mechanically in the long run. No price prediction would be wise though.

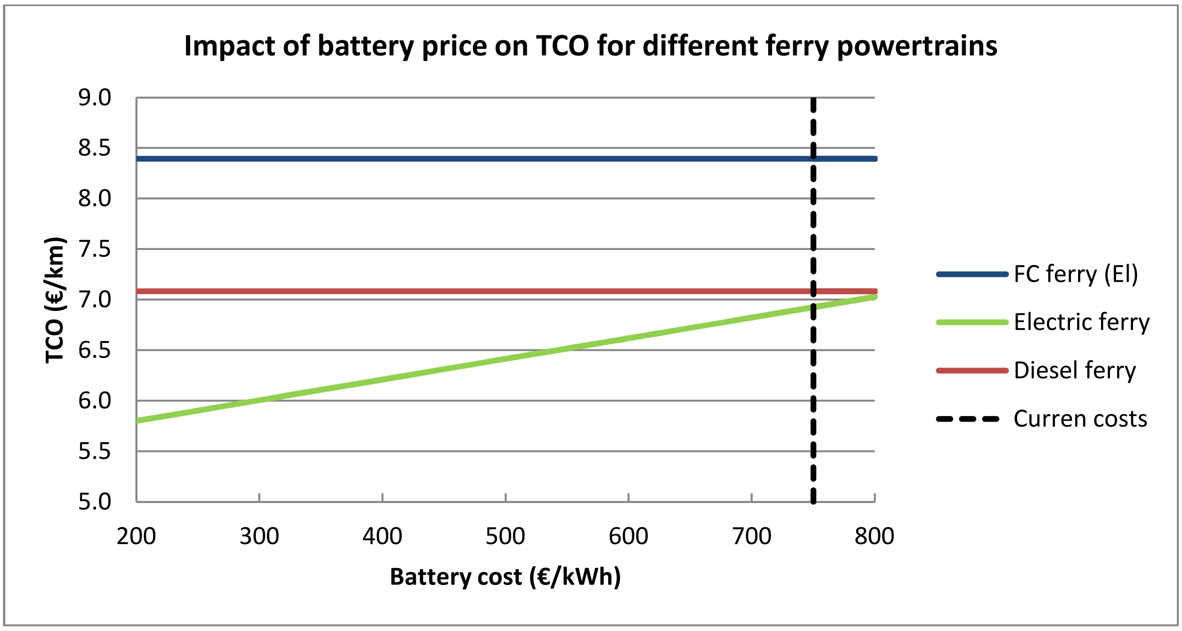


FIGURE 3-8 - FERRY STUDY CASE, IMPACT OF BATTERY PRICE

Comments

Here the variable is the battery price (margin included) therefore only the electric ferry is function of this parameter while the FC ferry's and diesel ferry's TCOs stay the same at 8.4€/km and 7.1€/km respectively. The battery cost is meant to decrease significantly in the years to come thanks to the economy of scale.

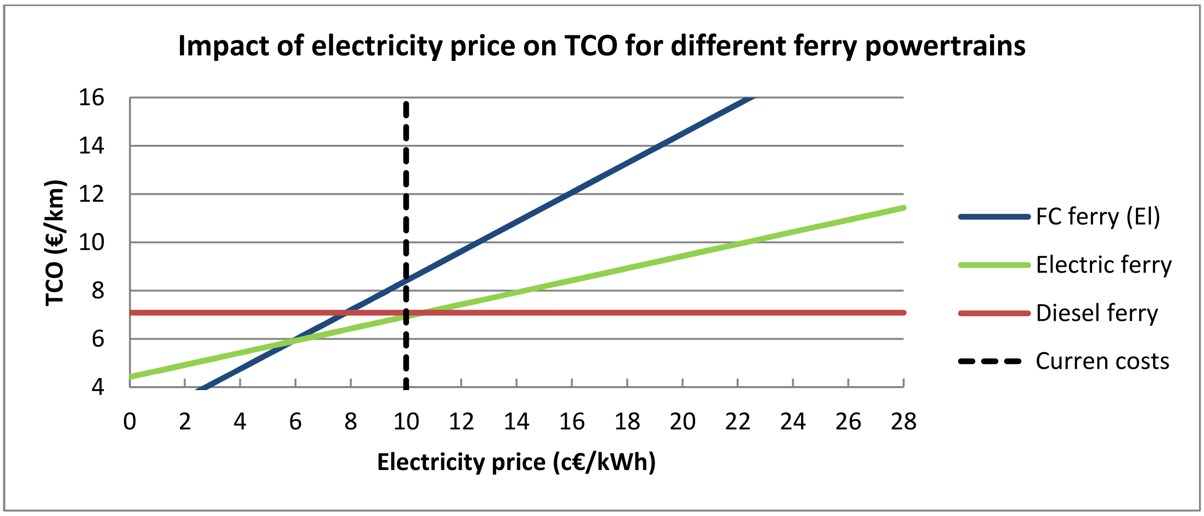


FIGURE 3-9 - FERRY STUDY CASE, IMPACT OF ELECTRICITY PRICE

Comments

Here the variable is the electricity price therefore the electric ferry as well as the hydrogen cost (electrolysis) are function of this parameter while the diesel ferry's TCOs stay the same at 7.1 €/km. It is very unlikely that the electricity price drops below 10 c€/kWhe because hydropower is one of the cheapest way to produce electricity and it represents 95% of Norway's production mix. However, if hydrogen is produced during overproduction period (solar plant, wind farm) then the hydrogen price could be lower.

3.4.3 RESULTS 2ND STUDY

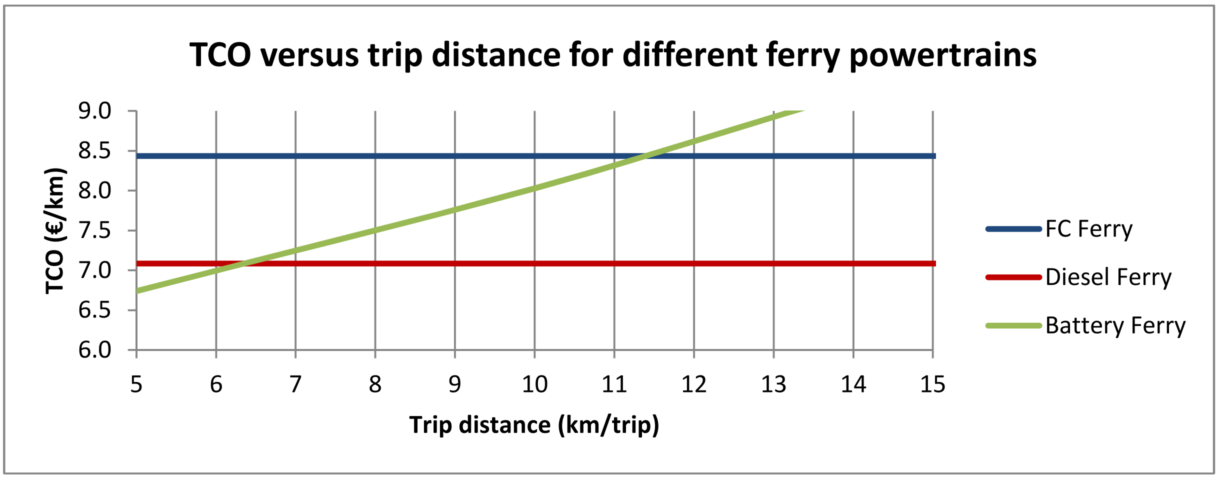


FIGURE 3-10 - FERRY STUDY CASE, IMPACT OF THE TRIP DISTANCE

Comments

Here, only the electric ferry’s TCO is increasing while the FC ferry’s and the diesel ferry’s TCOs stay constant at 8.43 €/km and 7.08 €/km respectively.

3.4.4 ANALYSIS

First of all it is important to note that for every technology the fuel purchase represents a major expense over the lifetime. This is due to the important amount of energy required for each trip (160 kWhoutput per trip) and to the full year operation of the ferry. As an element of comparison the TCO of a diesel passenger car is around 0.2 €/km and the ferry's TCO is about 7.1 €/km (thirty time higher). We will start by analyzing the diesel ferry, then the fuel cells ferry and finally the electric ferry.

The diesel powertrain has the second lowest TCO (7.1 €/km) and by looking at the TCO breakdown diagram we can see that 99% of this cost is related to the fuel which make the global TCO very sensitive to the MDO price variation. It is important to note that in the maritime case the fuel is marine diesel oil which is a lot cheaper (because less refined) than diesel. Thanks to this sensitivity we can see that as soon as the MDO price drops under 0.8 €/l the diesel ferry's TCO becomes more interesting than the battery option. However, this TCO sensitivity also shows that as soon as the MDO price is above 1 €/L the diesel ferry becomes more expensive to own than the FC ferry. If we look at the figure 3-10, we can see that with current prices the diesel powertrain become the most interesting option for trip distance longer than 6.5 km. Even if short term predictions are risky, we can state with confidence that oil prices will increase mechanically in the long run.

The fuel cells ferry has the highest TCO with 8.4 €/km. Like the diesel ferry, the fuel cells lifecycle cost is very sensitive to hydrogen prices which represent 72.4% of its current TCO. This sensitivity is important enough to make it competitive with diesel ferry and electric ferry in case of a low hydrogen cost (4.2 €/kgH2) but this range of price is only expected for 2045 (see fig 1-6). However, this observation is only valid with a high FC efficiency (58%). Indeed we can see that the TCO is also very sensitive to the FC efficiency as we can observe a cost difference of 44% between the highest efficiency (58%) and the lowest one (40%). This observation underlines the need of designing a fuel cell operating at low load level as shown in 3.2.1.1. An interesting piece of data from the fifth graph tells us that in case of a low electricity price (lower than 6 c€/kWhe), the electric ferry will be more expensive than the fuel cells one. This configuration can occur in case of an overproduction from a renewable source for instance. Then the first diagram shows us a significant share of the infrastructure cost (18%) as the ferry carries the cost of the entire refueling station. It is possible to reduce this cost if other boats or even cars share this infrastructure to power their own vehicles or boats. The figure 3-10 shows us that even though the FC ferry is not the best option for a 6 km trip, it becomes more interesting to invest in this technology for longer trips. Indeed the FC ferry has a lower TCO than the battery ferry for distances longer than 11.5 km.

The electric ferry powered by battery has the lowest TCO of the study with 6.9 €/km (-18% from FC ferry). Despite a high initial investment (infrastructure cost and batteries), the fuel expenses only represent 36% of the TCO. We can explain this difference thanks to the battery efficiency (85%) which is the most efficient technology today in terms of energy, but also thanks to the low electricity cost (10 c€/kWhe). Given the important energy consumption over the lifetime, a change in the battery cost does not have a very important impact on the overall TCO. However the lifecycle cost is much more sensitive to the electricity price as we can see in the fifth graph. Finally, the figure 3-10 shows us that the battery ferry is only relevant for short distance inferior to 6.5 km. For longer trips, what is saved thanks to the low fuel cost is not important enough to compensate the battery investment cost. This last figure underlines that battery technology is limited when it comes to medium and long range capability.

3.4.5 CONCLUSION AND LIMITATION OF THE STUDY

Thanks to the results discussed above it has been determined that the battery ferry is the most competitive compare to FC ferry or diesel ferry. This final result is mainly due to the high energy consumption of the ferry and the low energy price of electricity. However, the second study has underlined that this conclusion is supported only for short distance trips (lower than 6.5 km). Indeed, it has been determined that for longer range capability the diesel ferry became the cheapest option. Concerning the fuel cell ferry, this technology becomes cheaper than the battery ferry as soon as the trip distance exceeds 11.5 km. This conclusion can be relevant in further choices for zero emissions ferries.

However the TCO does not reflect everything as it does not include the available payload weight, the refueling time or the flexibility of the ferry. Indeed even though the electric ferry has the most interesting TCO it has less available weight to transport passengers and vehicles (10 tons battery powertrain against 7.5 tons power train for fuel cells). Also as mentioned in Chapter 2, the recharging time of a battery is really important and in our study case it would take the entire night to recover. This kind of drawback is overcome by hydrogen or diesel as 15 to 20 minutes should be sufficient to refuel the tank.

The interpretation of the results is limited to the Norwegian context but also to a specific ferry operation. As this specific duty cycle has been chosen it is hardly possible to extrapolate those results to any other type of boat (cargo boat, cruise boat, fishing boat,…). Indeed the required infrastructure for the recharge of the electric ferry is only possible with a ferry operation. However, thanks to the second study the interpretations can be, in a small extent, generalized to other types of operation (e.g. longer distances, sea transports).

This study was based on several assumptions that have influenced the results significantly. Among them, the maintenance cost for diesel has probably been underestimated. The refueling station cost does not include the civil engineering or the purchase of the land for instance. We also have assumed a constant battery performance over its lifetime which is very unlikely. Some suggestions of interesting study cases are listed later in the discussion below.

3.5 CONCLUSION

The maritime sector is subject to an increasing environmental pressure expressed through regulations, customer expectations and taxes. The implementation of catalysts for waste gas treatment onboard or the creations of new ECAs are some indicators of this growing attention. Those policies promote the use of hybrid powertrains and low emission fuels in specific zones close from populated areas. After the different fuels and powertrain technologies overview we can see two ideal fuels and one transitory fuel that match the expectations of the sector.

Thanks to their zero emission properties and competitive predicted costs the battery technology as well as PEMFC powertrain is the ideal fuel for the maritime sector in the long run. Because of their weight and cost, batteries are limited to "little" amount of energy storage so they are more likely to be used in short distances, low emission areas or as power sources during idling in port. We have seen that PEMFC are today limited to APU applications or to base load power in hybrid systems. But with increasing FC performance, decreasing hydrogen cost and deploying infrastructure, it is very likely to see medium or long ferry operations with PEMFC as main powertrain within a 10 years time frame. Also PEMFCs have the main advantage to be lighter and more flexible than batteries. According to our study case, they are very close to be competitive with diesel on ferry operations but this competitiveness is very dependent of the hydrogen and diesel prices.

If we focus more on the short term the use of natural gas seems to be the most relevant option from the economical and environmental perspective. It has a better efficiency than MDO, can be implemented quickly, can be produced from biomass (low GHGs emission) and can be used in a combustion engine as well as in a MCFC or SOFC. This combination of fuel cells as a base load completed by a combustion engine seems to be the most relevant choice for the maritime industry in the short term. However the other fuels considered in this study do not provide enough advantages in comparison to their drawbacks (biofuel, LPG).

If we look from the economical aspect it seems that because of the important amount of energy consumed the fuel cost is the main parameter to look at. For this reason it is interesting to consider the hydrogen production as a part of the balance of the grid. Indeed the increasing share of renewable like wind or solar (intermittent) increase the need of variable load in the grid to compensate the high production peaks. During those production peaks the electricity has a low price and so has the hydrogen. An entire master's thesis could have been dedicated to the effect of an intermittent power source on the average hydrogen price. It would have been interesting as well to determine the ideal design (balance between weight and cost) for a hybrid boat powered by fuel cells and batteries. The SWOT matrix in the next section aims to summarize what has been said along this chapter.

3.6 SWOT MATRIX

TABLE 3-6 - MARITIME SECTOR SWOT MATRIX

Strength	Weakness
Zero emission (PEMFC) or Low emissions (MCFC) Silent Less mechanic maintenance (less rotating components) Easier to control than diesel boat Variety of H2 production sources Modular design Use of different fuel cells types Fast refueling Lighter and more flexible than battery	Safety measures Less autonomy Storage issues Air quality (salinity, humidity rate) for the PEMFC Repetitive shocks on the hull Price (High initial investment) Lack of feedback Lifetime
Opportunities	**Treats**
Existing demonstration project with MCFC Short distance / round trip boat (ferry) Fuel efficiency = immediate profit Better working condition for fishermen International growing interest for HFC technologies Decreasing hydrogen price Instable diesel price Need of balancing the grid	Lack of regulation concerning H2 for propulsion Competition of other CO_2 lean technologies (Battery) Social acceptance Untrained technician/sailors Inexistant infrastructure

3.7 OPENING

Thanks to the study achieved through this section we have determined a few locations in Norway where the introduction of hydrogen vessels can be relevant. Those locations have been selected based on the line distance, the environmental context and the proximity of other hydrogen infrastructure. According to the conclusion, the ferries indicated below are meant to operate over distances superior to 11 km.

1) The Oslo ferries operated by Marine-Service. The trips are frequent way and back from main-land to the islands (short distances). There is an important environmental pressure in the Oslo region (high freshwater eutrophication, NOx and PM issues). Thanks to other hydrogen road transport projects the social acceptance is developed and a potential use of that infrastructure is feasible.

2) The line between Stavanger and Tau (13km) operates everyday of the year transporting people and cars. Due to the oil and gas activity of the region there is an important traffic of ship in direction of the offshore platform. The proximity of the E39 can be interesting for the installation of a common refueling station linked with specific pipeline.

3) The ferry lines between Halhjem and Sandvikvåg (located between Stavanger and Bergen) can also be an interesting location. This choice is due to the important local pollution (air and water), the proximity of E39 (for the same reasons as above) and the length of the line (around 20 km)

4

ROAD SECTOR: INTRODUCTION

4.1 INTRODUCTION AND ENVIRONMENTAL CONTEXT

4.1.1 INTRODUCTION

Currently the road transport sector uses largely the internal combustion engine with gasoline or diesel, and for our study we will focus on the diesel only. Indeed the most important criteria for a technology to comply with are the fast start and stop of the vehicle, its operating conditions (temperature and pressure close from ambient), its compactness (volume and weight), its safety and its driving range. Given those criteria, the PEM fuel cells is the favorite choice among the other fuel cells for road applications, especially after the ameliorations it has benefited from the R&D advances (price and lifetime). The aim of this chapter is mainly to regroup some information to avoid useless repetitions in the different sectors of the road transportation (trucks, cars, buses). Therefore, after a presentation of the environmental context, the common characteristics and common calculation inputs for the truck, car and bus sectors will be given. Those characteristics concern the applications of the PEMFC, the state-of-the-art for the infrastructure, some competing fuel information and economic data. Other specific details will be given if needed in each specific section (truck, car or bus). In order to summarize the essential of the content for each segment, a SWOT matrix will be given after each conclusion.

4.1.2 ENVIRONMENT

If we consider the global scale the road sector represents one third of the anthropogenic GHGs emissions in the world. In Norway the cars, the trucks and the public transports are responsible for 67% of the CO_2 emissions in the transport sector as illustrated below. [45]

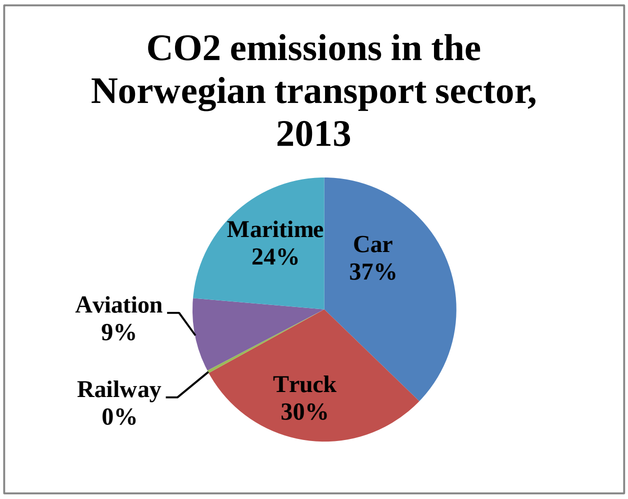


FIGURE 4-0-2 - CO_2 EMISSIONS IN THE NORWEGIAN TRANSPORT SECTOR

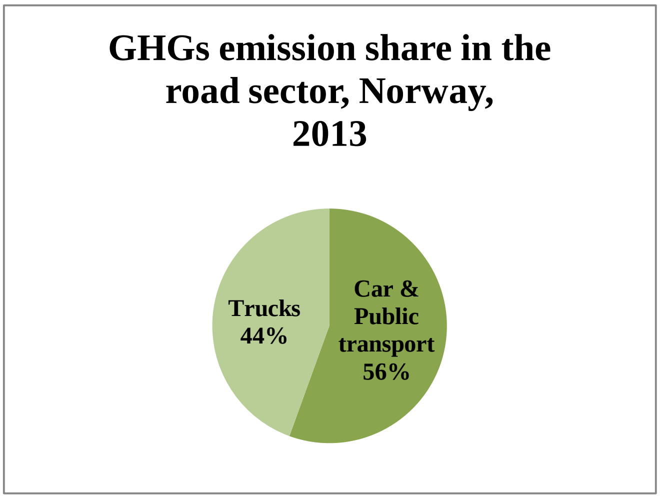
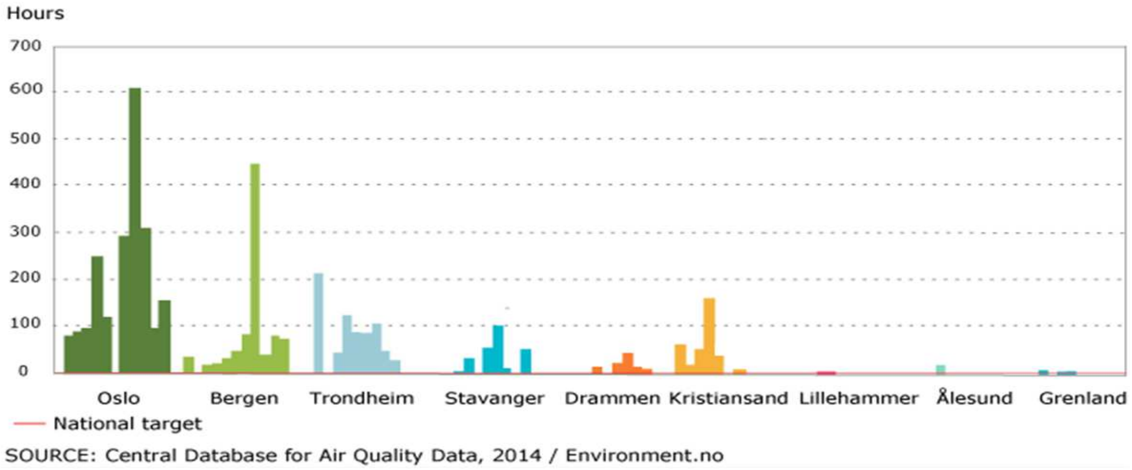


FIGURE 4-0-1 - ROAD SECTOR GHGS EMISSION SHARE BY SOURCE

However the CO_2 emissions are not the only environmental issue as local pollution is also a problem in large cities. Those local emissions concern principally the emission of NOx and particulate matter which impact directly the human health unlike to the CO_2. In 2014 the road sector was responsible for 22% (32,000 tons of NOx) of the national NOx emission. Thanks to regulations this rate decreases every year.



SOURCE: Central Database for Air Quality Data, 2014 / Environment.no

FIGURE 4-0-3 - NO_X EMISSIONS AND EXCESS RATE IN NORWEGIAN CITIES

Therefore the installation of Low Emission Zones (LEZs) is in discussion for Trondheim, Oslo and Bergen. Those LEZs establish a toll or a mandatory compliance to a norm (e.g. Euro 4) in a specific area (city center, entire city, specific zones). However, given the direct harmlessness of CO_2 for the human health this gas is not included in such regulations.

4.2 HYDROGEN GENERALITIES

4.2.1 DIFFERENT APPLICATIONS

Auxiliary power unit(APU), specific to duty vehicle

An important energy consumption is required for the refrigeration systems or the air conditioning of the duty vehicle merchandise and this energy has to be electrical (equivalent to 38 liter of diesel per day for a large truck) [59]. Instead of producing this electricity from an alternator powered by diesel (3 kWhel/liter of diesel = efficiency of 30%), it is possible to install a small fuel cells connected to a hydrogen tank. If we consider the same energy consumption (114 kWhel per day) and a fuel cells efficiency of 60%, we obtain a daily hydrogen consumption of 5.7kg. This hydrogen quantity (if refueled every day) corresponds to a tank of approximately 216 liters (26.7 gH2/liter) under 35MPa or 143 liters (40g/l) under 70MPa. The assumption of a refueling every day is compatible with some short circuit and local fleet applications.

Fuel cells Range Extender Vehicle (FC-REV)

If the vehicle is designed with an electrical motor it is possible to equip it with both a battery and a fuel cells system. The fuel cells system can be implemented on the existing battery in order to extend its driving range but it is more relevant to include the fuel cells system directly from the design phase to find the optimal configuration (battery size, fuel cells power) as we will see in the economical approach. The operator refuels the vehicle thanks to a hydrogen refueling station but also recharges it thanks to a recharging station or a sector plug. **[60]**

Fuel cells vehicle (FCV)

This vehicle relies completely on hydrogen for its propulsion. Unlike the FC-REV, the FCV uses only hydrogen as a fuel, there is no recharge of the battery by an external plug. In this configuration a small battery is necessary to smooth the power demand and to store the energy from the regenerative brakes but its size remains small compared to the FC-REV capacity.

4.2.2 INFRASTRUCTURE

There are currently 6 hydrogen refueling stations in Norway and 80 in Europe. Four of them are deployed in the Oslo area, one in Drammen and one in Porsgrunn (Greenland). This current spread of refueling stations does not allow a cover of the entire road network in Norway but it allows a connection with Sweden and Denmark. Due to this constraint, one special opportunity emerges to solve this lack of infrastructure: The captive fleet. A certain number of delivery companies or service companies use a fleet of vehicles that will come back to the main house every night at the end of the service. It means that the range provided by the vehicle only needs to comply with the distance for one day of operation. Therefore every vehicle will be fully recharged/refueled every night and will be ready to operate for one full day the next morning. This type of fleet is called a captive fleet. The city buses are also a captive fleet and one refueling station is enough to supply an entire bus fleet during one day of operation.

The NorWays report [23] has performed a prediction about the hydrogen geographical use in road transportation, and has also tried to determine the evolution of the hydrogen network and distribution. This study shows that the geographical distribution of the hydrogen production is strongly tied to the transport density of a region. As one can see on the maps below [23] the consumption increase strongly in the Oslo region and follow an expansion toward the main transport axes.

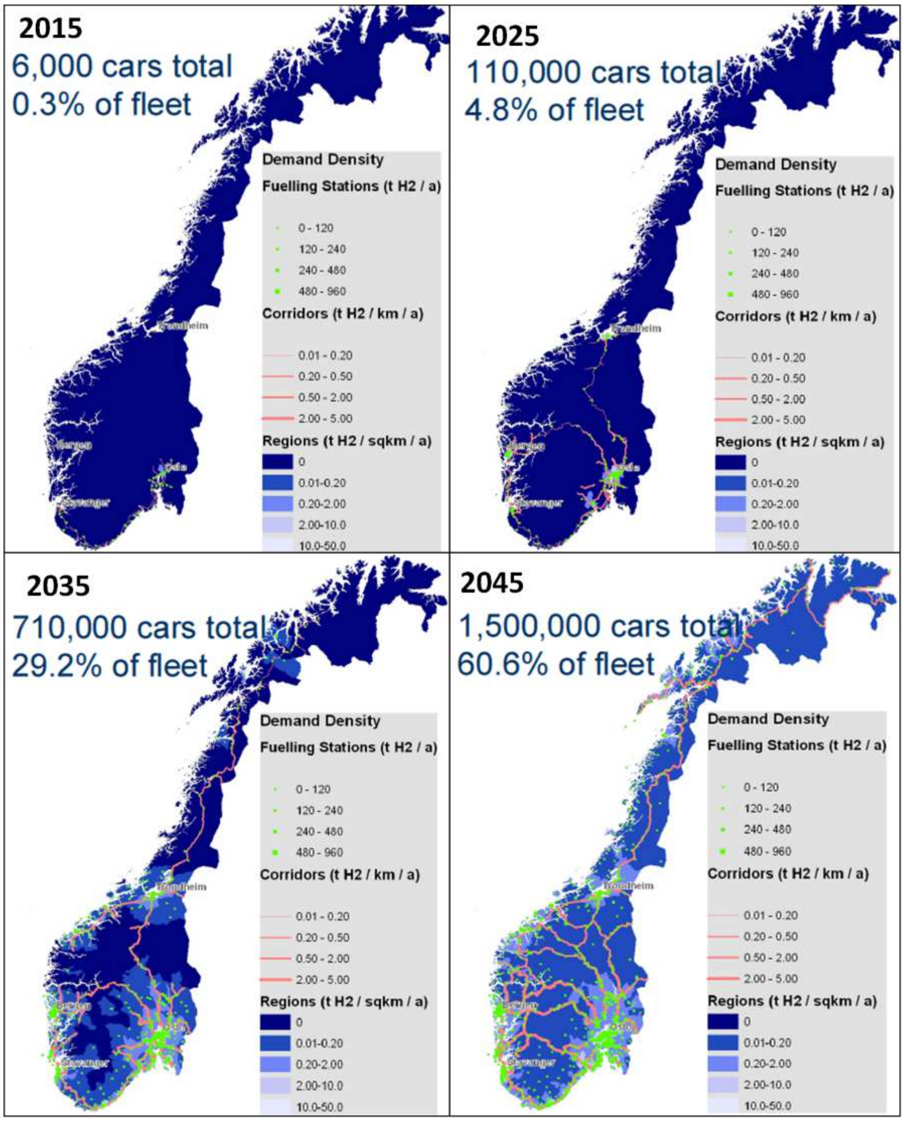
In order to develop a scenario for the distributed hydrogen demand on a national basis, it was presumed that hydrogen deployment is initiated in Oslo in 2010 (demonstration and fleet vehicles), and is then introduced in Trondheim, Bergen, Stavanger in 2015, and in Tromsø in 2025. For the supply of hydrogen along highways, the following was assumed:

2010: Oslo-Stavanger (HyNor project)

2025: Oslo-Bergen, Oslo-Trondheim, Bergen-Stavanger

2040: Trondheim-Tromsø

In order to estimate the propagation of hydrogen on a regional level and to facilitate commuting and short trips, it is further assumed that highways 50 km around areas with local vehicles are equipped with refueling stations. [23]



Source : NorWays report

FIGURE 4-0-4 - EXPECTED DEPLOYMENT OF THE HYDROGEN REFUELING STATION NETWORK

4.2.3 REFUELING

The refueling time is a function of the operating pressure (35MPa or 70MPa), of the capacity of the refueling station (the bigger the faster) and of course of the quantity of hydrogen transferred. As an example we can see the different refueling times with different parameters:

35MPa: 1 kg in 3min ; 35kg in 10min

70MPa: 4kg in 3min [54]

Hydrogen can be produced onsite either by electrolysis or by SMR (see chapter 2) and can also be regularly provided by truck or directly by a pipeline network (see chapter 2). The pressurized hydrogen is brought from the refueling pipe to the tank (located on the top or behind the cabin) by a small stainless steel pipe designed to support high hydrogen pressure.

4.3 OTHER COMPETING FUELS

4.3.1 DIESEL, GASOLINE AND INTERNAL COMBUSTION ENGINE

Diesel is more employed in trucks and gasoline cars. This partition is due to the fact that, even if more expansive to buy, diesel engines are more energy efficient than gasoline and enable some significant savings over long distances and long periods of use. The refueling station network for both fuels is well established and due to their liquid state, they are easy to store in order to reach long autonomy ranges. For instance a conventional light duty vehicle has a range of 1 100 km thanks to a 90l tank a medium duty vehicle has a range of 1 500km (200L) and heavy duty vehicle a range of 1 500 km (600L). However, with efficiency around 30% the combustion engine running on either gasoline or diesel is far from being energy efficient.

4.3.2 BATTERY

4.3.2.1 The full electric vehicle

This vehicle relies only on one or two batteries to provide all the power and energy needed. The battery has to be charged in average for 8 hours if it uses a standard plug but there are some fast charging stations that allow this time to be halved. However, this process diminishes the lifetime of the battery and the station network is not well developed at the moment.

4.3.2.2 The hybrid vehicle

To ensure a sufficient driving range it is possible to use diesel or gasoline as energy carrier and to transform this chemical energy into electricity thanks to an alternator. This concept has the advantage of using the combustion engine at its optimal operating point. Depending on the battery size it is possible for the user to run only on the battery for a few kilometers before starting again the thermal engine. This operation allows bringing the delivery into city centers or sensitive places. It is very popular in the USA where several companies (Coca-Cola, UPS) has equipped their fleet with hybrid trucks.

4.3.2.3 The plug-in hybrid vehicle

This vehicle is based on the same functionality as the hybrid one with the difference that it can be plugged to recharge the battery. This operation allows the user to increase the driving range with cheap energy during the stop time (nights or breaks). Like the hybrid it is possible to run only on the battery from 10 to 60 km depending on the battery size. The hybrid and plug in hybrid vehicles are very interesting for a variety of city usages that includes frequent idling (delivery, traffic congestion).

4.3.3 NATURAL GAS

4.3.3.1 Operation & infrastructure

Unlike maritime transport, it is not possible to use natural gas with a MCFC or a SOFC in a road vehicle due to the specific requirement of the sector. There are currently 18 filling stations for CNG in Norway (Oslo and Bergen) and few LNG stations [50].

4.3.3.2 Safety

The design of a natural gas vehicle is under the international standard ISO 26262 (previously IEC 61508) but there is no regulation so far. The American standard NFPA 52 also helps to design safely such a system.

4.4 ECONOMICAL APPROACH

In the "Trucks" and "Cars" section the study cases aim to assess the best powertrain technology from the economical perspective. This will be achieved thanks to several comparative studies of the different powertrains lifecycle cost (expressed in TCO*). We have selected the four main technologies under focus in this thesis: The battery electric vehicle (BEV), the fuel cell vehicle (FCV), the fuel cell range extender vehicle (FC-REV) and the conventional vehicle (CV). Even though the specific details for trucks and cars will be presented in their respective sections this introduction section aims to introduce the common assumptions and baseline values that were used.

* See maritime section for TCO method, section 3.4.1

4.4.1 MAIN ASSUMPTIONS AND METHOD

In order to complete the calculations we have used several technology cost numbers as well as component lifetime estimates and efficiencies. The references that have not been given previously will be provided all along the different studies and the values that had been assumed will be notified. The most important values and assumptions are given in the table below. In this thesis only the graphs will be displayed, therefore the calculation results will be provided in the appendices. Concerning the values:

TABLE 4-0-1 - GENERAL POWERTRAINS PROPERTIES

	BEV	**FCV**	**FC-REV**	**CV**
Lifetime	8 years (a)	153 000 km (a)	8 years and 306 000 km (h)	> 10 years (b)
Powertrain cost (g)	500€/kWh	See Ch1	500€/kWh and See Ch1	28 €/kW
Fuel cost	0.1 €/kWhe	9.9 €/kgH2 (c)	0.1 €/kWhe and 9.9 €/kgH2	1.64 €/l (d)
Technology efficiency	85%	58% (e)	49% (f)	25%
Road tax (d)	-	-	-	10.8 €/day
Infrastructure cost (i)	-	-	-	-

(a) Those values are used to obtain a renewal rate per year for each technology based on the annual distance or the time frame of the study.

(b) The renewal rate for the combustion engine was considered as nonexistent.

(c) The hydrogen price is the price at the pump (see figure 2-6)

(d) Provided by Posten for CVs and adapted to the Norwegian tax reduction for zero emission vehicles (no taxes). Those data correspond to a typical route for a Posten Vehicle but this could vary if the vehicle operates in cities without tolls.

(e) The efficiency of the FCV cumulates the electrochemical reaction efficiency (55%) and the hydrogen use efficiency (here assumed to be 100%).

(f) When organized in series the FC-REV configuration cumulates the FC and the battery efficiencies. When organized in parallel the FC-REV has a better global efficiency as it does not cumulate them. All the FC-REVs are assumed to be connected in series and the FCVs in parallel.

(g) The powertrain cost is given without margin. In the calculation a 50% margin has been added to simulate the final customer price.

(h) In a series configuration the FC-REV's fuel cells operates half of the time. Therefore it lasts twice longer than the fuel cells in the FCV.

(i) The fuel prices are equal to the pump price which includes already the price of the infrastructure. Therefore, even though the hydrogen refueling station network is not developed, we will assume a unique hydrogen price according to figure 1-6.

Concerning the other assumptions:

- This study focuses on a fleet operation where the vehicles come back to the same refueling station every night.
- The driving specifications (distance per year, road taxes) have been provided by Posten.
- The BEV specifications come from Renault Truck and the FC-REV configurations from the company Symbio FCell.

5

ROAD SECTOR: TRUCKS

5.1 INTRODUCTION AND ENVIRONMENTAL CONTEXT

5.1.1 INTRODUCTION

Despite the effort of the government to switch a more important share of the cargo transport from road to rail, the road sector activity keeps rising with 264 million tonnes in 2012 and 284 million tonnes in 2013 (+7.5%). In 2013 the road sector represented 58% of the goods transported inside Norway [45]. This gross has unfortunately also a price as the road sector represents 64% of the GHGs emission for transportation. This section is focused on the market segment of trucks which represents 20% of the transport sector GHGs emissions. The trucks can be used for a large variety of applications in the construction sector, in the delivery sector or in the industry. Despite their different applications in transportation it is possible to identify three main categories of trucks called Light duty vehicle (LDV), Medium duty vehicle (MDV) and Heavy duty vehicle (HDV). Those three categories correspond to a classification by weight as described below:

Gross vehicle weight rating = GVWR

TABLE 5-1 - DIFFERENT TRUCK CATEGORIES

Vehicle type	*GVWR*	*Max. Power*	*Average Energy consumption*	*Application*
Light duty vehicles (LDV)	Max 6.4 tons Class 1-2-3	105 kW	9 l/100km	Short distance, Supermarket delivery, small construction vehicle
Medium duty vehicles (MDV)	Max 11.8 tons Class 4-5-6	190 kW	13 l/100km	Medium distance, supermarket delivery, medium construction vehicle
Heavy duty vehicles (HDV)	>11.8 tons Class 7-8	300 kW	35 l/100km	Medium and long distances, heavy cargo, international freight, large construction vehicle.

First of all, the current environmental situation will be presented to understand the partition if emissions between those categories. Then some fuel specifications relative to the truck sector will be given in addition to the general information provided previously in Chapter 2 and in the "Road" section. Thanks to those data and to an external study we will compare economically a battery MDV, a Fuel cells range extender (FC-REV) MDV and a conventional MDV to determine the optimum configuration of each system. In addition to this a cost analysis of another MDV will be provided using real life data and including the Norwegian road taxes. All of those results and information will be discussed at the end of this section and will also be used later in the global conclusion about the best opportunities for hydrogen and fuel cells technology in the road sector.

5.1.2 ENVIRONMENTAL ASPECT

For the year 2011 the trucks emission represented a total of 2.2 million tonness of CO_2 (120 grams / tonne-km on average) and 11,900 tonnes of NOx. While trucks driven distance constituted barely 4 %, they contributed to 20 % of CO_2 emissions, 21 % of NOx emissions and 16 % of particulate emissions in Norway [48]. Given the pollution peaks that occurred in several Norwegian cities the trucks contribution to a national health issue is significant.

It is relevant to note that this pollution is mainly caused by the operation of the truck and not by its production or its end of life. As an example Renault truck has published several LCAs (life cycle assessment) about its trucks and we can see that 98% of the CO_2 emissions and 88% of the NOx emissions come from the operation due the fuel combustion. [61]

TABLE 5-2 - EXTERNAL MARGINAL COST FROM ROAD TRANSPORTATION, INSTITUTE OF TRANSPORT ECONOMICS, 2011

Class	*Distance (million km)*	*Consumption (million liters)*	CO_2 *(thousand tonnes)*	*NOx (tonnes)*	*NO2 (tonnes)*	*PM10 (tonnes)*
<7.5 tons (LDV)	381	54	145 (6%)	1010	69	76
Between 7.5 tons and 14 tons (MDV)	77	16	43 (1.6%)	293	21	17
Between 14 tons and 20 tons (LDV)	196	50	134 (5.2%)	875	66	42
> 20 tons (LDV)	1698	832	2214 (87%)	11902	895	434

[48]

It is important to note that the trucks exceeding 20 tonnes circulate over long distances (except construction trucks) and consequently spread emissions all along the road (over big areas) while other categories have a more localized operation. Consequently the smaller categories should have a more importance concerning local emissions. Thanks to this table we can also see that the global warming impact is mainly due to the HDV with 87% of the CO_2 emissions. We can therefore say that the LDV and MDV are mostly concerned by the local pollution whereas HDV are concerned by the global issue of climate change and GHGs emissions.

The noise level of trucks is also an important impact especially during city operations. When driving a truck produces in average 74dB due to the tires and from 3 to 10 additional decibel due to its combustion engine (LDV: 77-79dB; MDV: 77-82 dB; HDV: 79-84 dB). According to Statistic Norway (SSB), road traffic is the most important source of noise annoyance in Norway. [59]

5.2 HYDROGEN AND FUEL CELLS

5.2.1.1 Design

Due to the range required and the space available it is more interesting for a truck to have several hydrogen storage tanks. They can be either installed on the top of the cabin or behind it as it does not impact the friction coefficient with the air. To allow the hydrogen to be released easily into the open air, it is not recommended to install the tanks under the chassis. However it is possible to have the fuel cells under the chassis as long as it is strongly protected against any choc or water infiltration.

5.2.1.2 Maintenance

As specified in Chapter 2, the lifetime of a PEMFC is equal to 5,000 hours which correspond approximately to 150,000 km. In 2013 a Norwegian heavy transport truck drove in average 64 661 km [45] so with a simple calculation it is possible to estimate that the current technology enables a PEMFC to operate on a truck for two years at the maximum. This limited lifetime due to an intensive use is a real issue for the PEMFC technology. It is however possible to have access to the real time performance of the cells, to anticipate any degradation and to replace the stack as a usual maintenance process. This issue concerns mainly the truck driving a notable distance. The construction truck and the light duty vehicles are less exposed. In the other hand the electric vehicle generally speaking requires less maintenance than the conventional one due to the absence of alternator, SLI battery (starting, lightning and ignition battery), clutch, fuel filter, fuel injectors and pump, motor mounts, spark plug wires, starter motor and anything to do with regular transmissions (adjustment, fluids, filters).

5.2.1.3 Projects

The list below aims to illustrate the main application of hydrogen in the three truck categories. Only the complete vehicle has been looked at, but there are other companies who provide only the fuel cells system (e.g. Hydrogenics) and any truck company can implement it on its own vehicles.

TABLE 5-3 - NON EXHAUSTIVE LIST OF FUEL CELLS TRUCKS PROJECTS

Vehicle name & Company	**Maxity Renault trucks Symbio FCell**	**None TTSI Hydrogenics**	**Premium Renault trucks Symbio FCell**
Vehicle type	LDV	MDV, 15 tons	HDV
Driving range	200 km	350 km	500 km
Battery storage (lithium-ion)	42 kWh, 400 kg, 7 hours charging		80 kWh
Hydrogen storage (35MPa)	45 kWh, 4 kg, 2*75 liters		25 kg
Fuel cells power	20 kW	60 kW	160 kW

Maxity and Premium [53], TTSI [52]

5.3 OTHER FUELS

5.3.1 BATTERY

5.3.1.1 Economy

This part aims to give some simple prices and costs comparison related to the li-ion battery technology. A more accurate comparison with hydrogen and diesel is performed later in this section. The following prices have been found on the manufacturer's website and are a baseline for Europe.

TABLE 5-4 - COMPARISON OF CONVETIONAL AND BATTERY ELECTRIC TRUCKS

Type of vehicle	*Conventional model price*	*Electric model price*	*Price augmentation*
Nissan nv200	€15,420	€23,000	14%
Renault Maxity	€30,300	€50,000	40%

Currently the price of investment for a li-ion battery is very high (€400/kWh) [44] compared to the other options but on the other hand the energy consumption is lowered by 70% (compared to a diesel engine). In Norway the electricity price is about 10c€/kWh [45] and the state provides a lot of incentives to close the cost gap between the technologies. All-electric cars are exempted from purchase tax and VAT, receive a 90% discount on annual road tax, pay no road tolls or municipal parking fees, qualify for free ferry passage, and have access to bus lanes and thousands of public charging points.

5.3.1.2 Projects

TABLE 5-5 - NON EXHAUSTIVE LIST OF BATTERY ELECTRIC TRUCKS

Vehicle name	**Maxity**	**Fuso**	**Chevrolet Silverado**
Company	Renault trucks Symbio FCell	Mitsubishi	General Motors
Vehicle type	LDV	LDV hybrid	Plug-in hybrid
Driving range	100 km	600 km	650 km (64 km based on battery)
Battery storage (lithium-ion)	42 kWh, 400 kg	2 kWh	Around 25 kWh
Battery recharging time	7 hours		

5.3.2 NATURAL GAS

One interesting product is the dual fuel truck (40 tonnes) proposed by Volvo. This truck runs 75% on natural gas which is stored as LNG and it can achieve a 500km driving range. The typical additional cost for a HDV running on natural gas in comparison to its diesel counterpart lies in the range of EUR 30 000 to EUR 35 000. A LNG station with gas output of 800 Nm3/hour or 574 kg/h can refuel about 7 medium trucks per hour (500km refueling) hour. [51]

5.3.3 LPG

A truck conversion to LPG allows reaching the Euro 4 level without any catalyst component, and achieves a CO_2 level 10% better than diesel and eliminates almost the particulate matter.

FIGURE 5-1- MAXITY FUEL CELLS RANGE EXTENDER VERSION

Source: symbiofcell.com

The aim of those two studies is to determine the best powertrain technology from the economical perspective for the LDV truck type and the HDV truck type. This will be achieved thanks to several comparative studies of the different powertrains lifecycle cost expressed in Total cost of ownership (See Maritime chapter for detail). We have selected the four main technologies under focus in this thesis: The BEV, the FCV, the FC-REV and the CV. The main assumptions and baseline values has been presented in the introduction section “Road”.

5.4 LIGHT DUTY VEHICLE STUDY CASE: RENAULT TRUCKS - MAXITY

5.4.1 Objective

For this truck segment the focus of the first study case is the Maxity vehicle (LDV from Renault Truck). This truck is selected because it is widely sold with its conventional engine version (CV), its electric version has been on the road for more than one year now and the FC-REV version has started the test phase in February 2015. This study is divided in two parts, where the first part called "price study" assesses the economic impact of each technology price (hydrogen price, battery price, diesel price and electricity price), and where the second part called "range study" shows the different lifecycle costs for different range capabilities. This second part considers both the economical aspect and the payload available for each technology.

5.4.2 FIRST STUDY: IMPACT OF TECHNOLOGIES COST

5.4.2.1 Method, assumptions and input data

In addition to the values given in the introduction section "Road" we can find below the specific design of each powertrain for the Maxity.

TABLE 5-6 - MAXITY STUDY, LIGHT DUTY VEHICLE PROPERTIES

Vehicle type	**Light duty vehicle (LDV)**
Annual Distance	15 286 km/year
Energy consumption	0.36 kWhoutput/km or 0.14 Ldiesel/km or 24.6 gH2/km
Motor power	105 kW
Range requirement	200 km
Maximum payload	1.8 tonnes (a)
Study frame	10 years
Discount rate (NPV calculation)	4.1 %

(a) We assumed that the weight of the powertrain impacts directly the available payload. Available payload = Max payload - powertrain weight

TABLE 5-7 - MAXITY STUDY CASE, POWERTRAINS PROPERTIES

	BEV	**FC-REV**	**FCV**	**CV**
Energy storage	98 kWh (a)	42 kWh + 3 kgH2 (b)	5.7 kgH2	200 liters
Installed power		20 kW FC	105 kW	105 kW

(a) For a matter of comparison coherence (same range was needed) the size and the range of the BEV have been doubled.

(b) In order to use the same energy consumption and efficiencies as the other study cases the hydrogen storage has been changed from 4kg to 3kg.

5.4.2.2 Results

The graphs and table below show the result of the price study. Some descriptive comments are provided after each table and graph but a more accurate analysis that includes the two studies (prices and range) will be done later in this section. Below the summary table of the different TCO and weight based on the current technology and fuel costs.

TABLE 5-8 - MAXITY STUDY CASE, MAIN RESULTS FOR 15 286KM OF ANNUAL DISTANCE AND 200KM OF RANGE CAPACITY

	TCO (€/km)	*Available payload (tonnes)*
CV	0.43	1.64
BEV	0.45	1.0
FC-REV	0.34	1.27
FCV	0.20	1.45

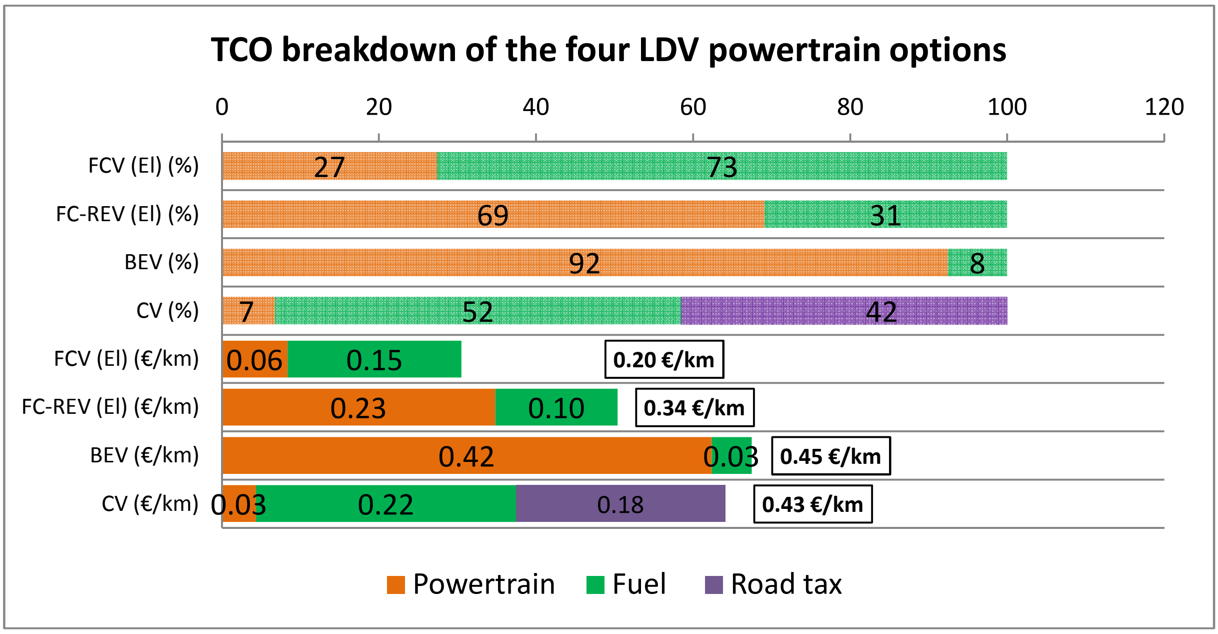


FIGURE 5-2 - MAXITY STUDY CASE, TCO BREAKDOWN

Comments
This bar chart allows us to see the partition of the costs for each TCO. The breakdown is made between the powertrain cost, the fuel cost and the road taxes. As mentioned before there is no direct hydrogen infrastructure cost as it is included in the fuel price at the pump.

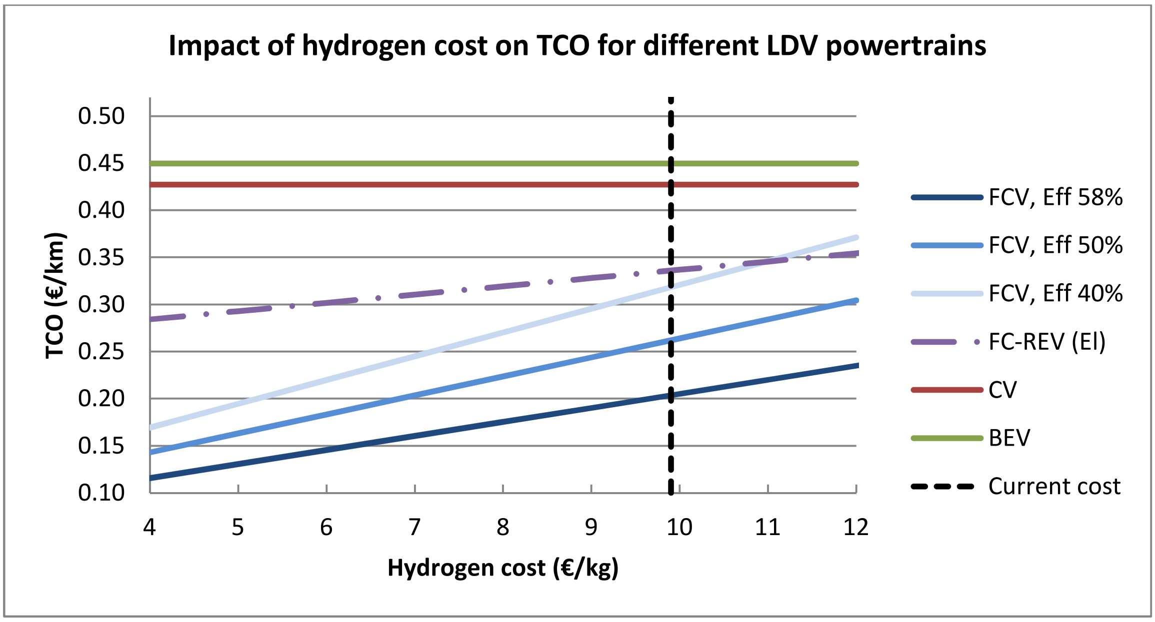


FIGURE 5-3 - MAXITY STUDY CASE, IMPACT OF HYDROGEN PRICE

Comments
Here the variable is the hydrogen cost and as expected only the FCV and the FC-REV are affected by this parameter. Different fuel cells efficiencies are displayed to simulate the effect on the TCO. The FC efficiency can be influenced by the load as shown in fig2-2. The CV's and BEV's TCO stay the same at 0.43 €/km and 0.45 €/km respectively. The hydrogen cost can be influenced by the electricity price, the manufacturing cost of the electrolyzer or by the size of the plant. For instance the electricity cost can be close to 0 c€/kWhe in case of a wind turbine overproduction. As mentioned in chapter 2 the hydrogen price at the pump is meant to decrease from today's price to 4.4 €/kgH2 by 2045.

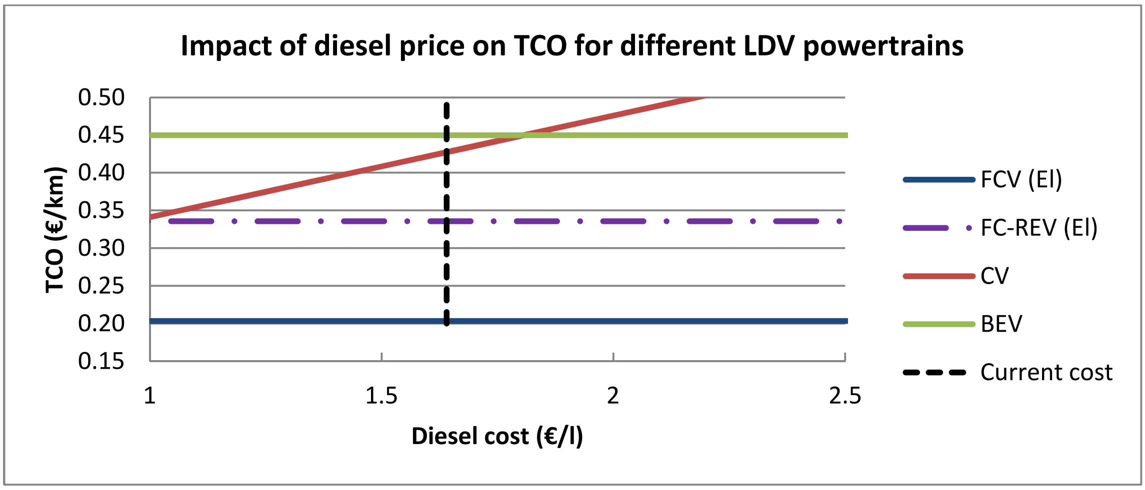


FIGURE 5-4 - MAXITY STUDY CASE, IMPACT OF DIESEL PRICE

Comments

Here the variable is the diesel price therefore only the CV is affected by this parameter while the FCV's, BEV's and FC-REV's TCOs stay the same at 0.20 €/km, 0.45 €/km and 0.34 €/km respectively. The diesel price is very volatile and is dependent of the international market rules. However, an increasing number of oil fields reach their production peak and given the increasing world energy demand a simple deduction leads to the conclusion that oil prices will increase mechanically in the long run. No price prediction would be wise though.

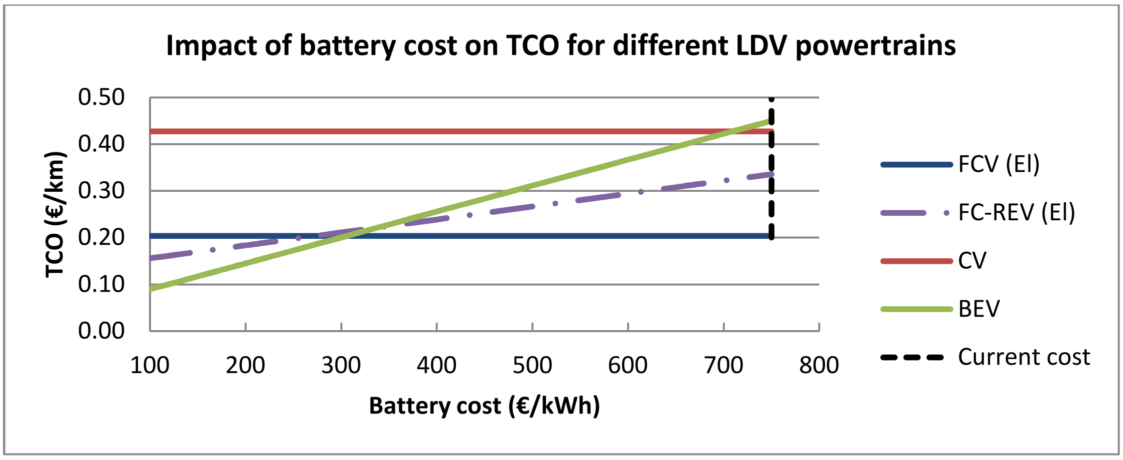


FIGURE 5-5 - MAXITY STUDY CASE, IMPACT OF BATTERY PRICE

Comments

Here the variable is the battery price (margin included) therefore only the BEV and the FC-REV are influenced by this parameter while the FCV's and the CV's TCOs stay the same at 0.20 €/km and 0.43 €/km, respectively. The battery cost is meant to decrease significantly in the years to come thanks to the saving of large scale production.

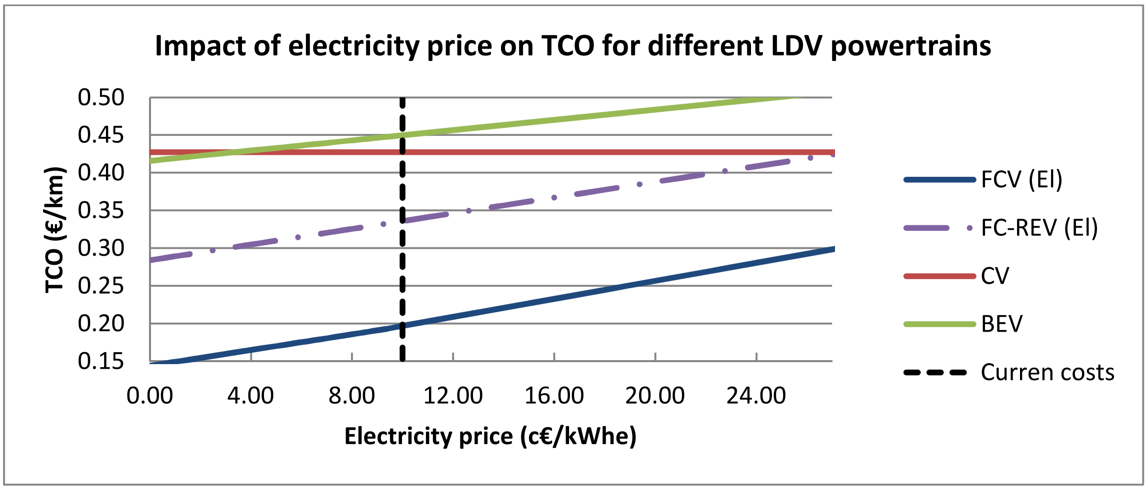


FIGURE 5-6 - MAXITY STUDY CASE, IMPACT OF ELECTRICITY PRICE

Comments

Here the variable is the electricity price therefore the BEV's TCO as well as the hydrogen cost (see excel file) are function of this parameter while the CV's TCOs stay the same at 0.43 €/km. It is very unlikely that the electricity price drops below 10 c€/kWhe because hydropower is one of the cheapest way to produce electricity and it represents 95% of Norway's production mix. However if hydrogen is produced during overproduction periods (solar plant, wind farm) then the hydrogen price could be lower.

5.4.3 *SECOND STUDY: IMPACT OF RANGE CAPABILITY*

5.4.3.1 Method, assumptions and input data

For this second study the variable is the range capability. A higher range capability allows some flexibility in the operation of the vehicle as it can complete different trip lengths (small delivery and longer transport in the same time). However, the longer the range the bigger the energy storage and the more expensive the powertrain is. In this study an annual distance of 16 000 kilometers has been assumed irrespective of the range capability.

Based on this assumption the corresponding TCO for the different powertrains has been established. It is important to remind that the battery lifetime is considered as dependent of time while the fuel cells renewal is considered as dependent of the distance. As mentioned before, given that a duty vehicle is under study, the available payload is also displayed. Unfortunately the design of a FC-REV for each range appears to be more complex than expected so this section includes only two relevant FC-REV designs. The TCO curve has laso been considered for the zero emission vehicles with road taxes which corresponds to the future scenario when the incentives will be gone.

5.4.3.2 Results

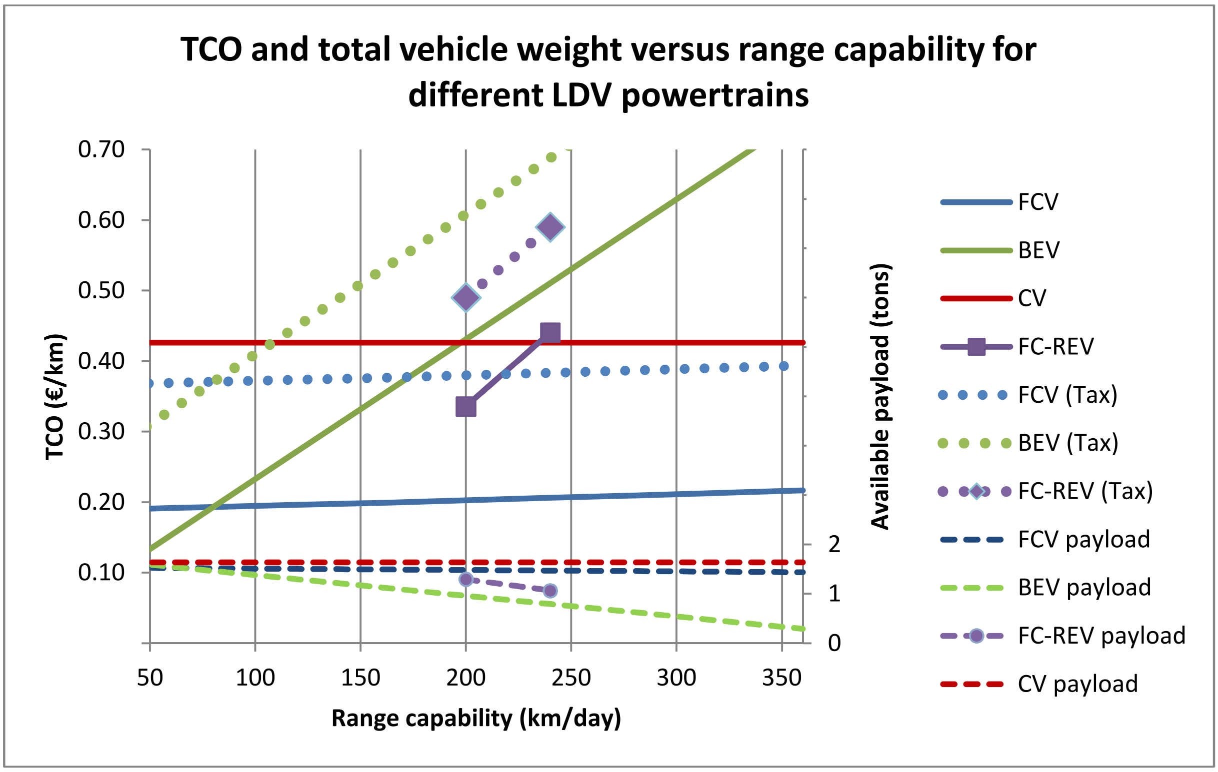


FIGURE 5-7 - MAXITY STUDY CASE, TCO AND WEIGHT VERSUS RANGE CAPABILITY

Comments

In order to compare also the future scenario where the same road taxes apply to all the vehicles, the zero emission vehicles are also displayed with tax (Tax) represented by dot curves. The four curves at the bottom of the graph (discontinuous lines) represent the available payload and are the only curves referring to the vertical axis on the right.

5.4.3.3 Analysis

With the current technology and fuel costs we can see from figure 5-2 that the FCV has the lowest TCO (0.20 €/km) then come the FC-REV (0.34 €/km) and the CV with the same lifecycle cost (0.43 €/km) and finally the BEV (0.45 €/km). For this analysis, given the several changing parameters, we will cover the powertrains one by one from the lowest TCO to the highest.

As the FCV uses only hydrogen for fuel it is very sensitive to its cost which represents 75% of the total TCO with current prices. However, even with a high price (11€/kgH2) the FCV's TCO stays the cheapest option. Furthermore the hydrogen price is meant to decrease thanks to a diminution of the retail cost as indicated in figure 1-6. Even if the FCV's lifecycle cost is sensitive to the electricity price as well, it is still the lowest TCO despite high prices given that other powertrain are also affected. This low TCO can be explained by the relatively low initial investment compared to BEV and FC-REV. Indeed despite a higher fuel cost per kilometer than the BEV or the FC-REV, the annual consumption is not important enough to make a significant difference for the FCV. However we have determined that a change in the fuel cells efficiency from 58% to 40% impacts significantly the TCO with an augmentation of 40%. This observation highlights the need of a good design in the fuel cells power (cf figure 2-2). If we look at the result of the "Range study" we can see that the FCV has the lowest TCO from a range capability of 80km. This is due to its powertrain's cost (storage and fuel cells) that rises slower with the distance than battery cost. If we consider the same level of road taxes as diesel it is very interesting to see that the FCV stay more interesting economically speaking than CV until a 360 km range capability, which is a good performance. Another advantage is the available payload which varies relatively little and stays acceptable for a duty vehicle (only 0.4 tons loss from a maximum payload of 1.8 tons).

Even if FC-REV’s powertrain (battery, fuel cells and storage) has a higher cost share than FCV (69% and 27% respectively) it has the main advantage of dedicating less TCO share to its fuel consumption (31% and 73% respectively). With current prices this compromise between initial investment and fuel consumption gives to the FC-REV the second lowest TCO with 0.34 €/km.

Given that this vehicle is made of the battery technology as well as the fuel cells technology it benefits from both cost reduction as we can see in figure 5-3 and 5-5. First of all the FC-REV's TCO is sensitive to hydrogen but stay lower than the CV’s or the BEV’s TCO even with 11€/kgH2. If we assist to a breakthrough in the battery manufacturing process that makes the battery price dropping under 250€/kWh (50% margin included) then the FC-REV would be cheaper than the FCV but in this economic configuration the BEV would be the cheapest option anyway. Also in the case where the electricity mix would change and the electricity price increases above 26c€/kWhe then the CV’s lifetime cost would be lower than FC-REV’s one. Finally it is difficult to interpret the "Range Study" for FC-REV with only two reference points but some relevant information are provided though. We can see that the FC-REV option is cheaper than BEV and CV for range shorter than 200km. Even though it is more expensive than FCV, the implementation of a FC-REV on an existing BEV can be a relevant investment to increase the range for a lesser price than by adding batteries. Interesting information lays also in the available payload curves. As we can see, the FC-REV's powertrain is lighter than the BEV's so it beneficiate from the lower cost and the lower weight of a fuel cell system. Therefore, this configuration is ideal to have longer range and maintaining a correct payload in the same time.

The CV has the particularity to be charged with road taxes while other vehicles are not and this expense represents 42% of its TCO. As mentioned earlier in chapter 4 those taxes are specific to an average vehicle from Posten but could be different in city operation where the tolls are less frequent. Cumulated with a high fuel cost we can understand the important lifecycle cost of this powertrain. Those taxes have an impact so important that even with a low diesel price (1 €/l) it is impossible for the CV to reach the FCV's TCO even though it does with the FC-REV at this diesel price. If we look at a configuration where the road tax rate is also applied to low emission vehicles then the CV's TCO much closer from FCV’s lifecycle cost but is still more expensive of few c€/km. Nonetheless, this technology has the main advantage of being relatively light so it can carry heavier payload than the other technologies under scope. Even if short term predictions are risky, we can state with confidence that oil prices will increase mechanically in the long run.

The BEV has the particularity to have been modified as the battery size has been doubled (and so its price) in order to match the range requirement of this study. This important battery size (84 kWh) generates a very high powertrain cost in the BEV's TCO breakdown (92%) with current prices and make it also very sensitive to battery price change. With the current cost it has the highest TCO with 0.50 €/km and the lightest payload (0.8 tons). If we assume that battery cost will decrease it will have to drop below 700 €/kWh (with margin) to be competitive with CV, 350 €/kWh to compete with FC-REV and below 300 €/kWh to compete with FCV. This first study has been done by considering a range of 200 km, however if we look at the second study we find that the BEV has the lowest TCO for small range capabilities (before 80 km). Furthermore the weight of the battery pack in those small ranges does not impact significantly the available payload.

For this first study about LDV the initial investments for the battery, the fuel cells or the hydrogen storage have a significant share in the TCO. It appears that the energy consumption per kilometer and the annual distance are not important enough to overcome the investment cost difference between BEV on one side and FC-REV, FCV and CV on the other side. That is why the second study will consider a Heavy Duty Vehicle with a higher energy consumption per kilometer and a longer annual distance.

We should note that the values used in this calculation (hydrogen price, FC cost, battery price) change very quickly in the real world and that the TCO did not include the entire lifecycle cost of the vehicle which could have produced a significant different result (maintenance cost, e-motor, assembly cost,…).

To make this first study about LDV more complete it would have been interesting to include more reference points for FC-REV as well as calculation for Plug-in Hybrid vehicles. Now a heavier type of truck will be studied which consume more energy per kilometer and which travel longer distances.

Source : favcars.com

FIGURE 5-8 - RENAULT PREMIUM, HEAVY DUTY VEHICLE

5.5 HEAVY DUTY VEHICLE STUDY CASE: RENAULT TRUCKS - PREMIUM

5.5.1 OBJECTIVE

For this truck segment our second study case will focus on the Premium truck (HDV from Renault Truck). This truck is selected because it is widely sold with its conventional engine version (CV) and its FC-REV version is on the way with the French company Symbio FCell. This study is divided in two parts where the first part assesses the economic impact of the various technologies' costs (hydrogen price, battery price, diesel price, electricity price) and where the second part shows the different lifecycle costs for different range capabilities. This second part considers both the economical aspect and the payload available for each technology.

5.5.2 FIRST STUDY: IMPACT OF TECHNOLOGIES COSTS

5.5.2.1 Method, assumptions and input data

In addition to the values given in the introduction section "Road" you can find below the specific design of each powertrain for the Premium.

TABLE 5-9 - PREMIUM STUDY CASE, HEAVY DUTY VEHICLE PROPERTIES

Vehicle type	**Heavy duty vehicle**
Annual Distance	151 000 km/year
Energy consumption	0.87 kWhe/km or 0.35 Ldiesel/km or 45 gH2/km
Motor power	300 kW
Range requirement	500 km
Maximum payload	10 tonnes
Study frame	10 years
Discount rate (NPV calculation)	4.1 %

(a) We assumed that the weight of the powertrain impacts directly the available payload. Available payload = Max payload - powertrain weight

TABLE 5-10 - PREMIUM STUDY CASE, POWERTRAIN PROPERTIES

	BEV	FC-REV	FCV	CV
Energy storage	513 kWh	80 kWh + 22.4 kgH2 (a)	22.6 kgH2	400 l
Installed power		160 kW FC	300 kW	300 kW

(a) In order to use the same energy consumption and efficiencies as the other study cases the hydrogen storage has been changed from 25kg to 22.4kg.

5.5.2.2 Results

The graphs and table below show the result of the price study. Some descriptive comments are provided after each table and graph but a more accurate analysis that includes the two studies (prices and range) will be done later in this section. Below the summary table of the different TCO and weight based on the current technology and fuel costs.

TABLE 5-11 - PREMIUM STUDY CASE, MAIN RESULTS

	TCO (€/km)	*Available payload (tonnes)*
CV	0.50	9.54
BEV	0.47	4.9
FC-REV	0.47	8.46
FCV	0.47	8.91

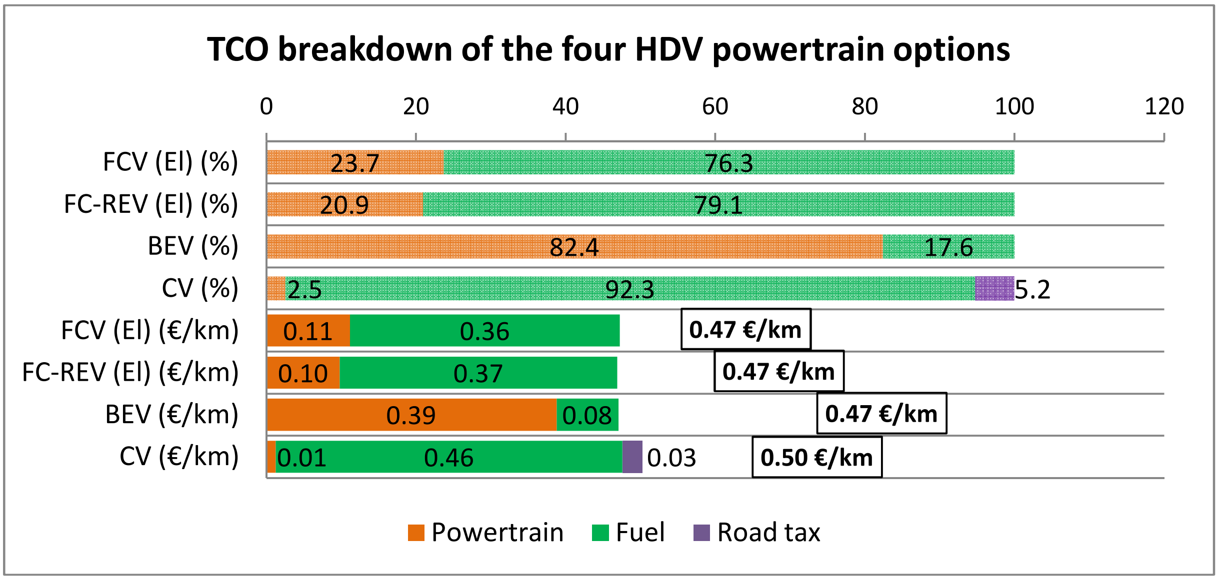


FIGURE 5-9 - PREMIUM STUDY, TCO BREAKDOWN

Comments

This bar chart allows us to see the repartition of the costs for each TCO. The breakdown is made between the infrastructure cost, the powertrain cost and the fuel cost. As mentioned before there is no direct hydrogen infrastructure cost as it is included in the fuel price at the pump.

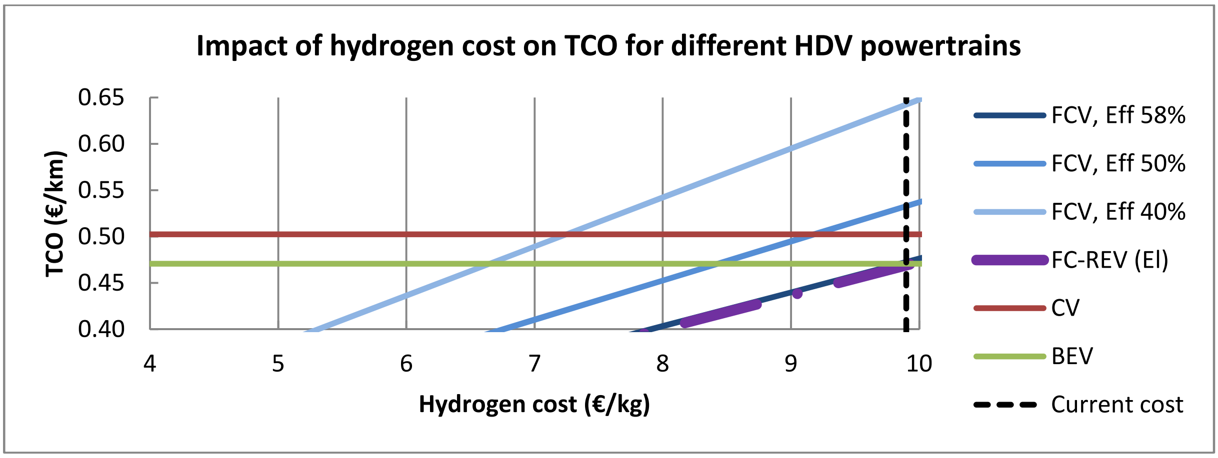


FIGURE 5-10 - PREMIUM STUDY CASE, IMPACT OF HYDROGEN PRICE

Comments

Here the variable is the hydrogen cost, and as expected only the FCV and the FC-REV are function of this parameter. Different fuel cells efficiencies are displayed to simulate the effect on the TCO. The FC efficiency can be influenced by the load as shown in fig2-2. The CV's and BEV's TCO stay the same at 0.50 €/km and 0.47 €/km respectively. The hydrogen cost can be influenced by the electricity price, the manufacturing cost of the electrolyser or by the size of the plant. For instance the electricity cost can be close to 0 c€/kWhe in case of a wind turbine overproduction. As mentioned in chapter 2 the hydrogen price at the pump is meant to decrease from today's price to 4.4 €/kgH2 by 2045.

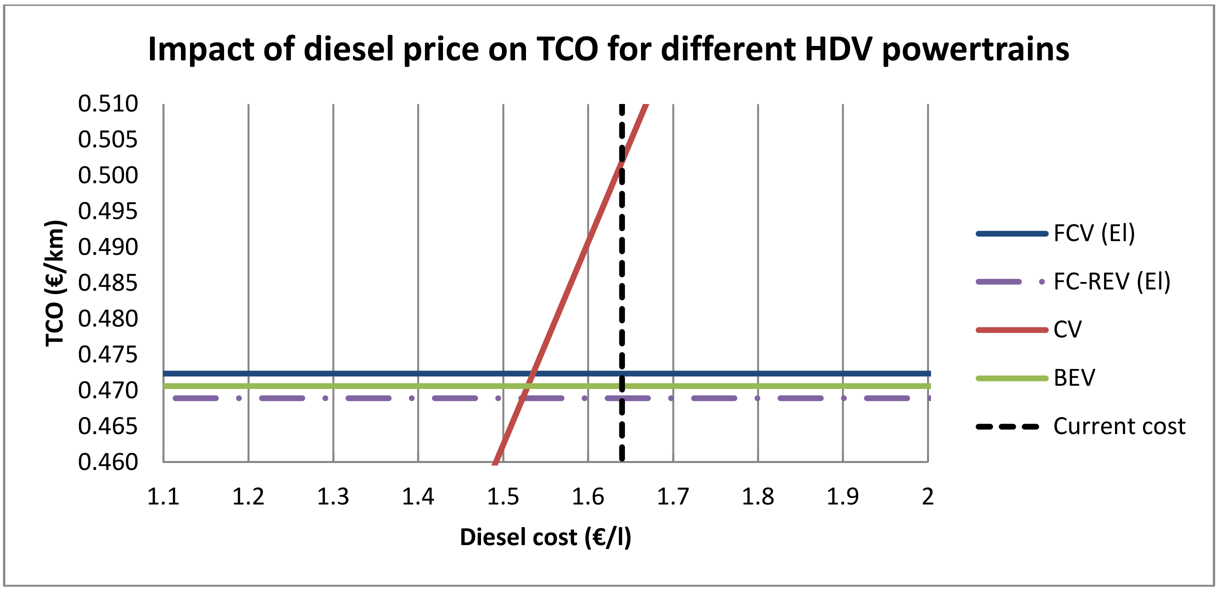


FIGURE 5-11 - PREMIUM STUDY CASE, IMPACT OF DIESEL PRICE

Comments

Here the variable is the diesel price therefore only the CV is function of this parameter while the FCV's, BEV's and FC-REV's TCOs stay the same at 0.47 €/km, 0.47 €/km and 0.47 €/km respectively. The diesel price is very volatile and is dependent of the international market rules. However an increasing number of oil fields reach their production peak and given the increasing world energy demand a simple deduction leads to the conclusion that oil prices will increase mechanically in the long run. No price prediction would be wise though.

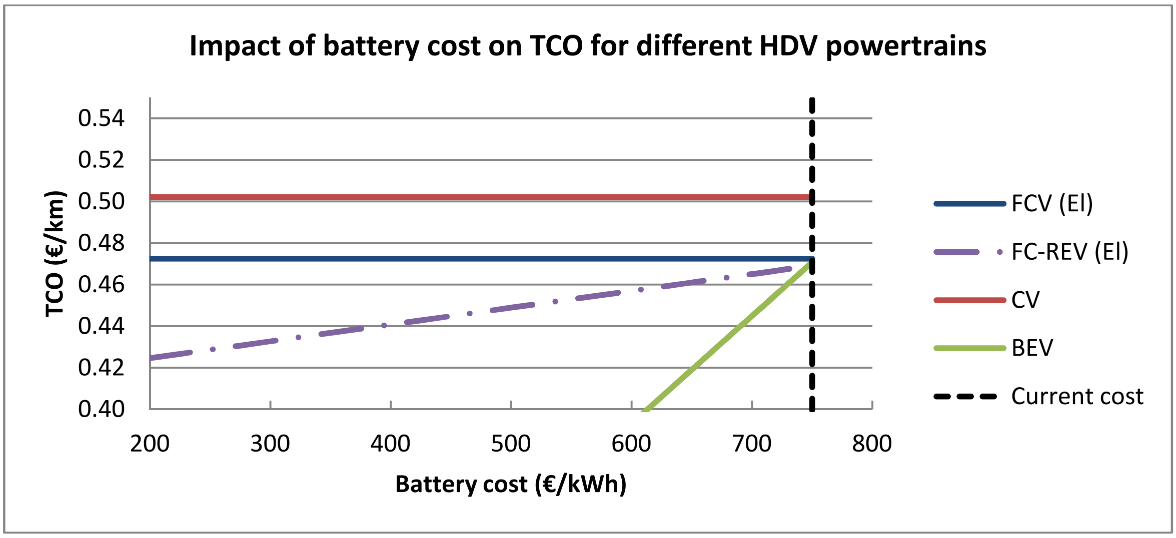


FIGURE 5-12 - PREMIUM STUDY CASE, IMPACT OF BATTERY PRICE

Comments
Here the variable is the battery price (margin included) therefore only the BEV and the FC-REV are function of this parameter while the FCV's and the CV's TCOs stay the same at 0.47 €/km and 0.50 €/km respectively. The battery cost is meant to decrease significantly in the years to come thanks to the saving of mass production.

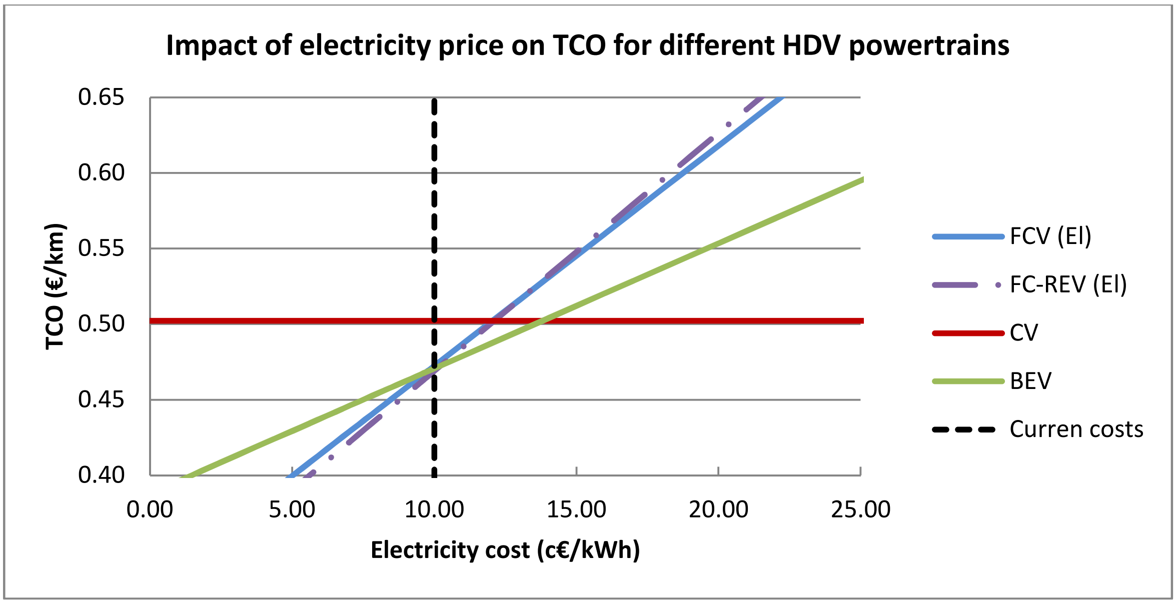


FIGURE 5-13 - PREMIUM STUDY CASE, IMPACT OF ELECTRICITY PRICE

Comments
Here the variable is the electricity price and therefore the BEV's TCO as well as the hydrogen cost (electrolysis) are functions of this parameter while the CV's TCOs stay the same at 0.50 €/km. It is very unlikely that the electricity price drops below 10 c€/kWhe because hydropower is one of the cheapest way to produce electricity and it represents 95% of Norway's production mix. However if hydrogen is produced during overproduction period (solar plant, wind farm) then the hydrogen price could be lower.

5.5.3 SECOND STUDY: IMPACT OF RANGE CAPABILITY

5.5.3.1 Method, assumptions and input data

For this second study the variable is the range capability. A higher range capability allows some flexibility in the operation of the vehicle as it can complete different trip lengths (small delivery and longer transport in the same time). However the longer the range, the bigger the energy storage, and the more expensive the powertrain is. In this study we have assumed an annual distance of 100 000 kilometers whatever the range capability.

Based on this assumption we have established the corresponding TCO for the different powertrains. It is important to remind that the battery lifetime is considered as dependent of the time while the fuel cells renewal is considered as dependent of the distance. As mentioned before given that we are studying a duty vehicle the available payload is also displayed. Unfortunately the design of a FC-REV for each range appears to be more complex than expected so this section includes only one relevant FC-REV designs. We also have considered the TCO curve for the zero emission vehicles with road taxes which correspond to the future scenario when the incentives will be gone.

5.5.3.2 Results

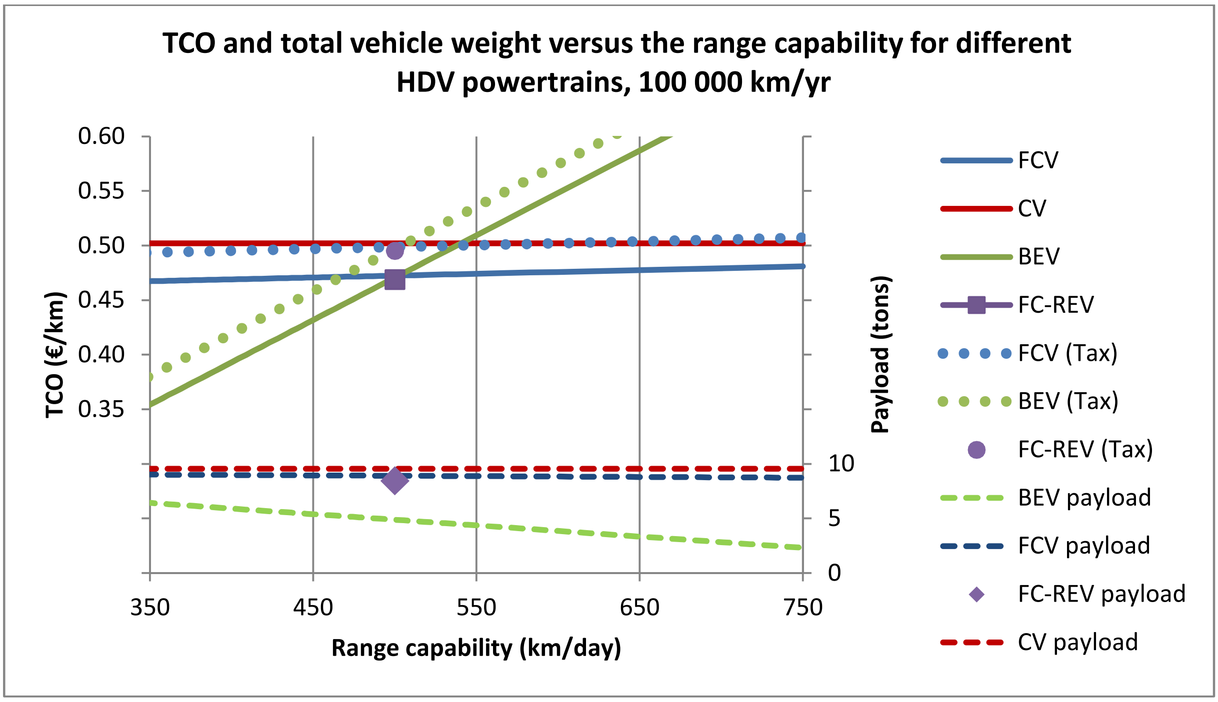


FIGURE 5-14 - PREMIUM STUDY CASE, TCO AND WEIGHT VERSUS RANGE CAPABILITY

Comment

In order to compare also the future scenario where the same road taxes apply to all the vehicles, the zero emission vehicles are also display with tax (Tax) represented by dot curves. The four curves at the bottom of the graph (discontinuous lines) represent the available payload and are the only curves referring to the vertical axis on the right.

5.5.3.3 Analysis

This second part of the truck section, focuses on the HDV, gives us interesting results in the way that they are different from the LDV’s. This time the vehicle drives almost ten times more kilometers per year and consumed two times more energy per kilometer. Like previously we will proceed to an analysis of the results powertrain by powertrain to determine what are the best parameters and distance range for each of them. This analysis will be followed by a common discussion including the two studies (LDV and HDV). The TCOs from the FCV, the FC-REV and the BEV are very close from each other so it is not very relevant to say that one powertrain is more interesting than another in this situation.

The FC-REV combines the advantages of a light fuel cells and cheap electricity. With current prices this hybrid truck has a lifecycle cost of 0.47 €/km and will benefit from every technology cost reduction (except from diesel). This configuration shows the benefits of finding the right design between battery, fuel cells and hydrogen as a good balance makes both investments and operational costs almost cheaper for FC-REV than for FCV. It is also relevant to point out that whatever the price variation (hydrogen or battery) the FC-REV is always cheaper than the FCV. Although if the electricity become more expensive than 10c€/kWhe then the FC-REV loses its advantage even if not significantly. The low TCO of this vehicle can be explained by the fact that for the same distance the FC-REV will use a part of electricity through a battery which is much cheaper and more efficient than hydrogen and fuel cells. This fraction of energy coming from the battery makes a significant difference given the important energy consumption and distance covered by the Renault Premium. However, because of the configuration in series the efficiency of the system is diminished for FC-REV and, in our specific case, almost cancels the gain from battery. Finally, the most interesting point is that for a lower TCO the FC-REV does not compensate by a significant loss of available payload contrarily to BEV. For a slightly lower TCO than BEV's the FC-REV can carry 73% more than the BEV (8.46 tons of available payload against 4.9). We can note however that the renewal frequency of the fuel cells is very high with a need for change every year.

In comparison with the LDV study case we can see that this time the BEV has a competitive TCO with 0.47 €/km despite a lighter available payload. We can explain this difference by the annual distance which is 8 times higher than the LDV’s while the battery size and cost are only 6 times higher. It has a high share of main component cost in its TCO (82.4% of battery) compared to the other technologies (23.7% for the FCV) but has the lowest fuel share (17.6% against 76.3% for the FCV and 92.3% for the CV). Therefore the total TCO drops significantly when the battery price decrease and put the BEV in first position for price lower than 750€/kWh. Furthermore, electricity is so cheap compare to other fuels and the battery is so efficient that even with a high investment cost the BEV catch up the other technologies thanks to its low operation cost. This operation price difference can have this magnitude only because the HDV has very important energy consumption and a high annual distance covered. Of course if we only focus on the powertrain lifecycle cost the BEV would have had the best position considering the price evolution of batteries but we have to take into account the payload as well, it means how much weight the truck can carry. Then we find the answer in the figure 5-14 where we can see that even with the lowest TCO the BEV loses a lot of available payload due to the battery weight. For instance with a range of 500 km the available payload is halved (5 tons loss for 10 initial tonnes). For this study there were no tools to assess the economic value of one tonne of payload but it is clear that this low payload capacity is a threshold that put aside the BEV as a reliable technology for heavy trucks over medium and long distances. Finally one important operational drawback is the need to consider the charging time and the power needed to do so.

The CV has the highest TCO (0.5 €/km) and the highest share of fuel expenses (92.3% of TCO). This high sensitivity makes the TCO very dependent of the price volatility and this relation can explain the struggle of transport companies in case of oil price peak. Given the long term price predictions a diesel price increase is very likely to occur. The Norwegian context offers a high diesel price (1.64 €/l) but with a fuel cost as low as 1.53€/l the CV compete with the other powertrain of the study. Finally, few percent of the final TCO are generated by the road taxes which are equal to zero for the other vehicles. This point will be treated in the next paragraph.

The FCV is also competitive in this study with a TCO of 0.47 €/km. As mentioned before the important energy requirement and covered distances give an important share to the fuel cost (76%). This sensitivity to energy consumption gives even more importance to the fuel cells design as a lower efficiency (50% instead of 58%) increases the TCO by 14%. Thanks to the “Range study” we can see that FCV, with FC-REV, are actually the most competitive option for all the ranges if we exclude the BEV because of its weight. In the case where the road taxes would be the same for all the vehicles then the FCV would still be the most interesting option but only until a 600km range. For longer range the CV would have the lowest TCO. Finally we can note that a heavy truck only powered by hydrogen would have the advantage of being able to carry a payload heavier (450 kg) than a FC-REV for the configuration of this study (500km, 300 kW,…). We can note however that the renewal frequency of the fuel cells is very high with a need for change every year.

5.6 COMMON DISCUSSION AND LIMITATIONS OF THE TWO STUDIES (LDV & HDV)

Thanks to the two previous studies about Light Duty Vehicle and Heavy Duty Vehicle a lot of relevant results and interpretations have been collected. Those two cases allow two conclude (in the limits of the assumptions) that for each range requirement (short, medium, long) and each energy requirement (LDV or HDV) there is one optimum powertrain among the FCV, the CV, the FC-REV and the BEV. Therefore we have determined that the BEV matches for both LDV and HDV within short distance requirements (shorter than 80km) which can correspond to short city delivery or construction vehicles. Concerning the FCV the results show that this technology is relevant from medium to long range requirements (80 km and above) but with a relatively low energy consumption which can correspond to an intercity delivery with medium capacity vehicle (e.g. Mercedes Sprinter). Despite a lack of relevant data the FC-REV seems to introduce the hydrogen technology to high energy consumption vehicles over medium and long distance which can correspond to international freight transport and shares this segment with the CV. Even with equal taxes for all the powertrain the FCV and the FC-REV are still competitive with the CV over medium distance (shorter than 600km). A particular attention should be paid to the design of the fuel cells to make sure that it operates at its maximum efficiency especially for high energy consumption vehicles which are very sensitive to this performance. Last but not least, this study has shown that for LDV the road taxes play a significant role in the economical feasibility of zero emission vehicles which is therefore specific to the Norwegian context and policies.

However those conclusions are limited to the frame of the assumptions which are based on specific study cases. For instance, it could have been relevant to include several models of duty vehicles, FC-REV especially, to extract some relevant trends and potentially reinforce the conclusion above. It is also important to remind that the maintenance cost considered here only includes the renewal of the main powertrain components but in real life the expenses are more various and important. The fuel cells and the battery performance degradation has not been considered. A tool to take into account the economic price of the payload could have been relevant. Also, even if the weight was considered as an important factor no estimation about the volume of the system was done, despite the fact that volume is also a relevant parameter in transportation.

5.7 CONCLUSION

After having approached the different aspects of this sector (environmental, operational and economical) it is really interesting to observe how all that information can be combined to make a promising market segment emerge for the introduction of fuel cells and hydrogen technology. The study cases achieved in this section have underlined two potential segments for this technology. Thanks to its light weight and its energy content the Fuel cells Vehicle appears to be the favorite option for Light Duty Vehicle over medium and long distance. Thanks to the benefits of two different technologies (light weight and cheaper energy) the FC-REV is able to compete with the Conventional Truck over medium and long distances for heavy duty vehicles. Furthermore, the price evolution is very likely to be favorable to the increasing economic competitivness of those vehicles. However the different operational aspects underline several difficulties that must be pay attention to. First of all the FCV application has a high fuel cells renewal rate with almost one new fuel cells required every year. This renewal operation is easily achievable but it requires a qualified staff. Secondly, the FC-REV includes a battery that has to be recharged with significant recharging time, and this constraint has to be considered for the operation (e.g. charging overnight). Finally, even if the infrastructure cost has been taken into account in the fuel price, the application of this study is restricted to a fleet operation for the moment.

It means that for longer trips over several days a real infrastructure network has to be implemented as illustrated in Chapter 4. An important point has also been made on the significant role of tax reduction for light duty vehicles which is necessary to the competitiveness of FCV.

The environmental aspect shows that local pollution has to be addressed through the light and medium duty vehicle while the global warming has to be considered through the heavy duty vehicle. Thanks to the previous analysis we can say that to reach the first national objective in terms of environment, which is the decarbonisation of the transport sector, the FC-REV is clearly a part of the answer.

Concerning the other fuels and technologies biodiesel can be a substitute to conventional diesel to limit the impact of CO_2 emissions (especially heavy trucks and long distance trips) but it increases the emission of NOx. Consequently it seems to be more a transitory option to reach the national CO_2 reduction than a long term solution. Another transitory option could be the natural gas from biomass (biogas). It has interesting environmental properties (locally and globally) and can be quickly implemented in the existing system and infrastructure (especially dual fuel). Biogas actually seems to be a better bridge toward a zero emission truck than biodiesel. Finally even if LPG is interesting economically speaking it generates more problems than it solves. It emits less CO_2 compared to diesel but this difference is small and this fuel does not bring significant environmental interest. Furthermore its use raises some safety issues that can be overcome but which restrict the access to certain areas.

In order to go further an entire master thesis can actually be dedicated to the design of the FC-REV. The number of possible combinations for a range extender system is very high as it includes the battery power, the fuel cells power, the hydrogen storage, the battery size, the configuration (series, parallel), the duty cycle, the operation mode (State of charge trigger) and has to match specific requirements like cost, weight, volume, range, refueling time or power.

5.8 SWOT MATRIX

TABLE 5-12 - TRUCK SECTOR SWOT MATRIX

Strength	**Weakness**
Silent Zero direct emission FC-REV competitive for HDV for medium and long range FCV competitive for LDV from 80km range Adaptability as APU Fast refueling Clean fuel chain (electrolysis)	Short distance range Cost of storage Cost of PEMFC Storage volume Lifetime Storage issues
Opportunities	**Treats**
Fleet operation Decreasing hydrogen price Decreasing battery price Diesel price volatility LEZ (low emission zones)	Lack of regulation Lack of infrastructure

6

ROAD SECTOR: CARS

6.1 INTRODUCTION AND ENVIRONMENTAL CONTEXT

6.1.1 INTRODUCTION

The car market is a complex topic where several industries meet and where new technologies have some difficulty to do their mark. This is due to the central place of the car in our society (economic dynamism, leisure, travel,…), therefore there are a lot of expectations concerning any newcomers. According to official prognosis (Nasjonal Transportplan, [95]), the passenger transport by cars is expected to increase by 0.8 % annually in the period 2012-2020 [23] and according to the national target of CO_2 emission and local pollution this sector faces important challenges. Currently the dominant technology is the internal combustion engine (ICE) powered by gasoline or diesel, both derivated from crude oil. Even though within the car sector it is possible to differentiate two segments represented by the urban areas and the rural areas, but this section will cover the car sector as one homogenous segment.

After a brief review of the environmental aspect we will cover the technical and operational aspects of the hydrogen and fuel cells in the car sector. Thanks to the European report "A portfolio of power trains for Europe a fact based analysis" and to our own calculations we will assess the economical feasibility of this technology through a general approach and a study case. A discussion and a SWOT matrix will conclude this section.

6.1.2 ENVIRONMENTAL CONTEXT

As mentioned in the section "Road" the cars and public transports are responsible for 56% of the road transport emissions. This is due to the large number of passenger cars on the road and their high frequency of use. Local pollution is also a consequence of this massive traffic especially in locations with high population density (cities). Like any incomplete combustion the internal combustion engine generate more NOx during the idling or start and stop phase (cross light, pedestrian road cross,…). Finally, the use of diesel generates less CO_2 per km than gasoline but release more NOx and particle matter (See chapter 2 for more details)

6.2 HYDROGEN AND FUEL CELLS APPLICATIONS

6.2.1 TECHNICAL ASPECT

As mentioned previously a PEMFC can be used in different ways in the transport sector. In the case of a car the PEMFC can either be used as a FC-REV or as a complete FCEV, the auxiliary power unit is not relevant in this case. Those two configurations will be illustrated below thanks to two existing vehicles. Here we compare the BEV (Battery Electric Vehicle), the PHEV (Plug-in Hybrid Electric Vehicle), the FCEV and the ICE. Each technology is illustrated by a bar representing its range of performance.

FIGURE 6-1 - CAR SECTOR, PERFORMANCE COMPARISON BETWEEN DIFFERENT POWERTRAINS

[70]

6.2.2 APPLICATIONS

6.2.2.1 The Toyota Mirai

The Mirai, a FCV, is a passenger car (Sedan type) released by Toyota on November 2014 and the sales has started in Japan from December 2014. It is one of the first fuel cells vehicles available on the market and it combines several technology advances concerning the fuel cells (PEM, lifetime, efficiency) and the storage (weight and pressure). The hydrogen is stored into two high pressure tanks and because of this design option the trunk is a little smaller than in a normal Sedan model.

Table 6-1 - Car sector, Toyota Mirai properties

Parameter	**Toyota Mirai [71]**
FC power	114 kW
Hydrogen storage	5 kg combined (2 tanks)
Storage pressure	70MPa
Autonomy	480 km
Hydrogen kit weight	144 kg (56 kg for FC + 88 kg for tanks)
Refueling time	3 minutes

FIGURE 6-2 - ILLUSTRATION OF THE TOYOTA MIRAI

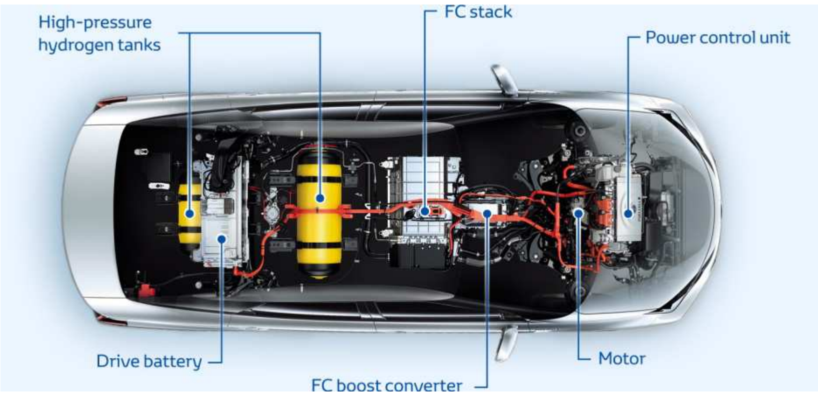


FIGURE 6-3 - TOYOTA MIRAI COMPOSITION OVERVIEW

With a simple calculation we can determine that the hydrogen consumption is equal to 1kg/100km which corresponds to the average consumption of a passenger FCV. In order to compare this type of vehicle to the other fuels and technologies we can refer to the study from the European Fuel cells and Hydrogen Joint Undertaking "*A portfolio of power trains for Europe a fact based analysis*". This study provides some technical information and a lot of economical data, the most relevant are displayed below. According to this recent study, a fuel cells stack can achieve a lifetime of 180,000 km.

6.2.2.2 The Renault HyKangoo

This FC-REV is based on the Kangoo Z.E model from Renault. This electric vehicle is used principally in fleet for post office companies or as individual small duty vehicle. The particularity of this vehicle from Renault is the possibility to install the hydrogen kit even after the production and the operation of the kangoo Z.E. Therefore it is possible to "transform" an entire fleet of electric Kangoo Z.E into Hykangoo like the French post office did in the Franche-Comté region.

TABLE 6-2 - CAR SECTOR, RENAULT HYKANGOO PROPERTIES

Parameter	**Renault HyKangoo [3], [1]**
Motor power	44 kW
Battery size	22 kWh
FC power	5 kW
Hydrogen storage	1.72 kg combined (1 tank of 74l)
Storage pressure	35MPa
Autonomy	320 km (160km battery + 160km H2)
Refueling time	3 minutes

FIGURE 6-4 - HYKANGOO ILLUSTRATION

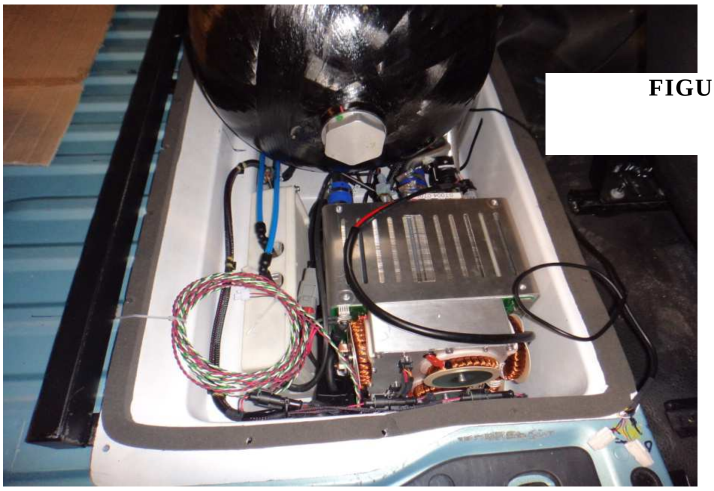


FIGURE 6-5 - HYKANGOO RANGE-EXTENDER KIT ILLUSTRATION

6.3 CAR SECTOR ECONOMIC STUDY CASE: RENAULT HYKANGOO

6.3.1 *OBJECTIVE*

For the car sector we have decided to focus our study case on the Renault Kangoo. We have selected this car because at least three of the four options are available on the market (CV, BEV and FC-REV). As we did for the truck sector we have compared four different powertrains lifecycle cost (battery, FC, FC-REV and ICE) over a period of 10 years with a fleet operation (Posten). This study is divided in two parts where the first part assesses the economic impact of each technology price (hydrogen price, battery price, diesel price, electricity price) and where the second part shows the different lifecycle costs for different range capabilities. All the results are expressed in Total Cost of Ownership (TCO, €/km, see Maritime sector for details)

6.3.2 *FIRST STUDY: IMPACT OF TECHNOLOGIES COSTS*

6.3.2.1 Method, assumptions and input data

In addition to the values given in the introduction section "Road" we can fin below the specific design of each powertrain for the Kangoo.

TABLE 6-3 - HYKANGOO STUDY CASE, VEHICLE PROPERTIES

Annual Distance	15 040 km/year
Energy consumption	0.12 kWhe/km or 0.06 Ldiesel/km or 7.3 gH2/km
Motor power	44 kW
Range requirement	360 km
Study frame	10 years
Discount rate (NPV calculation)	4.1 %

TABLE 6-4 - HYKANGOO STUDY CASE, POWERTRAIN PROPERTIES

	BEV	**FC-REV**	**FCV**	**CV**
Energy storage	44 kWh (a)	22 kWh + 1.14 kgH2 (b)	2.8 kgH2	50 liters
Installed power		5 kW FC	44 kW	44 kW

(a) For a matter of comparison coherence (same range was needed) the size and the range of the BEV have been doubled.

(b) In order to use the same energy consumption and efficiencies as the other study cases the hydrogen storage has been changed from 1.7kgH2 to 1.14kgH2.

6.3.2.2 Results

This section display the different results obtained after the calculations mentioned above. Short comments will be provided for each graph but a longer interpretation will be written in the next section dedicated to the analysis of those results. Below the summary bar chart of the different TCO based on the current technology and fuel costs.

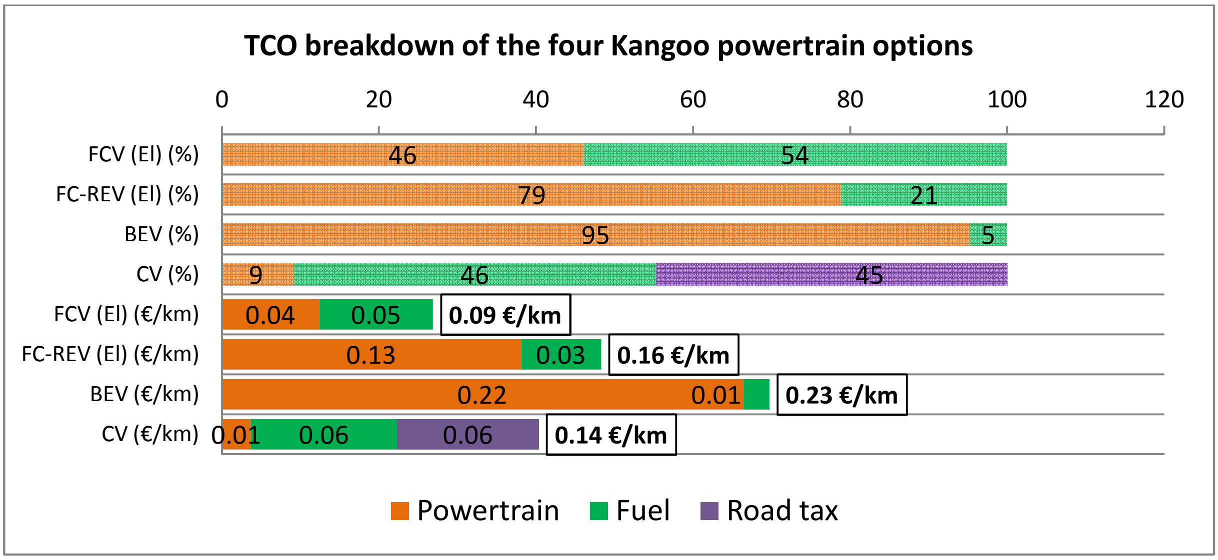


FIGURE 6-6 - HYKANGOO STUDY CASE, TCO BREAKDOWN

Comments

This bar chart allows us to see the partition of the costs for each TCO. The breakdown is made between the infrastructure cost, the powertrain cost and the fuel cost. As mentioned before, there is no direct hydrogen infrastructure cost as it is included in the fuel price at the pump.

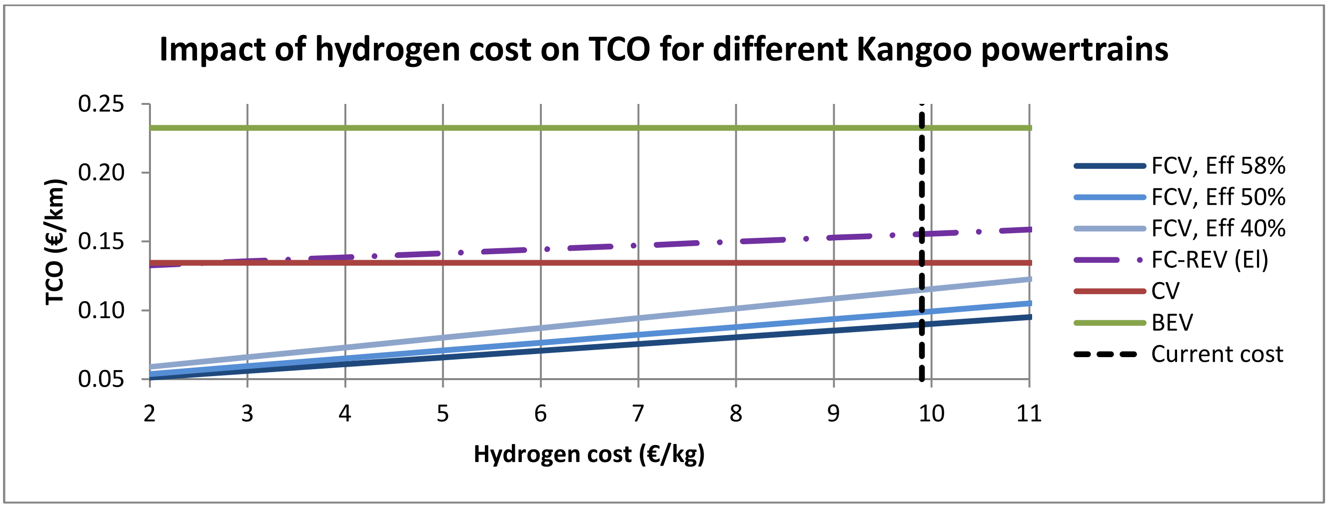


FIGURE 6-7 - HYKANGOO STUDY CASE, IMPACT OF HYDROGEN PRICE

Comments

The hydrogen cost can be influenced by the electricity price, the manufacturing cost of the electrolyzer or by the size of the plant. The electricity cost can be close to 0 c€/kWhe in case of a wind turbine overproduction. As mentioned in chapter 2 the hydrogen price at the pump is meant to decrease from today's price to 4.4 €/kgH2 by 2045.

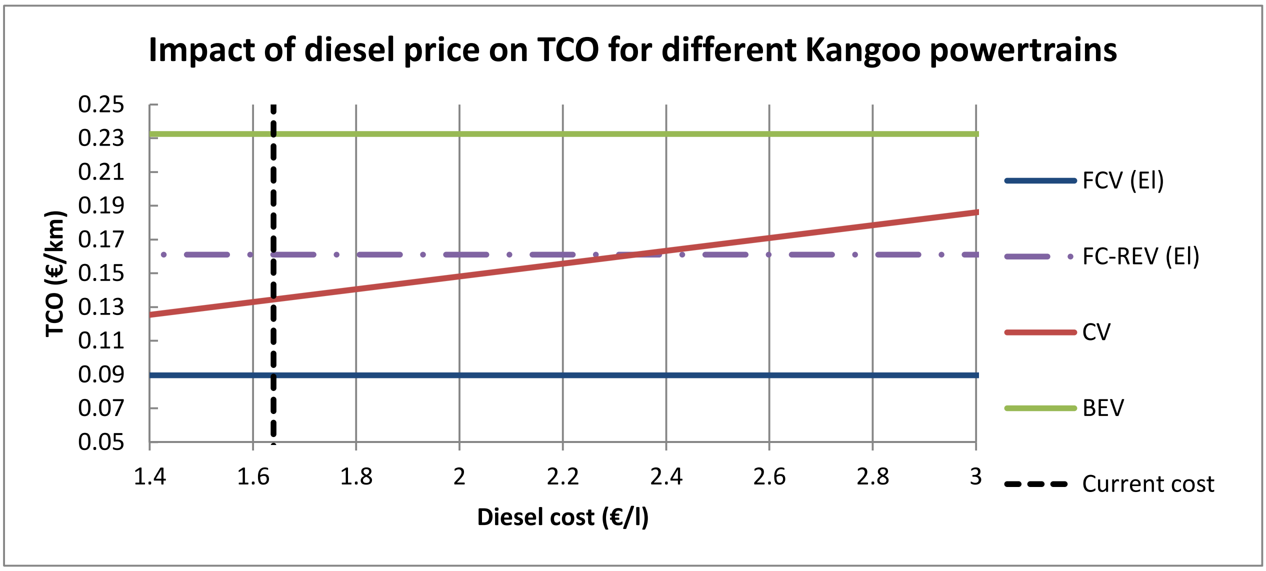


FIGURE 6-8 - HYKANGOO STUDY CASE, IMPACT OF DIESEL PRICE

Comments

Here the variable is the diesel price therefore only the CV is function of this parameter while the FCV's, BEV's and FC-REV's TCOs stay the same at 0.09 €/km, 0.23 €/km and 0.16 €/km respectively. The diesel price is very volatile and is dependent on the international market rules. However an increasing number of oil fields reach their production peak and given the increasing world energy demand a simple deduction leads to the conclusion that oil prices will increase mechanically in the long run. No price prediction would be wise though.

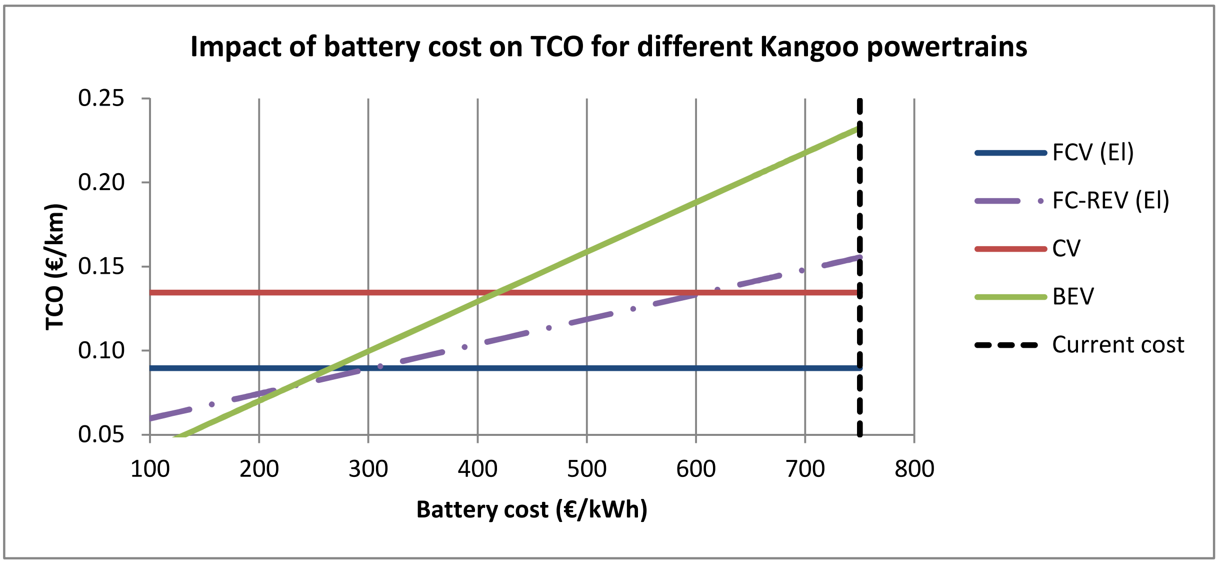


FIGURE 6-9 - HYKANGOO STUDY CASE, IMPACT OF BATTERY COST

Comments

Here the variable is the battery price (margin include) therefore only the BEV and the FC-REV are function of this parameter while the FCV's and the CV's TCOs stay the same at 0.09 €/km and 0.14 €/km respectively. The battery cost is meant to decrease significantly in the years to come thanks to the savings of mass production.

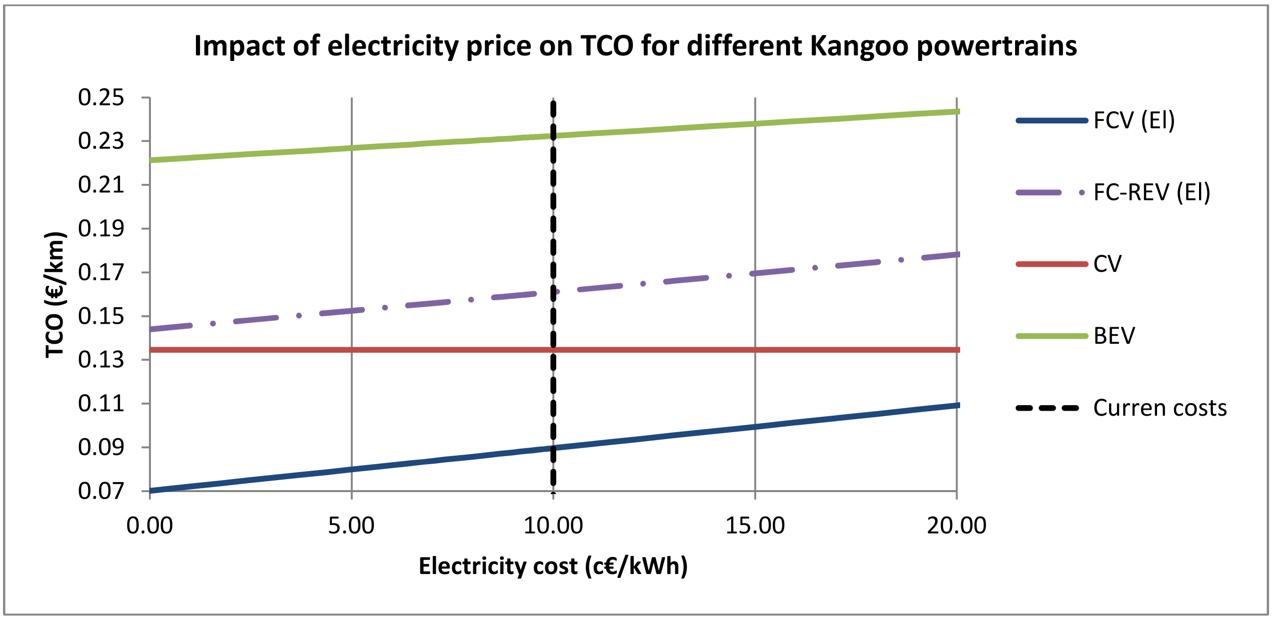


FIGURE 6-10 - HYKANGOO STUDY CASE, IMPACT OF ELECTRICITY PRICE

Comments
Here the variable is the electricity price therefore the BEV's TCO as well as the hydrogen cost (electrolysis) are function of this parameter while the CV's TCOs stay the same at 0.14 €/km. It is very unlikely that the electricity price drops below 10 c€/kWhe because hydropower is one of the cheapest way to produce electricity and it represents 95% of Norway's production mix. However, if hydrogen is produced during overproduction period (solar plant, wind farm) then the hydrogen price could be lower.

6.3.3 SECOND STUDY: IMPACT OF RANGE CAPABILITY

6.3.3.1 Method, assumptions and input data

For this second study the variable is the range capability. A higher range capability allows some flexibility in the operation of the vehicle as it can complete different trip lengths (small delivery and longer transport in the same time). However the longer the range the bigger the energy storage and the more expensive the powertrain will be. In this study we have assumed an annual distance of 15040 kilometers whatever the range capability.

Based on this assumption we have established the corresponding TCO for the different powertrains. It is important to remind that the battery lifetime is considered as dependent of the time while the fuel cells renewal is considered as dependent of the distance. Unfortunately, the design of a FC-REV for each range appears to be more complex than expected so this section includes only two relevant FC-REV designs. We also have considered the TCO curve for the zero emission vehicles with road taxes which correspond to the future scenario when the incentives will be gone.

6.3.3.2 Results

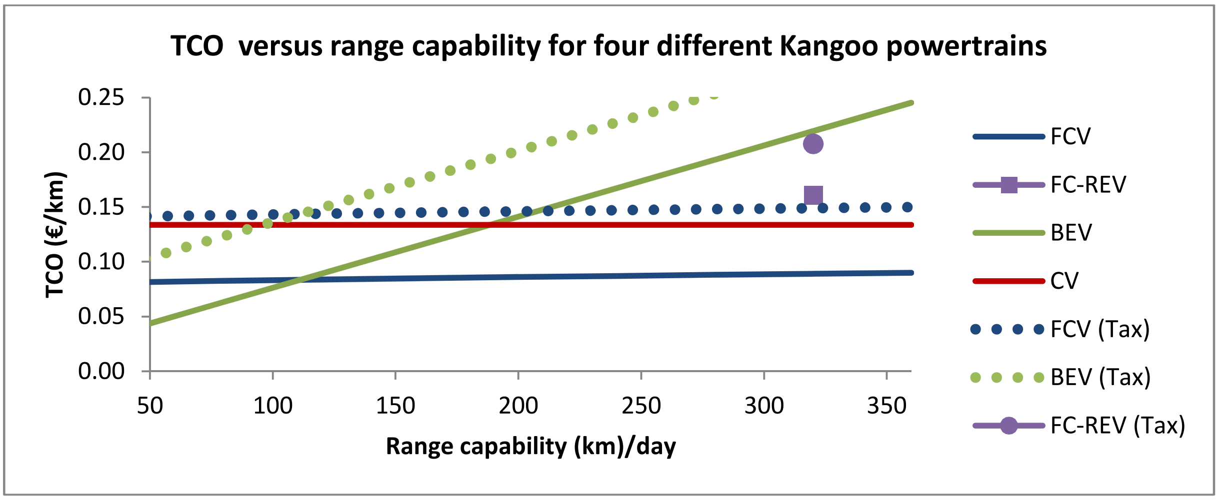


FIGURE 6-11 - HYKANGOO STUDY CASE, TCO VERSUS RANGE CAPABILITY

Comment
In order to compare also the future scenario where the same road taxes apply to all the vehicles, the zero emission vehicles are also display with tax (Tax) represented by dot curves.

6.3.3.3 Analysis

The FCV shows the lowest TCO with a lifecycle cost of 0.09 €/km which leaves an important gap with other powertrain options. Thanks to the bar chart we can observe that half of its TCO is composed of the initial investment (FC, hydrogen storage) and the other half by the fuel consumption. Because of the relatively low hydrogen consumption (less than 1 kg for 100km), the fuel price does not make the FCV more expensive than other option even with high price or low efficiency. The same conclusion can be made for the graph displaying a variation of the electricity price. However, this powertrain option is not the most relevant for short and medium distances as the FCV is only more interesting than the BEV for range requirements longer than 140 kilometers.

Even if its initial investment is very low the CV's TCO of 0.19 €/km is strongly impacted by the fuel expenses (47%) and the road taxes (44%). Given the high volatility price of oil, it is relevant to mention that the CV's lifecycle cost is close from the FC-REV's and that a diesel price of 2.3 €/l is enough to make it more expensive than the range extender vehicle. However, we can determine that if the road taxes for the CV would have been the same for the zero emission vehicles the results would have been totally different. This result, displayed in figure 6-11, shows that the CV could be, with equivalent taxes, the cheapest option for range requirements longer than 120 kilometers.

With a TCO of 0.20 €/km the FC-REV is not as interesting as the FCV for this Kangoo study case but it has a competitive potential in comparison to the CV and especially so if the battery price decreases below 600€/kWh or if the hydrogen price drops below 3 €/kgH2 (e.g. wind farm overproduction). Given that we only have one reference point for the FC-REV it is difficult to interpret further the FC-REV's TCO for other distances. The only thing we can say is that it is a relevant option if the objective is to extend the autonomy of an existing BEV. The implementation of a FC system on a BEV would be less expensive than the addition of batteries.

The BEV is not very competitive with current prices for the range under scope (0.23 €/km). However, if the battery cost drops below 410 €/kWh (with margin), then its lifecycle cost would be under the CV's one. It seems that the potential of the BEV does not lie in this range of distance as shown in the figure 6-11. Indeed, the vehicle's TCO is the lowest below 140km without taxes and below 120km with taxes.

6.4 CONCLUSION

The data collected and the calculations achieved allow us to state about the different fuel cells and hydrogen opportunities for the car sector. First of all we have determined that the Fuel cells Vehicle was the most competitive powertrain from a 140 kilometers range requirement. We have also shown that this conclusion was only reliable in the Norwegian context where the favorable road taxes play a significant role. Without those incentives only the battery electric vehicles would be competitive with the conventional vehicle but only for a range inferior to 120km. However, we can say that the technologies and fuels price evolution will give advantage to fuel cells technology, and that road tax policies will have a lesser weight in the economic balance. Secondly, we have determined that, with the current prices, FC-REVs are not interesting enough to be manufactured for this type of vehicles. However, there is a real opportunity for them to be implemented on existing Battery Electric Vehicles in order to extend the range with a competitive cost. In both cases the FCV and the FC-REV have the main advantage of being refueled quickly and to be safe thanks to demonstrations projects or even real market product like the Toyota Mirai or the Kangoo. Those conclusions are based on a fleet operation and the main drawback is still the lack of infrastructure to be able to generalize those results. Year after year the increasing environmental pressure and the corresponding policies of the car sector, will make a market with more and more opportunities for zero emission vehicles.

6.5 SWOT MATRIX

TABLE 6-5 - CARS SECTOR SWOT MATRIX

Strength	Weakness
Silent Zero direct emission FC-REV only relevant for range extension of existing BEV FCV competitive from 200 km Fast refueling Less maintenance than diesel Clean fuel chain (electrolysis)	Short distance range Cost of storage Cost of PEMFC Storage volume Lifetime Storage issues
Opportunities	**Treats**
Fleet operations Decreasing hydrogen price Decreasing battery price Diesel price volatility LEZ (low emission zones)	Lack of regulation Lack of infrastructure

7

OTHER SECTORS

This chapter aims to cover the bus sector, the train sector and the aviation sector but with a less detailed approach than in the previous chapters. The objective is to identify the main requirements and potential obstacles to the introduction of fuel cells and hydrogen. Each section will be illustrated by some projects example but without economic calculations like in chapter 3, 5 and 6. However, like before, a SWOT matrix will summarize the respective section.

7.1 BUSES

7.1.1 CONTEXT

With 6.6% of passenger transport on land the bus sector is not the most significant GHGs emission sector but it still is a key player in terms of local pollution. The current technology relies on diesel and the combustion engine which emits substantial quantities of pollutants in its operation area. As the trend in Norway is to empower the use of public transport it is more relevant than ever to make this switch having a significant environmental impact thanks to zero emission technologies. Like in the car sector it is possible to separate this bus sector into two major segments that are the long distance operation (rural) and the urban operation. Those two segments will not be treated separately in this section but some different opportunities will be outline though.

7.1.2 DESIGN AND SAFETY

It is possible to use the fuel cells technology in buses as the main powertrain but the hybrid configuration (minor fuel cells and priority battery) is also possible. A triple hybrid combination also exists (see projects). Buses require typically 250 kW of power under high demanding, intermittent conditions, with frequent starts and stops. Depending of their operation the driving range is between 200km and 500km and they have the advantage to come back at least once a day to the depot. According to this information and to the existing projects illustrated below, the average hydrogen storage is about 40kg in several compressed tanks. It is important to mention that Fuel cell buses (FCBs) use regenerative braking during their operation. Given that the duty cycle of a city bus is made of frequent starts and stops, a lot of energy is harvested at the stop and it improves significantly the global efficiency of the bus. For safety reasons and to make the design easier, most of the components (H2 tanks, battery, FC, cooling system) are located on the roof of the bus as illustrated below. This configuration allows a significant hydrogen storage without impacting the performance of the bus. The safety reasons are related to the easy evacuation of hydrogen in case of hydrogen leak during operation or during/after an accident.

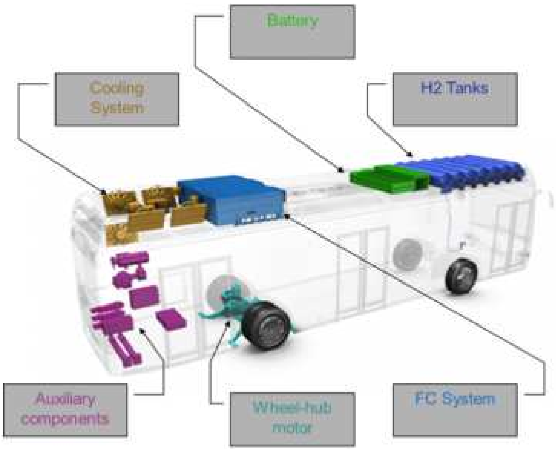


FIGURE 7-1 - FC BUS DESIGN ILLUSTRATION

Source : **[79]**

7.1.3 PROJECTS

It is first important to mention the CHIC (Clean Hydrogen in European Cities) as a major European project deploying a fleet of fuel cells electric buses and associated hydrogen refueling stations. CHIC project aims to further enhance fuel cells urban bus technology and offers a functional solution for European cities to decarbonise their fleets. This project covers a lot "smaller" project which includes the bus fleet in Oslo. The table below details several bus fleets representing the different applications of fuel cells buses. [72], [73], [74], [75]

TABLE 7-1 - NON EXHAUSTIVE LIST OF FC BUS PROJECTS

Project name	**London buses**	**Triple hybrid**	**ACT ZEBA**	**BCT AT**	**Oslo buses**
CustomerManuf.	Mayor of London Daimler Chrysler		AC Transit (US) ClearEdge Power	BC Transit/Ballard	Ruter Van hool
Type of bus	Fuel cells Electric Bus (FCEB)	Triple hybrid (Batteries, ultracap, PEMFC)	FCEB	Hybrid, fuel cells dominant	FCEB
Numb. of buses	3	1	12	20	5
Weight (tons)	14.2 30 seated 21 standees	18			17 74 seats
Motor power (kW)	190	120	120	150	150
H2 capacity (kg), 35 MPa	40 (9 Cylinders)	20	40 (8 cylinders)	56 (8 cylinders)	35 (7 cylinders)
FC (kW)	2 * 125	50	120	150	150
Battery (kWh)			17.4	47	17.4
Range (km)	192	250	352	480	

7.1.4 ECONOMY

When we look at the economical side of the FCB it is relevant to compare the TCO (Total cost of ownership) for the powertrain. This TCO includes the different expends related to the purchase and operation of the power train. A very interesting study has been published on the topic by the FCH JU (Fuel cells and Hydrogen Joint Undertaking, EU, [80]). Even though the input data are not the same for Norway (especially diesel price and taxation) the results of this study give us a good overview. The diagram below compares the different TCOs for each powertrain technology. This part of the study assumes a 12m bus which is the most common size in urban operations.

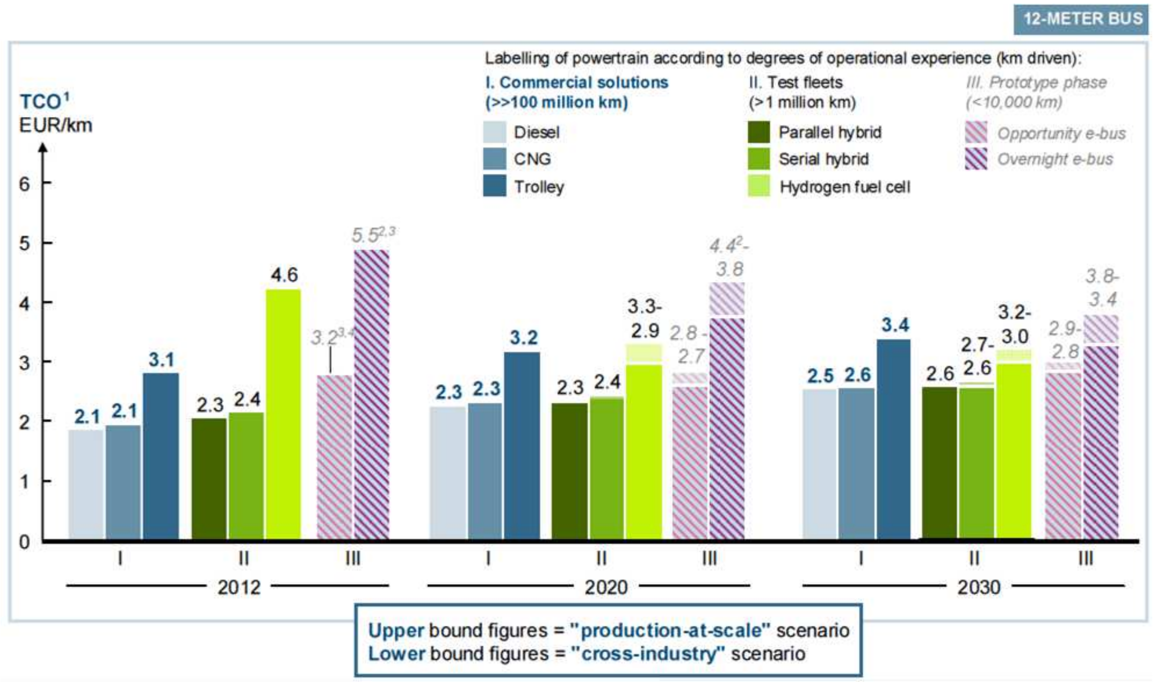


FIGURE 7-2 - CURRENT AND EXPECTED TCO FOR DIFFERENT BUS POWERTRAINS

[80]

Comments

The "Opportunity e-bus" is a bus with a small range (small battery) that recharge itself at each bus stop while the "Overnight e-bus" is a medium range bus that recharge itself at the depot overnight. Parallel hybrid and serial hybrid both include a diesel motor.

7.1.5 DISCUSSION

The results of the researches show that the FCB combines several operational advantages like a fast refueling, a high range, a high energy efficiency and of course no local emissions. It is interesting to compare those performances to a battery bus which is also a potential option for urban operation. The main argument that can be made against battery technology is the long recharging time but the "Opportunity e-bus" operation seems to partly solve this issue. However, if we enlarge the application field to rural buses with long distance operation (like BCT AT) the FCB becomes a reliable alternative solution and will be preferred to battery bus. The urban bus being a fleet vehicle by definition, it also gives a strong advantage to alternative technologies like FCBs or battery buses. Indeed, the need to invest in new infrastructure is limited to the depot location and the relatively low range requirement diminishes the need to invest in large onboard energy storage.

The economic analysis also gives us interesting results in term of technology cost comparison. Even though if the study's inputs for fuel cells cost, hydrogen and diesel prices seem to give a higher TCO for FCB than other technologies, it is very likely that with Norwegian fuels costs the result would be more advantageous for FCB. Of course time is also an important factor to consider as the study's diagram shows. Indeed, as oil derivate fuel prices are meant to increase while fuel cells components and hydrogen production costs are meant to decrease, the more time that passes the thinner the economic gap will become. We can also mention the results of Chapter 5 where we have determined that the combination of fuel cells and batteries is more interesting than a fuel cell all alone for vehicles with important energy consumption. However, this configuration has not been covered for buses in the study under scope even though we can see this design in several existing projects.

7.1.6 BUS SECTOR SWOT MATRIX

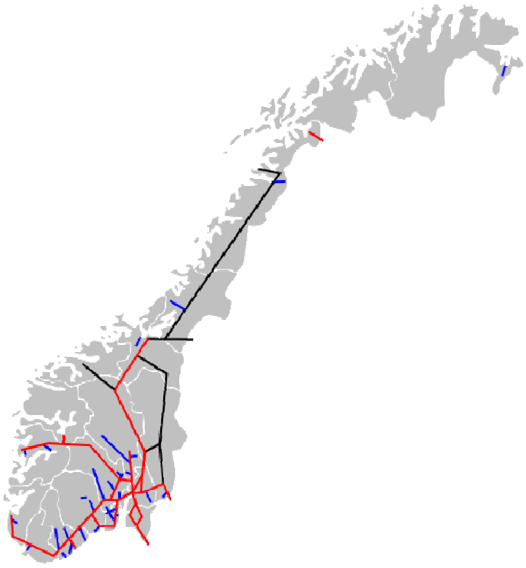
TABLE 7-2 - BUS SECTOR SWOT MATRIX

Strength	**Weakness**
Silent Storage possible on the roof Zero direct emission FC-REV interesting for long range FCV competitive in few years Adaptability as APU Fast refueling Clean fuel chain (electrolysis) Regenerative braking	Cost of storage Cost of PEMFC Lifetime
Opportunities	**Treats**
Fleet operation Decreasing hydrogen price Decreasing battery price Diesel price volatility LEZ (low emission zones)	Lack of regulation Lack of infrastructure

7.2 TRAINS

7.2.1 CONTEXT

In order to reduce GHGs emissions from road traffic due to freight transport Norway, has the policy to increase the share of cargo transport by train. In 2012 and 2013 this share increased from 9 million tonnes to 10 million tonnes carried by rail. The passenger transport has also known some improvement with almost 67.5 million passengers in 2013 which is an increase of 10 million passengers from 2012. This evolution in both sectors is meant to continue and the railway system (powertrain, technology, infrastructure) has to adapt. Currently most of the rail lines are electrified but an important share still runs with diesel locomotive. As one can see on the map below, the diesel lines are not close from the dense population areas therefore the impact in term of local pollution (particulate matter and nitrogen oxide) is not very important. Furthermore, given the small proportion of non-electrified lines the global GHGs emission is very low on the national scale (less than 1%).



— electrified lines — non-electrified lines — disused or heritage lines

FIGURE 7-3 - MAP OF THE RAILWAY LINES IN NORWAY

Source: [81]

7.2.2 TECHNICAL AND OPERATIONAL ASPECTS

[78]

Given the nature of railway (motion of heavy vehicle on preinstalled track with medium to higher speed) this sector has some specific technical and operational requirements. First of all a minimum weight is required to maintain the locomotive wheel adhesion to the track. Compared to a diesel engine alternator and its tank the combined weights of fuel cells and carbon-fiber hydrogen storage system are relatively lighter, therefore some additional weight can be installed to maintain the minimum load (steel-plate ballast for example).

The second important requirement comes from the fact that the locomotive is subject to vibrations and in some case to larger shocks. Therefore the power system has to be tested to verify its reliability under those conditions. The most important is to avoid a potential resonance with on-board equipment and track input frequencies. It is then advised to design the power system for low frequencies (3-7 Hz). It is also possible to dissipate vibration and shock energy thanks to some special primary and secondary suspension for the axles and bogies, respectively [96].

The third requirement is related to accelerations, especially longitudinal (braking, gain of speed). In the hybrid locomotive presented below the fuel cells equipment is resistant to 2.5 G.

Concerning the design it is possible to install the hydrogen modules either under the chassis or above the traction battery (roof). Two factors give advantage to the roof as preferred location: First the storage of hydrogen below void volumes in the locomotive platform, battery rack, and rear hood could lead to confinement of leaked hydrogen and increase the possibility of detonation. In contrast, roof-line storage allows for harmless upward dissipation of hydrogen in the event of a leak. Second, locating the hydrogen tanks at the roofline minimizes the likelihood of damage from common events such as derailment, track debris, and impact from yard traffic such as fueling trucks. Thanks to the relatively light weight of the hydrogen storage tanks (empty, 95 kg each), the roof location has minimal effect on vehicle center of gravity.

Regarding refueling the operating time of the fuel cells-hybrid between fueling operations depends on the duty cycle. Under the most demanding duty cycles, one could expect an operating interval as short as one day to 3-5 days for the least demanding. A major factor in the operating interval is the amount of idle time in the duty cycle. Refueling time should not exceed 1 hour.

For the purpose of commercialization, an advantage of the railway application is that the potential location for the refueling stations is limited by the number of train stations. This aspect simplifies the selection of a location unlike road applications where there are much more possibilities.

According to Jernbaneverket there are no regulations or standards at the moment for hydrogen or natural gas as a fuel in the railway sector.

7.2.3 POTENTIAL USES

7.2.3.1 Hybrid locomotive (Dominant fuel cells and minor Battery)

[78]

The prime mover, a hydrogen PEM fuel cells in this case, provides continuously at least the mean power of the duty cycle while the auxiliary energy storage device, batteries, stores sufficient energy to provide excess power use.

The following demonstration project aims to demonstrate the feasibility of a hybrid locomotive to reduce air and noise pollution in urban rail yards, increase energy security of the rail transport system by using a fuel independent of imported oil, serve as a mobile backup power source (“vehicle-to-grid” or “power-to-grid”). This demonstration occurs at the BNSF Commerce and Hobart yards in the Los Angeles, California, metro area.

TABLE 7-3 - FUEL CELLS LOCOMOTIVE MAIN CHARACTERISTICS

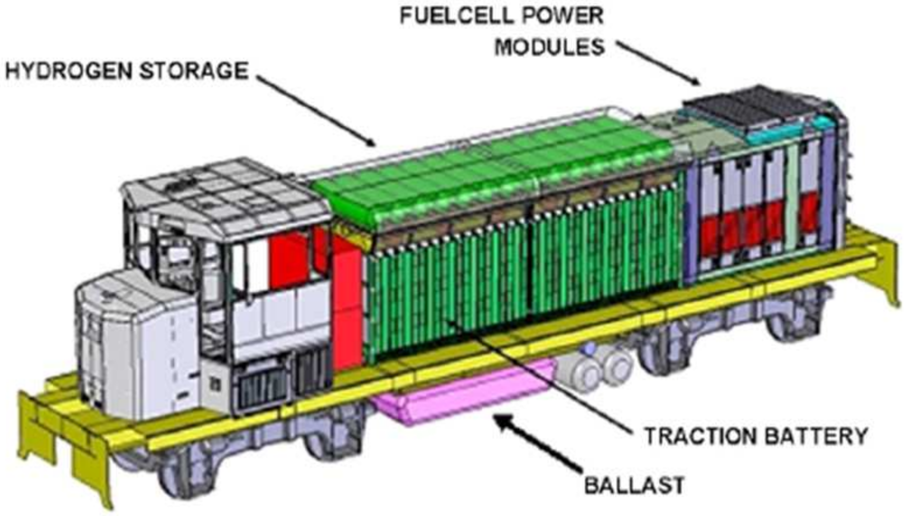
Weight	130 tons
FC Power	2 x 150 kW
*Transient power**	1MW
Hydrogen storage pressure	35 MPa
Hydrogen storage	70 kg, 2 modules of 7 tanks equivalent to 35 kgH2

*Transient power: Important amount of power required by the locomotive for a short period of time (several minutes). It is needed for the start of the locomotive or in some uphill parts.

We can note that this locomotive is not a very strong one compare to Norwegian one which has around 3-6 MW of power (transient power 10-20 % more) [96].

FIGURE 7-4 - RIGHT-REAR VIEW OF THE HYBRID LOCOMOTIVE

Source : [78]



SOURCE : [78]

FIGURE 7-5 - DESIGN ILLUSTRATION OF THE HYBRID LOCOMOTIVE

7.2.3.2 Mines and tunnels

Currently in mining and tunnel operations the powertrain of the locomotive relies on the combustion engine and this technology releases gases that need to be evacuated from the mining site. To cope with this issue, important amounts of money are spent into ventilation systems to remove the exhausted gases from the mine/tunnel to the outside. In order to avoid those expenses one interesting option is the use of electric locomotive powered by batteries or fuel cells. The battery option involve more weight than the fuel cells option depending of the load during the duty cycle. [78]

FIGURE 7-6 - FIRST FUEL CELLS LOCOMOTIVE USED FOR MINING

7.2.3.3 Unelectrified lines

The catenary-electric infrastructure required for the operation of a conventional electric train costs around 3.5 to 4.6 million Euros per km [78] and this important amount of money makes any other alternative energy option potentially interesting economically speaking. That is why lines with low traffic volumes are not economically relevant to invest in electrification but rather in diesel electric power trains. With the performance improvement of the PEMFC (price and lifetime) some train manufacturers have participated to some fuel cells train projects to demonstrate the feasibility of the technology from both operational and economical points of view.

The most recent example is the trains of Hermann-Hesse railway line (Germany, Black forest area) manufactured by Alstom.

7.2.3.4 Back-up power source for electrified lines

The electrified lines are directly related to the main grid but due to several reasons like weak grid, high loads in the rest of the grid or simple failure the power required by the train might not be achieved from time to time. That is why fuel cells are also considered to operate as stationary power systems in order to act as back-up power source and support any grid failure to maintain the correct train operation. Axane (Air liquide group) is testing back-up power generation on several sections of the electrified railway network in France.

7.2.4 DISCUSSION

As expected hydrogen and fuel cells powertrain appears to be technologically reliable despite the specific requirements of the railway sector. However due to the important load and power peaks a large battery seems to be required in order to provide the power needed. This combination shows again that the optimum configuration lies in the mix of different technologies. Contrarily to a road network the rail network makes the location of a refueling station easier, and it can be centralized and used more efficiently. Furthermore it appears that hydrogen can be used as a propulsion fuel but also as a back-up energy source which makes it even more interesting to install of electrolysers and fuel cells close to node points in the rail network.

Of course the railway industry has a long term planning with important investment policy so that is why the introduction of a new technology may take time but some demonstration projects already exist and the adoption of fuel cells seems to be a matter of time rather than a technologic and operational issue. The niche applications as mining locomotives or switcher/shunting locomotives are also worth considering given that they can give an important feedback for this decision industry with long investment horizons.

In Norway the environmental impact seems to be limited given the proportion of electrified lines but the economical aspect can be a real argument to consider this technology. Furthermore, even if not mentioned above, the new train technologies have to be considered. Indeed the increasing speed and the possibility to have easily separated autonomous wagon empower the adoption of onboard propulsion technologies like battery or fuel cells.

TABLE 7-4 - TRAIN SECTOR SWOT MATRIX

Strength	**Weakness**
More silent than conventional trains Enough storage space on roof Zero direct emission Fast refueling Less maintenance than diesel Clean fuel chain (electrolysis) Cheaper than electrified lines Autonomous traction locomotives	Cost of storage Cost of PEMFC Lifetime System too light - but can easily be ballasted
Opportunities	**Treats**
City operations (cargo transit) Mines and tunnels operation Unelectrified lines Back-up power source Decreasing hydrogen price Decreasing battery price Diesel price volatility Stricter air quality regulations	Sector with a long time of decision Lack of regulation Lack of infrastructure

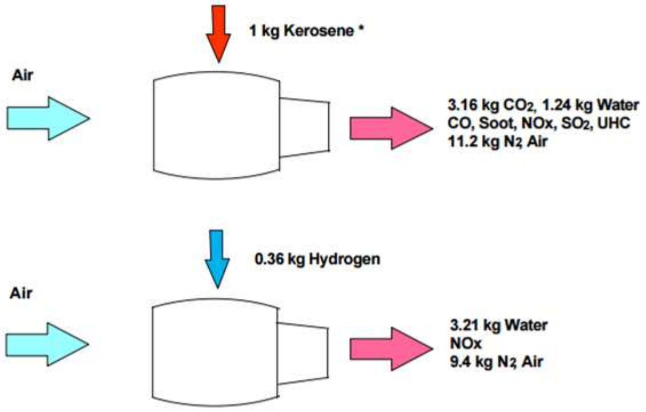
7.3 PLANES

7.3.1 INTRODUCTION

The air transportation is the mode that has known, with private car, the biggest growth in the transport sector the last decades. The number of passengers for domestic and international flight has increased by 20% between 2010 and 2014 and the growth curve has only begun to flatten. This mode of transport requires a lot of energy, especially during the take off which represents up to 25% of the energy consumption for short distance trips. Due to this large amount of energy necessary onboard, the only fuel used in aviation is kerosene. It is the most refined fuel derivated from oil, which means it has the highest energy content, and therefore is also the most expensive. That is why jet fuel is the second largest expense to airlines companies as it can require 20% of their operating expenses. If we consider energy technology, the aircraft industry is one of the industries with the most important inertia. This is due to safety and economic reasons and this industry cannot largely adopt any new technology until this new option has been approved by another sector with a significant feedback. However the aims of this section are to determine through a literature review if hydrogen and fuel cells technology has an opportunity in this specific sector. [84] After this brief introduction the environmental aspect of the topic will be treated, followed by a technical approach. With the illustration of some existing projects we will then discuss the feasibility of hydrogen in this sector.

7.3.2 ENVIRONMENT

Aviation is often pointed at as a very polluting sector but the national statistics show that only 1.7% (940,000 tones of CO_2) of the national GHGs emissions come from the airplanes' tailpipes. It is relevant to note that a large difference exists for this number as it depends if the international flights are included or not. We obtain an 8% contribution if both domestic and international flights are included while the emission represents only 1.7% for domestic flights. But the environmental issue goes actually a little further than this. Indeed, some studies [83] underline that the cruise altitude impact the greenhouse gas potential of CO_2 and NOx (the higher the more impacts). Therefore the quantity of CO_2 released might not be the only indicator. In terms of emissions if the hydrogen quantity equivalent to 1 kg of kerosene is burnt through a turbine we obtain the results displayed below.



Source : [85]

FIGURE 7-7 - EMISSIONS COMPARISON FOR KEROSENE AND HYDROGEN

The amount of CO_2 and NOx decreases significantly but the amount of water increases and the same studies mentioned above state that water might have some effects we do not understand yet at those altitudes.

7.3.3 TECHNICAL ASPECTS

The aircraft industry has some very strict requirements as any failure from the propulsion system can cause the crash of the plane. Therefore hydrogen and fuel cells have to comply with several criteria concerning safety and performance. First of all the system has to be light and the fuel must have a high energy density. In average a passenger plane carry 172 000 liters of kerosene which correspond awfully to 50 tonnes of hydrogen. For such quantities the only storage option is liquid hydrogen which has the advantage of being lighter and therefore to reduce the weight of the plane. However to store the same amount of energy, liquid hydrogen needs a volume 4 times bigger than kerosene and due to mechanical issues the tanks must have a spherical or cylindrical shape. This requirement results in a different plane configuration as we can see on the image below. According to the European Commission's report CRYOPLANE [85] large external tanks under the wing appear feasible for small aircraft with stiff wings and short design ranges.

FIGURE 7-8 - ILLUSTRATION OF HYDROGEN PLANE DESIGNS

Source : [85]

As no industry sector has provided a significant feedback about fuel cells technology so far the propulsion motor is very likely to remain the turbine. However, as the amount of energy required for auxiliaries is increasing it is possible to use a PEMFC to supply the electricity needed or even for ground operation and in case of failure the turbine can provide a security electricity supply. Here a fuel cells APU may offer better efficiency than turbine power units used today in spite of the necessary kerosene reformer. Furthermore, in-flight production of water is under investigation by several aircraft companies, e.g. Airbus.

Concerning the safety, hydrogen when spilled and ignited will not form a fire carpet as kerosene does. It burns very fast, but with very low heat radiation. According to the CRYOPLANE report it is expected that passengers can survive a post-crash fire by staying in the cabin. Given the low probability of having hydrogen onboard soon, no regulation exists so far.

7.3.4 PROJECTS

- The CRYOPLANE project is a European project that aims to determine the feasibility, opportunities and actions to undertake for the introduction of hydrogen as a fuel in the aircraft sector.
- A 90-kilowatt hydrogen fuel cells will be installed into an A320 owned by the German Aerospace Center with the aim of commencing test flights by 2015.
- In 2013, Boeing’s liquid hydrogen-powered Phantom Eye demonstrator successfully completed its second flight. This unmanned autonomous aircraft climb to an altitude of over 8,000 feet and remain in the air for 66 minutes traveling at a cruising speed of 62 knots. This improved upon the first flight, on which the aircraft stayed aloft for 28 minutes and reached an altitude of 4,080 feet.

FIGURE 7-9 - PHOTO OF THE BOEING'S HYDROGEN POWERED PLANE

Source: Boeing’s hydrogen-powered Phantom Eye goes higher for longer on second flight, Darren Quick, February 26, 2013

7.3.5 DISCUSSION

After this brief overview of the sector we can say the challenges are real for the aircraft industry. We have seen that hydrogen has several relevant advantages due to its light weight, its important energy density and its low environmental impact. The air transport market being very sensitive to safety issues, seems only be a follower in terms of technology adoption. However some specific applications like auxiliary power supply can be a first step toward the integration of fuel cells. For this conclusion we can quote one passage of the summary from the CRYOPLANE report:

"The CRYOPLANE analysis concludes that hydrogen could be a suitable alternative fuel for future aviation. Based on renewable energy sources it offers the chance to continue the long-term growth of aviation without damaging the atmosphere. Importantly no critical barriers to implementation were identified in the study. Further research is needed, but implementation could take place within 15 to 20 years"

As the PV plane Solar Impulse 2 has started its world round trip few months ago we can be optimistic for the future of aviation. Maybe we will see interesting combinations between solar planes and hydrogen back-up propulsion.

7.3.6 SWOT MATRIX

TABLE 7-5 - PLANE SECTOR, SWOT MATRIX

Strength	**Weakness**
Low direct emission Fast refueling Lighter fuel than kerosene Clean fuel chain (electrolysis)	Cost of storage Cost of PEMFC Lifetime Larger volume storage
Opportunities	**Treats**
APU (PEMFC) Propulsion fuel with turbine Decreasing hydrogen price Kerosene price volatility	Sector with a long time of decision Only technology with significant feedback are adopted Lack of regulation Lack of infrastructure

8

LIFE CYCLE ASSESSMENT POSTEN STUDY CASE

8.1 INTRODUCTION

8.1.1 CONTEXT

This chapter is articulated around the project led by Posten and Sintef to implement a fleet of fuel cells vehicles in the Trondheim Post service. The seed of the project is to replace the diesel forklift fleet by an entire fuel cells fleet. In order to amortize the investment cost of the refueling station it is being evaluated to extend this project to the road vehicles as well. The final objective of this project is to reduce as much as possible the GHGs emissions as well as improving the global energy efficiency of the fleet and retail house. The case of Trondheim's Post office is particularly interesting given that this project is considered as a demonstration for a potential application at the national scale. Therefore its outcome can potentially lead to the deployment of several fuel cells vehicle fleets for other Posten sites in Norway. This implementation of fuel cells vehicles in captive fleet is already undergoing for the French Post company and the feedback from this first experiment will be highly relevant for the Norwegian projects. The construction of this new infrastructure in Trondheim retail center should start as soon as June 2016.

8.1.2 FLEET DESCRIPTION

In order to introduce the support of the study we will start by a brief fleet description. More details will be provided later in this chapter.

The Posten fleet in Trondheim is composed of 16 trucks (medium and heavy duty), 35 vans (light duty) and 25 small vans for a total of 76 vehicles. Those vehicles operate in average 6 days a week, 302 days a year and they are all powered by diesel thanks to an internal combustion engine. The entire fleet consumes 6825 MWh of diesel each year and most of it is related to trucks operation as shown in the diagram below.

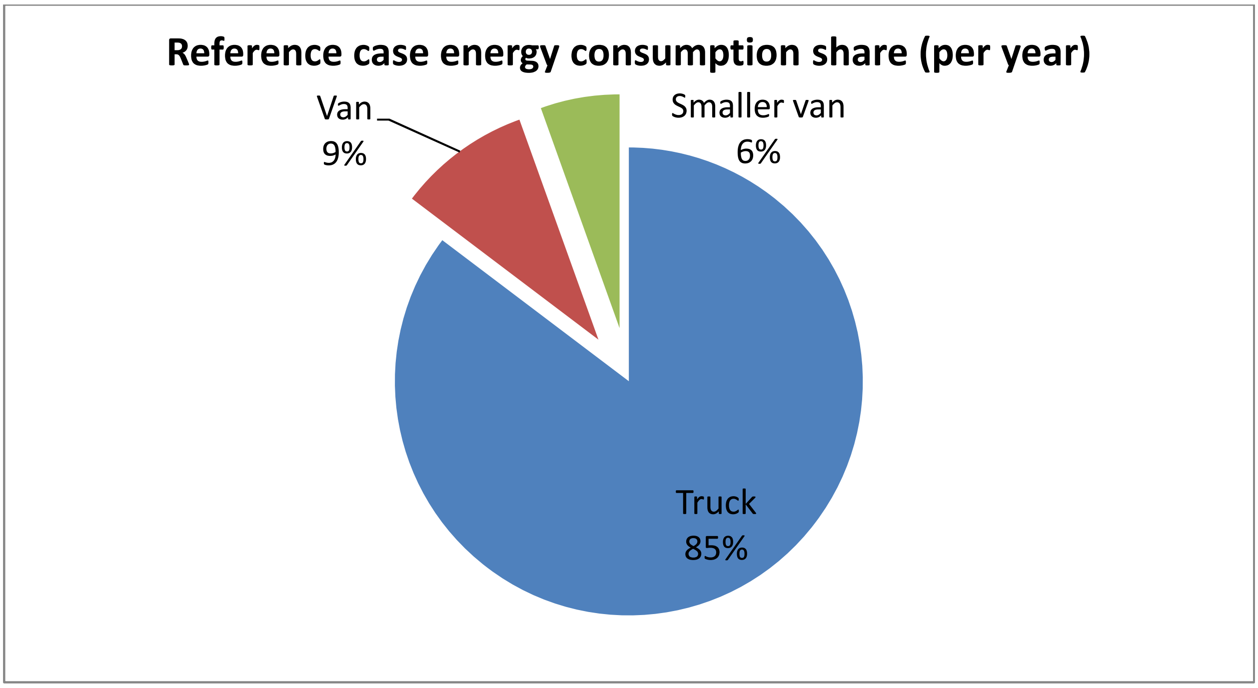


FIGURE 8-1 - FLEET ENERGY CONSUMPTION SHARE PER VEHICLE TYPE

In this study those three categories are replaced by their FC-REV equivalent (Renault Kangoo for small vans, Renault Maxity for vans and Renault Premium for trucks).

8.1.3 LCA STUDY PRESENTATION

The aim of the study is to provide a quantitative assessment of the potential CO_2 emissions reduction and energy saving for this project. These reductions and savings will be compared to a reference case which represents the current situation where the fleet is based on ICE and diesel. As this project is a real life project and therefore might be limited in its application, three different scenarios have been established corresponding to a gradual replacement of the fleet:

- The first case corresponds to a demonstration scale where only two vans and two small vans are replaced. It translates the first step toward the full implementation where the vehicles have to be tested and approved by the final user.
- The second case corresponds to a larger fleet penetration where all the vans and all the small vans are replaced. This configuration can occur in the case where Posten is ready to replace all the fleet but where the fuel cells trucks are not commercially available yet.
- The third case is the ideal one where the whole fleet is replaced.

To achieve this study we will use a Life Cycle Assessment (LCA) method explained in the next section. However, for a matter of resources and time, this study will be only focus on the fuel value chain and therefore cannot pretend to be a complete LCA as it does not cover the entire system. Furthermore the only indicators (also called stressors) under scope will be the primary energy consumption (kWhPE) and the CO_2 emissions ($kgCO_2$). In each LCA the set of the boundaries is very important as it impact the final result. Here we have decided to determine the impacts for three different boundaries configurations (see fig.7-2 for illustration):

- Tank-To-Wheel boundaries (TTW): The study is limited to the direct energy consumption of the vehicle and the direct CO_2 emission during the operation phase. It only considers the fuel from the moment it enters into the fuel tank.

- Well-To-Wheel boundaries with hydrogen based on water electrolysis (WTW, El): The study looks at the entire value chain of the fuel from its production to its final use. In this case we assume that hydrogen is produced thanks to the water electrolysis process (see Chapter 2).

- WTW boundaries with hydrogen based on natural gas reforming (WTW, NG): Same as before but this time hydrogen is produced by means of natural gas reforming.

After this introduction to the study we will present the input data as well as the LCA method through a calculation example. Then we will present the results and interpret them in the next section to finally conclude about the impact of this project.

8.2 METHOD AND MATERIALS

1.1.1 Vehicles and fleet characteristics

8.2.1.1 Vehicles characteristics

In this study we will compare different types of vehicle technology. Therefore it is relevant to first give the characteristics of each vehicle type and the properties of its corresponding replacement vehicle.

A letter is attribute to each vehicle type (A = Truck ; B = Vans ; C = Small vans)

TABLE 8-1 - ORIGINAL AND REPLACEMENT VEHICLES CHARACTERISTICS (C)

	Original vehicle (Diesel)	**Replacement vehicle (FC-REV)**
Name	Peugeot Partner	Renault HyKangoo
Diesel consumption	0.11 liter/km	-
Hydrogen storage	-	1.7 kgH2 (35MPa)
Hydrogen consumption	-	5.4 gH2/km
Battery storage	-	22 kWh
Electricity consumption	-	0.07 kWh/km
Range	-	320 km

TABLE 8-2 - ORIGNIAL AND REPLACEMENT VEHICLES CHARACTERISTICS (B)

	Original vehicle (Diesel)	**Replacement vehicle (FC-REV)**
Name	Mercedez Sprinter	Renault Maxity
Diesel consumption	0.13 liter/km	-
Hydrogen storage	-	4 kgH2 (35MPa)
Hydrogen consumption	-	13 gH2/km
Battery storage	-	22 kWh
Electricity consumption	-	0.14 kWh/km
Range	-	200 km

TABLE 8-3 - ORIGINAL AND REPLACEMENT VEHICLES CHARACTERISTICS (A)

	Original vehicle (Diesel)	**Replacement vehicle (FC-REV)**
Name	Scania Truck (from 15 to 51 pallets capacity)	Renault Premium
Diesel consumption	0.13 liter/km	-
Hydrogen storage	-	25 kgH2 (35MPa)
Hydrogen consumption	-	50 gH2/km
Battery storage	-	80 kWh
Electricity consumption	-	0.16 kWh/km
Range	-	500 km

Important:
The important assumption is made that each FC-REV fulfills the same operational requirement as the diesel vehicle. Therefore the number of vehicles in the fleet is still the same as well as the distance for each trip.

8.2.1.2 Fleet characteristics

After the vehicles technical characteristic this section aims to provide the distance and trip frequency used in this LCA study.

TABLE 8-4 - FLEET OPERATION TABLE

Vehicle Type	*Size*	*Route*	*Km/trip*	*Trips/week*	*Trips/year*	*Km/year*
Truck (A)	21 pallets	Røros	340	6	302	102 680
	23 pl	Åfjord	260	6	302	78 520
	21 pl	Hitra/Frøya	400	6	302	120 800
	18 pl	Oppdal	240	6	302	72 480
	21 pl	Oppdal	240	6	302	72 480
	18 pl	Brekstad	320	6	302	96 640
	33 pl	Verdal	400	6	302	120 800
	18 pl	Selbu	280	6	302	84 560
	18 pl	Meråker	175	6	302	52 850
	15 pl	Trondheim sentrum	50	5	255	12 750
	36 pl	Hanestad	525	5	255	133 875
	18 pl	Kyrksæterøra	340	6	302	102 680
	33 pl	Trondheim-Steinkjer	750	5.5	270	202 500
	51 pl	Trondheim-Steinkjer	275	5	255	70 125
	38 pl	Steinkjer-Trondheim-Namsos-Steinkjer	400	6	302	120 800
	33 pl	Steinkjer-Trondheim-Rørvik-Steinkjer	650	6	302	196 300
35 * Vans (B)	Parcel distribution	Trondheim	-	-	-	535 000
25 * Small vans (C)	Letter mail distribution	Trondheim	-	-	-	376 000

1.1.2 Fuels data

In order to perform the LCA we also need to provide the upstream values corresponding to three fuels under scope (Hydrogen, Electricity, Diesel). Given the hydrogen can be produced either with natural gas or electricity the upstream values cover the primary energy consumption and the CO_2 emissions of natural gas, electricity and diesel. The values presented in this example come from the European commission hydrogen WTW analysis (CONCAWE) and the Norway energy efficiency report from ABB [86], [88].

TABLE 8-5 - WELL TO WHEEL ELECTRICITY FACTORS

Electricity and electrolysis	
Electrolyser efficiency (El+comp) (kWhe/kWhH2)	1.53
Grid efficiency (kWhPE/kWhe$_{downstream}$)	1.24
Overall efficiency (kWhEP/kWhH2)	1.90
CO_2 emissions ($kgCO_2$/kWhe$_{downstream}$)	0.016
CO_2 emissions ($kgCO_2$/kWhH2)	0.02

TABLE 8-6 - WELL TO WHEEL NATURAL GAS FACTORS

Natural gas reforming	
Overall energy consumption (kWhPE/kWhH2)	1.99
Overall CO_2 emissions* ($kgCO_2$/kWhH2)	0.41

* We assume that natural gas comes from fossil resource, not biomass.

TABLE 8-7 - WELL TO WHEEL DIESEL FACTORS

Diesel	
Overall energy consumption (kWhPE/kWh diesel)	1.20
CO_2 emissions, TTW ($kgCO_2$/kWh diesel)	0.26
CO_2 emissions, WTW ($kgCO_2$/kWh diesel)	0.32

Comments

In this study, diesel is the only fuel which emits CO_2 directly at the tailpipe (TTW boundaries). Therefore we have displayed this value in the table above. The WTW value is the addition of the CO_2 emitted during the combustion and the CO_2 emitted for the production of diesel.

8.2.2 LCA METHOD

The Life cycle assessment is not a method that can be clearly explained in one section, therefore the following parts do not aim to explain the entire theory of each step. However they will provide sufficient information to understand the basics and to be able to go further with the help of the appropriate material (LCA method, Anders Hammer Strømman [87]). As our study covers three different types of vehicles we will focus only on the Truck type to explain the method but the logic is the same for the other vehicles. All the matrix calculation explained in the following sections has been performed with Matlab. Therefore the Matlab script is available in the appendix A.

8.2.2.1 Flowchart

In every LCA the first step is to represent the system interactions thanks to a flowchart. This flowchart allows us to clarify the relations between the components, the resources, the foreground (TTW) and the background (WTT). Here all the powertrains and fuels are covered given that their value chain is different.

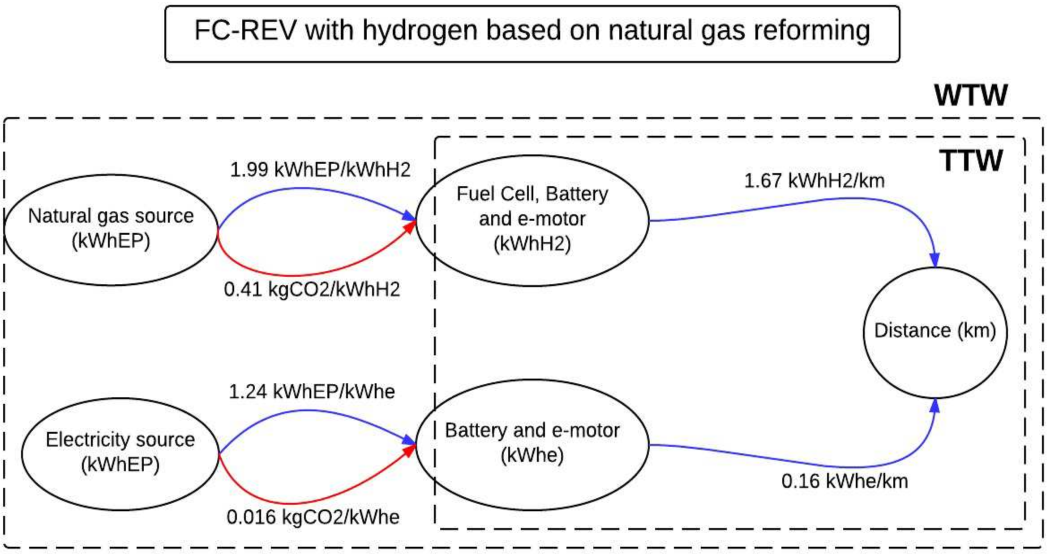


FIGURE 8-2 - LCA FLOWCHART OF FC-REV WITH HYDROGEN BASED ON NG REFORMING

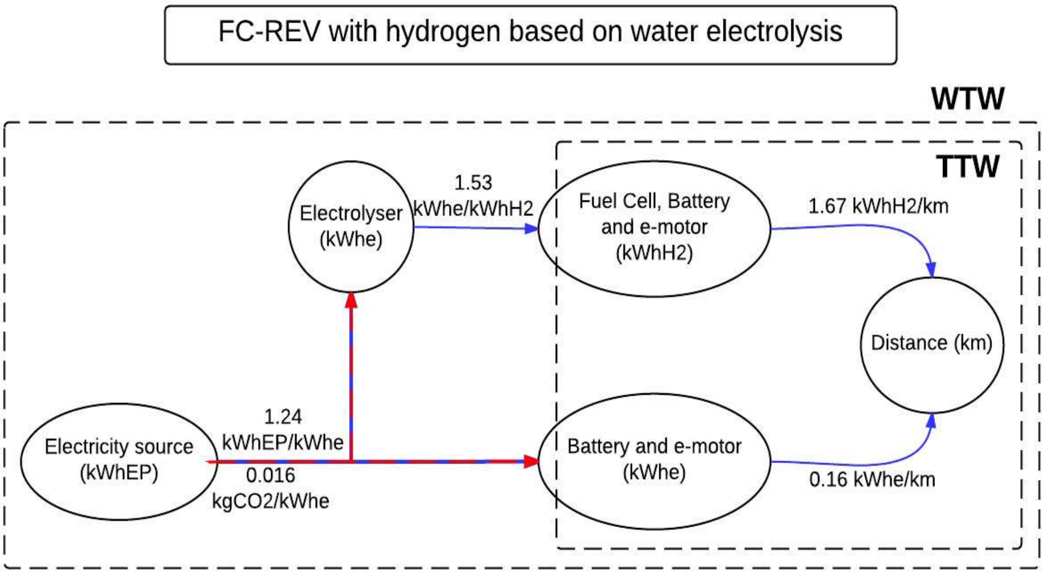


FIGURE 8-3 - LCA FLOWCHART, FC-REV, HYDROGEN BASED ON WATER ELECTROLYSIS

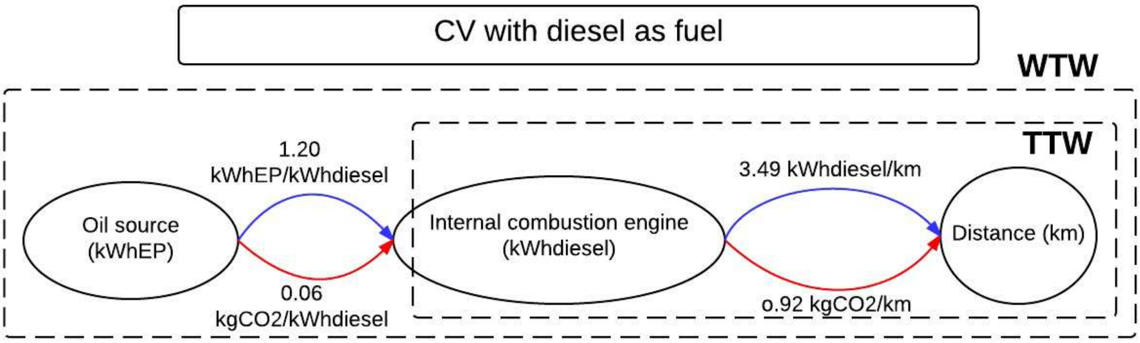


FIGURE 8-4 - LCA FLOWCHART OF CV POWERED BY DIESEL

8.2.2.2 A and S matrixes

The next step of the LCA is to translate this flowchart into two matrixes, known as “A” and “S” matrix. The A matrix is related to the interaction between the different parts of the system while the S matrix is related to the amount of stressors (here kWhEP and kgCO$_2$) released or consumed by those parts. To illustrate those matrixes we will focus on the case of the FC-REV with hydrogen based on water electrolysis, all the other configurations are available in the appendix B. Given that we wants to obtain results for both boundaries (WTW and TTW) the S matrix will have two forms as shown below:

TABLE 8-8 - A MATRIX EXAMPLE FOR TWT BOUNDARIES

A matrix	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Distance (km)	0	0	0
Fuel (kWh)	1.67	0	0
Electricity (kWh)	0.16	0	0

In this type of matrix we have to read column by column. The first column shows that to produce 1 kilometer we need 1.67 kWh of fuel (here hydrogen) and 0.16 kWh of electricity (stored in the battery). As we only look at the TTW boundary we stop the value chain here.

TABLE 8-9 - S MATRIX EXAMPLE FOR TTW BOUNDARIES

S matrix (TTW)	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Energy (kWhEP)	0	1	1
Emissions (kgCO$_2$)	0	0	0

As the TTW boundaries stop at the fuel cells and battery we consider that 1 kWh of hydrogen represent the same amount of primary energy. Same logic for the electricity in battery. None of them have direct emission given they are zero emission vehicles. In a complete LCA the S matrix considers all the stressors possible for the environment (CH4, CO$_2$, SO2, Resource depletion…) but here we focus only on the primary energy consumption and the CO$_2$ emissions.

TABLE 8-10 - A MATRIX EXAMPLE FOR WTW BOUNDARIES

A matrix	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Distance (km)	0	0	0
Fuel (kWh)	1.67	0	0
Electricity (kWh)	0.16	1.53	0

The reading is the same as the previous A matrix but this time we look further in the value chain. In order to produce 1 kWh of hydrogen we need to inject 1.53 kWh of electricity in the electrolyser and compressor (second column). To reach the final step of the value chain we have to address the S matrix.

TABLE 8-11 - S MATRIX FOR WTW BOUNDARIES

S matrix (WTW)	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Energy (kWhEP)	0	0	1.24
Emissions (kgCO_2)	0	0	0.016

Here we consider the WTW boundaries so the hydrogen does not represent primary energy anymore as the A matrix mentioned that it is produced from electricity. Therefore we can attribute to electricity its corresponding value of primary energy and CO_2 emissions.

8.2.2.3 I and L matrixes

The "I" matrix is the unity matrix and we use it with the A matrix to obtain the Leontief's inverse matrix "L" thanks to the formula given below. This L matrix will define the total amount of each input required per unit of output component. For further explanation we can refer to the LCA course content from the NTNU module [87].

In order to obtain the L matrix we use the following formula:

$$L = (I - A)^{-1}$$

TABLE 8-12 - I MATRIX EXAMPLE

I matrix	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Distance (km)	1	0	0
Fuel (kWh)	0	1	0
Electricity (kWh)	0	0	1

TABLE 8-13 - L MATRIX EXAMPLE FOR TTW BOUNDARIES

L matrix, TTW	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Distance (km)	1	0	0
Fuel (kWh)	1.67	1	0
Electricity (kWh)	0.16	0	1

TABLE 8-14 - L MATRIX EXAMPLE FOR WTW BOUNDARIES

L matrix, WTW	**Distance (km)**	**Fuel (kWh)**	**Electricity (kWh)**
Distance (km)	1	0	0
Fuel (kWh)	1.67	1	0
Electricity (kWh)	2.71	1.53	1

8.2.2.4 Y, X matrixes

The “Y” matrix is simply the matrix we can modify depending of the amount of unit output we want. In our case we will required only one kilometer because of the number of case to calculate. The variation of kilometer required will be done later thanks to the “e” matrix (see next section).

TABLE 8-15 - Y MATRIX EXAMPLE

Y matrix, TTW	**External demand**
Distance (km)	1
Fuel (kWh)	0
Electricity (kWh)	0

The “X” matrix is basically the combination of the L and Y matrix as detailed in the equation below. It give us the total amount of input we need to produce one kilometer. As we look at two different boundaries (TTW, WTW) we obtain two X matrixes:

$$X = L * Y$$

TABLE 8-16 - X MATRIX EXAMPLE, TTW BOUNDARIES

X matrix, TTW	**Total input**
Distance (km)	1.00
Fuel (kWh)	1.67
Electricity (kWh)	0.16

TABLE 8-17 - X MATRIX EXAMPLE, WTW BOUNDARIES

X matrix, WTW	**Total input**
Distance (km)	1.00
Fuel (kWh)	1.67
Electricity (kWh)	2.71

8.2.2.5 e and final matrix

The “e” matrix is the final matrix we need to do our calculation. It is the product of the X matrix and the S matrix. It gives us the quantity of kWhEP consumed and the amount of $kgCO_2$ released for one kilometer. In this example as we have two S matrixes we will also have two e matrixes. Instead we will directly display the final table use for the calculation which gather all the “e” matrix. All those “e” matrixes represent the different combination possible between FC-REV, CV ; Truck, Van, Small van and TTW boundaries or WTW boundaries (Electrolysis or Natural gas).

$$e = S * X$$

Thanks to this matrix we can establish a factor matrix which is nothing else than the respective values of the e matrix for each configuration. The final matrix is displayed below:

TABLE 8-18 - LCA POSTEN, FINAL FACTOR MATRIX FOR ALL THE CASES

Final matrix			*kWh/km*	*kg* CO_2*/km*
Truck	**FC-REV**	**TTW**	1.83	0.00
Truck	**FC-REV**	**WTW (EL)**	3.34	0.04
Truck	**FC-REV**	**WTW (NG)**	3.51	0.69
Truck	**Diesel**	**TTW**	3.49	0.92
Truck	**Diesel**	**WTW**	4.18	1.11
Van	**FC-REV**	**TTW**	0.58	0.00
Van	**FC-REV**	**WTW (EL)**	1.01	0.01
Van	**FC-REV**	**WTW (NG)**	1.06	0.19
Van	**Diesel**	**TTW**	1.29	0.34
Van	**Diesel**	**WTW**	1.55	0.41
Small van	**FC-REV**	**TTW**	0.25	0.00
Small van	**FC-REV**	**WTW (EL)**	0.42	0.01
Small van	**FC-REV**	**WTW (NG)**	0.44	0.07
Small van	**Diesel**	**TTW**	1.10	0.29
Small van	**Diesel**	**WTW**	1.31	0.35

The last step to obtain the results presented in the next section is simply to multiply the distance of each trip (see figure 7-4) by the corresponding factor of the table above.

8.3 RESULTS

This section presents the results obtained from the LCA calculation. As explained in the introduction of this chapter we look at two aspects of the fleet: The energy consumption and the CO_2 emissions. Therefore a first part displays the energy consumption results over one year for the different case scenarios and a second part provides the same for CO_2 emissions.

8.3.1 ENERGY CONSUMPTION

As the results depend of the boundaries assumption this section is divided in four parts. Each part covers one boundaries assumption and one final part summarizes the different results.

8.3.1.1 Tank-To-Wheel boundary

The following table indicates the energy consumption for the different case as well as the corresponding energy saving from the reference case.

TABLE 8-19 - ENERGY CONSUMPTION RESULTS, TTW BOUNDARY

	Replacement of	*Energy consumption (MWh/yr)*	*Energy saving (MWh/yr)*	*% reduction*
Case ref	No replacement	6 825	-	-
Case 1	2 vans + 2 small vans	6 778	47	1
Case 2	All the vans and small vans	6 125	700	10
Case 3	All the vehicles	3 399	3 426	50

8.3.1.2 WTW boundary, Hydrogen from water electrolysis

Here we have considered the entire value chain of the fuels. Concerning hydrogen we have assumed it was produced by water electrolysis.

TABLE 8-20 - ENERGY CONSUMPTION RESULTS, WTW (EL) BOUNDARY

	Replacement of	*Energy consumption (MWh/yr)*	*Energy saving (MWh/yr)*	*% reduction*
Case ref	No replacement	8 190	-	-
Case 1	2 vans + 2 small vans	8 147	44	1
Case 2	All the vans and small vans	7 563	627	8
Case 3	All the vehicles	6 187	2 004	24

8.3.1.3 WTW boundary, Hydrogen from natural gas reforming

Here we have considered the entire value chain of the fuels. Concerning hydrogen we have assumed it was produced by natural reforming. As mentioned in 7.2.2 the natural gas is considered as coming from fossil resource not from biomass.

TABLE 8-21 - ENERGY CONSUMPTION RESULTS, WTW (NG) BOUNDARY

	Replacement of	*Energy consumption (MWh/yr)*	*Energy saving (MWh/yr)*	*% reduction*
Case ref	No replacement	8 190	-	-
Case 1	2 vans + 2 smaller vans	8 149	42	1
Case 2	All the vans and smaller vans	7 594	596	7
Case 3	All the vehicles	6 491	1 700	21

8.3.1.4 Results summary

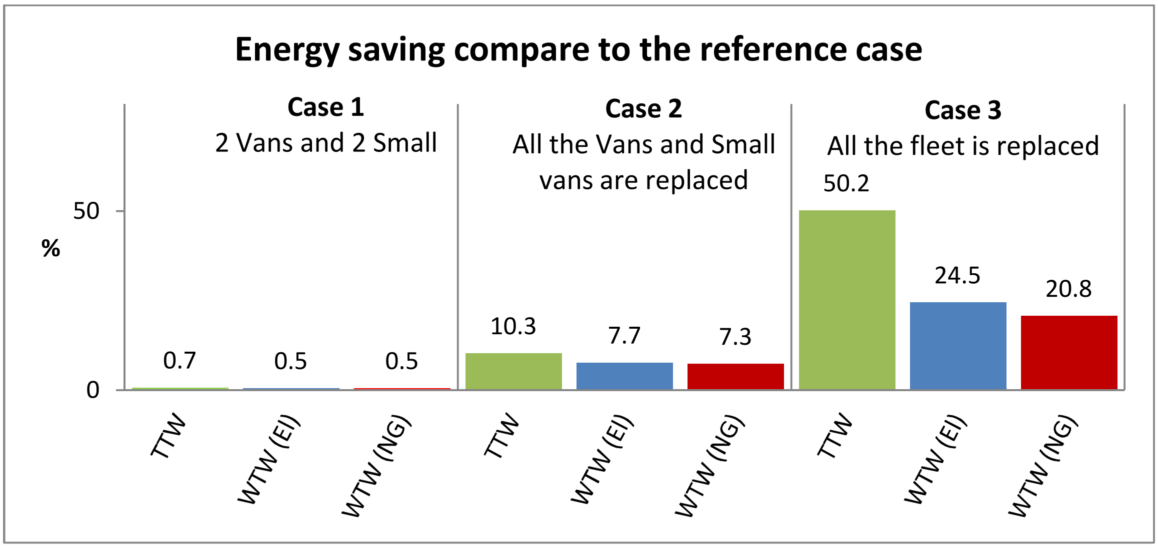


FIGURE 8-5 - LCA POSTEN CASE, RESULTS SUMMARY, ENERGY SAVING

8.3.2 CO_2 EMISSIONS

As the results depend of the boundaries assumption this section is divided in four parts. Each part covers one boundaries assumption and one final part summarizes the different results in one graph.

8.3.2.1 Tank-To-Wheel boundary

The following table indicates the CO_2 emissions for the different case as well as the corresponding reduction from the reference case.

TABLE 8-22 - CO_2 EMISSIONS RESULTS, TTW BOUNDARY

	Replacement of	*CO_2 emissions (tons/yr)*	*Emission reduction (Tons/yr)*	*% reduction*
Case ref	No replacement	1 801	-	-
Case 1	2 vans + 2 smaller vans	1 782	19	1
Case 2	All the vans and smaller vans	1 510	292	16
Case 3	All the vehicles	0	1 801	100

8.3.2.2 WTW boundary, Hydrogen from water electrolysis

Here we have considered the entire value chain of the fuels. Concerning hydrogen we have assumed it was produced by water electrolysis.

TABLE 8-23 - CO_2 EMISSIONS RESULTS, WTW (EL) BOUNDARY

	Replacement of	*CO_2 emissions (tons/yr)*	*Emission reduction (Tons/yr)*	*% reduction*
Case ref	No replacement	2 180	-	-
Case 1	2 vans + 2 smaller vans	2 157	23	1
Case 2	All the vans and smaller vans	1 836	344	16
Case 3	All the vehicles	80	2 100	96

8.3.2.3 WTW boundary, Hydrogen from natural gas reforming

Here we have considered the entire value chain of the fuels. Concerning hydrogen we have assumed it was produced by natural reforming. As mentioned in 7.2.2 the natural gas is considered as coming from fossil resource not from biomass.

TABLE 8-24 - CO_2 **EMISSIONS RESULTS, WTW (NG) BOUNDARY**

	Replacement of	CO_2 *emissions (tons/yr)*	*Emission reduction (Tons/yr)*	*% reduction*
Case ref	No replacement	2 180	-	-
Case 1	2 vans + 2 smaller vans	2 165	15	1
Case 2	All the vans and smaller vans	1 955	225	10
Case 3	All the vehicles	1 263	917	42

8.3.2.4 Results summary

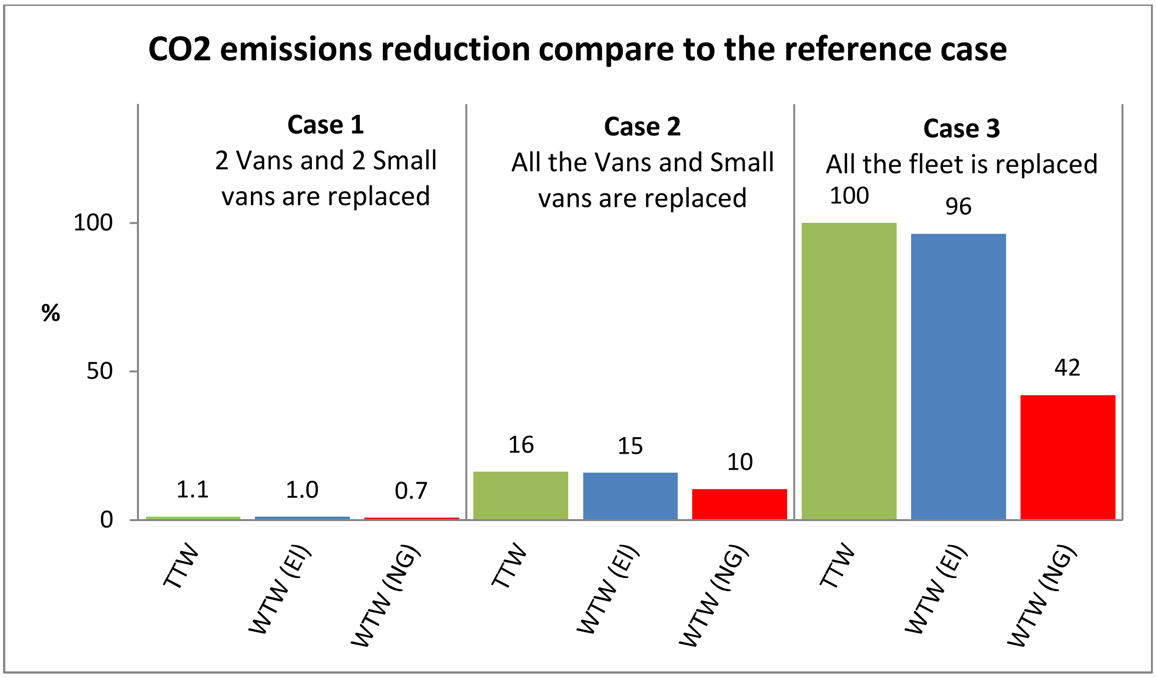


FIGURE 8-6 - LCA POSTEN CASE, RESULTS SUMMARY, CO_2 **EMISSIONS**

8.4 ANALYSIS

The results displayed in the previous parts show us a significant difference between the three boundary options and between the different hydrogen production processes. As they reflect a different value chain we will first cover the TTW results and then the WTW results. Generally speaking we can note that whatever the boundary chosen and the hydrogen origin it is obvious that the replacement of a diesel vehicle by a FC-REV reduces the fleet emission and energy consumption. We can also observe that the differences are stronger when all the fleet is replaced (Case 3). Therefore we will focus on the case 3 for the coming analysis.

First of all one can see that the TTW boundary has the best results of the study. As it composed of a shorter value chain it is logic that it has the least CO_2 emission and the least energy consumption. Hydrogen and battery have the advantage of not directly emitting any GHGs during the operation phase. Therefore it explains the 100% reduction in case of a total replacement of the fleet. Concerning the energy consumption the FC-REV transforms its energy through two systems (FC and battery) that have both a better efficiency than the ICE (60%, 85% and 25% respectively). It explains the important energy saving of 50.2% made over one year over the entire fleet. However the TTW analysis is very limited in its approach as it only covers a small part of the value chain. This type of boundary is more relevant when we look at the local pollution only (NOx, PM).

If we now focus on the WTW boundary we have determined that the hydrogen produced from water electrolysis allowed higher energy saving and lower CO_2 emissions than hydrogen from natural gas. Concerning the energy consumption we have mentioned previously that the value chain for water electrolysis was more efficient than the value chain for natural gas reforming (1.90 kWhEP/kWhH2 against 1.99 kWh/kWhH2). This slight different applied to thousands of kilometers driven leads to few more percent of energy saved with water electrolysis (24% for electrolysis against 21% for reforming). If this energy saving difference is not very important it is much more pronounced if we look at the CO_2 emissions. With 96% of emissions reduction with hydrogen from electrolysis against 42% with natural gas reforming the best option is clearly identified. To explain this difference we have to look at the CO_2 emission per kWh of hydrogen produced: The electrolysis only emit 0.02 $kgCO_2$/kWhH2 while natural gas reforming releases 0.41 $kgCO_2$/kWhH2 (twenty times more). This clean process is the consequence of the Norwegian CO_2 lean electricity based on hydropower. However as mentioned in chapter 2 another electricity mix, based on coal for instance, would have meant a much higher emission for the electrolysis (1.53 $kgCO_2$/kWhH2 in this case).

As mentioned in the introduction chapter we should have a look to the scenario 2 in the case where the fuel cells trucks would not be available. In the case 2 the same difference are observable but in a lesser magnitude. Therefore the WTW (el) has the best performance with 7.7% energy saving (against 7.3% for WTW (NG)) and 15% of CO_2 emissions reduction (against 10% for WTW (NG)). Those differences are caused by the same reason explained in the previous paragraph.

Our last analysis point is that the calculations above are based on average data which means that the hydrogen and electricity consumptions are flattened through an average value per kilometer driven. However as the FC-REV is a hybrid system (FC + battery) it is possible to run only on battery for half of the range without using hydrogen at all. Therefore if, for any reasons, the trip of a Premium, a Maxity or a Kangoo is shorter than the vehicle available range then there will be more electricity consumed than hydrogen and the overall energy consumption and CO_2 emissions will be less important.

8.5 CONCLUSION

Based on the previous analysis and assumptions we have determined that the TTW analysis was not a good tool to assess the performance of a fuel value chain, especially when it comes to hydrogen. Therefore by comparing the two WTW option (electrolysis and reforming) we have determined that the best performance was achieved when all the fleet is replaced and with hydrogen based on electrolysis. This option reduces by 24% the annual energy consumption and by 96% the annual CO_2 emissions. However given that the project will start in June 2016 it is very unlikely that a fuel cells truck format will be commercially available by this time. Therefore the real life situation is more likely to perform a 7.7% annual energy saving and a 15% CO_2 emissions annual reduction. This difference between those two scenarios underline that it is highly relevant to replace the truck as soon as possible. As the price of a refueling station is proportional to its size the best option would be to install a small or medium station sufficient for the few first vehicles plus the forklift fleet and then to develop the network of refueling station in Trondheim.

Concerning the comments about the study we can point four potential improvements. First, our last analysis paragraph pointed that a more accurate drive cycle data would have allowed a more accurate calculation which would have probably given a lesser energy consumption and CO_2 emission. Second, this study was only focused on the fuel value chain therefore it seems important to underline that, in the case of a battery for instance, most of the CO_2 is released during the manufacturing phase (energy intensive process). We can have the same comment for the fuel cells manufacturing and the emissions related to the extraction of platinum. Given that a FC-REV is composed of both battery and fuel cells the results of this study has to be considered with precaution. Third, the assumption saying that the FC-REVs will perfectly match with the previous vehicles operation requirement is a strong assumption and should be revisited with more accurate data about (payload, size, power). Four, we have only considered here the energy and the CO_2 but the operational aspect of an electrolyser and a natural gas reformer are different and significant as the supply of natural gas is much more complicated than an electricity supply.

It would have been really interesting to combine the tools and results of chapter 5 and 6 with this chapter. This could have led to estimate the best introduction strategy for the fleet by pondering the economic cost, the energy saving and the CO_2 emission reduction.

9

CONCLUSION

9.1 ANSWER TO THE PROBLEMATIC

Through this thesis we have covered most of the Norwegian transport market and have analyzed the potential applications for hydrogen and fuel cells. We have shown that several types of fuel cells and several ways to produce hydrogen exist, both with decreasing cost overtime. In Norway, despite a very important natural gas resource, the most relevant way of producing hydrogen appears to be water electrolysis thanks to the hydropower clean electricity. Also the PEMFC and the MCFC seem to be the most appropriate fuel cells types to penetrate respectively the road sector and the maritime sector in a short time perspective. In the different sectors we have seen that those technologies have no serious technical issues but have to compete with several other fuels on both zero emission aspect (battery) and operational performance (natural gas, diesel). We have also determined that the lack of a real infrastructure network limits the current applications to captive fleet operation (road) or short distance trips in loop (Maritime). A common point to all the sectors was the increasing environmental pressure (LEZ, EAC) and the volatility of oil prices which act as a catalyst for this clean technology.

Thanks to the study of the maritime sector we have determine that the very high energy consumption was a significant advantage for battery boat but that fuel cells boat brings more flexibility and can cover more distance. Therefore a combination of the two technologies could be the future of maritime transportation. For the short term the use of natural gas in a MCFC is the most interesting compromise between economy, operation and environment. However, already today, a room is available for fuel cells in the APU applications.

By analyzing the road sector we have figured out that the light weight and the energy content of fuel cells and hydrogen have a good potential for long range capabilities and high energy consumption vehicles. The combination of fuel cells and battery for high fuel consumption trips is a promising option as well. The road tax exemption has been proved efficient for cars and light duty vehicle to make fuel cells competitive but even without aid the fuel cells heavy trucks are competitive for long distances. That is why the bus segment is also interesting especially for long distance trip (rural application) rather than city operation where battery buses are currently more competitive.

Even though our focus was on maritime and road we have learnt that the railway sector was actually one of the most promising applications. Despite a very low GHGs emission we have seen that the combination of fuel cells and battery could be an application highly relevant from an economical aspect because of the current price of the electric infrastructure. The aviation sector gave us a less optimistic perspective given the inertia of the industry and the safety requirement. The adoption of this technology would mean less weight for planes but a change the design.

The LCA study has shown that a significant percentage of energy can be saved by using FC-REV instead of diesel vehicle as well as an important cut in the CO_2 emissions whatever the value chain considered.

As a conclusion we can say that today the best opportunities for fuel cells and hydrogen technology lay in the heavy trucks operating in captive fleet, in long distance buses, and in railway train. In a close future the maritime applications for medium and long distance based on natural and MCFC could be competitive and if a minimum infrastructure is deployed the long range cars will also be an opportunity.

9.2 CRITICS AND OPENING

After having completed this report we realized that each sector could have been a master's thesis by itself. This large frame delimited by the Norwegian transport sector was clearly too large to go sufficiently into detail, especially for the technical aspect. Nonetheless the economical aspect gave us valuable data even if the calculation was simplified through a reduce number of parameters. This master's thesis opened some tracks that have to be exploited in order to answer more precisely to the original question. Among those openings the design of hybrid systems made of fuel cells and battery was a topic which came repetitively in the several discussions along this report. Therefore the elaboration of a software or the use of an existing one to determine the optimal hybrid design could be a very interesting topic.

Finally even though this thesis was focused on the Norwegian context, the results and analysis are actually for most of them also relevant in the European and international context. It is possible to apply the calculation to any other context by changing the correct values in the excel files.

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11 APPENDICES

11.1 ATTACHMENT 1: TASK DESCRIPTION AND SUPERVISOR SIGNATURE

See next page

MASTER DEGREE THESIS
Spring 2015
for

Student: Karel Hubert

Economic and technical assessment of hydrogen and fuel cell opportunities in the Norwegian transport sector

BACKGROUND

Our century is facing two main challenges in term of energy use and supply. The first one is related to global warming as the UNs IPCC is warning the international community about the necessity to stay below a 2°C temperature increase. This issue is highly correlated to human activities through greenhouse gases, and our transport sector is responsible for one third of those emissions. The second challenge is related to energy supply itself due to the fossil fuel resource depletion. As our economies' growth relies on energy consumption, this resource factor will put an increasing pressure to find alternative energy sources and energy carriers.

In this situation hydrogen and fuel cell technology look like a potential answer to those challenges. Indeed, hydrogen could become the next energy carrier for the transport sector if used in combination with fuel cells to power electric motors. The interest of this option lays in the high energy content of hydrogen, the interesting efficiency of fuel cells and the properties of this system to release only water. However, hydrogen acts only as an energy carrier and it has to be produced somehow while fuel cell technology is quite expensive at the moment. Furthermore, fuel cells have to compete with other low emission technologies like biofuels and batteries while fulfilling the same requirement as fossil fuels. Therefore, finding the correct balance between economic competitiveness, environmental benefit and operational requirements for hydrogen and fuel cell technology is a real challenge directly related to climate and energy supply.

TASK

Task description
The aim of this thesis is to determine the most relevant segments of the Norwegian transport market for the introduction of hydrogen and fuel cell technology.

To achieve this, the student shall first cover the different sectors by collecting information about the existing projects related to this technology, the specific technical requirements of each sector and the main characteristics of the competitive fuels.

In addition, a more accurate analysis shall be provided for one or two sectors where this technology appears to be the most relevant. This analysis shall be composed, inter alia, of an economic comparative study between the different technological options for this segment.
To the extent that is relevant for the rest of the thesis, the student should make use of the project of Posten Norge, where fuel cell vehicles are planned to replace part of their existing fleet.

General about content, work and presentation
The text for the master thesis is meant as a framework for the work of the candidate. Adjustments might be done as the work progresses. Tentative changes must be done in cooperation and agreement with the professor in charge at the Department.

In the evaluation thoroughness in the work will be emphasized, as will be documentation of independence in assessments and conclusions. Furthermore the presentation (report) should be well organized and edited; providing clear, precise and orderly descriptions without being unnecessary voluminous.

The report shall include:

- Standard report front page (from DAIM, http://daim.idi.ntnu.no/)
- Title page with abstract and keywords.(template on: http://www.ntnu.no/bat/skjemabank)
- Preface
- Summary and acknowledgement. The summary shall include the objectives of the work, explain how the work has been conducted, present the main results achieved and give the main conclusions of the work.
- The main text.
- Text of the Thesis (these pages) signed by professor in charge as Attachment 1.

The thesis can as an alternative be made as a scientific article for international publication, when this is agreed upon by the Professor in charge. Such a report will include the same points as given above, but where the main text includes both the scientific article and a process report.

Advice and guidelines for writing of the report is given in "Writing Reports" by Øivind Arntsen, and in the departments "Råd og retningslinjer for rapportskriving ved prosjekt og masteroppgave" (In Norwegian) located at http://www.ntnu.no/bat/studier/oppgaver.

Submission procedure
Procedures relating to the submission of the thesis are described in DAIM (http://daim.idi.ntnu.no/). Printing of the thesis is ordered through DAIM directly to Skipnes Printing delivering the printed paper to the department office 2-4 days later. The department will pay for 3 copies, of which the institute retains two copies. Additional copies must be paid for by the candidate / external partner.

On submission of the thesis the candidate shall submit a CD with the paper in digital form in pdf and Word version, the underlying material (such as data collection) in digital form (e.g. Excel). Students must submit the submission form (from DAIM) where both the Ark-Bibl in SBI and Public Services (Building Safety) of SB II has signed the form. The submission form including the appropriate signatures must be signed by the department office before the form is delivered Faculty Office.

Documentation collected during the work, with support from the Department, shall be handed in to the Department together with the report.

According to the current laws and regulations at NTNU, the report is the property of NTNU. The report and associated results can only be used following approval from NTNU (and external cooperation partner if applicable). The Department has the right to make use of the results from the work as if conducted by a Department employee, as long as other arrangements are not agreed upon beforehand.

Tentative agreement on external supervision, work outside NTNU, economic support etc.
Separate description is to be developed, if and when applicable.
See http://www.ntnu.no/bat/skjemabank for agreement forms.

Health, environment and safety (HSE) http://www.ntnu.edu/hse
NTNU emphasizes the safety for the individual employee and student. The individual safety shall be in the forefront and no one shall take unnecessary chances in carrying out the work. In particular, if the student is to participate in field work, visits, field courses, excursions etc. during the Master Thesis work, he/she shall make himself/herself familiar with "Fieldwork HSE Guidelines". The document is found on the NTNU HMS-pages at http://www.ntnu.no/hms/retningslinjer/HMSR07E.pdf

The students do not have a full insurance coverage as a student at NTNU. If you as a student want the same insurance coverage as the employees at the university, you must take out individual travel and personal injury insurance.

Startup and submission deadlines
Startup and submission deadlines are according to information found in DAIM.

Professor in charge: Adjunct Professor Kjell Arne Skoglund

Other supervisors: Anders Ødegård, PhD, SINTEF Materials and Chemistry

Department of Civil and Transport Engineering, NTNU
Date: 09.06.2015

Kjell Arne Skoglund
Professor in charge (signature)

11.2 APPENDIX A: LCA CALCULATION, MATLAB SCRIPT

```
clear all;

%Entering the A matrix
A1 = xlsread('LCA_Posten.xlsx','A','B2:J10');
A2 = xlsread('LCA_Posten.xlsx','A','B13:J21');
A3 = xlsread('LCA_Posten.xlsx','A','B24:J32');
B1 = xlsread('LCA_Posten.xlsx','B','B2:J10');
B2 = xlsread('LCA_Posten.xlsx','B','B13:J21');
B3 = xlsread('LCA_Posten.xlsx','B','B24:J32');
C1 = xlsread('LCA_Posten.xlsx','C','B2:J10');
C2 = xlsread('LCA_Posten.xlsx','C','B13:J21');
C3 = xlsread('LCA_Posten.xlsx','C','B24:J32');

%Entering the Unity matrix
I = xlsread('LCA_Posten.xlsx','I','B2:J10');

%Calculating the Leontief inverse matrix
L1 = (I-A1)^(-1);
L2 = (I-A2)^(-1);
L3 = (I-A3)^(-1);
L4 = (I-B1)^(-1);
L5 = (I-B2)^(-1);
L6 = (I-B3)^(-1);
L7 = (I-C1)^(-1);
L8 = (I-C2)^(-1);
L9 = (I-C3)^(-1);

%Entering the Y external demand matrix
Y = xlsread('LCA_Posten.xlsx','Y','B2:B10');

%Calculating the x total outputs matrix
x1 = L1*Y;
x2 = L2*Y;
x3 = L3*Y;
x4 = L4*Y;
x5 = L5*Y;
x6 = L6*Y;
x7 = L7*Y;
x8 = L8*Y;
x9 = L9*Y;

%Entering the S stressor matrix
S1 = xlsread('LCA_Posten.xlsx','S','B2:J3');
S2 = xlsread('LCA_Posten.xlsx','S','B6:J7');

%Calculating the e stressors generated matrix
e1 = S1*x2;
e2 = S2*x1;
e3 = S2*x2;
e4 = S1*x3;
e5 = S2*x3;
e6 = S1*x5;
e7 = S2*x4;
e8 = S2*x5;
e9 = S1*x6;
e10 = S2*x6;
e11 = S1*x8;
```

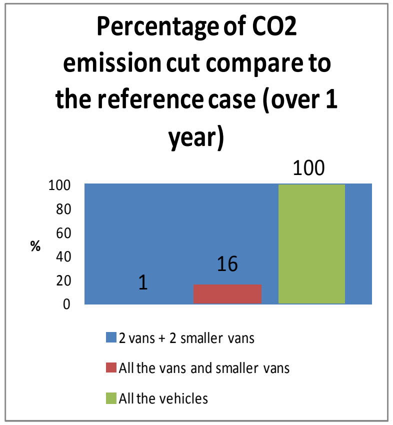
```
e12 = S2*x7;
e13 = S2*x8;
e14 = S1*x9;
e15 = S2*x9;

%Entering the e matrixes in the final table
xlswrite('LCA_Posten.xlsx',e1,'Results','B5');
xlswrite('LCA_Posten.xlsx',e2,'Results','C5');
xlswrite('LCA_Posten.xlsx',e3,'Results','D5');
xlswrite('LCA_Posten.xlsx',e4,'Results','E5');
xlswrite('LCA_Posten.xlsx',e5,'Results','F5');
xlswrite('LCA_Posten.xlsx',e6,'Results','G5');
xlswrite('LCA_Posten.xlsx',e7,'Results','H5');
xlswrite('LCA_Posten.xlsx',e8,'Results','I5');
xlswrite('LCA_Posten.xlsx',e9,'Results','J5');
xlswrite('LCA_Posten.xlsx',e10,'Results','K5');
xlswrite('LCA_Posten.xlsx',e11,'Results','L5');
xlswrite('LCA_Posten.xlsx',e12,'Results','M5');
xlswrite('LCA_Posten.xlsx',e13,'Results','N5');
xlswrite('LCA_Posten.xlsx',e14,'Results','O5');
xlswrite('LCA_Posten.xlsx',e15,'Results','P5');

%Demonstration matrix used as example in the report
xlswrite('LCA_Posten.xlsx',L2,'A','L13');
xlswrite('LCA_Posten.xlsx',L1,'A','L2');
xlswrite('LCA_Posten.xlsx',x1,'Y','B13');
xlswrite('LCA_Posten.xlsx',x2,'Y','D13');
```

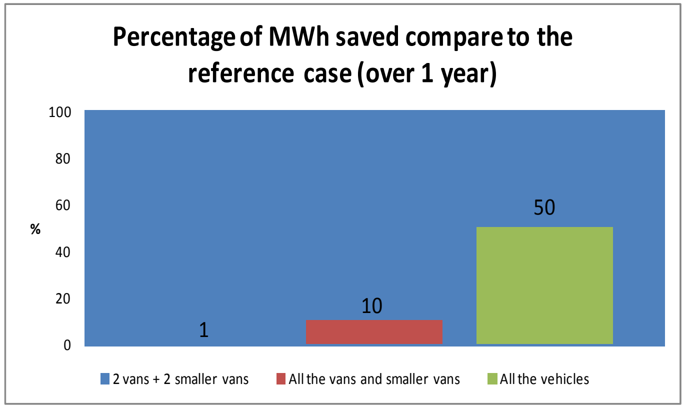
11.3 APPENDIX B: LCA CALCULATIONS, TABLES AND GRAPHS

11.3.1 SUMMARY, TTW CONFIGURATION (1)

Posten fuel cell range extender vehicle fleet

Value chain for the Fuel-cell Range extender vehicle (FC-REV):	Value chain for the Diesel vehicles:
TTW	TTW

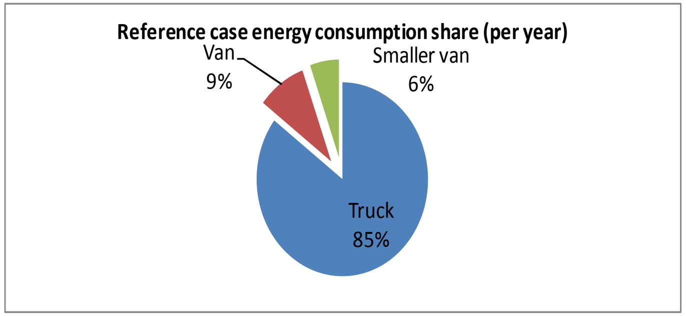




	Description	Tons CO2 per year	CO2 reduction from Case ref (Tons CO2/year)	% CO2 reduction per year	MWh per year	MWh saved per year	% MWh saved per year
Case ref	All diesel	1801			6825		
2 vans + 2 smaller vans	2 vans + 2 smaller vans replaced by 2 Maxitys and 2 Kangoos	1782	19	1	6778	47	1
All the vans and smaller vans	All the vans and smaller vans are replaced by Maxitys and Kangoos	1510	292	16	6125	700	10
All the vehicles	All the vehicles are replaced	0	1801	100	3399	3426	50

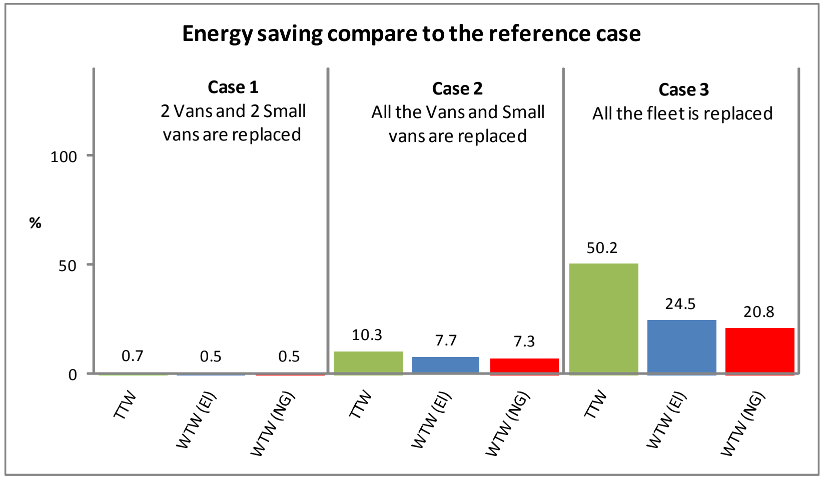
Presentation

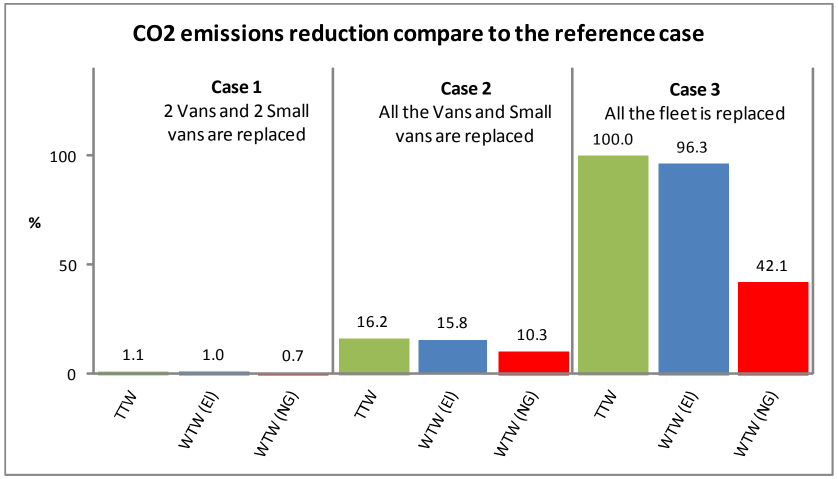
Summary: Selection of the study's boundary. Presentation of the main results in percentage and real value.
Cases: Data concerning the configuration of the three different cases. It is possible to modify them, the calculation is done automatically.
Hand calculations: Input data and efficiency and CO2 emission calculations.
Efficiency chains: Illustration of the efficiency chain and comparison with the matrix method
Posten data: Database about Posten fleet.
Results: Coefficients for the different vehicle configurations. They are obtained with the matrix method (LCA method).
A, B, C, S, I, Y: Used during the matrix calculation.
EMELx_xHx: Extract from the EU JRC WTW study version 4a. It provides the data concerning electricity.
GMCH1: Extract from the EU JRC WTW study version 4a. It provides the data concerning natural gas.



11.3.2 SUMMARY, TTW CONFIGURATION (2)

		CO2	Energy
Case 1	**TTW**	1.1	0.7
	WTW (El)	1.0	0.5
	WTW (NG)	0.7	0.5
Case 2	**TTW**	16.2	10.3
	WTW (El)	15.8	7.7
	WTW (NG)	10.3	7.3
Case 3	**TTW**	100.0	50.2
	WTW (El)	96.3	24.5
	WTW (NG)	42.1	20.8





11.3.3 REFERENCE CASE, TTW CONFIGURATION

Case ref

Trip reference	Vehicle type	Engine type	Boundary type	Yearly distance (km)	Number of vehicle	tons CO2 per year	MWh per year
1	**Truck**	**Diesel**	**TTW**	102680	1	94.5	358.0
2	**Truck**	**Diesel**	**TTW**	78520	1	72.3	273.7
3	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
4	**Truck**	**Diesel**	**TTW**	72480	1	66.7	252.7
5	**Truck**	**Diesel**	**TTW**	72480	1	66.7	252.7
6	**Truck**	**Diesel**	**TTW**	96640	1	88.9	336.9
7	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
8	**Truck**	**Diesel**	**TTW**	84560	1	77.8	294.8
9	**Truck**	**Diesel**	**TTW**	52850	1	48.6	184.3
10	**Truck**	**Diesel**	**TTW**	12750	1	11.7	44.5
11	**Truck**	**Diesel**	**TTW**	133875	1	123.2	466.7
12	**Truck**	**Diesel**	**TTW**	102680	1	94.5	358.0
13	**Truck**	**Diesel**	**TTW**	202500	1	186.3	706.0
14	**Truck**	**Diesel**	**TTW**	70125	1	64.5	244.5
15	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
16	**Truck**	**Diesel**	**TTW**	196300	1	180.6	684.4
17	**Van**	**Diesel**	**TTW**	15286	35	182.9	692.8
18	**Van**	**FC-REV**	**TTW**	15286	0	0.0	0.0
19	**Smaller van**	**Diesel**	**TTW**	15040	25	108.7	412.0
20	**Smaller van**	**FC-REV**	**TTW**	15040	0	0.0	0.0
					Total	1801.5	6825.2

11.3.4 CASE 1, TTW CONFIGURATION

Case 1

Trip reference	Vehicle type	Engine type	Boundary type	Yearly distance (km)	Number of vehicle	tons CO2 per year	MWh per year
1	**Truck**	**Diesel**	**TTW**	102680	1	94.5	358.0
2	**Truck**	**Diesel**	**TTW**	78520	1	72.3	273.7
3	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
4	**Truck**	**Diesel**	**TTW**	72480	1	66.7	252.7
5	**Truck**	**Diesel**	**TTW**	72480	1	66.7	252.7
6	**Truck**	**Diesel**	**TTW**	96640	1	88.9	336.9
7	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
8	**Truck**	**Diesel**	**TTW**	84560	1	77.8	294.8
9	**Truck**	**Diesel**	**TTW**	52850	1	48.6	184.3
10	**Truck**	**Diesel**	**TTW**	12750	1	11.7	44.5
11	**Truck**	**Diesel**	**TTW**	133875	1	123.2	466.7
12	**Truck**	**Diesel**	**TTW**	102680	1	94.5	358.0
13	**Truck**	**Diesel**	**TTW**	202500	1	186.3	706.0
14	**Truck**	**Diesel**	**TTW**	70125	1	64.5	244.5
15	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
16	**Truck**	**Diesel**	**TTW**	196300	1	180.6	684.4
17	**Van**	**Diesel**	**TTW**	15286	33	172.4	653.2
17	**Van**	**FC-REV**	**TTW**	15286	2	0.0	17.9
18	**Smaller van**	**Diesel**	**TTW**	15040	23	100.0	379.0
18	**Smaller van**	**FC-REV**	**TTW**	15040	2	0.0	7.4

Total	1782.3	6777.9

11.3.5 CASE 2, TTW CONFIGURATION

Case 2

Trip reference	Vehicle type	Engine type	Boundary type	Yearly distance (km)	Number of vehicle	tons CO2 per year	MWh per year
1	**Truck**	**Diesel**	**TTW**	102680	1	94.5	358.0
2	**Truck**	**Diesel**	**TTW**	78520	1	72.3	273.7
3	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
4	**Truck**	**Diesel**	**TTW**	72480	1	66.7	252.7
5	**Truck**	**Diesel**	**TTW**	72480	1	66.7	252.7
6	**Truck**	**Diesel**	**TTW**	96640	1	88.9	336.9
7	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
8	**Truck**	**Diesel**	**TTW**	84560	1	77.8	294.8
9	**Truck**	**Diesel**	**TTW**	52850	1	48.6	184.3
10	**Truck**	**Diesel**	**TTW**	12750	1	11.7	44.5
11	**Truck**	**Diesel**	**TTW**	133875	1	123.2	466.7
12	**Truck**	**Diesel**	**TTW**	102680	1	94.5	358.0
13	**Truck**	**Diesel**	**TTW**	202500	1	186.3	706.0
14	**Truck**	**Diesel**	**TTW**	70125	1	64.5	244.5
15	**Truck**	**Diesel**	**TTW**	120800	1	111.2	421.1
16	**Truck**	**Diesel**	**TTW**	196300	1	180.6	684.4
17	**Van**	**Diesel**	**TTW**	15286	0	0.0	0.0
17	**Van**	**FC-REV**	**TTW**	15286	35	0.0	312.4
18	**Smaller van**	**Diesel**	**TTW**	15040	0	0.0	0.0
18	**Smaller van**	**FC-REV**	**TTW**	15040	25	0.0	92.4

Total	1509.9	6125.3

11.3.6 CASE 3, TTW CONFIGURATION

Case 3

Trip reference	Vehicle type	Engine type	Boundary type	Yearly distance (km)	Number of vehicle	tons CO2 per year	MWh per year
1	**Truck**	**FC-REV**	**TTW**	102680	1	0.0	187.4
2	**Truck**	**FC-REV**	**TTW**	78520	1	0.0	143.3
3	**Truck**	**FC-REV**	**TTW**	120800	1	0.0	220.5
4	**Truck**	**FC-REV**	**TTW**	72480	1	0.0	132.3
5	**Truck**	**FC-REV**	**TTW**	72480	1	0.0	132.3
6	**Truck**	**FC-REV**	**TTW**	96640	1	0.0	176.4
7	**Truck**	**FC-REV**	**TTW**	120800	1	0.0	220.5
8	**Truck**	**FC-REV**	**TTW**	84560	1	0.0	154.3
9	**Truck**	**FC-REV**	**TTW**	52850	1	0.0	96.5
10	**Truck**	**FC-REV**	**TTW**	12750	1	0.0	23.3
11	**Truck**	**FC-REV**	**TTW**	133875	1	0.0	244.3
12	**Truck**	**FC-REV**	**TTW**	102680	1	0.0	187.4
13	**Truck**	**FC-REV**	**TTW**	202500	1	0.0	369.6
14	**Truck**	**FC-REV**	**TTW**	70125	1	0.0	128.0
15	**Truck**	**FC-REV**	**TTW**	120800	1	0.0	220.5
16	**Truck**	**FC-REV**	**TTW**	196300	1	0.0	358.2
17	**Van**	**FC-REV**	**TTW**	15286	35	0.0	312.4
17	**Van**	**Diesel**	**TTW**	15286	0	0.0	0.0
18	**Smaller van**	**FC-REV**	**TTW**	15040	25	0.0	92.4
18	**Smaller van**	**Diesel**	**TTW**	15040	0	0.0	0.0

Total	0.0	3399.3

11.3.7 INPUT DATA

Natural gas	
Additional energy spent to produce one kWhH2 (kWh/kWh H2)	0.99
Related efficiency (%)	**50**
Overall energy consumption (kWhPE/kWhH2)	**1.99**

kgCO2/MJ	0.115
MJ/kWh	3.6
Overall CO2 emissions (kgCO2/kWhH2)	**0.41**

Diesel	
Additional energy spent to produce one kWh of diesel	0.2
Related efficiency (%)	**83**
Overall energy consumption (kWhPE/kWh diesel)	**1.20**

kgCO2/MJ diesel (WTT)	0.0154
kgCO2/kg diesel (TTW)	3.16
LHV (MJ/kg)	43.1
MJ/kWh	3.6
kgCO2/kWh diesel (WTT)	0.06
kgCO2/kWh diesel (TTW)	**0.26**
kgCO2/kWh diesel (WTW)	**0.32**

	A	B	C
Diesel consumption (l/km)	0.35	0.13	0.11
LHV Diesel (kWh/l)	9.96		
Diesel consumption (kWh/km)	**3.49**	**1.29**	**1.10**

	A	B	C
H2 storage (kg)	25	4	1.7
LHV H2 (kWh/kg)	33.3		
Hydrogen storage (kWh)	832.5	133.2	56.61
Driving range (km)	500	300	320
Hydrogen consumption (kWhH2/km)	**1.67**	**0.44**	**0.18**

	A	B	C
Battery size (kWh)	80	42	22
Driving range (km)	500	300	320
Battery consumption (kWh/km)	**0.160**	**0.140**	**0.069**

Natural gas	
Overall energy consumption (kWhPE/kWhH2)	**1.99**
Overall CO2 emissions (kgCO2/kWhH2)	**0.41**

Diesel	
Overall energy consumption (kWhPE/kWh diesel)	**1.20**
kgCO2/kWh diesel (TTW)	**0.26**
kgCO2/kWh diesel (WTW)	**0.32**

11.3.8 FINAL "E" MATRIX

Final matrix			kWh/km	kg CO2/km
Truck	FC-REV	TTW	1.83	0.00
Truck	FC-REV	WTW (EL)	3.34	0.04
Truck	FC-REV	WTW (NG)	3.51	0.69
Truck	Diesel	TTW	3.49	0.92
Truck	Diesel	WTW	4.18	1.11
Van	FC-REV	TTW	0.58	0.00
Van	FC-REV	WTW (EL)	1.01	0.01
Van	FC-REV	WTW (NG)	1.06	0.19
Van	Diesel	TTW	1.29	0.34
Van	Diesel	WTW	1.55	0.41
Smaller van	FC-REV	TTW	0.25	0.00
Smaller van	FC-REV	WTW (EL)	0.42	0.01
Smaller van	FC-REV	WTW (NG)	0.44	0.07
Smaller van	Diesel	TTW	1.10	0.29
Smaller van	Diesel	WTW	1.31	0.35

11.3.9 A MATRICES

A matrix (A Vehicles, FC-REV, WTW El)	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (kWh)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	1	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	1	0	0	0	0	0	0	0
Battery (kWh)	0	80	0	0	0	0	0	0	0
ICE (X)	0	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0	0	0	0	0	0	0	0	0
H2 (El, kWh)	1.67	0	0	0	0	0	0	0	0
Electricity (kWh)	0.16	0	0	0	0	0	1.53	0	0
Diesel (kWh)	0	0	0	0	0	0	0	0	0

atrix (A Vehicles, FC-REV, TWT and WTW	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (kWh)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	1	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	1	0	0	0	0	0	0	0
Battery (kWh)	0	80	0	0	0	0	0	0	0
ICE (X)	0	0	0	0	0	0	0	0	0
H2 (NG, kWh)	1.67	0	0	0	0	0	0	0	0
H2 (El, kWh)	0	0	0	0	0	0	0	0	0
Electricity (kWh)	0.16	0	0	0	0	0	0	0	0
Diesel (kWh)	0	0	0	0	0	0	0	0	0

A matrix (A Vehicles, Diesel)	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (kWh)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	0	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	0	0	0	0	0	0	0	0
Battery (kWh)	0	0	0	0	0	0	0	0	0
ICE (X)	1	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0	0	0	0	0	0	0	0	0
H2 (El, kWh)	0	0	0	0	0	0	0	0	0
Electricity (kWh)	0	0	0	0	0	0	0	0	0
Diesel (kWh)	3.49	0	0	0	0	0	0	0	0

A matrix (B Vehicles, FC-REV, WTW El)	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (kWh)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	1	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	1	0	0	0	0	0	0	0
Battery (kWh)	0	42	0	0	0	0	0	0	0
ICE (X)	0	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0	0	0	0	0	0	0	0	0
H2 (El, kWh)	0.44	0	0	0	0	0	0	0	0
Electricity (kWh)	0.14	0	0	0	0	0	1.53	0	0
Diesel (kWh)	0	0	0	0	0	0	0	0	0

atrix (B Vehicles, FC-REV, TWT and WTW	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (kWh)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	1	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	1	0	0	0	0	0	0	0
Battery (kWh)	0	42	0	0	0	0	0	0	0
ICE (X)	0	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0.44	0	0	0	0	0	0	0	0
H2 (El, kWh)	0	0	0	0	0	0	0	0	0
Electricity (kWh)	0.14	0	0	0	0	0	0	0	0
Diesel (kWh)	0	0	0	0	0	0	0	0	0

A matrix (B Vehicles, Diesel)	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (kWh)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	0	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	0	0	0	0	0	0	0	0
Battery (kWh)	0	0	0	0	0	0	0	0	0
ICE (X)	1	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0	0	0	0	0	0	0	0	0
H2 (El, kWh)	0	0	0	0	0	0	0	0	0
Electricity (kWh)	0	0	0	0	0	0	0	0	0
Diesel (kWh)	1.29	0	0	0	0	0	0	0	0

A matrix (C Vehicles, FC-REV, WTW El)	Distance (km)	FC-REV (X)	Fuel Cell (X)	attery (kWh	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	1	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	1	0	0	0	0	0	0	0
Battery (kWh)	0	22	0	0	0	0	0	0	0
ICE (X)	0	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0	0	0	0	0	0	0	0	0
H2 (El, kWh)	0.18	0	0	0	0	0	0	0	0
Electricity (kWh)	0.07	0	0	0	0	0	1.53	0	0
Diesel (kWh)	0	0	0	0	0	0	0	0	0

atrix (C Vehicles, FC-REV, TWT and WTW	Distance (km)	FC-REV (X)	Fuel Cell (X)	attery (kWh	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	1	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	1	0	0	0	0	0	0	0
Battery (kWh)	0	22	0	0	0	0	0	0	0
ICE (X)	0	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0.18	0	0	0	0	0	0	0	0
H2 (El, kWh)	0	0	0	0	0	0	0	0	0
Electricity (kWh)	0.07	0	0	0	0	0	0	0	0
Diesel (kWh)	0	0	0	0	0	0	0	0	0

A matrix (C Vehicles, Diesel)	Distance (km)	FC-REV (X)	Fuel Cell (X)	attery (kWh	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
Distance (km)	0	0	0	0	0	0	0	0	0
FC-REV (X)	0	0	0	0	0	0	0	0	0
Fuel Cell (X)	0	0	0	0	0	0	0	0	0
Battery (kWh)	0	0	0	0	0	0	0	0	0
ICE (X)	1	0	0	0	0	0	0	0	0
H2 (NG, kWh)	0	0	0	0	0	0	0	0	0
H2 (El, kWh)	0	0	0	0	0	0	0	0	0
Electricity (kWh)	0	0	0	0	0	0	0	0	0
Diesel (kWh)	1.10	0	0	0	0	0	0	0	0

11.3.10 S MATRICES

S matrix (TTW)	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (X)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
kWh PE	0	0	0	0	0	1	1	1	1
kg CO2	0	0	0	0	0	0	0	0	0.26

S matrix (WTW)	Distance (km)	FC-REV (X)	Fuel Cell (X)	Battery (X)	ICE (X)	H2 (NG, kWh)	H2 (El, kWh)	Electricity (kWh)	Diesel (kWh)
kWh PE	0	0	0	0	0	1.99	0	1.24	1.2
kg CO2	0	0	0	0	0	0.41	0	0.016	0.32

11.3.11 I MATRIX

I matrix

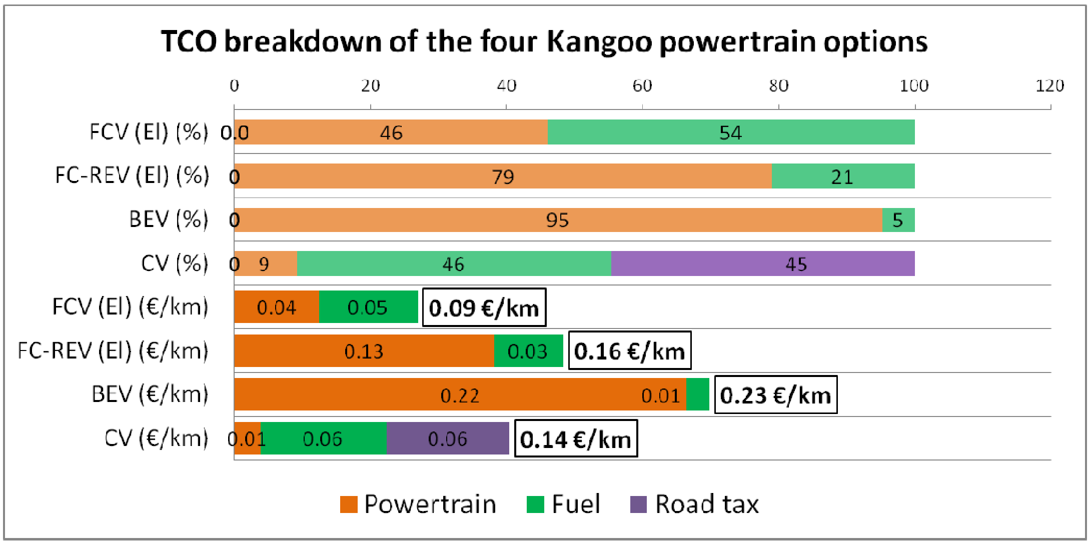
1	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0
0	0	0	0	1	0	0	0	0
0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	1

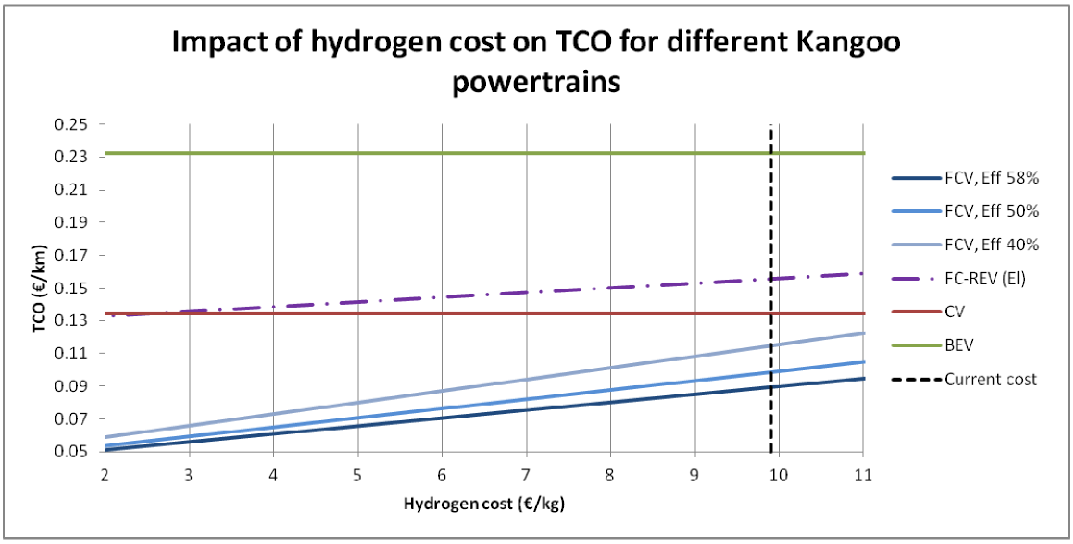
11.3.12 Y MATRIX

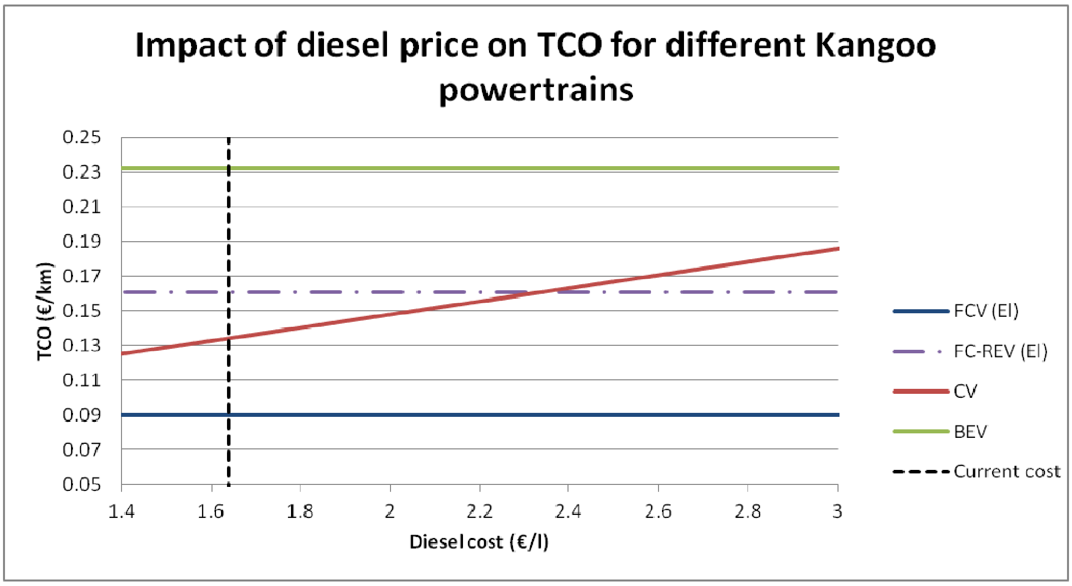
Y matrix	All
Distance (km)	1
FC-REV (X)	0
Fuel Cell (X)	0
Battery (X)	0
ICE (X)	0
H2 (NG, kWh)	0
H2 (El, kWh)	0
Electricity (kWh)	0
Diesel (kWh)	0

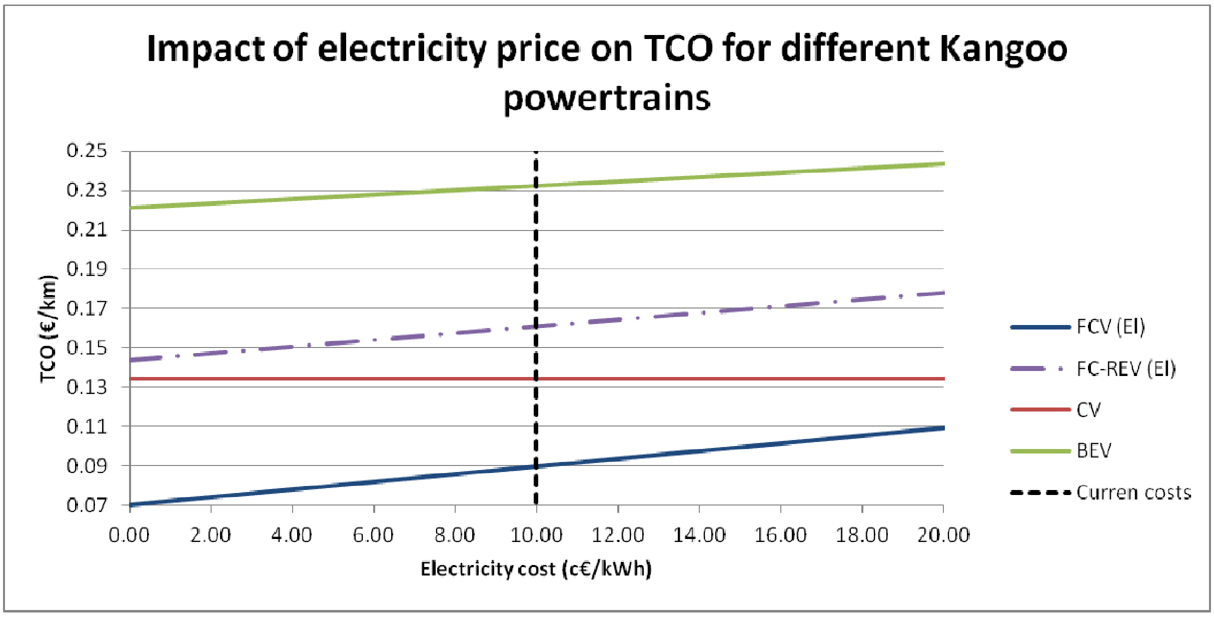
11.4 APPENDIX C: STUDY CASE

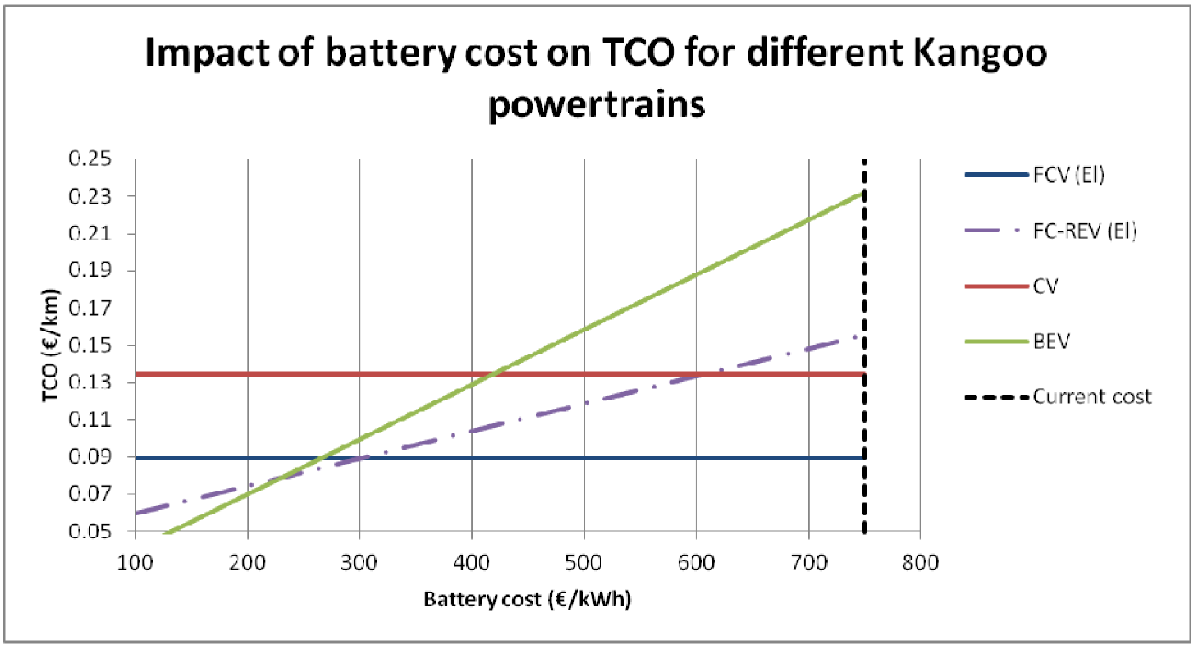
11.4.1 KANGOO STUDY CASE

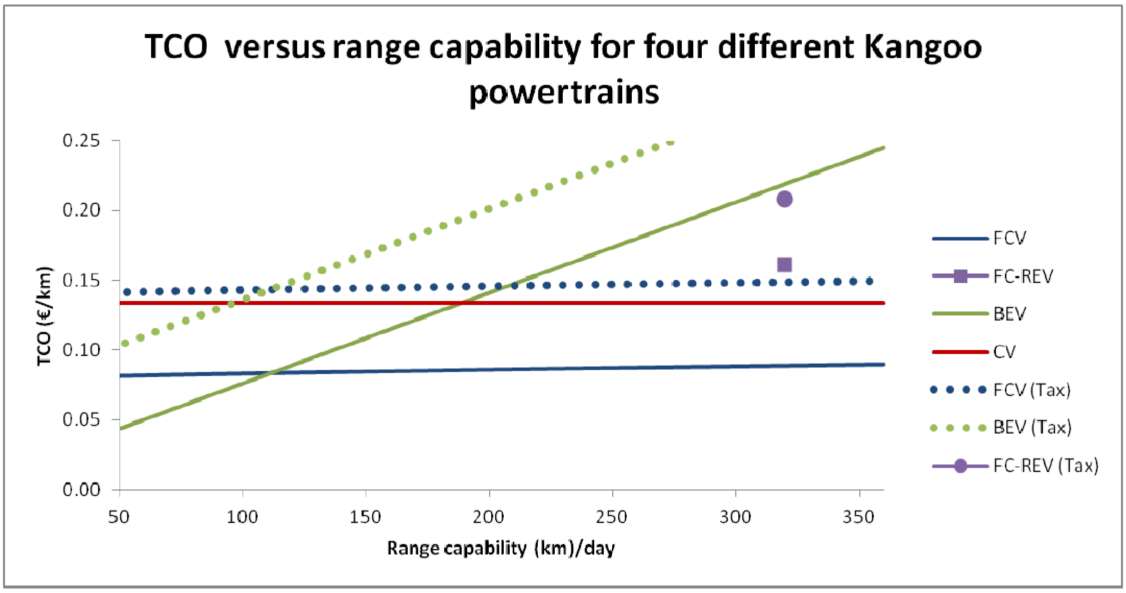







Impact of electricity price on TCO for different Kangoo powertrains
TCO (€/km)
0.25
0.23
0.21
0.19
0.17
0.15
0.13
0.11
0.09
0.07
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
Electricity cost (c€/kWh)
FCV (El)
FC-REV (El)
CV
BEV
Curren costs


Impact of battery cost on TCO for different Kangoo powertrains
TCO (€/km)
0.25
0.23
0.21
0.19
0.17
0.15
0.13
0.11
0.09
0.07
0.05
100
200
300
400
500
600
700
800
Battery cost (€/kWh)
FCV (El)
FC-REV (El)
CV
BEV
Current cost


TCO versus range capability for four different Kangoo powertrains
TCO (€/km)
0.25
0.20
0.15
0.10
0.05
0.00
50
100
150
200
250
300
350
Range capability (km)/day
FCV
FC-REV
BEV
CV
FCV (Tax)
BEV (Tax)
FC-REV (Tax)

System	CAPEX (k€)	OPEX (k€/year)	NPV, 10yr (k€)	TCO (€/km)	TCO (€/km)	Powertrain	Fuel	Road tax
CV (€/km)	1.8	2.3	20.2	0.13	0.13	0.01	0.06	0.06
BEV (€/km)	0.0	4.3	35.0	0.23	0.23	0.22	0.01	0.00
FC-REV (El) (€/km)	1.1	2.9	24.2	0.16	0.16	0.13	0.03	0.00
FCV (El) (€/km)	1.6	1.5	13.5	0.09	0.09	0.04	0.05	0.00
CV (%)	-	-	-	-	-	9	46	45
BEV (%)	-	-	-	-	-	95	5	0
FC-REV (El) (%)	-	-	-	-	-	79	21	0
FCV (El) (%)	-	-	-	-	-	46	54	0

	Specific H2 price (€/kgH2)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	9.9	9.9
FC-REV (El)	OPEX (k€)	2.3	2.3	2.4	2.4	2.5	2.6	2.6	2.7	2.7	2.8	2.8	2.9	2.9	3.0	3.0	3.1	3.1	3.2	3.3	3.3	2.8	2.8
	NPV OPEX (k€)	18.5	18.9	19.3	19.8	20.2	20.6	21.1	21.5	21.9	22.3	22.8	23.2	23.6	24.1	24.5	24.9	25.4	25.8	26.2	26.7	22.3	22.3
	NPV Total (k€)	19.5	20.0	20.4	20.8	21.3	21.7	22.1	22.6	23.0	23.4	23.9	24.3	24.7	25.2	25.6	26.0	26.4	26.9	27.3	27.7	23.4	23.4
	TCO (€/km)	0.13	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.16	0.16
FCV, Eff 58%	OPEX (k€)	0.7	0.8	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.8	1.9	2.0	2.1	2.2	2.3	2.4	1.5	1.5
	NPV OPEX (k€)	5.3	6.1	6.8	7.5	8.3	9.0	9.8	10.5	11.2	12.0	12.7	13.4	14.2	14.9	15.6	16.4	17.1	17.8	18.6	19.3	11.9	11.9
	NPV Total (k€)	6.94	7.68	8.41	9.15	9.88	10.61	11.35	12.08	12.82	13.55	14.29	15.02	15.76	16.49	17.23	17.96	18.69	19.43	20.16	20.90	13.48	13.48
	TCO (€/km)	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.09	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.13	0.14	0.09	0.09
FCV, Eff 50%	TCO (€/km)	0.05	0.05	0.06	0.07	0.07	0.08	0.08	0.09	0.09	0.10	0.10	0.11	0.12	0.12	0.13	0.13	0.14	0.14	0.15	0.16	0.10	0.10
FCV, Eff 40%	TCO (€/km)	0.05	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.11	0.12	0.12	0.13	0.14	0.14	0.15	0.16	0.17	0.17	0.18	0.19	0.11	0.11
CV	TCO (€/km)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
BEV	TCO (€/km)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
																					Current cost	0.05	0.3

	Diesel price (€/l)	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5	1.65	1.8	1.95	2.1	2.25	2.4	2.55	2.7	2.85	3	3.15	1.64	1.64
CV	OPEX (k€)	1.3	1.4	1.5	1.6	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	2.3	2.3
	NPV OPEX (k€)	10.7	11.6	12.5	13.3	14.2	15.0	15.9	16.7	17.6	18.4	19.3	20.1	21.0	21.9	22.7	23.6	24.4	25.3	26.1	27.0	18.4	18.4
	NPV Total (k€)	12.6	13.5	14.3	15.2	16.0	16.9	17.7	18.6	19.4	20.3	21.1	22.0	22.9	23.7	24.6	25.4	26.3	27.1	28.0	28.8	20.2	20.2
	TCO (€/km)	0.08	0.09	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.13	0.14	0.15	0.15	0.16	0.16	0.17	0.17	0.18	0.19	0.19	0.13	0.13
FC-REV (El)	TCO (€/km)	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
FCV (El)	TCO (€/km)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
BEV	TCO (€/km)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
																					Current cost	0	0.3

	Battery cost (€/kWh)	100	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	750	750
FC-REV (El)	OPEX (k€)	1.0	1.3	1.3	1.4	1.5	1.5	1.6	1.7	1.7	1.8	1.9	1.9	2.0	2.1	2.1	2.2	2.3	2.4	2.4	2.5	2.6	2.8	2.8
	NPV OPEX (k€)	7.9	10.1	10.7	11.2	11.8	12.3	12.9	13.4	14.0	14.5	15.1	15.6	16.2	16.8	17.3	17.9	18.4	19.0	19.5	20.1	20.6	22.3	22.3
	NPV Total (k€)	9.0	11.2	11.7	12.3	12.8	13.4	13.9	14.5	15.1	15.6	16.2	16.7	17.3	17.8	18.4	18.9	19.5	20.1	20.6	21.2	21.7	23.4	23.4
	TCO (€/km)	0.06	0.07	0.08	0.08	0.09	0.09	0.09	0.10	0.10	0.10	0.11	0.11	0.11	0.12	0.12	0.13	0.13	0.13	0.14	0.14	0.14	0.16	0.16
BEV	OPEX (k€)	0.8	1.3	1.4	1.6	1.7	1.9	2.0	2.1	2.3	2.4	2.5	2.7	2.8	3.0	3.1	3.2	3.4	3.5	3.6	3.8	3.9	4.3	4.3
	NPV OPEX (k€)	6.1	10.5	11.7	12.8	13.9	15.0	16.1	17.2	18.3	19.4	20.5	21.6	22.8	23.9	25.0	26.1	27.2	28.3	29.4	30.5	31.6	35.0	35.0
	NPV Total (k€)	6.11	10.55	11.66	12.77	13.88	14.99	16.10	17.21	18.31	19.42	20.53	21.64	22.75	23.86	24.97	26.08	27.19	28.30	29.41	30.52	31.63	34.96	34.96
	TCO (€/km)	0.04	0.07	0.08	0.08	0.09	0.10	0.11	0.11	0.12	0.13	0.14	0.14	0.15	0.16	0.17	0.17	0.18	0.19	0.20	0.20	0.21	0.23	0.23
CV	TCO (€/km)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
FCV (El)	TCO (€/km)	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
																						Current cost	0.05	0.3

	Electricity cost (c€/kWhe)	0.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00	25.00	26.00	27.00	28.00	10.00	10.00
	Corresponding hydrogen price (€/kgH2)	5.9	9.5	9.9	10.3	10.7	11.1	11.5	11.9	12.3	12.7	13.1	13.5	13.9	14.3	14.7	15.1	15.5	15.9	16.3	16.7	17.1	9.9	9.9
BEV	OPEX (k€/yr)	4.1	4.3	4.3	4.4	4.4	4.4	4.4	4.4	4.5	4.5	4.5	4.5	4.5	4.6	4.6	4.6	4.6	4.6	4.7	4.7	4.7	4.3	4.3
	NPV OPEX (k€)	33.3	34.8	35.0	35.1	35.3	35.5	35.6	35.8	36.0	36.1	36.3	36.5	36.6	36.8	37.0	37.1	37.3	37.5	37.6	37.8	38.0	35.0	35.0
	NPV total (k€)	33.29	34.79	34.96	35.13	35.29	35.46	35.63	35.80	35.96	36.13	36.30	36.46	36.63	36.80	36.96	37.13	37.30	37.46	37.63	37.80	37.96	34.96	34.96
	TCO (€/km)	0.22	0.23	0.23	0.23	0.23	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.23	0.23
FCV (El)	OPEX (k€/yr)	1.1	1.4	1.5	1.5	1.5	1.6	1.6	1.7	1.7	1.7	1.8	1.8	1.8	1.9	1.9	1.9	2.0	2.0	2.1	2.1	2.1	1.5	1.5
	NPV OPEX (k€)	8.9	11.6	11.9	12.2	12.5	12.8	13.1	13.4	13.6	13.9	14.2	14.5	14.8	15.1	15.4	15.7	16.0	16.3	16.6	16.9	17.2	11.9	11.9
	NPV total (k€)	10.54	13.19	13.48	13.77	14.07	14.36	14.65	14.95	15.24	15.54	15.83	16.12	16.42	16.71	17.01	17.30	17.59	17.89	18.18	18.47	18.77	13.48	13.48
	TCO (€/km)	0.07	0.09	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.12	0.12	0.12	0.12	0.12	0.12	0.09	0.09
FC-REV (El)	OPEX (k€)	2.5	2.8	2.9	2.9	2.9	3.0	3.0	3.0	3.1	3.1	3.1	3.2	3.2	3.2	3.2	3.3	3.3	3.3	3.4	3.4	3.4	2.9	2.9
	NPV OPEX (k€)	20.6	22.9	23.1	23.4	23.7	23.9	24.2	24.4	24.7	24.9	25.2	25.4	25.7	26.0	26.2	26.5	26.7	27.0	27.2	27.5	27.8	23.1	23.1
	NPV Total (k€)	21.7	24.0	24.2	24.5	24.7	25.0	25.2	25.5	25.8	26.0	26.3	26.5	26.8	27.0	27.3	27.5	27.8	28.1	28.3	28.6	28.8	24.2	24.2
	TCO (€/km)	0.14	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.19	0.19	0.19	0.19	0.16	0.16
CV	TCO (€/km)	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
																						Curren costs	0	1

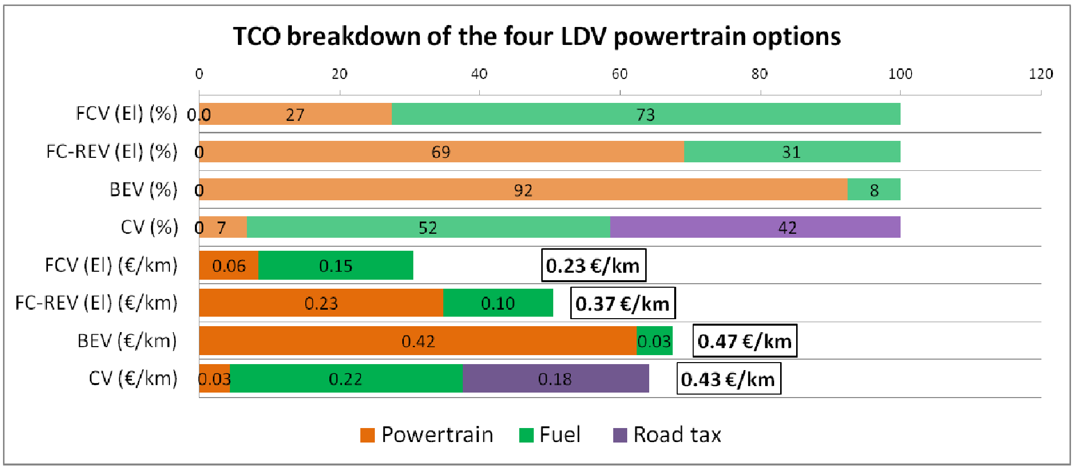
General		CV		BEV		FC-REV		FCV	
General requirements									
Annual distance (km/year)	15040	Diesel consumption (l/km)	0.047	Autonomy (km)	320	Autonomy (km)	320	Autonomy (km)	320
Daily distance (km/day)	48	Motor power (kW)	44	Battery size (kWh)	44	FC power (kW)	5	FC power (kW)	44
Energy consumption (kWhoutput/km)	0.12	Diesel consumption (€/km)	0.08			Battery size (kWh)	22		
Study time frame (yr)	10	Motor cost (€/km)	0.01						
Operating days per week	6	Diesel consumption, NPV-10yr (€/km)	0.06						
Number of operatin weeks	52								
Battery									
				Maintenance cost, year method (k€/year)	4.13	Maintenance cost, year method (k€/year)	2.06		
				Battery cost (€/km)	0.27	Battery cost (€/km)	0.14		
				Battery cost, NPV-10yr (€/km)	0.22	Battery cost, NPV-10yr (€/km)	0.11		
				Electricity cost (€/km)	0.01	Electricity cost (€/km)	0.01		
				Electricity cost, NPV-10yr (€/km)	0.01	Electricity cost, NPV-10yr (€/km)	0.01		
Fuel cell									
						Fuel cell cost (k€)	3.49	Fuel cell cost (k€)	5.81
						FC operating ratio (%)	50	Fuel cell lifetime (unit/year)	0.1
						Fuel cell lifetime (unit/year)	0.05	Maintenance cost (k€/year)	0.571
						Maintenance cost (k€/year)	0.17	Fuel cell cost (€/km)	0.04
						Fuel cell cost (€/km)	0.01	FC cost, NPV-10yr (€/km)	0.03
						FC cost, NPV-10yr (€/km)	0.01		
Hydrogen storage									
						H2 storage (kgH2)	1.14	H2 storage (kgH2)	1.94
						H2 storage cost (k€)	1.08	H2 storage cost (k€)	1.60
						H2 storage cost (€/km)	0.01	H2 storage cost (€/km)	0.01
Hydrogen consumption									
						Hydrogen consumption per km (kgH2/km)	0.004	Hydrogen consumption per km (kgH2/km)	0.006
						Hydrogen cost (€/km)	0.035	Hydrogen cost (€/km)	0.060
						Hydrogen cost, NPV-10yr (€/km)	0.03	Hydrogen cost, NPV-10yr (€/km)	0.05
						Hydrogen annual consumption (kgH2/year)	54	Hydrogen annual consumption (kgH2/year)	91
						Daily hydrogen consumption (kgH2/day)	0.17	Daily hydrogen consumption (kgH2/day)	0.29
						Infrastructure cost (k€)	0.0	Infrastructure cost (k€)	0.0
						Infrastructure cost (€/km)	0.00	Infrastructure cost (€/km)	0.00
Road tax									
		Road tax per day (€/day)	3.59	Road taxes (k€/year)	0	Road taxes (k€/year)	0.00	Road taxes (k€/year)	0.00
		Road taxes (k€/year)	1.12	Road taxes (€/km)	0.00	Road taxes (€/km)	0.00	Road taxes (€/km)	0.00
		Road taxes (€/km)	0.07						
		Road taxes, NPV-10yr (€/km)	0.06						

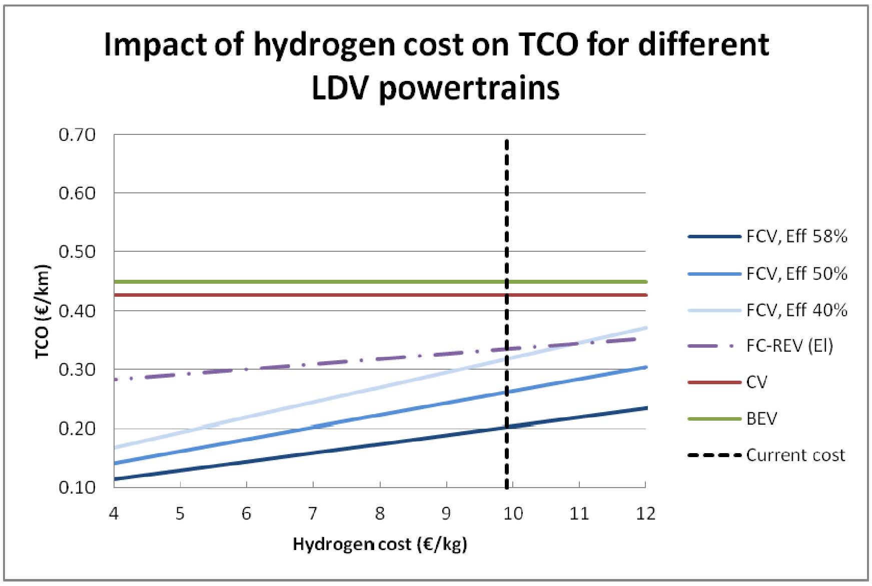
Energy consumption (kWhoutput/km)	Hydrogen consumption (kgH2/km)	Diesel consumption (l/km)	Vehicle power (kW)	EV Tax (k€/km/year)	CV tax (k€/km/year)	Specific energy battery (kg/kWh)
0.12	0.01	0.05	44	0.00E+00	7.45E-05	10

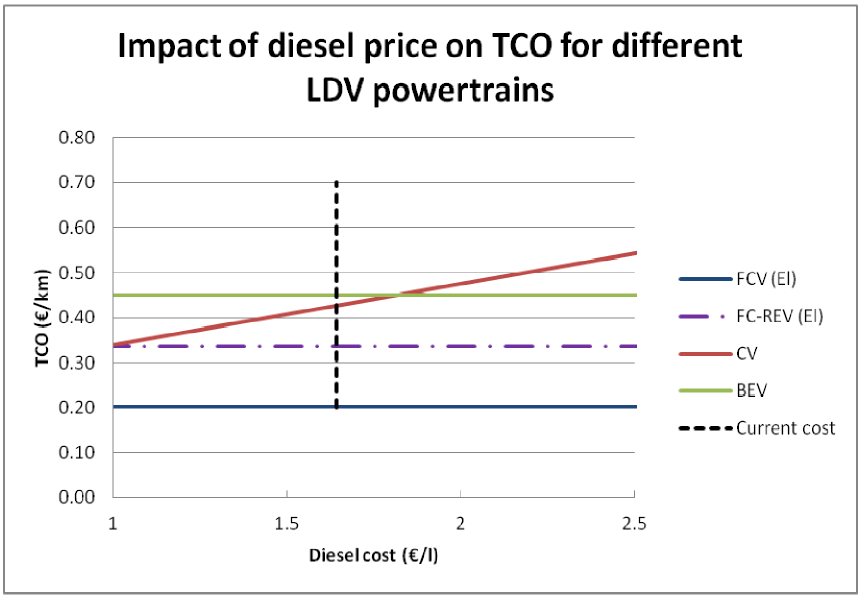
Autonomy requirement (km/day)	Actual yearly distance(km/year)	FC-REV	FC-REV (Tax)	Battery size (kWh)	Battery cost (k€)	Battery replacement/year (k€/yr)	BEV Fuel cost/year (k€/yr)	BEV OPEX (k€/yr)	BEV OPEX TAX (k€)	BEV	BEV (Tax)
40	16000			5.5	4.1	0.52	0.22	0.74	1.93	0.04	0.10
80	16000			11.0	8.3	1.03	0.22	1.25	2.44	0.06	0.12
120	16000			16.5	12.4	1.55	0.22	1.77	2.96	0.09	0.15
160	16000			22.0	16.5	2.06	0.22	2.28	3.47	0.12	0.18
200	16000			27.5	20.6	2.58	0.22	2.80	3.99	0.14	0.20
240	16000			33.0	24.8	3.09	0.22	3.31	4.51	0.17	0.23
280	16000			38.5	28.9	3.61	0.22	3.83	5.02	0.19	0.25
320	16000	0.16	0.21	44.0	33.0	4.13	0.22	4.35	5.54	0.22	0.28
360	16000			49.5	37.1	4.64	0.22	4.86	6.05	0.25	0.31

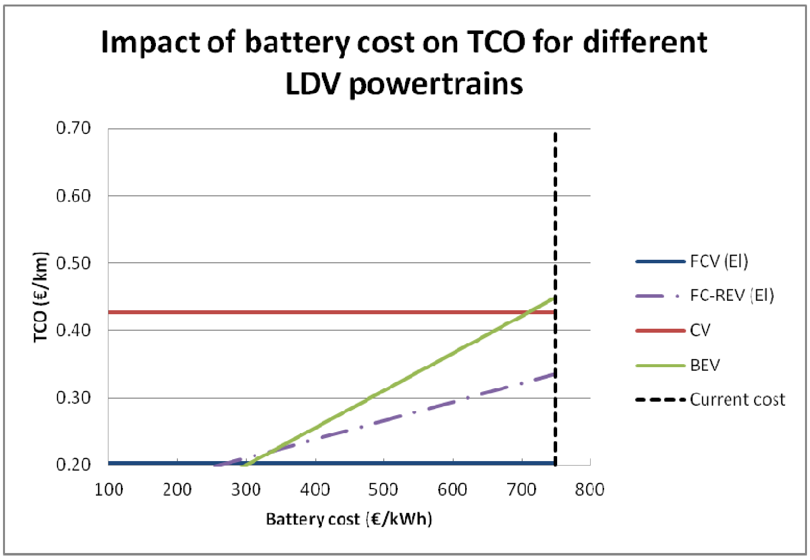
Autonomy requirement (km/day)	Hydrogen storage requirement (kg)	Hydrogen storage weight (tons)	H2 storage cost (k€)	FC cost (k€)	FC weight (tons)	FC replacement / Year (k€/yr)	H2 fuel cost/year (k€/yr)	Infrastructure cost (k€)	FC CAPEX (k€)	FC OPEX (k€)	FC OPEX TAX (k€)	FCV	FCV (Tax)	CV CAPEX (k€)	CV OPEX (k€)	CV
40	0.24	0.004	0.34	5.81	0.11	0.61	0.96	0.00	0.34	1.57	2.76	0.08	0.14	1.85	2.42	0.13
80	0.48	0.007	0.57	5.81	0.11	0.61	0.96	0.00	0.57	1.57	2.76	0.08	0.14	1.85	2.42	0.13
120	0.73	0.011	0.77	5.81	0.11	0.61	0.96	0.00	0.77	1.57	2.76	0.08	0.14	1.85	2.42	0.13
160	0.97	0.015	0.95	5.81	0.11	0.61	0.96	0.00	0.95	1.57	2.76	0.08	0.15	1.85	2.42	0.13
200	1.21	0.018	1.13	5.81	0.11	0.61	0.96	0.00	1.13	1.57	2.76	0.09	0.15	1.85	2.42	0.13
240	1.45	0.022	1.29	5.81	0.11	0.61	0.96	0.00	1.29	1.57	2.76	0.09	0.15	1.85	2.42	0.13
280	1.69	0.025	1.45	5.81	0.11	0.61	0.96	0.00	1.45	1.57	2.76	0.09	0.15	1.85	2.42	0.13
320	1.94	0.029	1.60	5.81	0.11	0.61	0.96	0.00	1.60	1.57	2.76	0.09	0.15	1.85	2.42	0.13
360	2.18	0.033	1.74	5.81	0.11	0.61	0.96	0.00	1.74	1.57	2.76	0.09	0.15	1.85	2.42	0.13

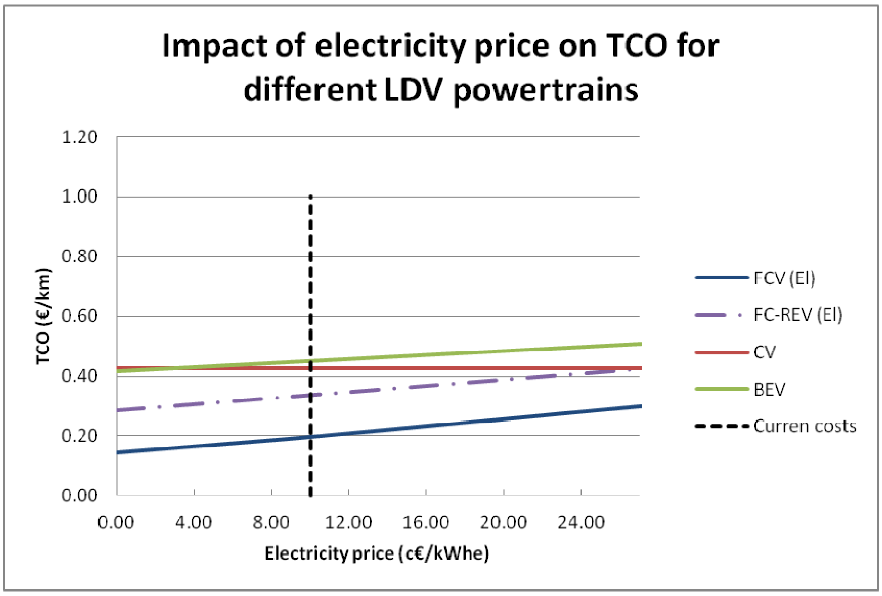
11.4.2 MAXITY STUDY CASE

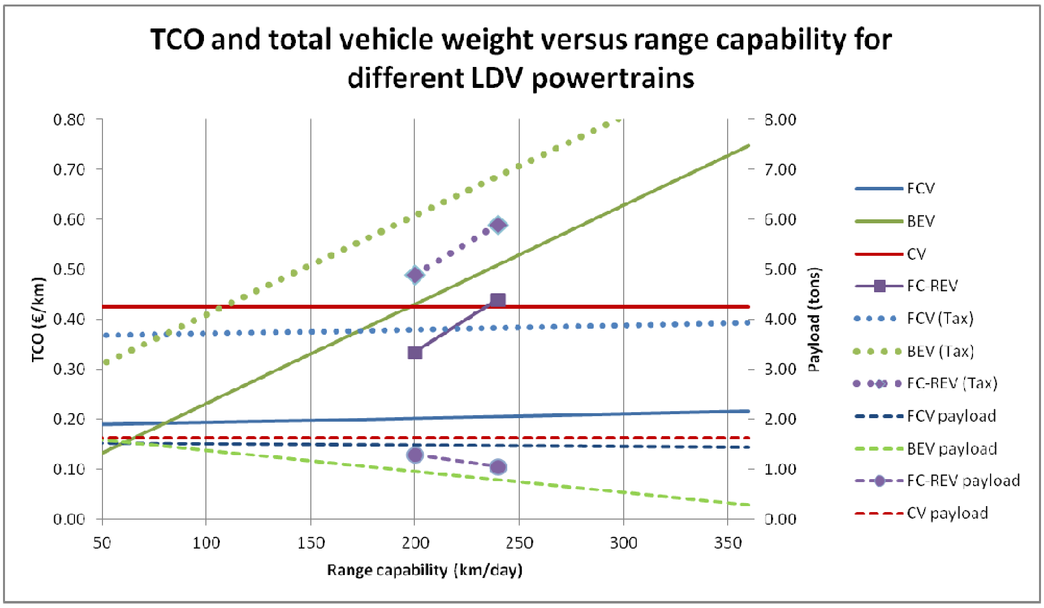







Impact of battery cost on TCO for different LDV powertrains
TCO (€/km)
0.70
0.60
0.50
0.40
0.30
0.20
100
200
300
400
500
600
700
800
Battery cost (€/kWh)
FCV (El)
FC-REV (El)
CV
BEV
Current cost


Impact of electricity price on TCO for different LDV powertrains
TCO (€/km)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
Electricity price (c€/kWhe)
FCV (El)
FC-REV (El)
CV
BEV
Curren costs


TCO and total vehicle weight versus range capability for different LDV powertrains
TCO (€/km)
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Payload (tons)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
50
100
150
200
250
300
350
Range capability (km/day)
FCV
BEV
CV
FC REV
FCV (Tax)
BEV (Tax)
FC-REV (Tax)
FCV payload
BEV payload
FC-REV payload
CV payload

System	CAPEX (k€)	OPEX (k€/year)	NPV, 10yr (k€)	TCO (€/km)	TCO (€/km)	Powertrain	Fuel	Road tax
CV (€/km)	4.4	7.5	65.3	0.43	0.43	0.03	0.22	0.18
BEV (€/km)	0.0	8.5	68.7	0.45	0.45	0.42	0.03	0.00
FC-REV (El) (€/km)	1.7	6.1	51.3	0.34	0.34	0.23	0.10	0.00
FCV (El) (€/km)	2.8	3.5	31.1	0.20	0.20	0.06	0.15	0.00
CV (%)	-	-	-	-	-	7	52	42
BEV (%)	-	-	-	-	-	92	8	0
FC-REV (El) (%)	-	-	-	-	-	69	31	0
FCV (El) (%)	-	-	-	-	-	27	73	0
FC-REV (El), NREL	4.1	7.8	82.5	67.3	0.44			

	Specific H2 price (€/kgH2)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	9.9	9.9
FC-REV (El)	OPEX (k€)	4.7	4.8	5.0	5.2	5.3	5.5	5.7	5.8	6.0	6.2	6.3	6.5	6.7	6.8	7.0	7.2	7.3	7.5	7.7	7.8	6.1	6.1
	NPV OPEX (k€)	37.7	39.0	40.3	41.7	43.0	44.4	45.7	47.0	48.4	49.7	51.1	52.4	53.8	55.1	56.4	57.8	59.1	60.5	61.8	63.1	49.6	49.6
	NPV Total (k€)	39.4	40.7	42.1	43.4	44.8	46.1	47.4	48.8	50.1	51.5	52.8	54.2	55.5	56.8	58.2	59.5	60.9	62.2	63.5	64.9	51.3	51.3
	TCO (€/km)	0.26	0.27	0.28	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.35	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.42	0.34	0.34
FCV, Eff 58%	OPEX (k€)	1.0	1.3	1.6	1.8	2.1	2.4	2.7	3.0	3.3	3.5	3.8	4.1	4.4	4.7	5.0	5.2	5.5	5.8	6.1	6.4	3.5	3.5
	NPV OPEX (k€)	8.0	10.3	12.6	14.9	17.1	19.4	21.7	24.0	26.3	28.6	30.8	33.1	35.4	37.7	40.0	42.2	44.5	46.8	49.1	51.4	28.3	28.3
	NPV Total (k€)	10.80	13.08	15.36	17.64	19.92	22.20	24.48	26.76	29.04	31.32	33.60	35.88	38.16	40.44	42.73	45.01	47.29	49.57	51.85	54.13	31.10	31.10
	TCO (€/km)	0.07	0.09	0.10	0.12	0.13	0.15	0.16	0.18	0.19	0.20	0.22	0.23	0.25	0.26	0.28	0.29	0.31	0.32	0.34	0.35	0.20	0.20
FCV, Eff 50%	TCO (€/km)	0.08	0.10	0.12	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.28	0.30	0.32	0.34	0.36	0.39	0.41	0.43	0.45	0.47	0.26	0.26
FCV, Eff 40%	TCO (€/km)	0.09	0.12	0.14	0.17	0.19	0.22	0.24	0.27	0.30	0.32	0.35	0.37	0.40	0.42	0.45	0.47	0.50	0.52	0.55	0.57	0.32	0.32
CV	TCO (€/km)	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
BEV	TCO (€/km)	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Current cost																						0.1	0.7

	Diesel price (€/l)	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5	1.65	1.8	1.95	2.1	2.25	2.4	2.55	2.7	2.85	3	3.15	1.64	1.64
CV	OPEX (k€)	4.1	4.5	4.9	5.3	5.7	6.0	6.4	6.8	7.2	7.6	8.0	8.3	8.7	9.1	9.5	9.9	10.3	10.6	11.0	11.4	7.5	7.5
	NPV OPEX (k€)	33.3	36.4	39.5	42.6	45.7	48.8	51.8	54.9	58.0	61.1	64.2	67.3	70.4	73.5	76.6	79.7	82.7	85.8	88.9	92.0	60.9	60.9
	NPV Total (k€)	37.7	40.8	43.9	47.0	50.1	53.2	56.3	59.3	62.4	65.5	68.6	71.7	74.8	77.9	81.0	84.1	87.2	90.2	93.3	96.4	65.3	65.3
	TCO (€/km)	0.25	0.27	0.29	0.31	0.33	0.35	0.37	0.39	0.41	0.43	0.45	0.47	0.49	0.51	0.53	0.55	0.57	0.59	0.61	0.63	0.43	0.43
FC-REV (El)	TCO (€/km)	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
FCV (El)	TCO (€/km)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
BEV	TCO (€/km)	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Current cost																						0.2	0.7

	Battery cost (€/kWh)	100	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	750	750
FC-REV (El)	OPEX (k€)	2.7	3.3	3.4	3.5	3.7	3.8	3.9	4.0	4.2	4.3	4.4	4.6	4.7	4.8	5.0	5.1	5.2	5.4	5.5	5.6	5.8	6.1	6.1
	NPV OPEX (k€)	22.1	26.3	27.4	28.4	29.5	30.5	31.6	32.6	33.7	34.8	35.8	36.9	37.9	39.0	40.1	41.1	42.2	43.2	44.3	45.4	46.4	49.6	49.6
	NPV Total (k€)	23.8	28.0	29.1	30.2	31.2	32.3	33.3	34.4	35.4	36.5	37.6	38.6	39.7	40.7	41.8	42.9	43.9	45.0	46.0	47.1	48.2	51.3	51.3
	TCO (€/km)	0.16	0.18	0.19	0.20	0.20	0.21	0.22	0.22	0.23	0.24	0.25	0.25	0.26	0.27	0.27	0.28	0.29	0.29	0.30	0.31	0.32	0.34	0.34
BEV	OPEX (k€)	1.7	2.7	3.0	3.3	3.5	3.8	4.1	4.3	4.6	4.8	5.1	5.4	5.6	5.9	6.2	6.4	6.7	6.9	7.2	7.5	7.7	8.5	8.5
	NPV OPEX (k€)	13.7	22.1	24.2	26.4	28.5	30.6	32.7	34.8	37.0	39.1	41.2	43.3	45.4	47.6	49.7	51.8	53.9	56.0	58.1	60.3	62.4	68.7	68.7
	NPV Total (k€)	13.66	22.13	24.25	26.37	28.49	30.60	32.72	34.84	36.96	39.08	41.20	43.32	45.43	47.55	49.67	51.79	53.91	56.03	58.15	60.26	62.38	68.74	68.74
	TCO (€/km)	0.09	0.14	0.16	0.17	0.19	0.20	0.21	0.23	0.24	0.26	0.27	0.28	0.30	0.31	0.32	0.34	0.35	0.37	0.38	0.39	0.41	0.45	0.45
CV	TCO (€/km)	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
FCV (El)	TCO (€/km)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Current cost																							0.2	0.7

	Electricity cost (c€/kWhe)	0.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00	25.00	26.00	27.00	28.00	10.00	10.00
	Corresponding hydrogen price (€/kgH2)	5.9	9.5	9.9	10.3	10.7	11.1	11.5	11.9	12.3	12.7	13.1	13.5	13.9	14.3	14.7	15.1	15.5	15.9	16.3	16.7	17.1	9.9	9.9
BEV	OPEX (k€/yr)	7.9	8.5	8.5	8.6	8.6	8.7	8.8	8.8	8.9	9.0	9.0	9.1	9.2	9.2	9.3	9.4	9.4	9.5	9.5	9.6	9.7	8.5	8.5
	NPV OPEX (k€)	63.6	68.2	68.7	69.3	69.8	70.3	70.8	71.3	71.8	72.4	72.9	73.4	73.9	74.4	75.0	75.5	76.0	76.5	77.0	77.5	78.1	68.7	68.7
	NPV total (k€)	63.56	68.22	68.74	69.26	69.77	70.29	70.81	71.33	71.85	72.37	72.88	73.40	73.92	74.44	74.96	75.47	75.99	76.51	77.03	77.55	78.06	68.74	68.74
	TCO (€/km)	0.42	0.45	0.45	0.45	0.46	0.46	0.46	0.47	0.47	0.47	0.48	0.48	0.48	0.49	0.49	0.49	0.50	0.50	0.50	0.51	0.51	0.45	0.45
FCV (El)	OPEX (k€/yr)	2.4	3.4	3.5	3.6	3.7	3.8	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0	5.1	5.2	5.3	5.4	5.5	3.5	3.5
	NPV OPEX (k€)	19.2	27.4	28.3	29.2	30.1	31.1	32.0	32.9	33.8	34.7	35.6	36.5	37.4	38.4	39.3	40.2	41.1	42.0	42.9	43.8	44.7	28.3	28.3
	NPV total (k€)	21.97	29.15	30.07	30.98	31.89	32.80	33.71	34.63	35.54	36.45	37.36	38.27	39.19	40.10	41.01	41.92	42.84	43.75	44.66	45.57	46.48	30.07	30.07
	TCO (€/km)	0.14	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.23	0.24	0.24	0.25	0.26	0.26	0.27	0.27	0.28	0.29	0.29	0.30	0.30	0.20	0.20
FC-REV (El)	OPEX (k€)	5.2	6.0	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	6.1	6.1
	NPV OPEX (k€)	41.6	48.8	49.6	50.4	51.2	52.0	52.8	53.6	54.4	55.2	56.0	56.8	57.6	58.3	59.1	59.9	60.7	61.5	62.3	63.1	63.9	49.6	49.6
	NPV Total (k€)	43.4	50.5	51.3	52.1	52.9	53.7	54.5	55.3	56.1	56.9	57.7	58.5	59.3	60.1	60.9	61.7	62.5	63.3	64.1	64.9	65.7	51.3	51.3
	TCO (€/km)	0.28	0.33	0.34	0.34	0.35	0.35	0.36	0.36	0.37	0.37	0.38	0.38	0.39	0.39	0.40	0.40	0.41	0.41	0.42	0.42	0.43	0.34	0.34
CV	TCO (€/km)	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Curren costs																							0	1

General requirements

General	
Annual distance (km/year)	15286
Daily distance (km/day)	49
Energy consumption (kWhoutput/km)	0.3570
Study timeframe (yr)	10
Operating day per week	6

CV	
Diesel consumption (l/km)	0.167
Motor power (kW)	105
Diesel consumption (€/km)	0.27
Motor cost (€/km)	0.03
Diesel consumption, NPV-10yr (€/km)	0.22

BEV	
Autonomy (km)	200
Battery size (kWh)	84

FC-REV	Maxity	NREL
Autonomy (km)	200	250
FC power (kW)	20	21
Battery size (kWh)	42	60

FCV	
Autonomy (km)	200
FC power (kW)	105

Battery

BEV	
Maintenance cost, year method (k€/year)	7.88
Battery cost (€/km)	0.52
Battery cost, NPV-10yr (€/km)	0.42
Electricity cost (€/km)	0.04
Electricity cost, NPV-10yr (€/km)	0.03

FC-REV	Maxity	NREL
Maintenance cost, year method (k€/year)	3.94	3.94
Battery cost (€/km)	0.26	0.26
Battery cost, NPV-10yr (€/km)	0.21	0.21
Electricity cost (€/km)	0.02	0.02
Electricity cost, NPV-10yr (€/km)	0.02	0.02

Fuel cell

FC-REV	Maxity	NREL
Fuel cell cost (k€)	4.83	4.88
FC operating ratio (%)	50	50
Fuel cell lifetime (unit/year)	0.05	0.05
Maintenance cost (k€/year)	0.24	0.24
Fuel cell cost (€/km)	0.02	0.02
FC cost, NPV-10yr (€/km)	0.01	0.01

FCV	
Fuel cell cost (k€)	7.13
Fuel cell lifetime (unit/year)	0.1
Maintenance cost (k€/year)	0.71
Fuel cell cost (€/km)	0.05
FC cost, NPV-10yr (€/km)	0.04

Hydrogen storage

FC-REV	Maxity	NREL
H2 storage (kgH2)	2.17	5.44
H2 storage cost (k€)	1.74	4.08
H2 storage cost (€/km)	0.01	0.03

FCV	
H2 storage (kgH2)	3.7
H2 storage cost (k€)	2.77
H2 storage cost (€/km)	0.02

Hydrogen consumption

FC-REV	Maxity	NREL
Hydrogen consumption per km (kgH2/km)	0.011	0.022
Hydrogen cost (€/km)	0.11	0.22
Hydrogen cost, NPV-10yr (€/km)	0.09	0.17
Hydrogen annual consumption (kgH2/year)	166	332
Daily hydrogen consumption (kgH2/day)	0.53	1.07
Infrastructure cost (k€)	0.0	0.0
Infrastructure cost (€/km)	0.00	0.00

FCV	
Hydrogen consumption per km (kgH2/km)	0.02
Hydrogen cost (€/km)	0.18
Hydrogen cost, NPV-10yr (€/km)	0.15
Hydrogen annual consumption (kgH2/year)	283
Daily hydrogen consumption (kgH2/day)	0.91
Infrastructure cost (k€)	0.0
Infrastructure cost (€/km)	0.00

Road tax

CV	
Road tax per day (€/day)	10.77
Road taxes (k€/year)	3.36024
Road taxes (€/km)	0.22
Road taxes, NPV-10yr (€/km)	0.18

BEV	
Road taxes (k€/year)	0
Road taxes (€/km)	0.00

FC-REV	Maxity	NREL
Road taxes (k€/year)	0.00	0.00
Road taxes (€/km)	0.00	0.00

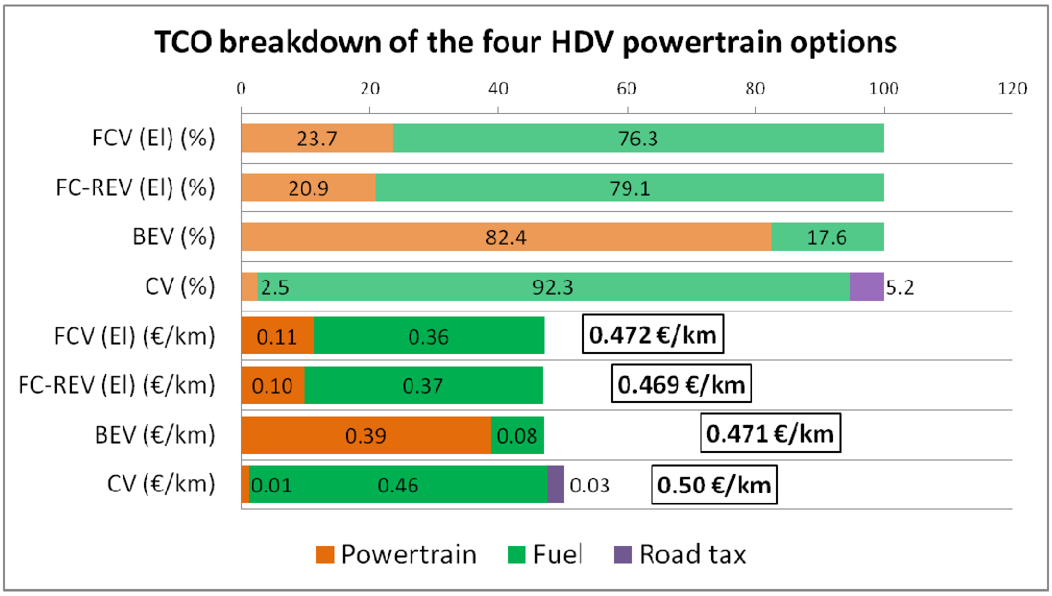
FCV	
Road taxes (k€/year)	0.00
Road taxes (€/km)	0.00

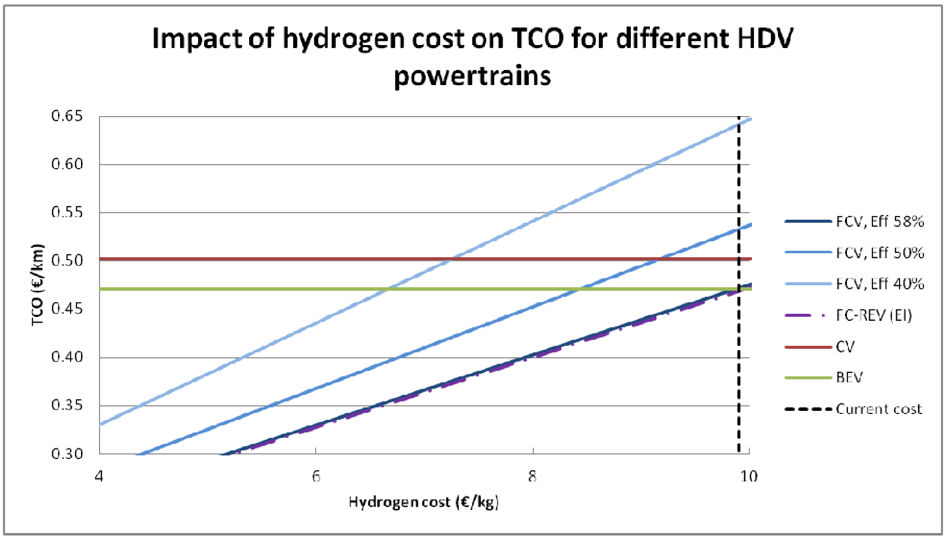
Energy consumption (kWhoutput/km)	Vehicle initial payload (tons)	Hydrogen consumption (kgH2/km)	Diesel consumption (l/km)	Vehicle power (kW)	EV Tax (k€/km/year)	CV tax (k€/km/year)	Specific energy battery (kg/kWh)
0.36	1.80	0.02	0.17	105	0.00E+00	2.20E-04	10

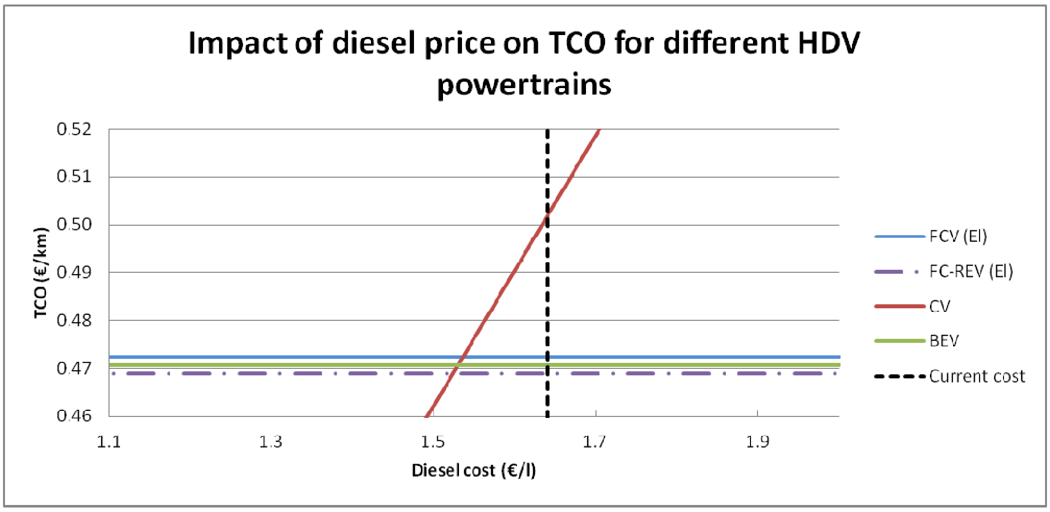
Autonomy requirement (km/day)	Actual yearly distance(km/year)	FC-REV	FC-REV (Tax)	FC-REV payload	Battery size (kWh)	BEV payload	Battery cost (k€)	Battery replacement/year (k€/yr)	BEV Fuel cost/year (k€/yr)	BEV OPEX (k€/yr)	BEV OPEX TAX (k€)	BEV	BEV (Tax)
40	16000				16.8	1.6	12.6	1.58	0.67	2.25	5.76	0.11	0.29
80	16000				33.6	1.5	25.2	3.15	0.67	3.82	7.34	0.19	0.37
120	16000				50.4	1.3	37.8	4.73	0.67	5.40	8.91	0.27	0.45
160	16000				67.2	1.1	50.4	6.30	0.67	6.97	10.49	0.35	0.53
200	16000	0.34	0.49	1.30	84.0	1.0	63.0	7.88	0.67	8.55	12.06	0.43	0.61
240	16000	0.44	0.59	1.07	100.8	0.8	75.6	9.45	0.67	10.12	13.64	0.51	0.69
280	16000				117.6	0.6	88.2	11.03	0.67	11.70	15.21	0.59	0.77
320	16000				134.4	0.5	100.8	12.60	0.67	13.27	16.79	0.67	0.85
360	16000				151.2	0.3	113.4	14.18	0.67	14.85	18.36	0.75	0.93

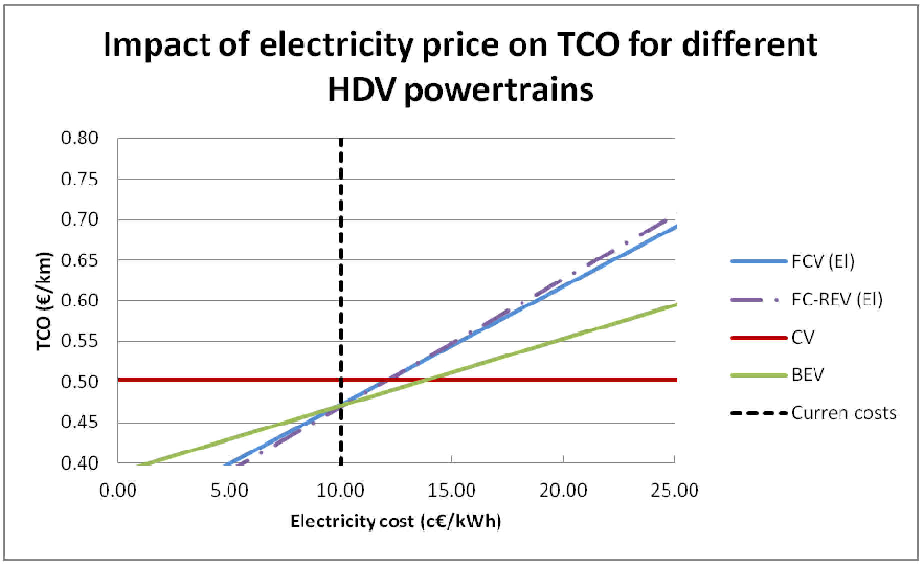
Autonomy requirement (km/day)	Hydrogen storage requirement (kg)	Hydrogen storage weight (tons)	H2 storage cost (k€)	FC cost (k€)	FC weight (tons)	FC replacement / Year (k€/yr)	H2 fuel cost/year (k€/yr)	Infrastructure cost (k€)	FC CAPEX (k€)	FC OPEX (k€)	FC OPEX TAX (k€)	FCV	FCV (Tax)	FCV payload	CV CAPEX (k€)	CV OPEX (k€)	CV	CV payload
40	0.74	0.011	0.78	7.13	0.26	0.75	2.93	0.00	0.78	3.67	7.19	0.19	0.37	1.53	4.41	7.90	0.43	1.64
80	1.48	0.022	1.31	7.13	0.26	0.75	2.93	0.00	1.31	3.67	7.19	0.19	0.37	1.52	4.41	7.90	0.43	1.64
120	2.22	0.033	1.77	7.13	0.26	0.75	2.93	0.00	1.77	3.67	7.19	0.20	0.37	1.50	4.41	7.90	0.43	1.64
160	2.96	0.044	2.19	7.13	0.26	0.75	2.93	0.00	2.19	3.67	7.19	0.20	0.38	1.49	4.41	7.90	0.43	1.64
200	3.70	0.055	2.77	7.13	0.26	0.75	2.93	0.00	2.77	3.67	7.19	0.20	0.38	1.48	4.41	7.90	0.43	1.64
240	4.44	0.067	3.33	7.13	0.26	0.75	2.93	0.00	3.33	3.67	7.19	0.21	0.38	1.47	4.41	7.90	0.43	1.64
280	5.18	0.078	3.88	7.13	0.26	0.75	2.93	0.00	3.88	3.67	7.19	0.21	0.39	1.46	4.41	7.90	0.43	1.64
320	5.91	0.089	4.44	7.13	0.26	0.75	2.93	0.00	4.44	3.67	7.19	0.21	0.39	1.45	4.41	7.90	0.43	1.64
360	6.65	0.100	4.99	7.13	0.26	0.75	2.93	0.00	4.99	3.67	7.19	0.22	0.39	1.44	4.41	7.90	0.43	1.64

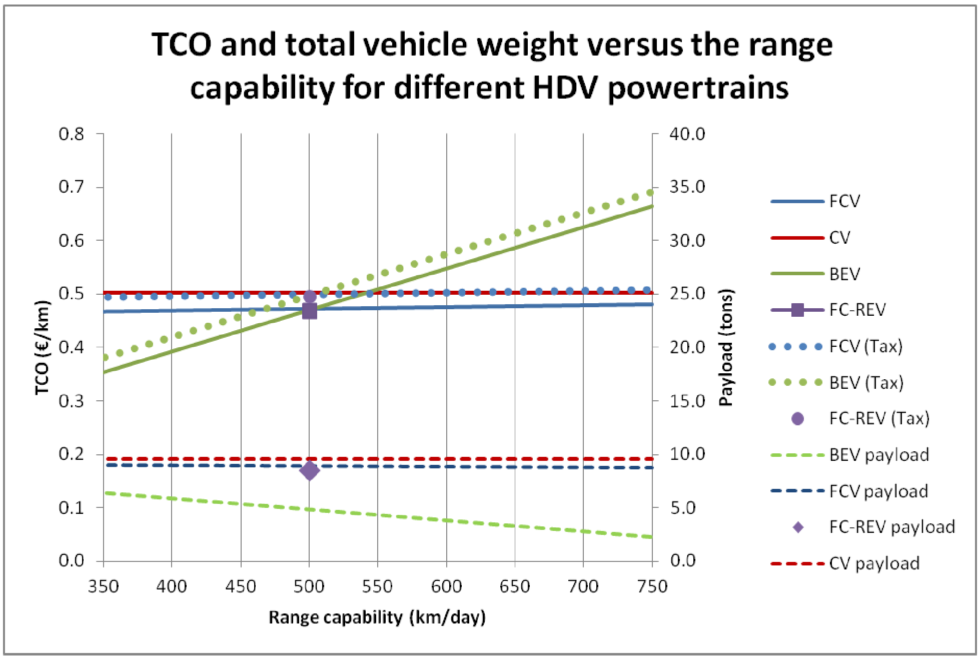
11.4.3 PREMIUM STUDY CASE

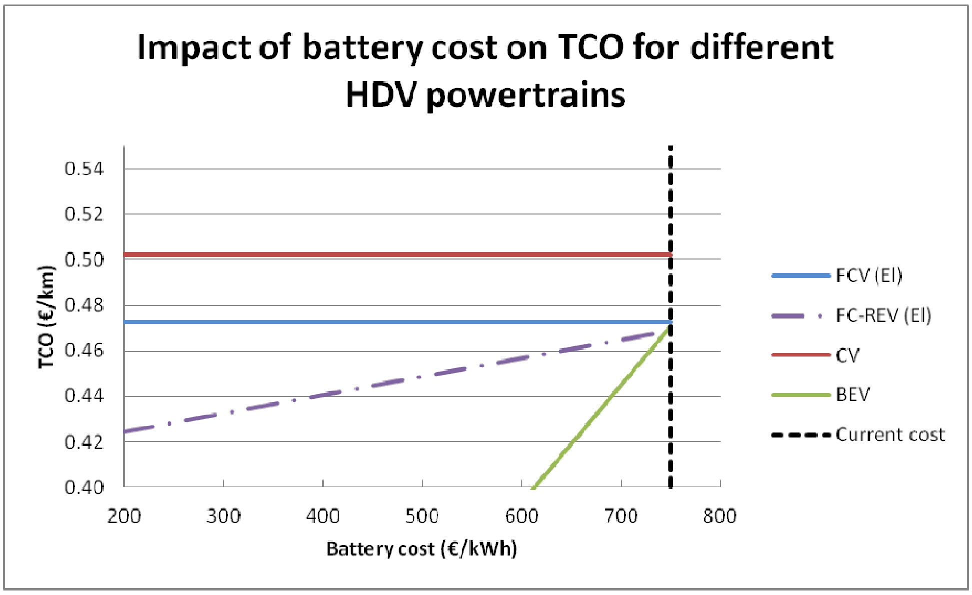







Impact of electricity price on TCO for different HDV powertrains
TCO (€/km)
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.00
5.00
10.00
15.00
20.00
25.00
Electricity cost (c€/kWh)
FCV (El)
FC-REV (El)
CV
BEV
Curren costs


TCO and total vehicle weight versus the range capability for different HDV powertrains
TCO (€/km)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Payload (tons)
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
350
400
450
500
550
600
650
700
750
Range capability (km/day)
FCV
CV
BEV
FC-REV
FCV (Tax)
BEV (Tax)
FC-REV (Tax)
BEV payload
FCV payload
FC-REV payload
CV payload


Impact of battery cost on TCO for different HDV powertrains
TCO (€/km)
0.54
0.52
0.50
0.48
0.46
0.44
0.42
0.40
200
300
400
500
600
700
800
Battery cost (€/kWh)
FCV (El)
FC-REV (El)
CV
BEV
Current cost

System	CAPEX (k€)	OPEX (k€/year)	NPV, 10yr (k€)	TCO (€/km)	TCO (€/km)	Powertrain	Fuel	Road tax
CV (€/km)	12.6	60.7	502.1	0.50	0.502	0.01	0.46	0.03
BEV (€/km)	0.0	58.3	470.6	0.47	0.471	0.39	0.08	0.00
FC-REV (El) (€/km)	16.8	56.0	469.0	0.47	0.469	0.10	0.37	0.00
FCV (El) (€/km)	16.9	56.4	472.4	0.47	0.472	0.11	0.36	0.00
CV (%)	-	-	-	-	-	2.5	92.3	5.2
BEV (%)	-	-	-	-	-	82.4	17.6	0.0
FC-REV (El) (%)	-	-	-	-	-	20.9	79.1	0.0
FCV (El) (%)	-	-	-	-	-	23.7	76.3	0.0

	Specific H2 price (€/kgH2)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	9.9	9.9
FC-REV (El)	OPEX (k€)	16.2	20.6	25.1	29.6	34.1	38.6	43.0	47.5	52.0	56.5	61.0	65.4	69.9	74.4	78.9	83.4	87.8	92.3	96.8	101.3	56.0	56.0
	NPV OPEX (k€)	130.4	166.5	202.7	238.8	275.0	311.1	347.3	383.5	419.6	455.8	491.9	528.1	564.3	600.4	636.6	672.7	708.9	745.0	781.2	817.4	452.2	452.2
	NPV Total (k€)	147.2	183.3	219.5	255.6	291.8	327.9	364.1	400.3	436.4	472.6	508.7	544.9	581.1	617.2	653.4	689.5	725.7	761.8	798.0	834.2	469.0	469.0
	TCO (€/km)	0.15	0.18	0.22	0.26	0.29	0.33	0.36	0.40	0.44	0.47	0.51	0.54	0.58	0.62	0.65	0.69	0.73	0.76	0.80	0.83	0.47	0.47
FCV, Eff 58%	OPEX (k€)	16.3	20.8	25.3	29.8	34.3	38.8	43.4	47.9	52.4	56.9	61.4	65.9	70.4	74.9	79.4	84.0	88.5	93.0	97.5	102.0	56.4	56.4
	NPV OPEX (k€)	131.4	167.8	204.2	240.6	277.0	313.5	349.9	386.3	422.7	459.1	495.5	532.0	568.4	604.8	641.2	677.6	714.0	750.5	786.9	823.3	455.5	455.5
	NPV Total (k€)	148.29	184.70	221.12	257.54	293.96	330.37	366.79	403.21	439.63	476.04	512.46	548.88	585.29	621.71	658.13	694.55	730.96	767.38	803.80	840.21	472.40	472.40
	TCO (€/km)	0.15	0.18	0.22	0.26	0.29	0.33	0.37	0.40	0.44	0.48	0.51	0.55	0.59	0.62	0.66	0.69	0.73	0.77	0.80	0.84	0.47	0.47
FCV, Eff 50%	TCO (€/km)	0.16	0.20	0.24	0.28	0.33	0.37	0.41	0.45	0.49	0.54	0.58	0.62	0.66	0.71	0.75	0.79	0.83	0.87	0.92	0.96	0.53	0.53
FCV, Eff 40%	TCO (€/km)	0.17	0.23	0.28	0.33	0.38	0.44	0.49	0.54	0.59	0.65	0.70	0.75	0.81	0.86	0.91	0.96	1.02	1.07	1.12	1.18	0.64	0.64
CV	TCO (€/km)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
BEV	TCO (€/km)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Current cost																						0.00	0.80

	Diesel price (€/l)	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5	1.65	1.8	1.95	2.1	2.25	2.4	2.55	2.7	2.85	3	3.15	1.64	1.64
CV	OPEX (k€)	13.8	19.0	24.3	29.5	34.8	40.0	45.3	50.5	55.8	61.0	66.3	71.5	76.8	82.0	87.3	92.5	97.8	103.0	108.3	113.5	60.7	60.7
	NPV OPEX (k€)	111.0	153.4	195.7	238.1	280.5	322.9	365.2	407.6	450.0	492.3	534.7	577.1	619.5	661.8	704.2	746.6	788.9	831.3	873.7	916.1	489.5	489.5
	NPV Total (k€)	123.6	166.0	208.3	250.7	293.1	335.5	377.8	420.2	462.6	504.9	547.3	589.7	632.1	674.4	716.8	759.2	801.5	843.9	886.3	928.7	502.1	502.1
	TCO (€/km)	0.12	0.17	0.21	0.25	0.29	0.34	0.38	0.42	0.46	0.50	0.55	0.59	0.63	0.67	0.72	0.76	0.80	0.84	0.89	0.93	0.50	0.50
FC-REV (El)	TCO (€/km)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
FCV (El)	TCO (€/km)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
BEV	TCO (€/km)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Current cost																						0.2	0.8

	Battery cost (€/kWh)	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	750	750
FC-REV (El)	OPEX (k€)	50.5	50.8	51.0	51.3	51.5	51.8	52.0	52.3	52.5	52.8	53.0	53.3	53.5	53.8	54.0	54.3	54.5	54.8	55.0	55.3	56.0	56.0
	NPV OPEX (k€)	407.8	409.8	411.8	413.8	415.8	417.9	419.9	421.9	423.9	425.9	427.9	430.0	432.0	434.0	436.0	438.0	440.1	442.1	444.1	446.1	452.2	452.2
	NPV Total (k€)	424.6	426.6	428.6	430.6	432.6	434.7	436.7	438.7	440.7	442.7	444.8	446.8	448.8	450.8	452.8	454.8	456.9	458.9	460.9	462.9	469.0	469.0
	TCO (€/km)	0.42	0.43	0.43	0.43	0.43	0.43	0.44	0.44	0.44	0.44	0.44	0.45	0.45	0.45	0.45	0.45	0.46	0.46	0.46	0.46	0.47	0.47
BEV	OPEX (k€)	23.1	24.7	26.3	27.9	29.5	31.1	32.7	34.3	35.9	37.5	39.1	40.7	42.3	43.9	45.5	47.1	48.7	50.3	51.9	53.5	58.3	58.3
	NPV OPEX (k€)	186.2	199.1	212.0	225.0	237.9	250.8	263.8	276.7	289.6	302.5	315.5	328.4	341.3	354.3	367.2	380.1	393.1	406.0	418.9	431.8	470.6	470.6
	NPV Total (k€)	186.18	199.11	212.04	224.97	237.90	250.83	263.76	276.69	289.62	302.55	315.48	328.41	341.34	354.27	367.20	380.13	393.05	405.98	418.91	431.84	470.63	470.63
	TCO (€/km)	0.19	0.20	0.21	0.22	0.24	0.25	0.26	0.28	0.29	0.30	0.32	0.33	0.34	0.35	0.37	0.38	0.39	0.41	0.42	0.43	0.47	0.47
CV	TCO (€/km)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
FCV (El)	TCO (€/km)	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Current cost																						0.2	0.8

	Electricity cost (c€/kWhe)	0.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00	25.00	26.00	27.00	28.00	10.00	10.00
	Hydrogen price (€/kgH2)	5.9	9.5	9.9	10.3	10.7	11.1	11.5	11.9	12.3	12.7	13.1	13.5	13.9	14.3	14.7	15.1	15.5	15.9	16.3	16.7	17.1	9.9	9.9
BEV	OPEX (k€/yr)	48	57	58	59	60	61	62	63	64	65	67	68	69	70	71	72	73	74	75	76	77	58	58
	NPV OPEX (k€)	387.9	462.4	470.6	478.9	487.2	495.5	503.7	512.0	520.3	528.6	536.8	545.1	553.4	561.7	569.9	578.2	586.5	594.8	603.0	611.3	619.6	470.6	470.6
	NPV total (k€)	387.88	462.36	470.63	478.91	487.18	495.46	503.73	512.01	520.28	528.56	536.83	545.11	553.38	561.65	569.93	578.20	586.48	594.75	603.03	611.30	619.58	470.63	470.63
	TCO (€/km)	0.39	0.46	0.47	0.48	0.49	0.50	0.50	0.51	0.52	0.53	0.54	0.55	0.55	0.56	0.57	0.58	0.59	0.59	0.60	0.61	0.62	0.47	0.47
FCV (El)	OPEX (k€/yr)	38	55	56	58	60	62	64	65	67	69	71	73	74	76	78	80	82	84	85	87	89	56	56
	NPV OPEX (k€)	309.8	440.9	455.5	470.0	484.6	499.2	513.7	528.3	542.9	557.4	572.0	586.6	601.1	615.7	630.3	644.8	659.4	674.0	688.5	703.1	717.7	455.5	455.5
	NPV total (k€)	326.73	457.83	472.40	486.97	501.53	516.10	530.67	545.23	559.80	574.37	588.94	603.50	618.07	632.64	647.20	661.77	676.34	690.90	705.47	720.04	734.60	472.40	472.40
	TCO (€/km)	0.33	0.46	0.47	0.49	0.50	0.52	0.53	0.55	0.56	0.57	0.59	0.60	0.62	0.63	0.65	0.66	0.68	0.69	0.71	0.72	0.73	0.47	0.47
FC-REV (El)	OPEX (k€)	36.5	54.1	56.0	58.0	59.9	61.9	63.8	65.8	67.7	69.7	71.6	73.6	75.5	77.5	79.4	81.4	83.4	85.3	87.3	89.2	91.2	56.0	56.0
	NPV OPEX (k€)	294.6	436.4	452.2	467.9	483.7	499.4	515.2	530.9	546.7	562.4	578.2	594.0	609.7	625.5	641.2	657.0	672.7	688.5	704.2	720.0	735.7	452.2	452.2
	NPV Total (k€)	311.4	453.2	469.0	484.7	500.5	516.2	532.0	547.7	563.5	579.2	595.0	610.8	626.5	642.3	658.0	673.8	689.5	705.3	721.0	736.8	752.5	469.0	469.0
	TCO (€/km)	0.31	0.45	0.47	0.48	0.50	0.52	0.53	0.55	0.56	0.58	0.59	0.61	0.63	0.64	0.66	0.67	0.69	0.71	0.72	0.74	0.75	0.47	0.47
CV	TCO (€/km)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Curren costs																							0	1

General | **CV** | **BEV** | **FC-REV** | **FCV**

General requirements

General	
Annual distance (km/year)	100000
Daily distance (km/day)	331
Energy consumption (kWhoutput/km)	0.8715
Maximum payload (tons)	10
Study time frame (yr)	10
Operating day per week	5.8

CV	
Diesel consumption (l/km)	0.35
Motor power (kW)	300
Motor cost (€/km)	0.01
Diesel consumption (€/km)	0.57
Diesel consumption, NPV-10yr (€/km)	0.46

BEV	
Autonomy (km)	500
Battery size (kWh)	513

FC-REV	
Autonomy (km)	500
FC power (kW)	160
Battery size (kWh)	80

FCV	
Autonomy (km)	500
FC power (kW)	300

Battery

BEV	
Maintenance cost, year method (k€/year)	48.06
Battery cost (€/km)	0.48
Battery cost, NPV-10yr (€/km)	0.39
Electricity cost (€/km)	0.10
Electricity cost, NPV-10yr (€/km)	0.08

FC-REV	
Maintenance cost, year method (k€/year)	7.50
Battery cost (€/km)	0.08
Battery cost, NPV-10yr (€/km)	0.06
Electricity cost (€/km)	0.02
Electricity cost, NPV-10yr (€/km)	0.01

Fuel cell

FC-REV	
Fuel cell cost (k€)	7.87
FC operating ratio (%)	50
Fuel cell lifetime (unit/year)	0.33
Maintenance cost (k€/year)	2.57
Fuel cell cost (€/km)	0.03
FC cost, NPV-10yr (€/km)	0.02

FCV	
Fuel cell cost (k€)	18.00
Fuel cell lifetime (unit/year)	0.7
Maintenance cost (k€/year)	11.76
FC cost (€/km)	0.12
FC cost, NPV-10yr (€/km)	0.09

Hydrogen storage

FC-REV	
H2 storage (kgH2)	22.4
H2 storage cost (k€)	16.80
H2 storage cost (€/km)	0.02

FCV	
H2 storage (kgH2)	22.6
H2 storage cost (k€)	16.92
H2 storage cost (€/km)	0.02

Hydrogen consumption

FC-REV	
Hydrogen consumption per km (kgH2/km)	0.045
Hydrogen cost (€/km)	0.44
Hydrogen cost, NPV-10yr (€/km)	0.36
Hydrogen annual consumption (kgH2/year)	4480
Daily hydrogen consumption (kgH2/day)	14.8
Infrastructure cost (k€)	0.0
Infrastructure cost (€/km)	0.00

FCV	
Hydrogen consumption per km (kgH2/km)	0.045
Hydrogen cost (€/km)	0.45
Hydrogen cost, NPV-10yr (€/km)	0.36
Hydrogen annual consumption (kgH2/year)	4512
Daily hydrogen consumption (kgH2/day)	14.9
Infrastructure cost (k€)	0.0
Infrastructure cost (€/km)	0.00

Road tax

CV	
Road tax per day (€/day)	10.77
Road taxes (k€/year)	3.2538324
Road taxes (€/km)	0.03
Road taxes, NPV-10yr (€/km)	0.03

BEV	
Road taxes (k€/year)	0
Road taxes (€/km)	0.00

FC-REV	
Road taxes (k€/year)	0.00
Road taxes (€/km)	0.00

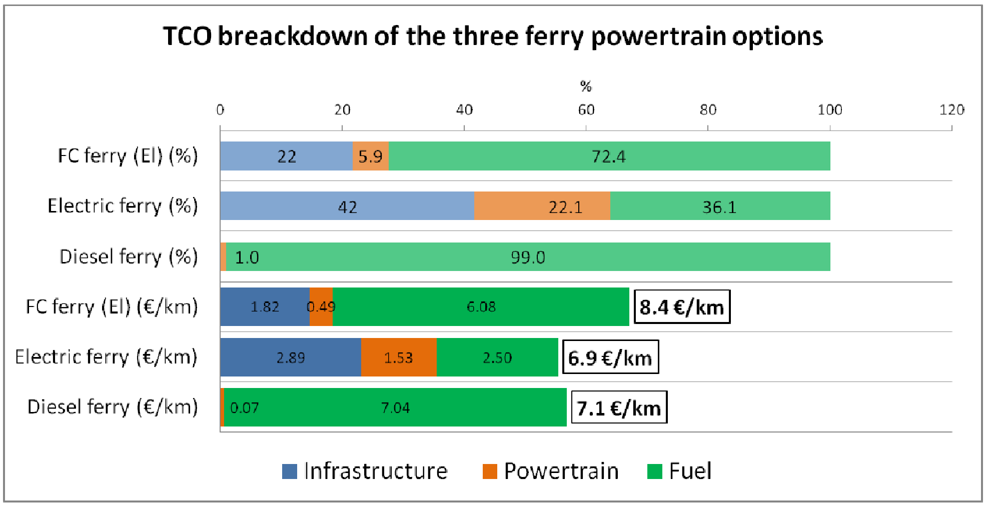
FCV	
Road taxes (k€/year)	0.00
Road taxes (€/km)	0.00

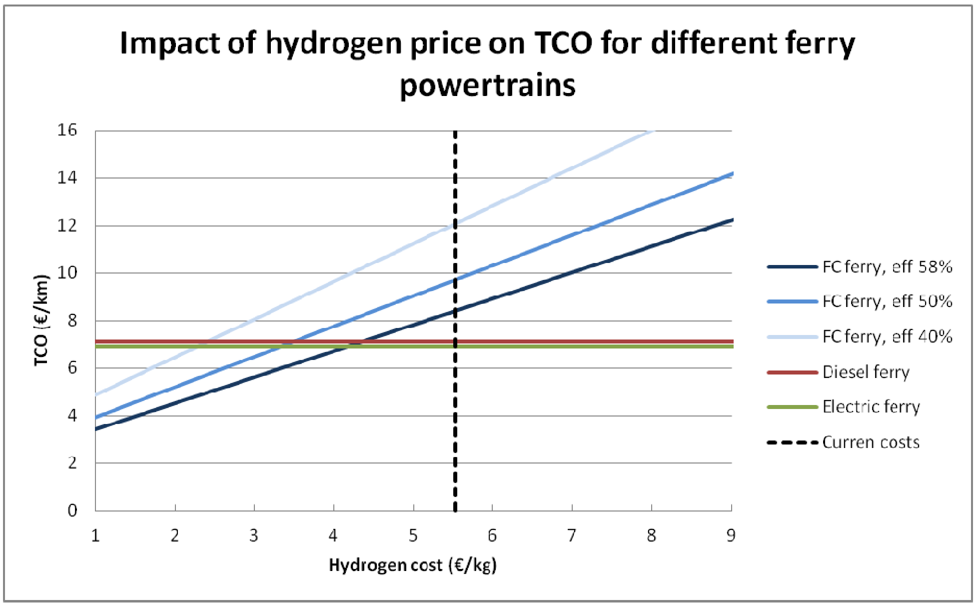
Energy consumption (kWhwork/km)	Maximum payload (tons)	Specific energy consumption (kWhoutput/kg/km)	Hydrogen consumption (kgH2/km)	Diesel consumption (l/km)	Vehicle power (kW)	EV Tax (k€/km/year)	CV tax (k€/km/year)	Specific energy battery (kg/kWh)
0.87	10.00	8.72E-05	0.05	0.35	300	0.00E+00	3.25E-05	10

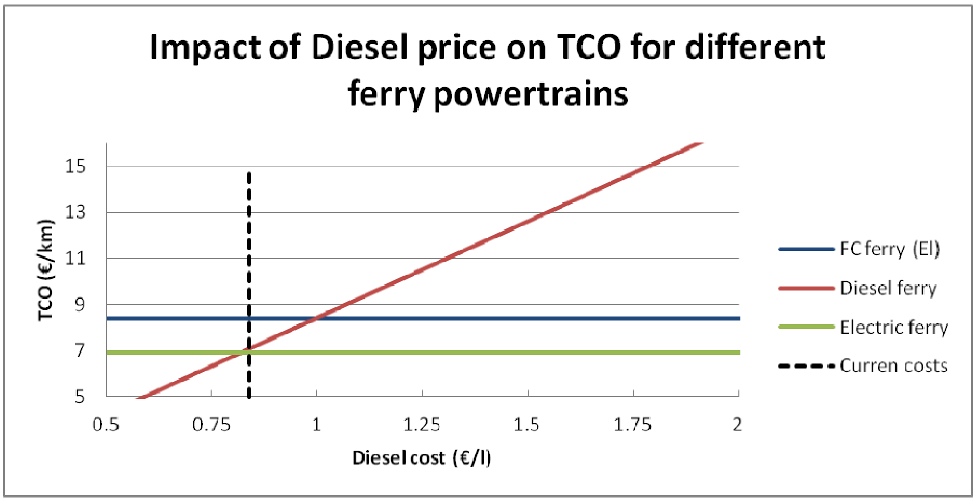
Autonomy requirement (km/day)	Actual yearly distance(km/year)	FC-REV	FC-REV (Tax)	FC-REV payload	Battery size (kWh)	BEV payload	Battery cost (k€)	Battery replacement/year (k€/yr)	BEV Fuel cost/year (k€/yr)	BEV OPEX (k€/yr)	BEV OPEX TAX (k€)	BEV	BEV (Tax)
50	100000				51.3	9.5	38.4	4.81	10.25	15.06	18.31	0.12	0.15
175	100000				179.4	8.2	134.6	16.82	10.25	27.07	30.33	0.22	0.24
240	100000				246.1	7.5	184.6	23.07	10.25	33.32	36.58	0.27	0.30
280	100000				287.1	7.1	215.3	26.91	10.25	37.17	40.42	0.30	0.33
320	100000				328.1	6.7	246.1	30.76	10.25	41.01	44.27	0.33	0.36
340	100000				348.6	6.5	261.5	32.68	10.25	42.93	46.19	0.35	0.37
400	100000				410.1	5.9	307.6	38.45	10.25	48.70	51.96	0.39	0.42
500	100000	0.469	0.50	8.46	512.6	4.9	384.5	48.06	10.25	58.31	61.57	0.47	0.50
750	100000				769.0	2.3	576.7	72.09	10.25	82.34	85.60	0.66	0.69

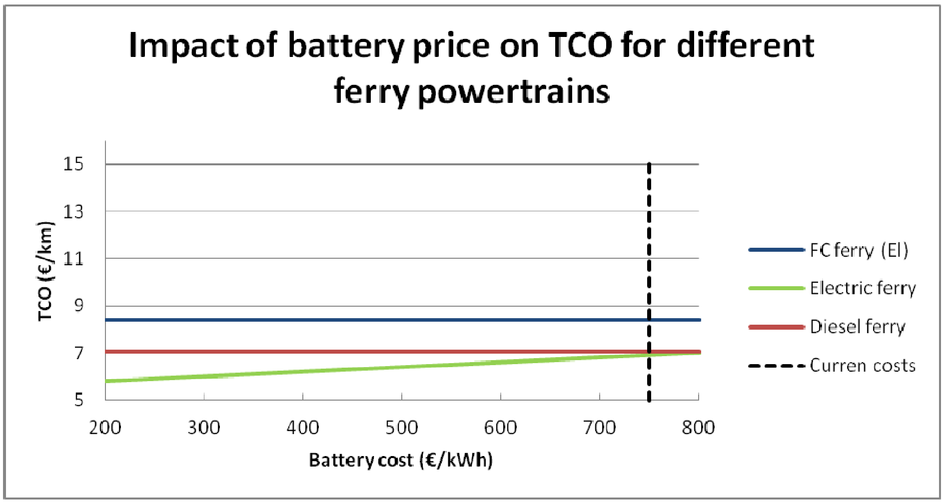
Autonomy requirement (km/day)	Hydrogen storage requirement (kg)	Hydrogen storage weight (tons)	H2 storage cost (k€)	FC cost (k€)	FC weight (tons)	FC replacement / Year (k€/yr)	H2 fuel cost/year (k€/yr)	Infrastructure cost (k€)	FC CAPEX (k€)	FC OPEX (k€)	FC OPEX TAX (k€)	FCV	FCV (Tax)	FCV payload	CV CAPEX (k€)	CV OPEX (k€)	CV	CV payload
50	2.26	0.034	1.79	18.00	0.75	11.76	44.67	0.00	1.79	56.44	59.69	0.46	0.48	9.22	12.60	60.65	0.50	9.54
175	7.90	0.118	5.92	18.00	0.75	11.76	44.67	0.00	5.92	56.44	59.69	0.46	0.49	9.13	12.60	60.65	0.50	9.54
240	10.83	0.162	8.12	18.00	0.75	11.76	44.67	0.00	8.12	56.44	59.69	0.46	0.49	9.09	12.60	60.65	0.50	9.54
280	12.63	0.189	9.48	18.00	0.75	11.76	44.67	0.00	9.48	56.44	59.69	0.46	0.49	9.06	12.60	60.65	0.50	9.54
320	14.44	0.216	10.83	18.00	0.75	11.76	44.67	0.00	10.83	56.44	59.69	0.47	0.49	9.03	12.60	60.65	0.50	9.54
340	15.34	0.230	11.51	18.00	0.75	11.76	44.67	0.00	11.51	56.44	59.69	0.47	0.49	9.02	12.60	60.65	0.50	9.54
400	18.05	0.271	13.54	18.00	0.75	11.76	44.67	0.00	13.54	56.44	59.69	0.47	0.50	8.98	12.60	60.65	0.50	9.54
500	22.56	0.338	16.92	18.00	0.75	11.76	44.67	0.00	16.92	56.44	59.69	0.47	0.50	8.91	12.60	60.65	0.50	9.54
750	33.84	0.507	25.38	18.00	0.75	11.76	44.67	0.00	25.38	56.44	59.69	0.48	0.51	8.74	12.60	60.65	0.50	9.54

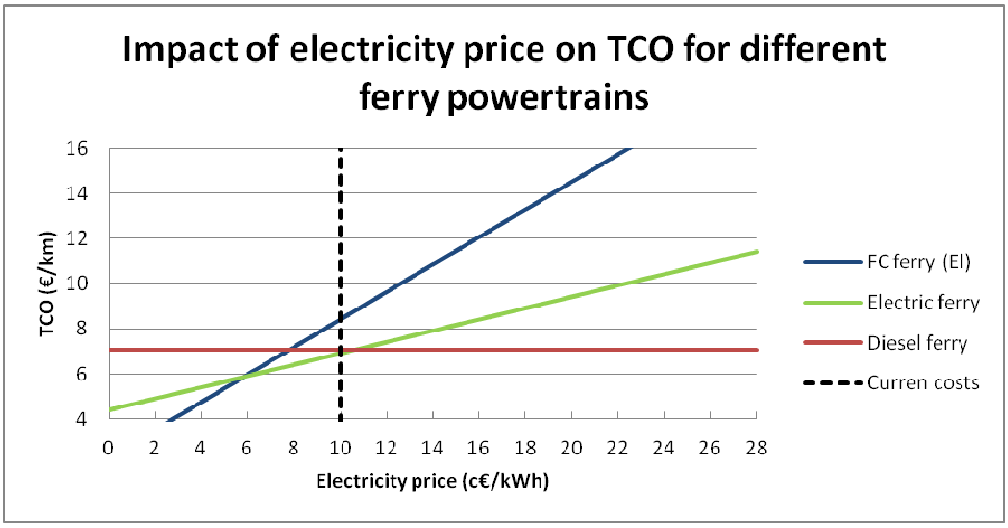
11.4.4 SOGNEFJORD STUDY CASE

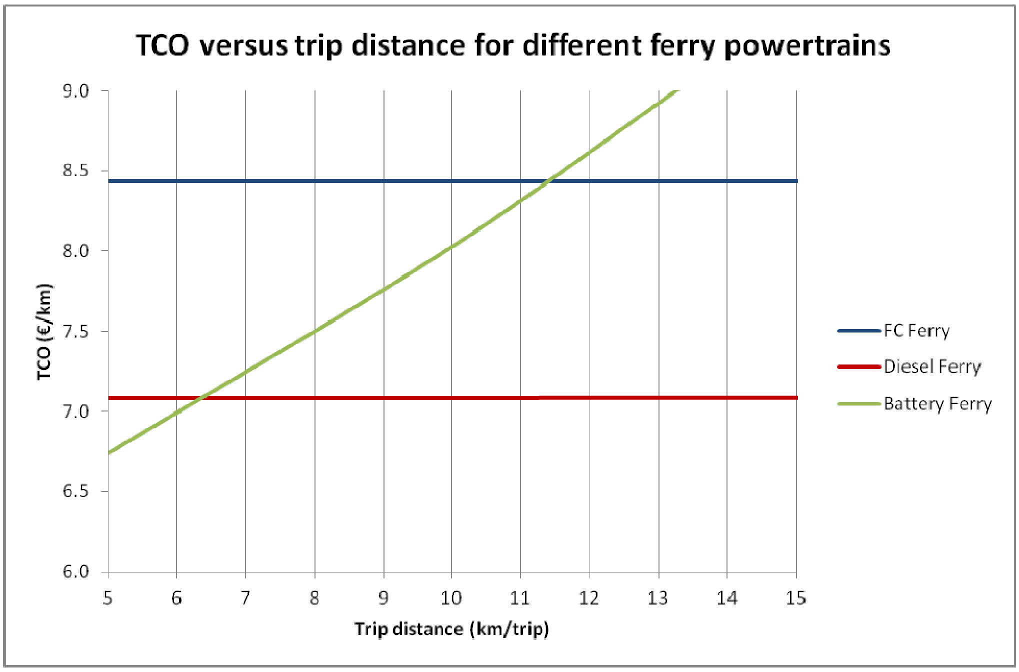







Impact of battery price on TCO for different ferry powertrains
TCO (€/km)
15
13
11
9
7
5
200
300
400
500
600
700
800
Battery cost (€/kWh)
FC ferry (El)
Electric ferry
Diesel ferry
Curren costs


Impact of electricity price on TCO for different ferry powertrains
TCO (€/km)
16
14
12
10
8
6
4
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Electricity price (c€/kWh)
FC ferry (El)
Electric ferry
Diesel ferry
Curren costs


TCO versus trip distance for different ferry powertrains
TCO (€/km)
9.0
8.5
8.0
7.5
7.0
6.5
6.0
5
6
7
8
9
10
11
12
13
14
15
Trip distance (km/trip)
FC Ferry
Diesel Ferry
Battery Ferry

System	CAPEX (k€)	OPEX (k€/year)	NPV, 10yr (k€)	TCO (€/km)	TCO (€/km)	Infrastructure	Powertrain	Fuel
Diesel ferry (€/km)	33.6	649.4	5274.5	7.08	7.11	0	0.07	7.04
Electric ferry (€/km)	3292.2	230.8	5155.1	6.92	6.92	2.89	1.53	2.50
FC ferry (El) (€/km)	1565.5	580.4	6249.9	8.39	8.39	1.82	0.49	6.08
Diesel ferry (%)	-	-	-	-	-	0.0	1.0	99.0
Electric ferry (%)	-	-	-	-	-	42	22.1	36.1
FC ferry (El) (%)	-	-	-	-	-	22	5.9	72.4

H2 price variation

	Specific H2 price (€/kgH2)	1	2	3	4	5	5.52	5.52	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	5.52	5.52
FC ferry, eff 58%	OPEX (k€/yr)	121.2	222.8	324.4	426.0	527.6	580.4	580.4	629.2	730.8	832.3	933.9	1035.5	1137.1	1238.7	1340.3	1441.9	1543.4	1645.0	1746.6	1848.2	1949.8	2051.4	580.4	580.4
	NPV OPEX (k€)	978.5	1798.4	2618.2	3438.1	4258.0	4684.3	4684.3	5077.8	5897.7	6717.6	7537.4	8357.3	9177.2	9997.0	10816.9	11636.8	12456.6	13276.5	14096.4	14916.2	15736.1	16556.0	4684.3	4684.3
	NPV total (k€)	2544.06	3363.93	4183.79	5003.66	5823.52	6249.85	6249.85	6643.39	7463.25	8283.12	9102.98	9922.85	10742.72	11562.58	12382.45	13202.31	14022.18	14842.04	15661.91	16481.77	17301.64	18121.51	6249.85	6249.85
	TCO (€/km)	3.42	4.52	5.62	6.72	7.82	8.39	8.39	8.92	10.02	11.12	12.23	13.33	14.43	15.53	16.63	17.73	18.83	19.93	21.03	22.14	23.24	24.34	8.39	8.39
FC ferry, eff 50%	TCO (€/km)	3.93	5.21	6.48	7.76	9.04	9.70	9.70	10.32	11.59	12.87	14.15	15.42	16.70	17.98	19.26	20.53	21.81	23.09	24.37	25.64	26.92	28.20	9.70	9.70
FC ferry, eff 40%	TCO (€/km)	4.86	6.45	8.05	9.65	11.24	12.07	12.07	12.84	14.44	16.03	17.63	19.23	20.82	22.42	24.02	25.61	27.21	28.81	30.40	32.00	33.60	35.19	12.07	12.07
Diesel ferry	TCO (€/km)	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08
Electric ferry	TCO (€/km)	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92
Curren costs																								0	16

Diesel price variation

	Diesel price (€/l)	0.3	0.45	0.6	0.75	0.9	1.05	1.2	1.35	1.5	0.84	0.84	1.65	1.8	1.95	2.1	2.25	2.4	2.55	2.7	2.85	3	3.15
Diesel ferry	OPEX (k€/yr)	231.9	347.9	463.8	579.8	695.8	811.7	927.7	1043.6	1159.6	649.4	649.4	1275.5	1391.5	1507.5	1623.4	1739.4	1855.3	1971.3	2087.3	2203.2	2319.2	2435.1
	NPV OPEX (k€)	1871.7	2807.6	3743.5	4679.3	5615.2	6551.1	7486.9	8422.8	9358.7	5240.9	5240.9	10294.5	11230.4	12166.3	13102.1	14038.0	14973.9	15909.8	16845.6	17781.5	18717.4	19653.2
	NPV total (k€)	1905.3	2841.2	3777.1	4712.9	5648.8	6584.7	7520.5	8456.4	9392.3	5274.5	5274.5	10328.1	11264.0	12199.9	13135.7	14071.6	15007.5	15943.4	16879.2	17815.1	18751.0	19686.8
	TCO (€/km)	2.56	3.82	5.07	6.33	7.59	8.84	10.10	11.36	12.61	7.08	7.08	13.87	15.13	16.38	17.64	18.90	20.16	21.41	22.67	23.93	25.18	26.44
FC ferry (El)	TCO (€/km)	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39
Electric ferry	TCO (€/km)	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92
Curren costs											5	15											

Battery price variation

	Battery cost (€/kWh)	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550	575	600	600	625	650	675	700	725	750
Electric ferry	OPEX (k€/yr)	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8	230.8
	NPV OPEX (k€)	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9	1862.9
	NPV total (k€)	4319.13	4357.13	4395.13	4433.13	4471.13	4509.13	4547.13	4585.13	4623.13	4661.13	4699.13	4737.13	4775.13	4813.13	4851.13	4889.13	4927.13	4927.13	4965.13	5003.13	5041.13	5079.13	5117.13	5155.13
	TCO (€/km)	5.80	5.85	5.90	5.95	6.00	6.06	6.11	6.16	6.21	6.26	6.31	6.36	6.41	6.46	6.52	6.57	6.62	6.62	6.67	6.72	6.77	6.82	6.87	6.92
Diesel ferry	TCO (€/km)	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08
FC ferry (El)	TCO (€/km)	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39	8.39
Curren costs																		5	15						

Electricity price variation

	Electricity cost (c€/kWhe)	0.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00	25.00	26.00	27.00	28.00	10.00	10.00
Electric ferry	OPEX (k€/yr)	0	208	231	254	277	300	323	346	369	392	415	439	462	485	508	531	554	577	600	623	646		
	NPV OPEX (k€)	0.0	1676.6	1862.9	2049.2	2235.5	2421.8	2608.1	2794.4	2980.7	3167.0	3353.3	3539.6	3725.9	3912.1	4098.4	4284.7	4471.0	4657.3	4843.6	5029.9	5216.2		
	NPV total (k€)	3292.20	4968.83	5155.13	5341.42	5527.71	5714.01	5900.30	6086.59	6272.88	6459.18	6645.47	6831.76	7018.05	7204.35	7390.64	7576.93	7763.23	7949.52	8135.81	8322.10	8508.40		
	TCO (€/km)	4.42	6.67	6.92	7.17	7.42	7.67	7.92	8.17	8.42	8.67	8.92	9.18	9.43	9.68	9.93	10.18	10.43	10.68	10.93	11.18	11.43		
FC ferry (El)	OPEX (k€/yr)	20	525	582	638	694	750	806	863	919	975	1031	1087	1144	1200	1256	1312	1368	1424	1481	1537	1593		
	NPV OPEX (k€)	158.6	4240.3	4693.8	5147.3	5600.8	6054.3	6507.8	6961.4	7414.9	7868.4	8321.9	8775.4	9228.9	9682.4	10135.9	10589.5	11043.0	11496.5	11950.0	12403.5	12857.0		
	NPV total (k€)	1724.19	5805.82	6259.33	6712.85	7166.36	7619.87	8073.39	8526.90	8980.41	9433.93	9887.44	10340.95	10794.47	11247.98	11701.50	12155.01	12608.52	13062.04	13515.55	13969.06	14422.58		
	TCO (€/km)	2.32	7.80	8.41	9.02	9.62	10.23	10.84	11.45	12.06	12.67	13.28	13.89	14.50	15.11	15.72	16.32	16.93	17.54	18.15	18.76	19.37		
Diesel ferry	TCO (€/km)	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08	7.08		
Curren costs																							0	20

Duty cycle

Diesel ferry

Battery electric ferry

Fuel cell ferry

General requirements

Operating days (days/year)	365
Annual distance (km/year)	74460
Daily distance (km/day)	204
Energy consumption (kWhoutput/km)	26.4
Time per trip (hours)	0.33
Cruise speed (hours/km)	0.055
Trip per year (trip/year)	12410
Timeframe (years)	10

Diesel consumption (l/km)	10.4
Diesel cost (€/km)	8.72
Motor power (kW)	800
Motor cost (€/km)	0.07

Battery onboard, B1 (kWh)	1000
Batteries onshore, B2 & B3 (kWh)	260

Autonomy (km)	204
FC power (kW)	800

Battery

B1 Maintenance cost, year method (k€/year)	75.00
B2 & B3 Maintenance cost, year method (k€/year)	19.50
Batteries cost (€/km)	1.53
Infrastructure cost (k€)	2152.2
Infrastructure cost (€/km)	2.89
Electricity cost (€/km)	3.10

Fuel cell

Fuel cell cost (k€)	48.00
Fuel cell lifetime (unit/year)	0.41
Maintenance cost (k€/year)	19.66
Fuel cell cost (€/km)	0.26

Hydrogen storage

H2 storage (kgH2)	278.3
CH2 storage cost (k€)	208.74
CH2 storage cost (€/km)	0.28

Hydrogen consumption

Hydrogen consumption per km (kgH2/km)	1.36
Hydrogen cost (€/km)	7.53
Hydrogen annual consumption (kgH2/year)	101585
Daily hydrogen consumption (kgH2/day)	278.3
Refueling station cost (k€)	1356.8
Refueling station cost (€/km)	1.8

Infrastructure cost (k€)	Operation time per day (hours)	Cruise speed (hours/km)	Energy consumption (kWhoutput/km)	Hydrogen consumption (kgH2/km)	Diesel consumption (l/km)	Vehicle power (kW)
2152.2	11	0.055	26.35	1.36	10.38	800

Trip distance (km/trip)	Number of trips per day	Actual yearly distance(km/year)	B1 size (kWh)	B2/B3 size (kWh)	Battery cost (k€)	BEV OPEX (Fuel cost/year) (k€/yr)	Battery Ferry
5	40	73000	822	217	941.6	226.30	6.74
10	20	73000	1643	434	1883.3	226.30	8.03
15	13	71175	2465	651	2824.9	220.64	9.49
20	10	73000	3286	868	3766.5	226.30	10.61
25	8	73000	4108	1085	4708.1	226.30	11.90
30	6	65700	4929	1302	5649.8	203.67	14.38
35	5	63875	5751	1519	6591.4	198.01	16.19
40	5	73000	6572	1736	7533.0	226.30	15.77
45	4	65700	7394	1953	8474.6	203.67	18.68

Trip distance (km/trip)	Hydrogen storage requirement (kg)	Hydrogen storage weight (tons)	H2 storage cost (k€)	FC cost (k€)	FC weight (tons)	FC replacement / Year (k€/yr)	H2 fuel cost/year (k€/yr)	Infrastructure cost (k€)	FC CAPEX (k€)	FC OPEX (k€)	FC Ferry	CV CAPEX (k€)	CV OPEX (k€)	Diesel Ferry
5	272.86	4.091	204.64	48.00	2.00	22.90	549.76	1330.20	1534.85	572.66	8.43	33.60	636.64	7.08
10	272.86	4.091	204.64	48.00	2.00	22.90	549.76	1330.20	1534.85	572.66	8.43	33.60	636.64	7.08
15	266.04	3.989	199.53	48.00	2.00	22.33	536.01	1296.95	1496.48	558.34	8.43	33.60	620.72	7.09
20	272.86	4.091	204.64	48.00	2.00	22.90	549.76	1330.20	1534.85	572.66	8.43	33.60	636.64	7.08
25	272.86	4.091	204.64	48.00	2.00	22.90	549.76	1330.20	1534.85	572.66	8.43	33.60	636.64	7.08
30	245.57	3.682	184.18	48.00	2.00	20.61	494.78	1197.18	1381.36	515.39	8.43	33.60	572.97	7.09
35	238.75	3.579	179.06	48.00	2.00	20.04	481.04	1163.93	1342.99	501.08	8.43	33.60	557.06	7.09
40	272.86	4.091	204.64	48.00	2.00	22.90	549.76	1330.20	1534.85	572.66	8.43	33.60	636.64	7.08
45	245.57	3.682	184.18	48.00	2.00	20.61	494.78	1197.18	1381.36	515.39	8.43	33.60	572.97	7.09