# HYDROGEN

## APPLICATION FOR FREIGHT TRANSPORT

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Aalborg | October 2014

Høje-Taastrup Kommune
FDT
ENERGI STYRELSEN

# Preface

Today's transport sector is heavily dependent on fossil fuels, which causes significant increases in air pollution. This is in particular crucial in urban areas with high density of transportation. The transition towards alternative fuels is a key factor to fight pollution and to achieve decarbonisation, sustainability and competitiveness of the transport sector.

In Denmark, Høje-Taastrup Municipality is especially concerned and proactive in this area. The project Høje-Taastrup Going Green was launched on 1st of January 2014, where one of the main goals is promoting a fossil free transport sector. Particularly the freight sector is targeted due to the high level of pollution it creates.

A main objective of the project is to create a platform for further use and development of alternative fuels in the freight transportation sector. A special focus is therefore on illustrating the possibilities and perspectives of the alternative fuels: electricity, hydrogen, gas (CNG, LNG and biogas) and biodiesel. At the moment, the application of alternative fuels is not competitive with traditional fossil based propellants. Thus, it is important to prospectively set up the framework and establish the infrastructure to integrate and foster alternative fuels in Høje-Taastrup Municipality.

In line with the project, a set of catalogues of different propellants were developed, focusing on the utilisation of electricity, hydrogen, gas and biodiesel for freight vehicles. Each catalogue analyses the propellant in terms of technology, environmental impact, economics and related policy instruments, in order to point out its applicability and hurdles.

The following catalogue will elaborate on hydrogen driven vehicles.

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# 1 OVERVIEW

## 1.1 EU and Danish Goals and Targets

The EU's goal is to reduce emissions by 80 to 95% by 2050 compared to 1990 levels. The transport sector is a significant and still growing source of greenhouse gas (GHG) emissions. Therefore, a reduction of at least 60% of GHGs by 2050 with respect to 1990 is required from the transport sector, which is then followed by a comparable reduction in oil dependency. In order to achieve the target, the EU white paper on transport includes these relevant goals:

- "Halve the use of 'conventionally fuelled'[1] cars in urban transport by 2030;
- Phase them out in cities by 2050;
- Achieve essentially $CO_2$-free city logistics in major urban centres by 2030". [1]

To strengthen this, Denmark has a challenging goal to reach 100% fossil fuel independence within the transport sector by 2050. Regarding this, almost the entire vehicle fleet needs to become zero-emission.

As a fact, EU transport is 95% dependant on oil and its products. Figure 1 illustrates the final energy consumption in the transport sector in 2011 by type of fuel and emphasise the need of taking actions towards greener transport.

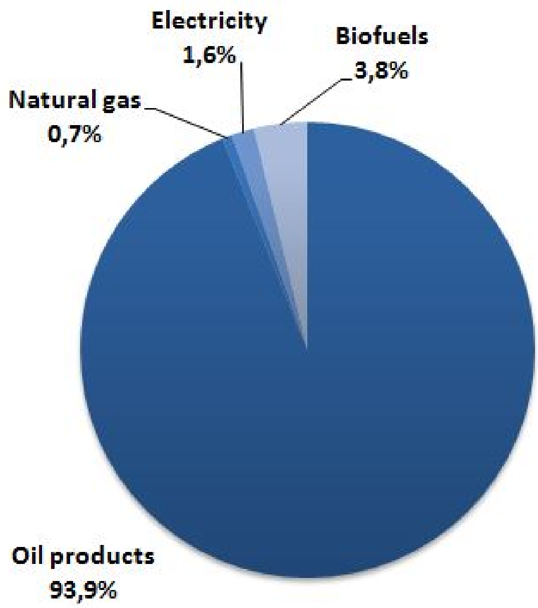


Figure 1: Final energy consumption in EU transport sector by type of fuel

[1] The term refers to vehicles using non-hybrid, internal combustion engines.

## 1.2 Application of Alternative Fuels

The transport sector cannot rely only on one single type of alternative fuel. In the long run, it should be based on a mix of several different fuels, with respect to the needs of each transport mode. The coverage of travel range by different alternative fuels is summarised in Table 1 for urban, light-duty and heavy-duty vehicles. Biofuels stand for biodiesel and methane stands for CNG/CBG (compressed natural gas/biogas) and LNG/LBG (liquefied natural gas/biogas). [2]

| Vehicle |  |  | | |  | | |
|---|---|---|---|---|---|---|---|
| Range | Urban | Short | Medium | Long | Short | Medium | Long |
| Electricity | | | | | | | |
| Hydrogen | | | | | | | |
| Biofuels | | | | | | | |
| Methane | | | | | | | LNG/LBG |

**Table 1: Application of alternative fuels for different transport modes [2]**

To conclude, electricity can be applied only for short travel distances, hydrogen and CNG/CBG up to medium distances, and biofuels and LNG/LBG up to long distances. [2]

Electricity, both battery vehicles and fuel cell vehicles, is expected to be applied mainly for the car fleet. Regarding heavy-duty transport, biofuels and methane are prioritised due to the technical reasons. As a result, for the freight transport sector, in particular for long-distance transportation, limited alternative fuels are available. [2]

However, the set of catalogues examines all the different alternative fuels (electricity, hydrogen, biodiesel, CNG/CBG and LNG/LBG) and their possibility to be applied to heavy-duty vehicles.

Due to the novel technology of fuel cells powered by hydrogen and its little application to vehicles, information available is scarce. This green technology is still being investigated further and is considered as an alternative propulsion system for the near future. In general, harnessing of alternative fuel for light-duty vehicles is simpler and thus more common than for heavy-duty vehicles. Therefore, some information refers to fuel cell passenger vehicles, which then provides a general understanding of prospects and hurdles of the technology.

# 2 INTRODUCTION

Hydrogen fuel cell electric vehicles (FCEVs) are considered one of several possible pathways for low-carbon transportation in the long run. At EU level, hydrogen and fuel cell technologies are identified being essential to achieve a targeted 60-80% reduction in greenhouse gases by 2050. Hydrogen is recognised as a significant element of the future fuel mix for transport, boosting energy security, reducing oil dependency and carbon footprint.

In order to reach the domestic goal of being 100% fossil independent by 2050, the Danish Government has announced an Energy Plan 2020 that includes establishment of a range of initiatives for hydrogen infrastructure and FCEVs.

## 2.1 Stakeholders

The Scandinavian Hydrogen Highway Partnership (SHHP) aims to make the Nordic Region one of the first regions in Europe, where hydrogen is commercially available and used in a network of filling stations. The main three collaborating national bodies are HyNor (Norway), Hydrogen Sweden (Sweden) and Hydrogen Link (Denmark). In order to develop and broaden the area of innovation, they involve local and regional industries, research institutions and governments. [3]

Hydrogen Link is an association established in 2005 who works to foster the use of hydrogen for transport, by creating market frame conditions and introducing necessary supporting infrastructure in Denmark. [4]

SHHP is a platform for demonstrating and deploying FCEVS. This is done through company-, organisation- and private owned FCEVs, from which SHHP has access to passenger vehicles and five busses in Oslo for demonstration. [3]

## 2.2 Fuel Production Method and Availability

Hydrogen is a potentially emissions-free alternative fuel that can be produced using diverse domestic resources. As the most common and lightest element of all, hydrogen gas consists of two atoms ($H_2$). Although abundant on earth as an element, hydrogen is almost always found as part of another substance, such as water ($H_2O$), hydrocarbons (such as methane, $CH_4$), alcohols, and other organic matter (such as biomass). Mainly, hydrogen can be produced from fossil fuels (coal and natural gas), nuclear, renewable energy power (wind, solar, geothermal, hydro, biomass). There are several ways of hydrogen production:

- Natural gas reforming. In this process, natural gas is reacted with high temperature steam or by partial oxidation. Hereby a mixture of hydrogen, carbon monoxide and a small amount of carbon dioxide is created. Carbon monoxide is then reacted with water in order to produce additional hydrogen. Catalysts are used in the processes. This method of producing hydrogen is considered to be the cheapest and most efficient. The processes can be described as follows:

$$CH_4 + H_2O \text{ (+heat)} \rightarrow CO + 3H_2 + CO_2$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+small amount of heat)}$$

- Electrolysis. This is a method where water is split into hydrogen and oxygen by an electric current in electrolyser. In case electricity is from renewable sources, the produced hydrogen is considered to be renewable as well, as it results in zero GHG emissions. Simplified reaction:

$$2H_2O \text{ (+electric current)} \rightarrow O_2 + 2H_2$$

In this way hydrogen production can also balance the electricity grid when more intermittent energy sources are introduced.

- Coal or biomass gasification. Here, coal or biomass is reacted with high temperature steam and oxygen in a pressurised gasifier and thereby converted into gaseous components; hydrogen and carbon monoxide. The latter is then again reacted with steam to produce more hydrogen:

$$C_xH_yO_z + H_2O + O_2 \text{ (+heat)} \rightarrow CO + H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+small amount of heat)}$$

- Renewable liquid reforming. Renewable liquid fuels, such as ethanol, are reacted with high temperature steam to produce hydrogen. Another component, carbon monoxide, is reacted with steam again to produce additional hydrogen. Simplified reactions in case of ethanol are as follows:

$$C_2H_5OH + H_2O \text{ (+heat)} \rightarrow 2CO + 4H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2 \text{ (+small amount of heat)}$$

- Fermentation. In fermentation biomass is converted into sugar-rich feedstock which can be then directly fermented to produce hydrogen, ethanol and other chemicals. [5]

Some other methods are under the development, such as high temperature water splitting, photo biological water splitting, and photo electrochemical water splitting. [5]

In order to use hydrogen for vehicles, it should be produced at a maximum purity. Even small impurities can damage fuel cells severely, therefore should be carefully removed. The cleanest way to produce hydrogen is from water and electricity. Moreover, electricity, produced from renewable energy sources, are the most preferable, as it makes hydrogen production carbon free. [5]

Denmark is well known worldwide for being skilled at capturing the power of wind and exploiting its resources for electricity generation. Regarding hydrogen production, wind energy should be considered as a great potential source and a key factor in addressing environmental issues. However, large extent integration of hydrogen production from fluctuating renewable power requires well developed optimisation, which enables to use electricity when the prices are the lowest, i.e. a smart grid. [5]

Regarding hydrogen production from natural gas, this could be also seen as an attractive option due to the sufficient natural gas reserves in the North Sea and well developed gas distribution across Denmark. Moreover, the Danish gas grid is connected to other European countries, which means extra security in both short and long run. [5]

Today, hydrogen is not widely used as a fuel in the transport sector due to the complex technology and high cost of production, thus making hydrogen cost uncompetitive with conventional fuels. However, the development toward the energy and cost efficient, clean, and safe hydrogen production, as well as FCEVs, has been carried on. The further growth exhibits a “chicken-and-egg” problem though: vehicle manufacturers are unwilling to produce vehicles if there is no guaranteed hydrogen supply, while hydrogen suppliers are unwilling to produce fuel if there is no demand. [6]

# 3 TECHNOLOGY

The main reasons for using hydrogen as an alternative fuel for transport are:

- Zero-emissions;
- Potentially high efficiency of FCEV (2-3 times higher than conventional internal combustion engine);
- Potential for domestic production.

However, FCEVs and the infrastructure to fuel them are at an early stage of deployment. [7]

## 3.1 Technology Description

Once produced, pure hydrogen gas is compressed at high pressure to increase driving range and stored directly in the tank on-board. The tank provides hydrogen to the fuel cells, where it is used along with oxygen (component of the air, provided by the air compressor) to cleanly generate electricity by an electrochemical process. The produced electricity is then used to power the motor, which is located near the vehicle's wheels. The electric motor propels the vehicle and can also recover energy during deceleration. The vehicle is able to regenerate braking energy that is stored in the battery and can be used again later to facilitate the motor during acceleration. The flow of electricity, either from the fuel cell or the battery, is governed by the power control unit, in accordance with driving conditions. [5, 7]

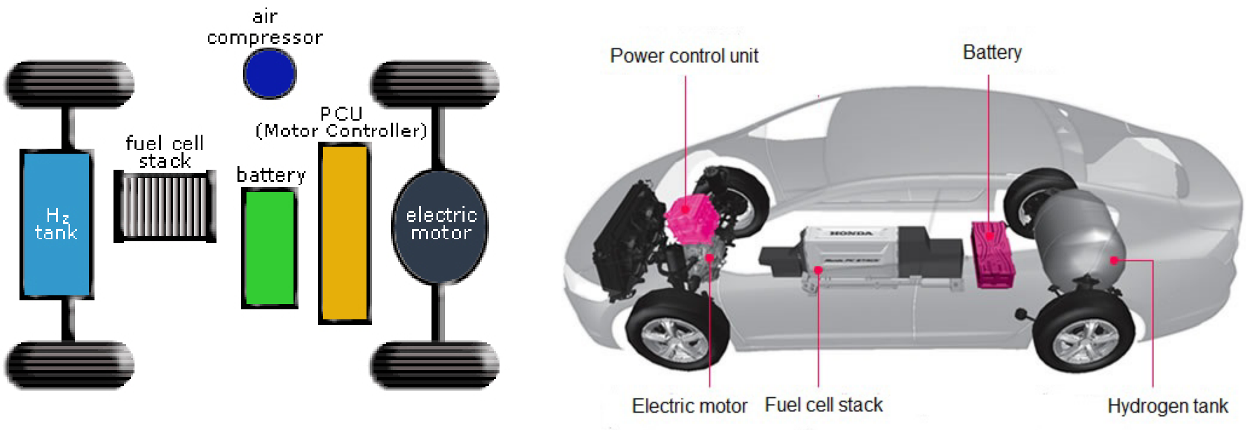


**Figure 2: Schematic of a fuel cell vehicle [7]**

The hydrogen fuel cell technology is maturing and is being demonstrated and applied in passenger cars, city buses, light vans and inland ships. Their performance, travel range and refuelling time are similar to those of gasoline and diesel vehicles. [8]

## 3.2 Main Characteristics

### *3.2.1 Fuel*

Under standard conditions, hydrogen is a colourless and odourless gas. When stored, it is either compressed at 20-70 MPa or liquefied, which is though less common. Mostly pressure in storage tanks for FCEVs is 70 MPa. [7]

The main characteristics of electricity as an alternative fuel for vehicles are presented in Annex. Due to the fact that hydrogen is the lightest chemical element, it has the highest energy content by weight: higher calorific value is 142 MJ/kg, which is around three times higher compared to the other fuels. However, a volumetric energy content of hydrogen is low, 5,7 MJ/l (under 70 MPa). Therefore, in order to compete with conventional vehicles and have an equal driving range, it is important for a FCEV to store enough fuel on-board and thus have a larger fuel tank compared to most conventional vehicles. [7]

### *3.2.2 Tank*

The amount of stored energy is directly linked to the size of the tank. A fuel tank that allows a driving range similar to conventional vehicles would be too big for the typical passenger car, yet suitable for the heavy-duty vehicles. This is partly solved by compressing gaseous hydrogen in high pressure tanks (up to 70 MPa), designed and certified to withstand high pressure, which provide an adequate driving range. Some other technologies, such as solid storage (bonding hydrogen chemically with other materials), promises advantages and possible breakthroughs, yet are needed more research. [7]

For instance, Hyundai ix35 has a driving range of almost 600 km, which is provided by 5,64 kg of fuel stored. Knowing that the density of hydrogen is around 40 kg/m$^3$ under 70 MPa, it results in around 140 l fuel tank.

On average, FCEVs have a capability to be refuelled in three to five minutes and the driving range can be more than 480 km on a single tank on average. In regard to this, on the contrary to electric vehicles, FCEVs can compete with those fuelled by gasoline. [7]

### *3.2.3 Fuel Cell*

The fuel cell is the “core” element and determines the power of the vehicle. The amount of power produced depends on the fuel cell type, size, temperature at which it operates and pressure at which the fuel is supplied to the cell. A single fuel cell can only practically produce around 0,7 V. In order to increase the amount of electricity generated, fuel cells are combined in series to make a fuel cell stack, which may consist of hundreds of fuel cells. [5]

A polymer electrolyte membrane (PEM) fuel cell is one of the most common types of fuel cell used in vehicles. The PEM fuel cell consists of a positive electrode (cathode) and a negative electrode (anode) with an electrolyte membrane in between. Hydrogen passes through the anode where molecules break apart into protons and electrons due to the electrochemical reaction in the catalyst. Protons flow directly through the electrolyte to the cathode while electrons are forced to move via external electric circuit, generating electricity. Finally, protons and electrons combine with oxygen (component of air), passing through the cathode, to form water, which flows out of the cell. The process is illustrated in Figure 3. [7]

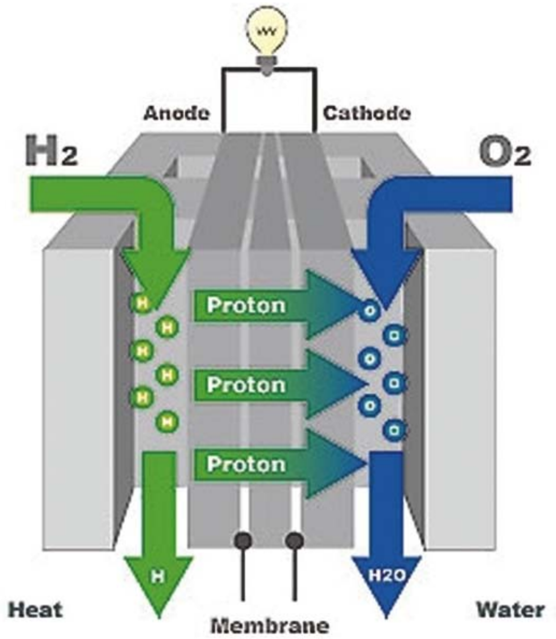


Figure 3: Technology of the fuel cell

Since energy in fuel cells is created electrochemically, and not by burning fuel, they are basically more efficient than internal combustion systems. The efficiency of a fuel cell is around 40-60%, which means that it uses 40-60% of the energy available from hydrogen. In comparison to conventional internal combustion engines, powered by gasoline, it has only 20% efficiency, although this is expected to increase in further years. [6] Only electric vehicles have higher efficiency than FCEVs, which can reach up to 90%. [9]

As an example, a few models of passenger FCEVs have the fuel economy equivalent to 22 and 25 km/l of gasoline (Mercedes-Benz F-Cell 2011 and Honda FCX Clarity 2011 respectively). In comparison, the average fuel economy for gasoline passenger cars from model year 2010 is 14 km/l of gasoline and the most efficient hybrid electric vehicle from the same model year has a fuel economy of 21 km/l of gasoline. [6]

### *3.2.4 Battery*

The battery is used to achieve higher efficiency of the vehicle by capturing and storing the energy, lost during the deceleration. [7] The size and type of the battery depend on the amounts of power, required from the fuel cell stack and from the battery. [6]

### *3.2.5 Motor*

Similar to electric vehicles, high torque from the electric motor gives quick starts and excellent acceleration. Electric motors generate maximum torque at zero speed, where the maximum torque is needed to pull away from a start. Thus, strong and smooth acceleration is guaranteed. [6] For instance, the hydrogen powered Hyundai ix35 can accelerate from 0 to 100 km/h in 12,5 seconds.

## 3.3 Fuelling Infrastructure

A penetration of FCEVs requires not only improvements in technology performance and reductions in cost, but also a substantial development of hydrogen refuelling infrastructure. This includes the equipment and systems necessary to produce, distribute, store, monitor and fuel the vehicles.

### *3.3.1 Infrastructure & Requirements*

Hydrogen can be produced either on-site or near the place it is used. Distribution of hydrogen from the point of production to the point of use can then be done in different ways: by pipelines, high-pressure tube trailers or liquefied hydrogen tankers. The last two can be done by using different modes of transportation: trucks, railcars or ships, which is the most common. The pipeline solution, however, is the cheapest option. [6]

One solution to limit distribution issues is to produce hydrogen regionally or locally. Another is to use a step-by-step approach. At first, distribution hubs could be concentrated in a few key areas. Later, distribution network could be expanded to geographic corridors and then, gradually, to other regions. This would be the most rational way of establishing well functioning infrastructure. [6]

Regarding alternative fuels, EU emphasise the importance of having common EU-wide standards for the equipment needed, such as fuel hoses and permitting for fuel stations, so that it can be used for vehicles cross-nationally both in- and outside the EU. As a result, it can help to foster the deployment of alternative fuel vehicles. Common standards for the vehicles and filling stations are expected to be developed and implemented by 2015. [10]

### *3.3.2 Current Situation in Denmark*

Currently, the infrastructure for distributing hydrogen is not comparable to that for fossil fuels. It is at an early phase with around 200 filling stations worldwide, 120 of which are established in EU. [10]

The project called Hydrogen Infrastructure for Transport (HIT) aims at fostering the deployment of hydrogen refuelling infrastructure serving FCEVs along key TEN-T corridors. The HIT project will develop a comprehensive Synchronised Implementation Plan (SIP) for refuelling station roll-out along a first 1000 km corridor from Gothenburg to Rotterdam, with a part of Denmark in between, indicating hydrogen as a long distance alternative fuel. It will demonstrate state of the art refuelling technology by setting up three pilot stations in Denmark and Netherlands. [11]

Denmark has taken some significant steps towards establishment of hydrogen filling stations across the country. The main goal of Hydrogen Link is, in the short term, to establish local filling stations, so called Local H2 HUBs, which provide hydrogen for local fleet. In the long term, Local H2 HUBs need to be connected in a larger network across the Nordic countries. At the moment, there are three publicly accessible stations in operation in Denmark (in Copenhagen, Vejle and Holstebro), three stations are under construction (two in Copenhagen and one in Aalborg) and five stations are planned to be built in 2015 or later (in Esbjerg, Herning, Aarhus, Odense and Zealand). The map of stations can be seen in Figure 4. Stations in operation are marked in green, under construction in yellow, planned in 2015 or later in red. The existing stations provide with the compressed hydrogen gas under 70 MPa for passenger cars. [4]

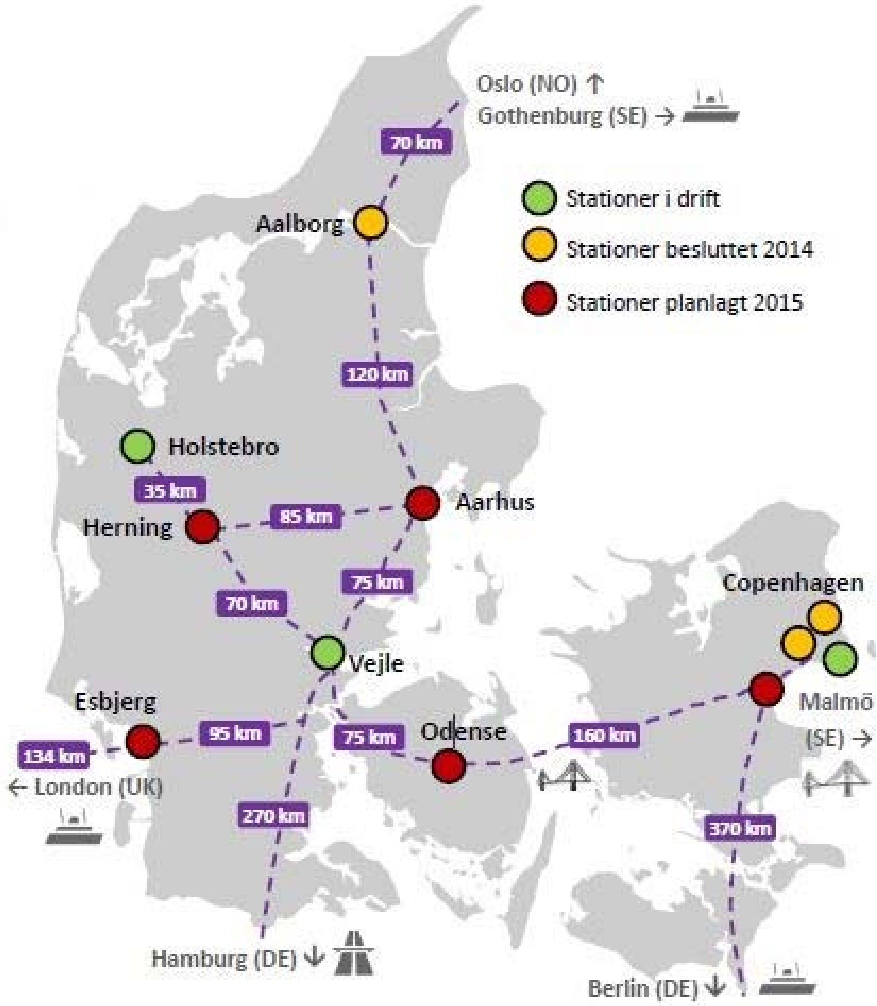


Figure 4: Hydrogen filling stations in Denmark

The fact that several stations are currently under development is a significant step forward to the creation of a sufficient distribution network at national level, enabling FCEVs to be refuelled all over the country and fostering the market of hydrogen cars. Denmark is relatively small geographically, and therefore the distances between the mentioned filling stations fit the driving range provided by the hydrogen. For instance, the distance between Aalborg and Vejle is around 180 km, Vejle and Copenhagen – 240 km. The new prospective filling stations will reduce the distances between fuelling opportunities significantly.

In the long run, the number of hydrogen stations is expected to increase further to match roll-out of FCEVs. According to Hydrogen Link, it is expected that 100-200 filling stations will be established in Denmark by 2025 and 500-1.000 filling stations by 2050. [4] This is also in line with the Clean Power for Transport, which addresses a sufficient number of publicly available hydrogen filling stations, with maximum distances of 300 km between them. [10]

### *3.3.3 Suppliers*

The leading Danish manufacturer of hydrogen filling stations is H2 Logic. In Denmark, hydrogen for filling stations is produced by electrolysis, on-site or remotely. The technology of electrolysis is also applied for the stations under construction. The water is split using electricity from renewable energy sources and therefore the hydrogen supply is based on 100% renewable energy and results in no $CO_2$ emissions. This is entirely in line with the Danish goal of ensuring independence from fossil fuels by 2050 in energy and transport sectors. [4]

Regarding hydrogen filling stations, H2 Logic provides FCEVs with the fast fuelling and long driving range. In 2012 a new type of stations was launched after years of development, which emphasised the shift from customised solutions to standardised products. H2Station CAR-100 provides 70 MPa fast filling with a capacity of 100 kg/day. All the equipment is integrated in compact station model, so that the stations can be delivered and installed in two days. This new technology results in reduced cost and delivery time as well as improved availability, which is crucial towards roll-out and use of the infrastructure. [12]

## 3.4 Operation & Maintenance Facilities

When compared to internal combustion engines, fuel cell has considerably less moving parts. Here the moving parts consist of only a pump, blower and compressor. Therefore, it requires less maintenance and thus reduced operation cost. For instance, no oil changes are necessary. Also, fuel cells can be monitored remotely and any problems can be dealt easily. [13]

## 3.5 Safety

Safety is one of the most important factors among all. Hydrogen is considered as safe and easy to handle as other fuels and energy carriers, if certain things are taken into consideration. In general, hydrogen gas is transient and disappears in open air quickly. However, hydrogen gas is explosive under certain conditions. Therefore, as for other energy sources and carriers, special safety requirements have been established. At the moment, due to the experience in using hydrogen in industries, there is a great knowledge of how to deal with it to minimise the risk of accidents. [3]

There are already existing ISO and SAE standards providing globally harmonised requirements regarding hydrogen:

- Refuelling interface;
- Fuel quality;
- Filling station safety and requirements. [14]

# 4 ENVIRONMENTAL IMPACT

## 4.1 Emissions

FCEVs are the least polluting vehicles of all vehicle types that consume fuel directly, and do not produce any harmful tailpipe exhaust at the operation phase. The only emissions are water vapour, heat and a small amount of hydrogen. At the fuel production phase, depending on what feedstock is used to produce the hydrogen, GHG emissions exist, but they are substantially lower in comparison with conventional vehicles, as it can be seen in Figure 5. A FCEV has near-zero life cycle GHG emissions, in case the hydrogen is produced by electrolysis powered by renewable electricity. [6]

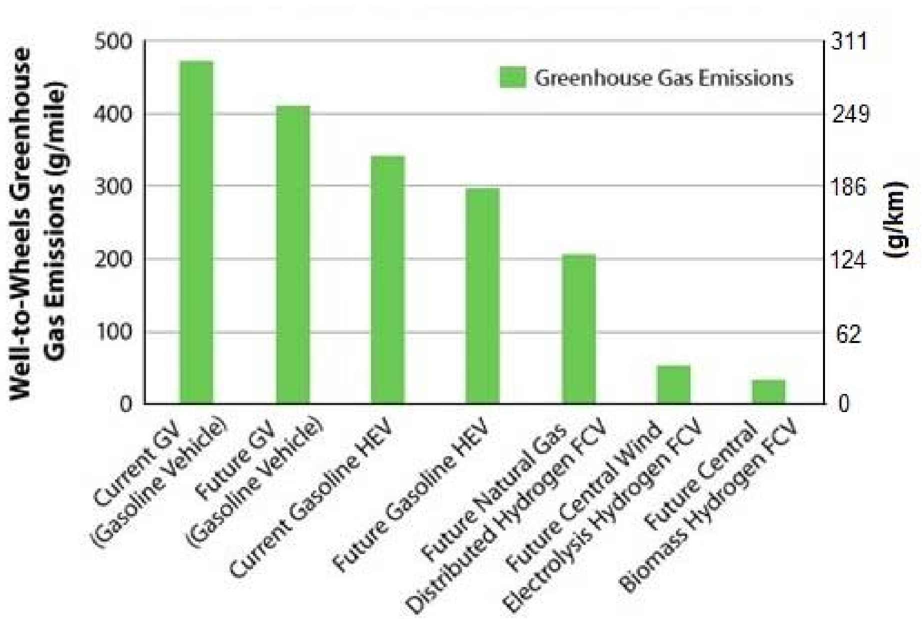


Figure 5: GHG emissions of fuel cell and gasoline vehicles [15]

From a broader perspective, Figure 6 compares gasoline, diesel, electric and fuel cell electric vehicles in terms of driving range and $CO_2$ emissions in the period of 2010-2050. BEV stands for battery electric vehicle, PHEV – plug-in hybrid electric vehicle, ICE – internal combustion engine vehicles. Together with electric vehicles, FCEVs can achieve significantly low $CO_2$ emissions in the future. The advantage of FCEVs is a considerably longer driving range, compared to electric vehicles.

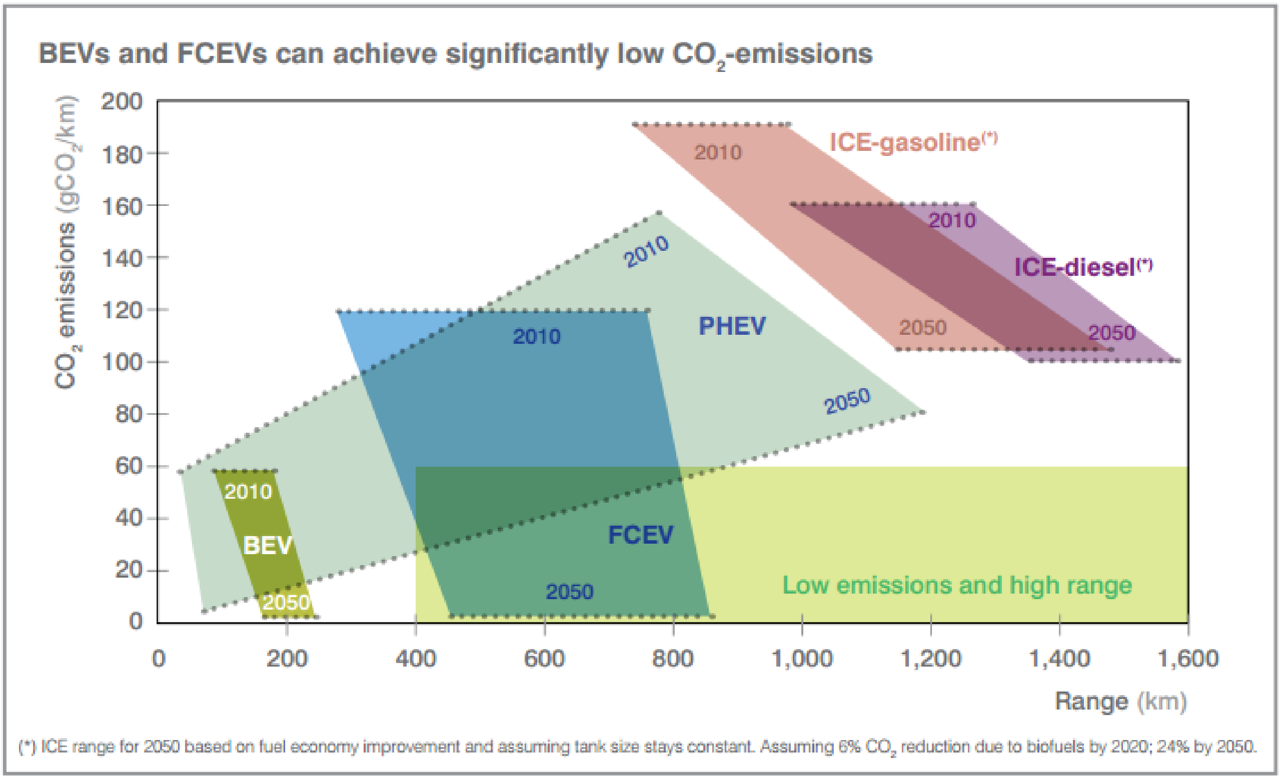


Figure 6: Comparison of $CO_2$ emissions [14]

Considering water vapour emitted during the operation, low outside temperatures can be an issue, due to the fact that water freezes below 0°C. However, it is being researched and, according to SHHP, passenger vehicle users experience no problems even at extremely low outside temperatures, such as below -20°C, neither during the operation, nor during long term parking. [3] Considering Denmark, the average temperature in winter is around 0°C.

## 4.2 Smell

Since FCEVs emit only heat and small amount of water vapour, no smell problems are identified.

## 4.3 Noise

Fuel cells along with the hydrogen also reduce noise emissions. Extremely low operating noise is assured as there is no combustion (explosions) or moving parts. It can be comparable to electric vehicles. When fuel cell is integrated into a vehicle system, air pumps or fans are typically used, which can be seen as the only source of noise on a FCEV. [6]

# 5 ECONOMICS

Manufacturing FCEVs and constructing the necessary infrastructure remains an issue due to high purchase and operation costs. However, manufacturers target 2015 for initial commercial sales and upcoming widespread adoption of FCEVs. Hydrogen application for freight sector, however, needs more time and further investigation.

## 5.1 Investment Cost

### *5.1.1 Vehicles*

Recently, the cost of fuel cells has decreased significantly. However, the total cost for a fuel cell system is still almost double compared to an internal combustion engine. In addition to this, the cost of on-board fuel storage is considerably higher. As an example from the US, in 2010 the cost of fuel cell system was approximately 37,5 €/kW. It is expected to decrease to 29 €/kW. On-board storage currently costs around 11-13 €/kWh, depending on the tanks pressure. [6]

Due to the high cost of fuel cells, the overall cost for the FCEV is also substantially higher than that for the conventional vehicle. As an example, Toyota has announced plans to sell the FCEV for 38.000 € in 2015, as the minimum cost, which is twice as high as for the comparable conventional vehicle. [6] While recent hydrogen powered passenger vehicle Hyundai ix35 costs around 950.000 DKK (130.000 €) (before VAT). This is 2-3 times higher than similar Hyundai models. [16] However, in the long-term overall prices are expected to decrease due to the improvement of technology and issues on energy and environment impacts. [6] According to industry studies, the costs can be reduced to the levels of conventional fuel vehicles by 2025. [8]

### *5.1.2 Fuelling Infrastructure*

Due to the low volumetric energy density of hydrogen, distribution, storage and final delivery costs are higher than those for conventional gasoline or diesel. It is expected, the more FCEVs are on the market, the cheaper the infrastructure in terms of total cost of ownership (TCO) becomes. [14]

As it was mentioned, distribution by pipelines is the least expensive choice. However, initial construction phase is then necessary, what makes it expensive and in particular difficult in urban areas due to the existing infrastructure. [6]

One solution of cost effective establishment of hydrogen refuelling infrastructure is to supplement existing refuelling sites with hydrogen dispensing systems, in this way reducing initial investments.

## 5.2 Fuel Production Cost

There is no current market price for hydrogen as it is not yet sufficiently used in high enough quantities as a vehicle fuel. As a result, hydrogen production is not yet competitive with conventional fuels in terms of both maturity of technology and cost.

## 5.3 Lifetime

Regarding fuel cells, material development for enhanced lifetimes remains the major challenge. In mobile applications a lifetime of fuel cell technology is around 5.000 hours. [17] Thus, under FCEV operating, the typical lifetime of PEM fuel cell can reach over 160.000 km. This is far behind the conventional internal combustion engine, which life span is around 400.000 km. [18]

However, the reconciliation of high-performance materials with low degradation and low-cost targets is an extremely challenging issue. Consequently, achieving acceptable market costs remains the main obstacle of FCEV market deployment. [17]

# 6 POLICY INSTRUMENTS

Since 1986 the EU investment in hydrogen and fuel cell energy technologies has been progressively increasing and the EU has funded some 200 projects with a total contribution of over 550 million €. These projects focused on:

- Hydrogen production, including from renewable sources, distribution and storage;
- More durable and cost-effective fuel cells;
- Hydrogen fuelled vehicles and refuelling infrastructure;
- Best cross-cutting policies (regulations, codes and standards) to promote a transition to a cleaner energy system benefiting from hydrogen technologies. [17]

The projects bring together different organisations that are active in the same scientific area. By working together they exchange experience, create links and follow cooperation possibilities. Furthermore, research is channelled towards marketable solutions, as businesses and universities co-operate and partners are found to create supply chains. [17] These initiatives foster the roll-out of hydrogen as an alternative fuel for the transport sector, which is still at the early stage.

In 2008, the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) – the European Commission, Industry (NEW-IG) and the Research community (N.ERGHY) – was founded to implement a targeted R&D programme. In 2014, new FCH 2 JU was established to run from 2014 to 2024 with the following specific objectives:

- Reducing the cost of fuel cell systems for transport sector by a factor of 10;
- Demonstrating the viability of large scale hydrogen production with electricity generated from renewable energy [14].

The budget is provided by EU and private contributors. [14]

However, new financial instruments are needed to finance first commercial applications and to support market introduction. New sector based support mechanisms, both financial and non-budgetary, should be investigated and the existing ones should be updated. Combining different programmes from the European Investment Bank (EIB) or regional funds should be facilitated, as should it be to combine other EU and national support programmes. Furthermore, adequate mechanisms should be developed to attract a wider range of private investors and investment funds. [14] A joint effort from public and private partners is needed.

A key factor to the successful roll-out of hydrogen vehicles and the necessary infrastructure is well functioning policy instruments. In Denmark, the roll-out of country-wide infrastructure for FCEVs is supported by several instruments [19]:

- Hydrogen vehicles are exempted from registration taxes. For the vans under 2,5 tons, first 13.700 DKK of the base purchase price is untaxed and 50% tax is applied on the rest. Furthermore, FCEVs are inherently exempted from annual green taxes, which are based on the fuel consumption per km. Exemptions are in force until and including 2015.
- Tax exemptions of up to 0,08 €/kWh (0,6 DKK/kWh) on electricity for hydrogen production are implemented, supporting renewable hydrogen supply.

- Another instrument to foster the FCEVs integration is financial support for a number of demonstration projects to promote this pathway.
- The environmental zones are established in Denmark with strict regulations. The best example is the majority of Copenhagen and all of Frederiksberg, which has been an environmental zone since 2008. All diesel powered vehicles above 3,5 tons must either meet at least Euro IV emission standard or be improved with an effective filter. All heavy-duty diesel powered vehicles, both domestic and foreign, are required to have an environmental zone label in case they want to enter an environmental zone. It is also implemented in Aarhus, Aalborg and Odense. [20]

# 7 EXAMPLES OF FCEVs FOR DISTRIBUTION

The main focus is put on manufacturing and show casing fuel cell powered passenger vehicles, buses or material handling vehicle, such as forklifts. However, in addition to this, the logistics sector is also a promising market, identified as the market that can reduce overall cost as a result of its scale.

## 7.1 Heavy-Duty Class 8 Trucks

The Tyrano is the world's first hydrogen fuel cell powered Class 8 Truck with a hybrid hydrogen-electric propulsion system, manufactured in America and applied for on-road drayage in California. The main characteristics of performance and dimensions can be seen in Table 2. [21]

The chassis of the truck has fuel cells under the hood, electric motors on each axle and compressed hydrogen storage tanks along the frame. [22]

The Tyrano outputs three times the torque compared to the diesel powered truck and can reach 4475 Nm. An operating power is about 300 kW. It is capable of holding speeds in a wide range of load or grade, enabling to deal with big hills. The total carrying capacity is around 36,3 tons, including both truck and freight. Maximum weight of curb is 8,5 tons, meaning that available cargo is around 27,8 tons. Refuelling time is about the same as Tyrano's diesel counterpart requires. [22]

Outwardly, the Tyrano looks exactly the same as any other large heavy truck on the road. In addition to this, it is capable of more power, better performance, has no tailpipe emissions and is also completely quiet. Besides, it avoids idling, and the power for the truck is instant-on. [22]

According to the manufacturer, the Tyrano heavy-duty truck is 35% cheaper to operate than current diesel powered trucks and 50% cheaper than liquefied natural gas. [22] The lifetime of the Tyrano is around 8 years. The approximate initial price is 270.000 $ (205.000 €). [21]


| | |
|---|---|
| Manufacturer: | Vision Industries |
| **Performance** | |
| Motor: | |
| Type | Electric |
| Torque | 4475 Nm |
| Power | 400 kW peak |
| Acceleration: | |
| Top Speed | 105 km/h at 36,3 tons GCVWR[2] |
| Battery: | |
| Chemistry | Lithium-ion with an integrated Battery Management System |
| Expected Battery Life | 10.000 hours |
| Fuel Cells: | |
| Output | Up to 65 kW |
| Fuel: | |
| Storage | 20-40 kg of gaseous hydrogen (depending on configuration) |
| Range | 320 drayage km with the standard hydrogen fuel tank configuration |
| Refuelling Time | Average refuelling time of 4-7 minutes |
| Operating Limits: | |
| Temperature | Ambient temperature limits of -26°C to +43°C |
| Drive System | Vision's proprietary $H_2$ fuel cell/plug-in electric hybrid drive |
| Weight | 36,3 tons GCVWR |
| **Dimensions** | |
| Exterior Dimensions: | |
| Overall Length | 8,4 m |
| Overall Height | 2,95 m |
| Wheel Base | 5,2-5,7 m (based on requirements) |
| Front Track | 2,4 m |
| Rear Track | 2,5 m |
| Curb Weight | ~8,5 tons (depending on configuration) |
| Interior Dimensions: | |
| Leg Room | 1,45 m |
| Front Head Room | 1,2 m |
| Front Shoulder Room | 0,6 m |

**Table 2: Main characteristics of Tyrano heavy-duty truck**

[2] Gross combined vehicle weight rating – max allowable combined weight of the tow vehicle and the attached cargo container

## 7.2 Zero Emission Terminal Tractor (ZERO-TT)

The Zero-TT is the ultimate terminal tractor for ports, logistics and transportation hubs. It is used for movement of containerised cargo within a facility. The main characteristics of performance can be seen in Table 3. [21]

| | |
|---|---|
| Manufacturer: | Vision Industries |
| **Performance** | |
| Motor: | |
| Type | Electric |
| Power | 170 kW peak |
| Battery: | |
| Chemistry | Lithium-ion with Advanced Battery Management System |
| Expected Battery Life | 10000 hours |
| Fuel Cells: | |
| Output | 16,5 kW |
| Fuel: | |
| Storage | 10-15 kg of gaseous hydrogen (depending on configuration) |
| Usage | Charges batteries on the fly – used as range extenders |
| Range | Two eight-hour shifts before refuelling with Hydrogen |
| Refuelling Time | Average refuelling time of 4-7 minutes |
| Operating Limits: | |
| Temperature | Ambient temperature limits of -26°C to +43°C |
| Drive System | Vision's proprietary $H_2$ fuel cell/plug-in electric hybrid drive |
| Weight | 65 tons GCVWR |

Table 3: Main characteristics of Zero-TT

## 7.3 Fuel Cell Range-Extender

Recently, FedEx Delivery Company in America develops the idea of integrating hydrogen fuel cell range-extender into their Smith Electric Vehicles delivery vans, which have a range of about 130 km per charge. In this way, the range would be effectively doubled, avoiding additional emissions, which could appear in the case of gasoline-powered or diesel-powered extender. The additional weight would be also trivial. [23] Technology of range-extender integrated into electric vehicle can be seen in Figure 7.

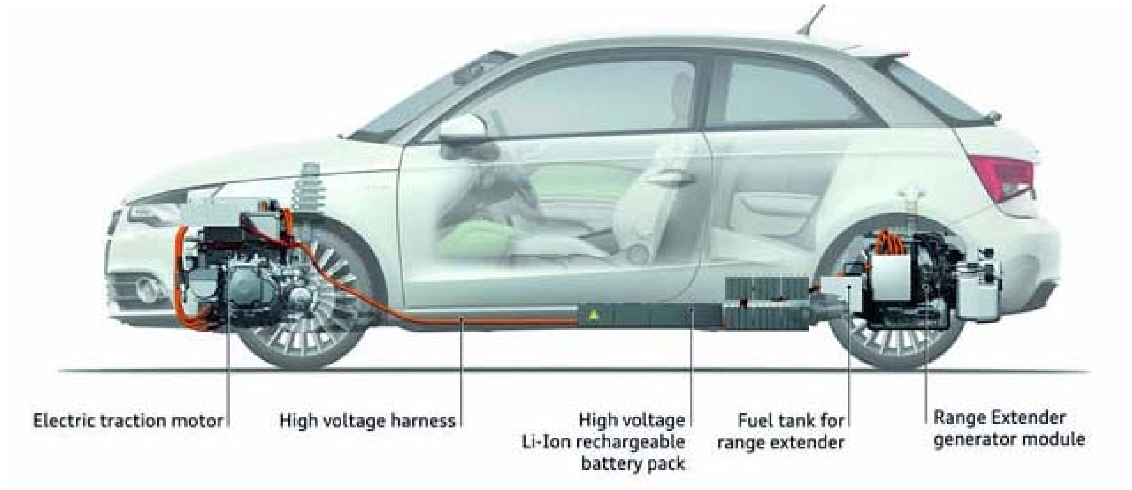


Figure 7: Fuel cell range-extender integration [24]

The French postal service, La Poste, is also going to test fuel cell range-extenders in three Renault Kangoo ZE small electric delivery vans (see Figure 8). Fuel stacks are fitted under the cargo floors and should double the driving range. Another advantage of hydrogen range-extender is that electric battery life span is extended as deep discharging can be avoided. Finally, waste heat from the fuel stack can be utilised to warm the cabin and reduce the load on the battery. [23]

Figure 8: Renault HyKangoo electric van with fuel cell range extender [23]

## 7.4 Hyundai ix35

Hyundai ix35 (South Korea) is a first mass produce and commercially available fuel cell powered car. It is a medium size passenger vehicle, yet could be applied to service transportation, such as post delivery. The main characteristics of performance can be seen in Table 4. [25]

| | |
|---|---|
| Manufacturer: | Hyundai Motor Company |
| **Performance** | |
| Motor: | |
| Type | Electric |
| Torque | 300 Nm |
| Power | 100 kW peak |
| Acceleration: | |
| Top Speed | 160 km/h |
| | Achieving 100 km/h in 12,5 seconds |
| Battery: | |
| Chemistry | 24 kW Lithium-ion polymer battery |
| Fuel Cells: | |
| Output | 100 kW |
| Fuel: | |
| Storage | 5,64 kg |
| Fuel economy | 1,07 kg $H_2$/100 km (27,8 km/l gasoline equivalent) |
| Range | 594 km |
| Refuelling Time | 3-4 minutes |
| Operating Limits: | |
| Temperature | It can start reliably in temperatures as low as -20°C |
| Payload | 375 kg |
| Curb weight | 1830 kg |
| Gross weight | 1980 kg |

Table 4: Main characteristics of Hyundai ix35

# 8 SUMMARY

Table 5 summarises the main findings about hydrogen as an alternative fuel for the transport sector and technology of fuel cell electric vehicles, with a focus on freight transport. Strengths and weaknesses are found in terms of technology, environment, economics and policy instruments.

| | Strengths | Weaknesses & Improvements needed |
|---|---|---|
| Technology | High energy content by weight<br>Fast refuelling<br>Long driving range<br>High overall efficiency (2-3 times higher than internal combustion engine)<br>Potential domestic hydrogen production | Low volumetric energy content<br>Roll-out of hydrogen production and refuelling infrastructure<br>Improvements in performance and lifetime of fuel cells<br>Further development of technology applicable to heavy-duty vehicles<br>Selection of vehicles |
| Environment | No harmful tailpipe emissions, only heat and water<br>No smell and extremely low noise<br>Renewable energy used for hydrogen production avoids life cycle emissions | |
| Economics | | Lowering the costs which are still high compared to conventionally fuelled vehicles due to new technology<br>“Chicken-and-egg” problem regarding fuel cell vehicle manufacturers and hydrogen suppliers |
| Policy | Registration and annual tax exemption<br>Tax exemption on electricity for hydrogen production<br>Financial support for research and investigations from EU and Denmark | |

**Table 5: Strengths and weaknesses of hydrogen and fuel cell electric vehicles**

In conclusion, technology of fuel cell electric vehicles powered by hydrogen is not ready for wide commercial application yet, in particular of freight transport. Technology should be developed and further improved, thereby reducing costs, which are rather high, compared to conventionally fuelled vehicles. On the other hand, TCO can be reduced due to high tax exemptions applied to alternative zero-emission vehicles, which are in line with the Denmark’s goal to have fossil fuel free transport sector in 2050.

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# ANNEX: FUEL PROPERTIES COMPARISON

Table 6 gives an overview of the main properties of different alternative fuels, which can then be compared to conventional fuels. These are the following:

- **Physical state**.
- **Feedstock**.
- **Composition**.
- **Gasoline gallon equivalent** is the amount of alternative fuel, which has the same energy content as one gallon of gasoline. This factor is used to compare the energy content of different competing alternative fuels to the conventional fuels.
- **Density** is mass of certain substance per unit volume.
- **Calorific value** of the fuel shows the amount of energy released as heat by the complete combustion of fuel (unit of mass or volume).
- **The flash point** of a volatile liquid is the lowest temperature where the fluid evaporates to form a combustible concentration of gas. It indicates how easy a chemical may burn. Chemicals with higher flash points are less flammable or hazardous, making the fuel safer to handle and transport. [26]
- **The autoignition temperature** is the minimum temperature at which gas or vapour spontaneously self-ignites in air without external source of ignition (spark or flame). Higher autoignition temperature typically indicates a safer substance. [26]

The values of the properties are approximate and can differ depending on the fuel composition.

| Characteristics | Units | Conventional fuels | | Alternative fuels | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Petrol (gasoline) | Diesel | Electricity | Hydrogen | Biodiesel | CNG/CBG | LNG/LBG |
| **Physical state** | - | Liquid | Liquid | Electricity | Compressed gas or liquid | Liquid | Compressed gas | Cryogenic liquid |
| **Fuel material (feedstock)** | - | Crude oil | Crude oil | Coal, nuclear, natural gas, hydro, wind and solar | Natural gas, methanol, electrolysis of water | Fats and oils from sources such as soy beans, waste cooking oil, animal fats, and rapeseed | NG: Underground reserves<br>BG: Biomass, sewage, agricultural waste, certain industrial wastes, municipal waste, energy crops | |
| **Composition** | - | $C_4$ to $C_{12}$ | $C_8$ to $C_{25}$ | N/A | $H_2$ | Methyl esters of $C_{12}$ to $C_{22}$ fatty acids | $CH_4$ (83-99%), $C_2H_6$ (1-13%)[3] | $CH_4$ |
| **Gasoline gallon equivalent** | - | 100% | 1 gallon of diesel has 113% of the energy of 1 gallon of gasoline | 33,7 kWh has 100% of the energy of 1 gallon of gasoline | 1 kg of H2 has 100% of the energy of 1 gallon of gasoline | 0,96 gallon of B100 or 0,90 gallon of B20 has 100% of the energy of 1 gallon of gasoline | 3,9 gallons (2,6 kg) of CNG has 100% of the energy of 1 gallon of gasoline | 1,56 gallons of LNG has 100% of the energy of 1 gallon of gasoline |
| **Density (average)** | **kg/m3** | 749 | 851 | N/A | 40 | 860-890 | 175 | 455 |
| **Lower calorific value** | **MJ/l** | 32,4 | 35,8 | 3,6 (MJ/kWh) | 4,8 | 33,4 (B100) | 8,2 | 20,8 |
| | **MJ/kg** | 43,3 | 42,1 | | 121 | 38,2 | 47,1 | 45,7 |
| **Flash point** | **°C** | -45 | 126 | N/A | N/A | min. 120 | -184 | -188 |
| **Autoignition temperature** | **°C** | 257 | 210 | N/A | 500 | 373-448 (B100) | 580 | 580 |

**Table 6: Comparison of different alternative and conventional fuels**

[3] Composition of row biogas: CH4 (50-80%), CO2 (20-50%)