D6.2.: Environmental impact assessment of hydrogen vehicles

CO_2 scenarios for passenger cars in the large-scale demonstration phase and air quality in the commercialisation phase for buses

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New Energy World JTI
fuel cells & hydrogen for sustainability

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Disclaimer

This document is the result of a collaborative work between NextHyLights Industry and Institute partners. The results of the research were subsequently elaborated and presented in a coherent manner, which involved extensive stakeholder consultation in locations around the world as well as feedback from the NextHyLights Industry Partners.

The ideas presented in this document were reviewed by certain NextHyLights project partners to ensure broad general agreement with its principal findings and perspectives. However, while a commendable level of consensus has been achieved, this does not mean that every consulted stakeholder or NextHyLights Industry Partner necessarily endorses or agrees with every finding in the document. The producer of this document is the sole responsible for its content and recommendations.

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Executive summary

This report presents the environmental impact assessment for the deployment of hydrogen fuel cell vehicles (HFCVs) subdivided in the segments passenger vehicles, special vehicles and buses. Separate chapters present the results for the carbon dioxide emission reduction potential related to the deployment of HFCVs for all vehicle segments. In addition, the potential for air quality improvements for the bus segment is presented. The results in this report are based on information available from recent international fuel cell demonstration projects and from bilateral dialogues with the members of the NextHyLights consortium.

Carbon dioxide emission calculations are performed for demonstration to large deployment stages of hydrogen vehicles. Under the assumption of low market penetration up to 2020, the expected CO_2 emission reductions are of marginal impact, depending on the vehicle segment. Although carbon dioxide emissions will slowly start decreasing within the next decade, the choice of infrastructure setup for hydrogen production, delivery and distribution via refuelling stations could either reduce emissions moderately compared to those of ICE vehicles, or could importantly reduce emissions compared to business as usual on the long-term until 2050.

Passenger vehicles

A large deployment of HFC passenger vehicles, suitable with hydrogen production and distribution by SMR and through compressed hydrogen pipelines respectively, may contribute to carbon emissions reduction. Higher carbon abatement can be achieved if CCS is implemented or if methane originates from zero emission sources, such as biomass. Hydrogen produced by electrolysis powered by electricity from the grid will not contribute to emissions reductions unless dedicated renewable energy sources (RES) are utilized. Technical improvements of conventional vehicles could lead to 44% of emissions reduction. In addition to the latter, the rapid deployment of HFC passenger vehicles supplied in hydrogen by low carbon well-to-tank routes, might contribute to further 292% reduction by 2050 compared to business-as-usual (BaU) (see figure A). Making hydrogen refuelling stations (HRS) suitable to deliver hydrogen produced from zero emissions methane will become a challenge when HFC vehicles start to commercially deploy.

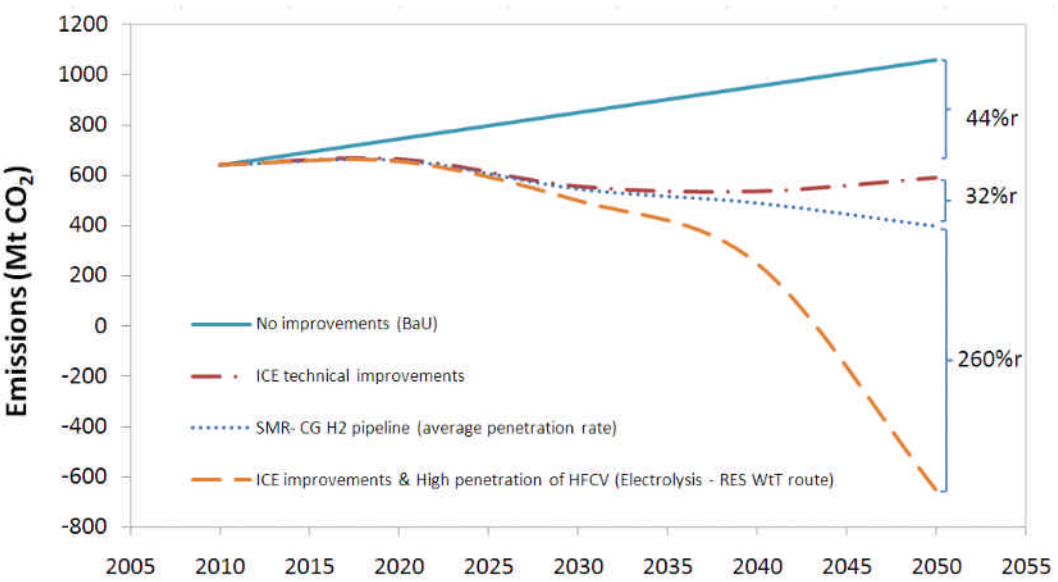

Figure A. Carbon dioxide emissions in the passenger vehicles segment until 2050.

Niche Vehicles

Hydrogen forklifts represent a high potential for emissions reductions. Although values for the European forklift's stock are not available, based on sales figures of the forklift market it is possible to estimate the carbon emissions reduction. When hydrogen is produced by any of the SMR pathways or electrolysis with renewable energy sources, carbon emission reductions are possible. Hydrogen production via electrolysis powered by grid mix electricity does not represent a tangible pathway to achieve emission reductions.

Buses

Current demonstration projects for buses mainly produce hydrogen via the SMR process. In the long-term carbon dioxide emissions will decrease even if hydrogen is still produced by conventional SMR. Hydrogen production via electrolysis supplied with high carbon power sources is one of the less attractive routes to achieve carbon dioxide emission reductions. The market arrival of diesel hybrid vehicles might strongly contribute to emission reductions beyond 2015, however, this is beyond the scope of this report. In the mean time, deployment of HRS for HFC buses appears an attractive option to obtain more expertise and knowledge on hydrogen technologies. The use of HRS to refuel both passenger vehicles and buses seems to be an important way to reduce emissions while getting passenger vehicle users familiarized with the technology.

Germany, France, Italy and the UK combined have the biggest share of the passenger vehicle and bus markets in Europe (~72%). Upcoming large-scale demonstration activities for FCVs are highly anticipated to take place in these countries (to a lesser extent in Italy and France), hence higher carbon emission reductions might be expected in these countries earlier than the rest of Europe in the mid-term. In the long term, technology transfer and commercialization plans of HFCVs to spread this technology will depend on OEMs strategies and infrastructure availability. Initiatives such as H2 Mobility, looking into a near-future hydrogen infrastructure rollout in Germany, together with the existing and forthcoming FCH

JU lighthouse projects in Scandinavia and elsewhere in the EU will represent the backbone for a gradual spread out of infrastructure to adjacent countries.

Compared to other emission sources, such as industry and power plants, road transport is a major source of health relevant air pollution. Since HFC vehicles do not emit air pollutants via tailpipe their introduction will improve air quality and health.

Air quality assessments show that substituting diesel by HFC-buses has the largest benefits on air quality and health in city centres, because of: (1) the dense population and consequently large number of people exposed; and (2) the municipal building structure, with “street canyons”, limiting dilution of exhaust gases, and associated relative high impact on the atmospheric concentration of pollutants.

Even the advanced conventional bus fleets will in 2025 emit amounts of pollutants with non-negligible impact on local air quality and related health impacts. Consequently, the deployment of hydrogen buses will improve air quality, and related health benefits. For the city of Amsterdam, the maximum emission reduction potential was estimated at about 90 tons for NOx and about 0,55 ton for PM10 (see figure B). Indicatively, these reductions would correspond to a decrease of about 10% of all transport related air pollution in the city centre of Amsterdam. For London, the maximum achievable reductions were estimated at about 2000 tons for NOx and about 12,5 tons for PM10.

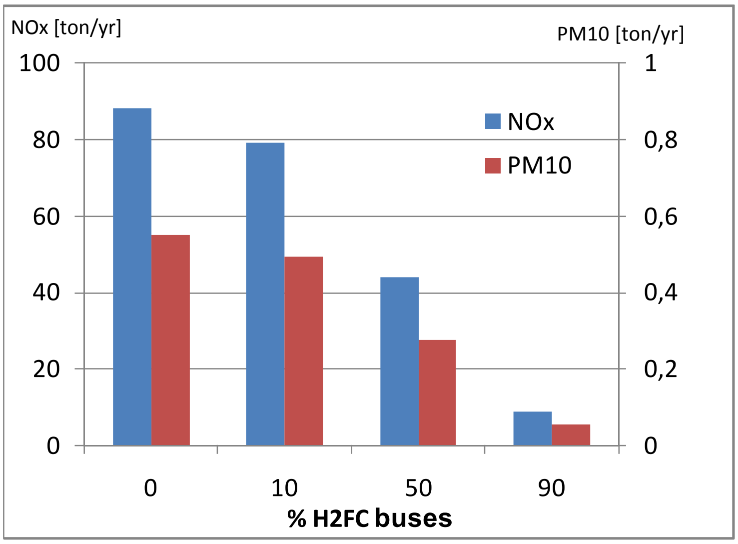

Figure B. Prevented emissions of NOx and PM10 in 2025 as a function of the assumed fleet share of HFC buses in Amsterdam.

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1 INTRODUCTION AND OBJECTIVES

1.1 Background

Currently, the reduction of greenhouse gas emissions in transport is high on all agenda's. Hydrogen fuel-cell powered vehicles (HFCVs) seem to have the potential to strongly reduce transport emissions, especially in the medium and long term. Together with national and local governments, industry stakeholders and European organisations have initiated the demonstration phase and early deployment of hydrogen vehicles as means of cleaner transport means. The main objectives of this deployment are: (1) to familiarize stakeholders and end-users with this new technology; and (2) to arrive at a better understanding on the possible long-term reductions of carbon dioxide emissions, compared to the conventional fossil-fuel internal combustion engine (ICE) vehicles. Already in the early deployment phases, hydrogen fuelled vehicles can contribute to eliminate local carbon dioxide emissions and particularly improve local air quality. However, the production and dispensing pathways of hydrogen are the decisive factors whether hydrogen vehicles can contribute on a larger scale in the fight against increasing greenhouse gas emissions in the transport sector.

Although noise variation is out of the scope of this report, it is important to be aware that road traffic is by far the predominant source of exposure to transport noise in large European agglomerations. Large numbers of people still live in hot spots where transport noise levels are likely to have severe effects on human health (TERM, 2009). A shift to HFC vehicles would almost completely avoid engine vehicle noise, the dominant factor in traffic noise at low speeds. HFC vehicles would therefore also contribute to the efforts of member states to meet the requirements of the EU Environmental Noise Directive that requires Member States to make 'strategic noise maps' for major agglomerations and major roads.

1.2 Objectives

The aim of this report is to present the environmental impact assessment for the deployment of hydrogen vehicles (HFCVs), subdivided in the segments passenger vehicles, special vehicles and buses. Separate chapters present the results for the carbon dioxide emission for the three vehicle segments and the potential for air quality improvement for the bus segment.

1.3 Report outline

Carbon dioxide emissions – Chapter 2

Regarding carbon dioxide emissions, particular attention is paid to the environmental impacts of all HFCV vehicles to be deployed by means of demonstration project schemes and to analyse to what extent the infrastructure implemented in this early phase may impact the carbon dioxide emissions by 2050. Information of the hydrogen pathways is included in this work and it is intended to fulfil the lack of emissions data between the current early niche markets and the large deployment stages. Estimations of emissions are derived from a model built under assumptions of a Well-to-Wheel (WtW) approach for several hydrogen pathways per vehicle segment. Emissions data adopted for hydrogen production/transport/use and expected improvements are retained from the JRC/EUCAR/Concawe study (Edwards et al., 2008), from previous work in NextHyLights and

ECN database. First, the structure of the carbon dioxide emissions model and production pathways from Well-to-Tank (WtT) for fossil and hydrogen fuels will be presented. Secondly, the considered data for the Tank-to-Wheel (TTW) part, the expected deployment per segment of FC vehicles and results are presented.

Local air-quality improvement– Chapter 3

Studies of local air-quality improvements related to the introduction of hydrogen buses in cities, such as Amsterdam and London, are included. The latter derives from the fact that buses often are operated in restricted areas and major improvements on air quality can be expected.

2 CARBON DIOXIDE EMISSIONS

In this chapter the methodology and results for carbon dioxide emission estimations are presented. This analysis includes the three vehicle segments considered in NextHylights: passenger vehicles, special vehicles and buses.

The first section of this chapter describes the methodology, the assumptions and the approach retained to evaluate the carbon dioxide emissions of hydrogen fuel cell vehicles (HFCV) that replace conventional internal combustion engine (ICE) vehicles. In addition, we describe a model to estimate carbon dioxide emission reductions from business-as-usual (BaU) scenarios.

In the second section of this chapter we present results and discussions about emissions at EU level in the three vehicle segments. For the passenger vehicle and bus segments, emission calculations are forecasted for 2050 and include assumptions for a transition period from demo-projects towards large deployment based on information documented in NextHyLights Deliverables 2.1 and 3.1. Emissions in the special vehicle segment are only extrapolated to the year 2030, based on information available from the NextHyLights Deliverables 4.1 and 4.2.

2.1 Methodology and emissions modelling

Regardless for which fuel - whether hydrogen, gasoline or diesel - the total carbon dioxide emissions result from the energy consumed for its production, transport, delivery and subsequent end-usage, either by combustion (ICE) or electrochemical reactions (HFCV). This inclusion of the total fuel chain in emissions calculation is referred to as the Well-to-Wheel approach (WtW). The WtW approach and can be seen as a two step process that includes: (1) each stage to produce a fuel and to bring it available to the user (Well-to-Tank or WtT); and (2) the stage of the conversion of the fuel into useful energy in a vehicle (Tank-to-Wheel or TtW) (See Figure 1).

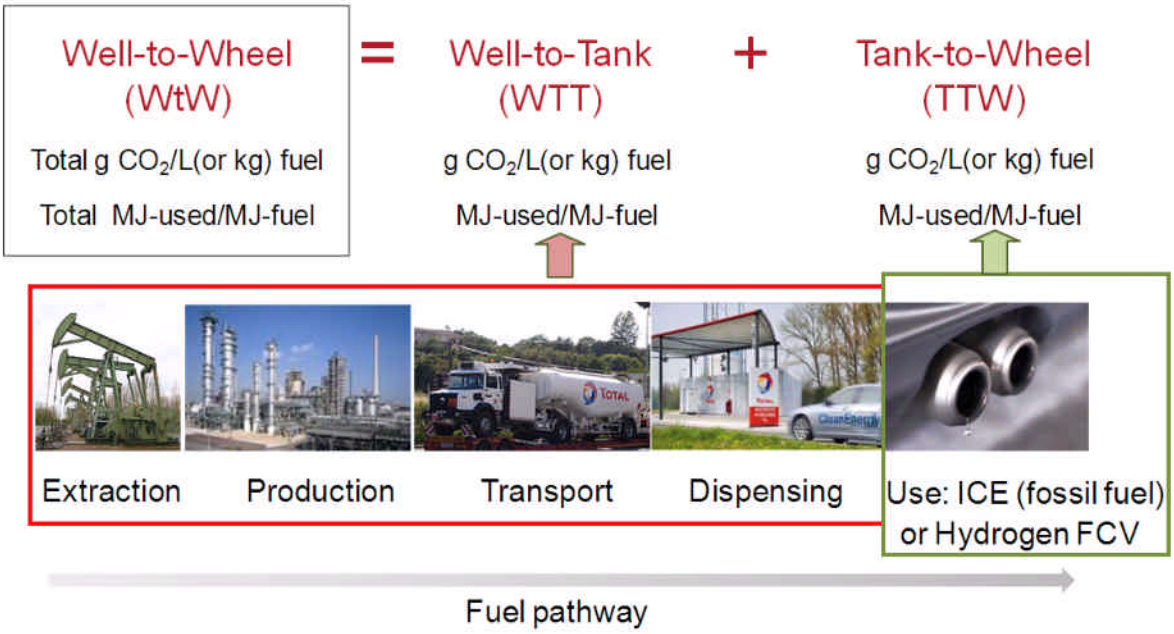

Figure 1 WtW components retained

The WtT component remains constant independently of the vehicle segment and depends only on the chosen pathway to produce and deliver a specific kind of fuel. On the other hand, the TtW component differs on each vehicle segment as they present different characteristics concerning fuel consumption, local usage, density, availability, etc. The impacts on emission reductions are then assessed relative to the vehicle type and its context (TtW). For instance, this chapter deals with the carbon emissions and air quality improvements are presented in Chapter 3.

The model used to estimate the carbon emissions is graphically represented in Figure 2.

a) The WtW part corresponds to the database of emissions, energy efficiency (both per unit of fuel) and assumptions for technology improvements in both ICE and HFC vehicles. Current values for energy efficiency and emissions during the extraction (if applicable), production, transport and delivery of fuel are collected from the JRC/EUCAR/Concawe study (Edwards et al., 2008). Data for future energy efficiency and emissions up to 2030 (special vehicles) and 2050 (passenger vehicles and buses) are generated by combining the JRC/EUCAR/Concawe data with the values that reflect the performance and technology improvement expected in the vehicles (TtW) (NextHyLights deliverables 2.1, 3.1, 4.2). Specific information referred to each vehicle segments is presented in subchapters 2.2.1, 2.2.2 and 2.2.3.

b) The vehicle market module serves to estimate the hydrogen-energy required to fuel an expected hydrogen vehicle fleet. The fleet consumption is estimated under assumptions for annual vehicle run, energy efficiency, fleet size and penetration rates (EU Statistics, 2010). Specific information referred to each vehicle segments is presented in subchapters 2.2.1, 2.2.2 and 2.2.3.

Both model parts generate values for energy use to produce fossil fuel, as well as values for the energy required by the hydrogen fleet for a specific year. Straight forward calculations allow obtaining values for the energy of the fossil fuel replaced by hydrogen. The output of the model is the variation in carbon emissions based on the fossil fuel energy replaced, which means the emissions' variation in contrast to ICE vehicles.

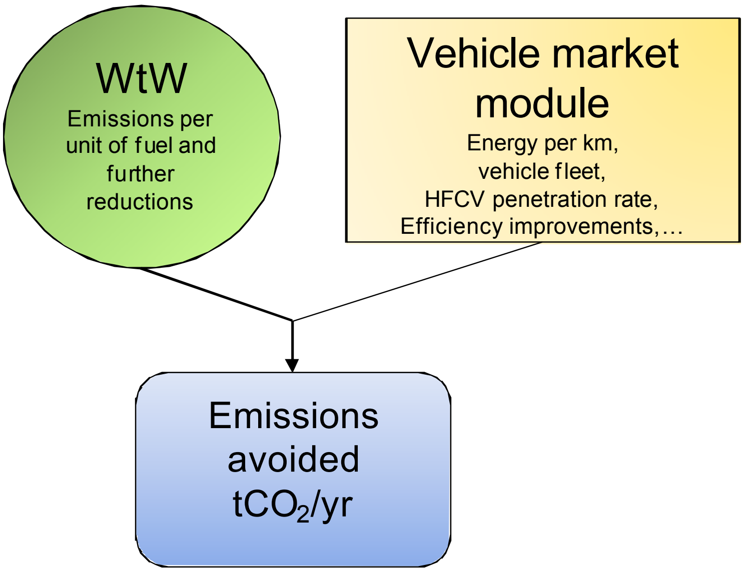

Figure 2 Schematic representation of the carbon emissions WtW model

In order to assess the impact of ICE technical improvements and hydrogen vehicle deployment on the emissions of a particular vehicle segment, a BaU level is set. We assume for this level that the vehicle performances (of current fleet) and market trends remain constant. For the assessment of ICE technical and energy efficiency improvements impact on carbon emissions, we compare the calculated emissions of the fleet with the BaU level. Emissions inherent to hydrogen vehicles deployment are added to the fleet emissions calculated under assumptions for ICE improvements.

The model allows several hydrogen WtT routes to be compared with the ICE improvements scenarios at European level, however, country specific information will be commented based on demonstration project planned for the mid-term if applicable.

2.1.1 Production routes of fossil fuels

The WtT carbon dioxide emissions of fossil fuels can change in the future due to substantial space for technological improvements of refineries, especially in the distillation and vacuum distillation parts. Retrofitting more efficient distillation columns can improve the efficiency of the refinery by 13% and an entirely new refinery, a so called green field refinery, will have a 30% better energy efficiency than current refineries (Wilde, 2010). However, due to restrictions on air polluting emissions by international shipping, refineries are no more allowed to commercialize residual fuels, the heaviest fraction of the crude oil, which then by economic reasons are converted in gasoline and diesel by the so called deep conversion process (cracking and hydrogenation). This deep conversion process for the production of gasoline and diesel, at full conversion of all the residual fuels, could counterbalance the gain of refinery's efficiency by higher CO_2 emission by about 30% (Wilde and Roeterdink, 2009).

To accurately estimate the WtT energy efficiency and emissions of gasoline and diesel for 2050 we found that not enough information is available at EU-27 level. Moreover, the sensitivity analysis on how efficiency improvements in refineries, in the order of 30%, could impact WtT emissions shows limited impact on WtW carbon emissions lower than 5%. Hence, we have not included improvements on carbon emissions referred to the WtT part.

2.1.2 Production routes for Hydrogen

The data concerning WtT energy efficiency and emissions for several hydrogen production routes derive from the JRC/EUCAR/Concawe study (Edwards et al., 2008). Currently, the conventional and most competitive route to produce large amounts of hydrogen is the central production from methane, via Steam Reforming (SMR – Steam Methane Reforming), and pipeline transport. However, current hydrogen demand from HFC vehicles in most EU countries remains very small and does therefore not yet justify dedicated hydrogen production e.g. by means of SMR. Hydrogen technology is in the phase of demonstration/early deployment and still undergoing a technological learning process. Hence, different pathways for hydrogen production are available and will be implemented until HFC vehicles will be deployed on commercial scales, thus driving larger hydrogen demand.

From Hyways (2007), the EU Member States' Vision document on hydrogen deployment has been considered and for the short term, both SMR on-site, SMR decentralized and electrolysis (electricity supplied by renewable energy sources (RES) or from the network) are the most suitable and expected production processes. A shift to centralized SMR with carbon capture and storage (CCS) and electrolysis (supplied only by RES) processes may occur in most of the countries in the mid (2020-2030) to long-term period (2050). In order to include these dominant production pathways, we will estimate the energy efficiency and emissions avoided accounting the diverse characteristics of five hydrogen production-transport routes:

- Electrolysis – EU Mix: Electrolysis of water. Electricity is supplied by the network to produce hydrogen on-site (suitable for both demo projects and deployment of HFCV).

- Electrolysis – RES: Electrolysis of water. Electricity is supplied by low carbon technologies, with average emissions between wind turbines and nuclear, to produce hydrogen on-site via electrolysis (suitable for both demo projects and large deployment of HFCVs).

- SMR – CG H2 pipeline: Piped NG to central hydrogen production, pipeline distribution and on-site compression (more suitable to larger HFCV deployment). Hydrogen is produced by SMR (pipeline of 4000 km) in a central plant, then distributed by pipeline to a max. 80km distribution network before compression to 88 MPA at the refuelling station.

- SMR – LH2 trucking: Piped NG to central production of liquid hydrogen, road distribution and on-site vaporisation/compression. Hydrogen is produced by SMR (pipeline 4000 km) in a central plant and subsequently liquefied. Liquid hydrogen is transported by tube trailer and *delivered as liquid* (suitable for both early and full deployment of HFCV).

- SMR – LH2VC trucking: Piped NG to central production of liquid hydrogen, road distribution and on-site vaporization/compression. Hydrogen is produced by SMR (pipeline 4000 km) in a central plant and subsequently liquefied. Liquid hydrogen is transported by tube trailer and *delivered as compressed gas* (suitable for both early and full deployment of HFCV).

Information related to the chosen hydrogen routes for on-going and planned demonstration projects of the three vehicles segments is compared to the five routes above mentioned in order to assess its contribution to the abatement of carbon emissions. Comments on specific routes follow the current trends in hydrogen demonstration projects. Annex A shows the existing hydrogen energy chains considered in several EU countries and in Annex B comments on electrolysis pathways that are included.

2.2 Vehicle segments

In this subchapter the assumptions and retained data used in the model for passenger vehicles, special vehicle and bus segments are presented.

2.2.1 Passenger Vehicles

Over the past years, passenger vehicles have reached a substantial increase in energy efficiency that is linked to a significant reduction in emissions per kilometer. Although the emissions for the new vehicle fleet on average are beyond 150 gCO_2/km, small new vehicles have reduced their emissions from 190 gCO_2/km to less than 120 gCO_2/km in 1990s and 2010 respectively (Volkswagen, 2002; ACEA, 2010, TERM 2009). This downwards trend is expected to continue for the coming decades leading to further emission reductions. Part of the increased vehicle efficiency improvements is related to the increasing share of diesel vehicles in the market for ICE vehicles over the last decade. Since diesel engines have an intrinsically higher efficiency compared to gasoline vehicles, the increasing “dieselisation” of the vehicle fleet explains part of the downwards trend of carbon emissions per kilometre.

Table 1 provides an overview on: (1) the WtW ICE vehicle emissions; (2) the energy required for TtW hydrogen vehicles; and (3) the diesel/gasoline market share considered in this report. For the first item, data is collected from a literature survey and provided by the project partners. For the second item, technical improvements in hydrogen vehicles are expressed in TtW terms due to the fact that carbon emissions only take place in the hydrogen WtT chain and depend on the energy required by the hydrogen vehicles. The third, market share of diesel and gasoline vehicles data, results from the extrapolation of the increasing share of diesel sales (since 2000) limited up to 61% of the market. This obeys the increase of diesel vehicle deployment, following an S-curve behaviour that seems to stabilize and intersects with the cumulative fleet of diesel vehicles by the year 2030 and beyond (ACEA, 2008, Pock, 2007).

Table 2 Vehicle emissions and share of gasoline/diesel fleet by 2050 (Gül, 2008, Uyterlinde, 2009, Pock, 2007, ACEA, 2008, Edwards et al., 2008, private communications with consortium partners)

	2010	2020	2030	2040	2050
Emissions WtW					
Gasoline (gCO_2/MJ)	84,5	84,0	83,5	82,9	82,4
Diesel (gCO_2/MJ)	88,5	87,9	87,2	86,6	85,9
Emissions TtW					
Hydrogen (MJ/km)	1,0	0,82	0,70	0,70	0,70
Market					
Share of gasoline fleet	67%	53%	39%	39%	39%
Share of diesel fleet	33%	47%	61%	61%	61%

The increase on the vehicle stock and sales is extrapolated linearly until 2050 based on the current trend obtained from historical data, as shown in Figure 3 (EU Statistics, 2010).

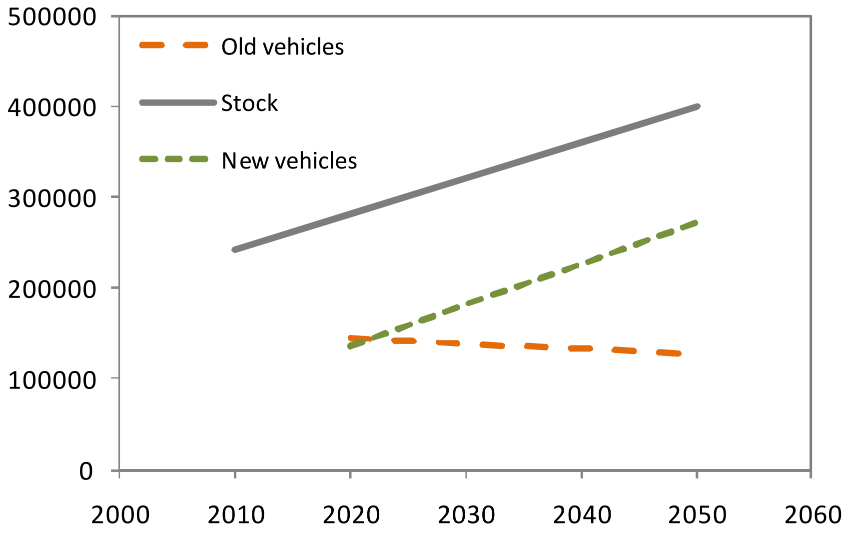

Figure 3 Forecast of passenger vehicle fleet size and share of new and old vehicles, based on historical data (EU Statistics, 2010).

Deliverable 2.1 (Assessment of former and current demo projects & technology status quo) has shown that there is still strong interest in the deployment of hydrogen vehicles in Europe. In addition, several car manufacturers have confirmed their continuous interest in deploying larger numbers of vehicles (e.g. Daimler, Toyota). In order to assess the emission reductions derived from the transition period between demonstration to full deployment of hydrogen vehicles and the benefits of shifting from ICE to HFC vehicles, we considered two penetration scenarios (moderate and high) that include the same values of penetration rates presented in the HyWays reports (Hyways, 2007b). In the moderate penetration scenario, by

2020 and 2050 annual passenger HFCV sales reach 111,500 and 3,900,000 units respectively. This scenario matches with OEM expectations on passenger HFCVs deployment by 2020. In the high penetration scenario, which is rather optimistic, by 2020 and 2050 sales reach 690,000 and 9,000,000 respectively.

For both ICE and HFC vehicles, calculations are based on an annual run of 15,000 km.

2.2.2 Special vehicles

Current fleet status of special vehicles position them in a much smaller market with low carbon emission contribution compared to passenger and bus HFCVs. However, major expectations on local air quality and potential health improvements can be expected from them.

Deliverable 4.2 compiles information of the on-going demonstration projects in Europe regarding three main kind of special vehicles: sweepers, leisure boats and material handling (MH) vehicles (mainly forklifts). This last vehicle sub-segment is retained for carbon dioxide emission calculation as it accounts with the highest amount of available information. Moreover, MH diesel vehicles currently present a dynamic market and they are frequently used in reduced surfaces, which lead to local air quality degradation. Although air quality improvement related to substitution of ICE powered forklifts by the FC-alternative is not addressed in this report, there are many parallels with the deployment of FC-buses (see chapter 3).

As limited carbon emissions and energy efficiency data are available for both ICE and hydrogen MH vehicles, we assumed that within the period 2010-2050 any technical improvements could take place. The lack of vehicle stock data also hampers the carbon emission estimations for the fleet. Nevertheless, MH market data is available and allow the variation on emissions to be estimated for the five hydrogen WtT routes previously presented. In Table 2 we compile the data used for our calculations.

Table 3 Vehicle emissions and share of gasoline/diesel fleet by 2050 (Deliverable 4.2)

Emissions WtW, 2010 - 2050 Diesel (gCO_2/MJ)	75,1		
Emissions WtW, 2010 - 2050 Hydrogen (MJ/h)	47,9		
Operating time per year	1250 h		
Market growth	2010	2020	2030
Diesel MH sales (thousands)	326	485	645

Diesel MH sales are separated for East and West European countries. Because of the slow increase on the number of demonstration projects in Europe, we assumed market penetration rates of hydrogen MH vehicles fixed at 1% and 10% for low and high scenarios respectively.

2.2.3 Buses

Several large cities in the EU, mainly those being part of the Hydrogen Bus Alliance[1] (HBA), have shown increased interest and commitment to replace diesel by hydrogen buses. Although the total carbon dioxide emissions from buses are relatively low compared to those from passenger vehicles, the replacement of diesel buses contributes to a non-negligible reduction of GHG gases. In addition, the deployment of hydrogen buses will enhance air quality in the cities due to the reduction of pollutants in a reduced geographical space (see chapter 3). On-going and planned demonstration projects are documented in deliverable 3.1.

Similar to passenger vehicles, diesel buses have increased their energy efficiency and lowered the carbon dioxide emissions per kilometer. In the next decades new ICE configurations, such as diesel-hybrid buses, might be able to better compete with hydrogen buses. Nevertheless, advanced FC-buses will always be more energy efficient than the diesel alternative, given the intrinsically lower maximum achievable efficiency of diesel engines compared to advanced fuel cells. In order to assess the carbon emissions of diesel buses, we modelled the emission by 2050 assuming different scenarios for ICE technology improvements, hydrogen technology improvements and HFC buses deployment.

Table 3 shows data for WtW ICE diesel bus emissions compared to energy required for TtW hydrogen vehicles. For the diesel buses, data is collected from a literature survey and our partners. For the hydrogen alternative, technical improvements in vehicles are expressed in TtW terms due to the fact that carbon emissions only take place in the hydrogen WtT chain and depend of the energy required in by the hydrogen vehicles. The increase on the vehicle stock and sales has been also considered and results from the linear extrapolation until 2050 of historical data, as shown in Figure 4 (EU Statistics, 2010).

Table 4 Bus energy efficiency by 2050 (data calculated based on Deliverable 3.1 and private communications with consortium partners)

	2010	**2020**	**2030**	**2040**	**2050**
Emissions WtW					
Diesel (MJ/km)					
Low technological improvement	15,3	15,3	15,3	15,3	15,3
High technological improvement	15,3	14,1	12,9	11,7	10,5
Hydrogen (MJ/km)					
Low technological improvement	12,6	12,0	11,4	10,8	10,2
High technological improvement	12,6	10,8	9	9	9

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[1] http://www.hydrogenbusalliance.org/about.html

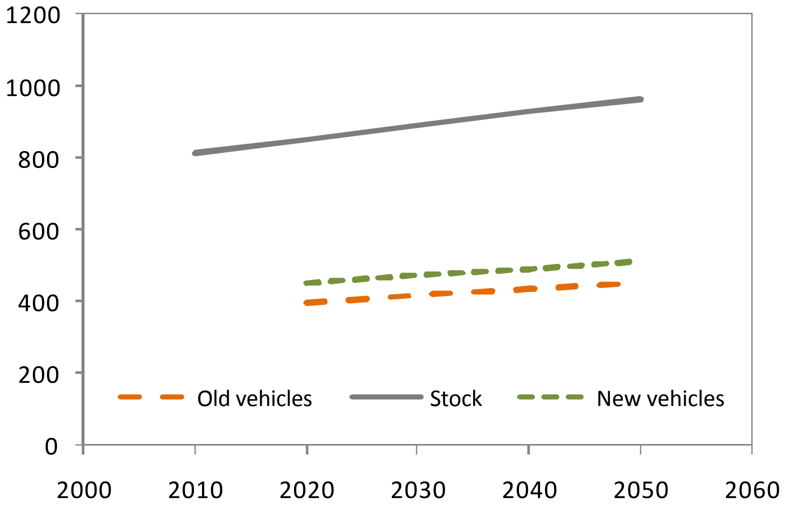

Figure 4 Forecast bus fleet size and share of new and old vehicles based on historical data (EU Statistics, 2010).

Hydrogen demonstration projects are documented in deliverable 3.1. The assessment of the emission reductions is based on an annual run of 96,000 km per bus and derives from the transition period between demonstration to full deployment of hydrogen buses. We considered two penetration scenarios (moderate and high) that respectively assume the values presented in Figure 5.

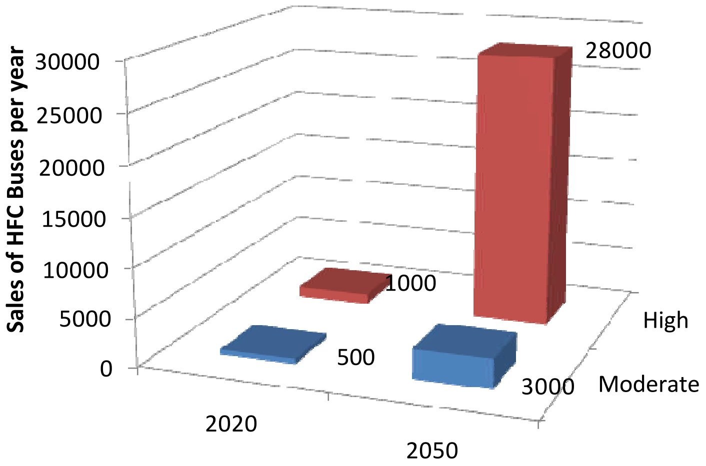

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Figure 5 Market penetration scenarios for HFC Buses.

Penetration rates and technological improvements for ICE and hydrogen buses give a set of combinations that lead to different carbon emission reductions. Five combinations between these three variables are evaluated in this study (See Table 4).

Table 5 HFC Bus penetration scenarios from demonstration phase to 2050.

No.	Energy Efficiency Improvement on ICE buses	Energy Efficiency Improvement on HFC buses	HFC bus penetration rate	Code
1	High (H)	Low to Moderate (L)	High (H)	H-L-H
2	Low to Moderate (L)	Low to Moderate (L)	High (H)	L-L-H
3	Low to Moderate (L)	High (H)	High (H)	L-H-H
4	High (H)	Low to Moderate (L)	Low to Moderate (L)	H-L-L
5	High (H)	High (H)	Low to Moderate (L)	H-H-L
6	High (H)	High (H)	High (H)	H-H-H

Results for the most relevant scenario in terms of carbon emissions reduction will be presented in Chapter 2.3. For more results, please refer to the Annex C.

2.3 Results and discussion

2.3.1 Passenger vehicles

The variation on annual carbon dioxide emissions under assumptions of a high penetration rate of HFC passenger vehicles and for the five hydrogen WtT routes is presented in Figure 6. In general, the five routes only differentiate from each other in the long term, at least beyond 2020. When the current hydrogen processes and energy supplies are considered to fuel the HFC fleet by 2050, only Electrolysis – EU mix routes drive emissions to higher levels than ICE vehicles by 2050. On-site hydrogen production via electrolysis supplied by power from the electric network (current European mix) has the strongest negative impact on emissions in the long run. Low carbon electricity production technologies (Renewables, nuclear, CCS) may further reduce carbon emissions of the electrolysis based hydrogen production. Electrolysis – RES route validates the later. All SMR pathways even without capture and storage of carbon dioxide (CCS) contribute to reduce emissions.

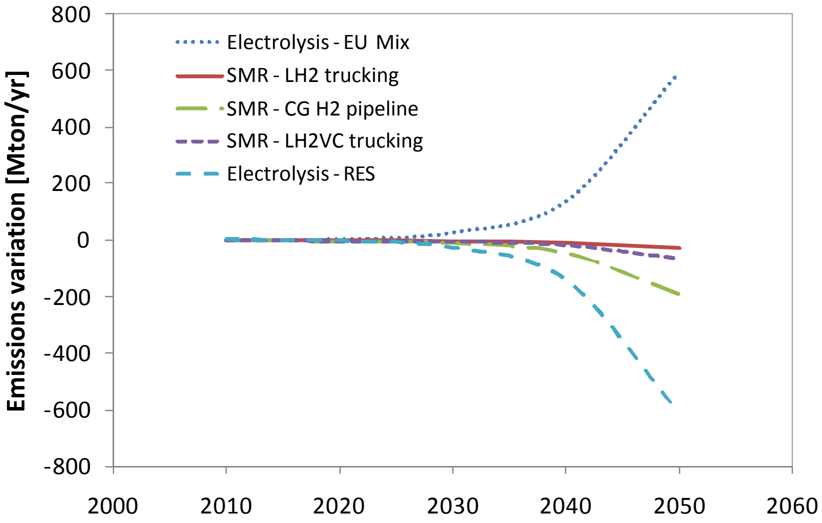


Figure 6 Scenario High HFC passenger vehicles penetration rate: emission variations for five WtT hydrogen routes in the HFC passenger vehicles segment

If technical performances and growth of the current European passenger vehicle fleet are to remain stable for the period 2010 – 2050 (BaU), annual carbon emissions may reach about 1,5 Gt by 2050 (See Figure 7). Car manufacturers, however, expect technological improvements that may contribute up to 44% reduction of carbon emissions by 2050. Although these improvements bend the upward emissions trend by 2020, the important growth in the vehicle fleet counterbalances the emission reductions achieved and the upward trend is settled again by 2050. A large deployment of HFC passenger vehicles, suitable with hydrogen production and distribution by SMR and through compressed hydrogen pipelines respectively, may contribute to carbon emissions reduction. Higher carbon abatement can be achieved if CCS is implemented or if methane originates from zero emission sources, such as biomass. Finally, ICE technical improvements in addition to the rapid deployment of HFC passenger vehicles supplied in hydrogen by low carbon WtT routes, such as Electrolysis – RES, might contribute to a net reduction from 2025 onwards.

High technical improvements could lead to a fierce market competition between HFC and ICE vehicles, thus a lower penetration rate for FCVs, if carbon emissions level and vehicles cost are close to each other.

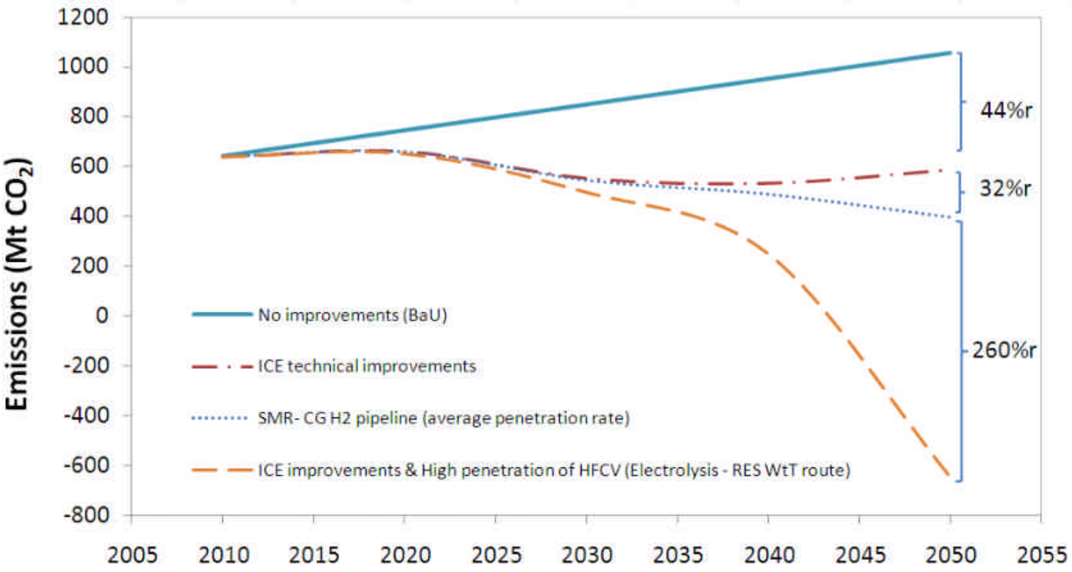


Figure 7 Carbon dioxide emissions in the passenger vehicles segment by 2050

EU-wide hydrogen refuelling stations (HRS) mostly apply on-site hydrogen production by a SMR unit. Although these HRS are demonstration projects or projects in the planning phase (Deliverable 2.1), the use of fossil-methane to produce hydrogen seems to moderately contribute to lower carbon dioxide emissions in the mid to long-term. As it can be observed, a net impact on emissions reduction/increase is not clearly visible before 2020 because of the still small size of the HFCV fleet. However, within the next decade, most hydrogen technologies and production of methane from other sources such as biomass and waste will become increasingly available, thereby promoting solid emission reductions in the long run. Another option is to include CCS technology in SMR plants.

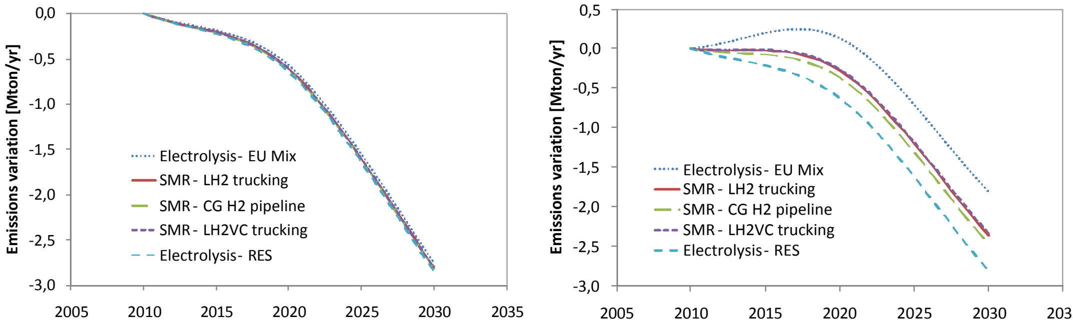
This technology, however, has a long way to become competitive enough to avoid carbon emissions from SMR processes fuelled with fossil-methane.

Although Electrolysis - RES seems the most transcendent WtT hydrogen route towards a low carbon FCV fleet - all HRSs are unlikely to use this route due to infrastructure requirements. For example, the use of dedicated low carbon technologies depend on local renewable energy potential or the distance of the HRS from a nuclear or thermal-CCS power plant of the HRS location. Although electrolysis WtT routes seem a second suitable option to produce hydrogen, after SMR, the source of electricity should emit at least 20% less carbon than the current EU-mix per kWh if carbon dioxide emissions are targeted. EU countries with a high share of RES in their electricity mix and planning hydrogen production via electrolysis would have important advantages concerning emission reduction opportunities in this vehicle segment.

From market figures, it is intended to describe what could be expected for HFCV deployment at country level. The current market of ICE vehicles shows that Germany, France, Italy and the UK have the biggest share of the market (72%). Upcoming large-scale demonstration activities for FCVs are highly anticipated to take place in these countries (to a lesser extent in Italy and France), hence higher carbon emission reductions might be expected in these countries than the rest of Europe in the mid-term. In the long term, technology transfer and commercialization plans of HFCVs to spread this technology will depend on OEMs strategies and infrastructure availability. Initiatives such as H2 Mobility, looking into a near-future hydrogen infrastructure rollout in Germany, together with the existing and forthcoming FCH JU lighthouse projects in Scandinavia and elsewhere in the EU will represent the backbone for a gradual spread out of infrastructure to adjacent countries.

2.3.2 Special vehicles

In Figure 8, the variation on annual carbon emissions under assumptions of low penetration rate of HFV MH vehicles and for the five hydrogen WtT routes is presented. Due to the fact that HFC MH vehicles require half the energy of comparable diesel or gas MH vehicles, four of the five hydrogen WtT routes might present an important reduction of carbon emissions. On-site hydrogen production via electrolysis supplied by power from the electric network (current European mix) is the only route that presents a negative impact on emissions. As for HFC passenger vehicles, Electrolysis with power supply from low carbon technologies presents the higher potential for carbon emissions reductions.



(a) (b)

Figure 8 Scenario low (a - 1%) and high (b - 10%) HFC special vehicles penetration rate: emission variations for five WtT hydrogen routes

Based on market data, in the mid-term (2020-2030), Western European countries will benefit from larger carbon emission reductions and air quality improvements than Eastern European countries. Beyond 2030, Eastern Europe is expected to retrieve a similar market size (order of magnitude) as Western Europe. Hence in the long run similar improvements will be found in both parts of Europe for MH vehicles.

2.3.3 Bus segment

The variation on annual carbon emissions under assumptions of high penetration rate and technical improvements of HFC buses and high diesel technical improvements is presented in Figure 9. SMR routes only differentiate from each other in the long term, at least beyond 2035. SMR and Electrolysis routes start to differ from the beginning of 2020 and increase to deviate up to nearly an order of magnitude by 2050. As in the previous two vehicle segments, Electrolysis – EU mix route shows higher emissions levels than ICE vehicles by 2050. Among the SMR routes, the SMR CG H2 pipeline route presents the highest reduction on emissions in the long run. Results for five additional scenarios are presented in Annex B.

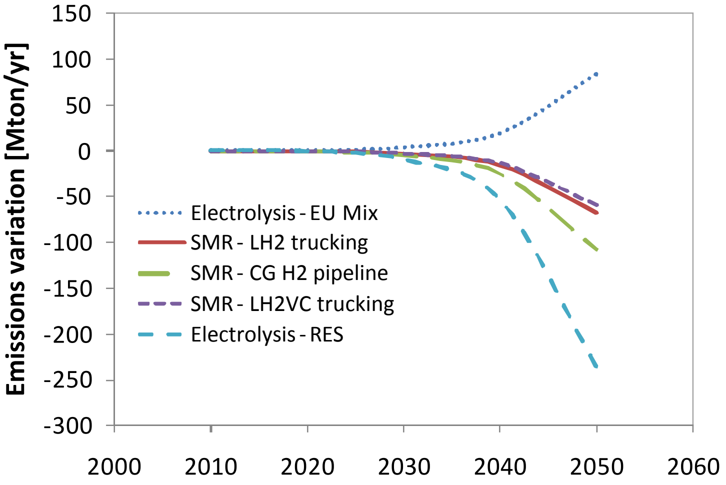


Figure 9 Scenario L-H-H: Emission variations for five WtT hydrogen routes in the bus segment

If technical performances and growth of the current European bus fleet are to remain stable for the period 2010 – 2050 (BaU), annually 125 Mt of carbon dioxide might be emitted by 2050 (See Figure 10). Large deployment of HFC buses strongly contributes to emission reductions by 2050 compared to BaU.

The WtT hydrogen route accounting for the SMR process contributes to carbon emission reductions. It could be expected that CCS and zero emission methane sources will enhance this contribution. The later opens several on-site hydrogen routes to be interesting from an emissions perspective. A major net impact on emission reduction by HFC buses relative to the diesel-hybrid scenario will not be perceived until 2025, since vehicle numbers will be too low before that time.

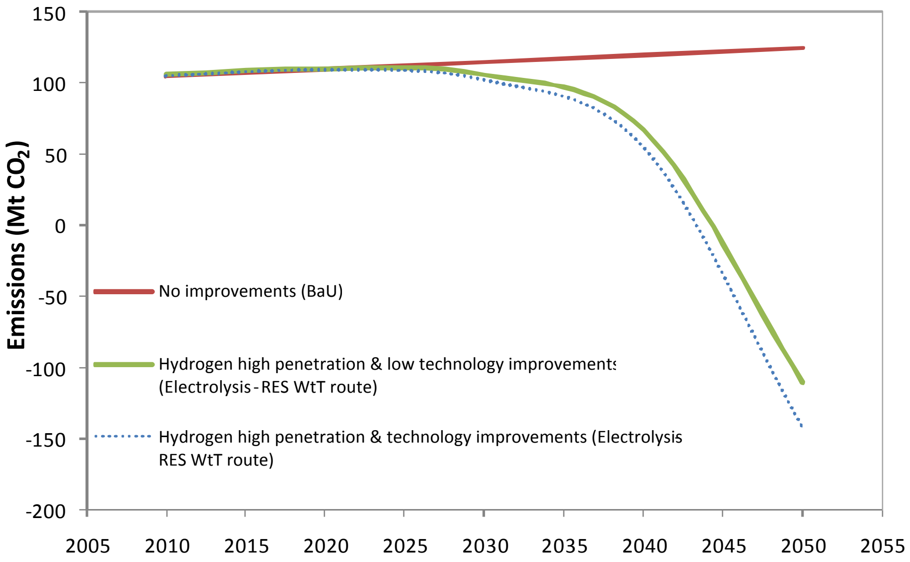


Figure 10 Carbon dioxide emissions in the bus segment by 2050

Similar to passenger vehicles, France, Germany, UK and Italy are the major market players in the bus-segment with a total share of 72%. Cities in Germany, Spain and UK have shown interest and commitment to hydrogen buses through the Hydrogen Bus Alliance. Italy and France have their own hydrogen bus deployment activities. As the characteristics of bus fleets differ completely from passenger vehicles, on-site SMR HRS deployment contributes to lower carbon dioxide emissions from the beginning of the HFC bus projects. Although a net difference will not be perceived until 2020, the advantage of HRS for HFC buses is that they can provide additional knowledge on hydrogen technologies and the infrastructure handling. Important synergies might be found by making HRS for buses, additionally available for passenger vehicle users.

2.4 Conclusions

Hydrogen production routes currently considered by hydrogen demonstration projects have different, but not immediate, impacts on emissions reduction depending on the vehicle segment. Although carbon dioxide emissions will slowly start decreasing within the next decade, the choice of infrastructure setup for hydrogen production, delivery and distribution via refuelling stations could either reduce emissions moderately compared to those of ICE vehicles, or could importantly reduce emissions compared to business as usual on the long-term until 2050.

Calculations performed under assumptions for WtW approach showed that:

- Most of current demonstration projects for passenger vehicles produce hydrogen via SMR, which in the mid-term will not significantly contribute to reduce carbon dioxide emissions. However, from a HRS perspective, in the long run the current SMR route need to be adapted and further studied in order to strongly contribute to emission reductions. Although there are emissions reductions with the SMR route, potential barriers for enhanced carbon dioxide reduction in the mid-term may be limited sources for the production of non-fossil methane and/or sufficient implementation of CCS technologies in SMR plants. Hence, familiarization with hydrogen technologies performed by demonstration projects will improve knowledge and implementation capacity of non-fossil methane production and/or CCS technology.

- If ICE passenger vehicles continue to rapidly increase their energy efficiency up to 2050, a passenger vehicle fleet dominated by hydrogen produced via SMR may moderately contribute to additional reduction of carbon dioxide emissions. However, hydrogen vehicles can induce substantial additional reductions of carbon dioxide emissions beyond 2020 when the hydrogen originates from methane from zero-emission sources, such as biomass, and/or is produced by electrolysis with renewable electricity.
- Current demonstration projects for buses mainly produce hydrogen via the SMR process. Contrary to passenger vehicles, in the long-term carbon dioxide emissions may sensibly decrease even if hydrogen is still produced by SMR. Hydrogen production via electrolysis supplied with high carbon power sources seems to be one of the routes that will disable hydrogen buses to contribute for carbon dioxide emission reductions. Deployment of HRS for HFC buses appears an attractive option to obtain more expertise and knowledge on hydrogen technologies. The use of HRS to refuel both passenger vehicles and buses seems to be an important way to reduce emissions while getting passenger vehicle users familiarized with the technology.

3 AIR QUALITY IMPROVEMENTS – DEPLOYMENT OF HYDROGEN FUEL CELL BUSES

3.1 Methodology and scope

Compared to other emission sources, such as industry and power plants, road transport is a major source of health relevant air pollution. An important additional advantage of hydrogen fuel cell vehicles is that they do not cause air pollution during driving. Consequently, the introduction of fuel cell vehicles leads to an improved local air quality and associated less adverse effects on human health. The health impact of current diesel buses and other vehicles is predominantly related to the emissions of particulate matter (PM10) and to a lesser extent to Nitrogen Oxides (NOx). Both pollutants involve increased occurrence of respiratory and cardiovascular diseases. PM emissions are the dominant factor in terms of increased morbidity and mortality. PM (particulate matter), often referred to as PM_{10}[2], is a complex mix of particles in the air that varies in size and chemical composition. Epidemiological studies have indicated that traffic related PM10 emissions involve substantial health implications (e.g. Kunzli, 2000). For example in the Netherlands, traffic related PM is associated with thousands of premature deaths per year (Hoek et al. 2002; Keuken et al., 2009). In many European cities the air quality exceeds the thresholds set by the EU air-quality directive (2008/50/EG), see e.g. www.airqualitynow.eu, resulting in serious limitations for spatial planning especially regarding new infrastructure and buildings. Several member states have asked for a few years delay to meet the air quality targets, under the condition that they implement stringent air quality improvement plans. Reducing transport emissions, especially at busy municipal hot spots, is a key element in most of these action plans.

3.1.1 Clean hydrogen fuelled city buses

For buses the HFC concept is an almost zero emission alternative to their diesel counter-parts, that can also cope with the high power demand, driving time and ranges required. Battery electric powered buses, would offer comparable air quality improvements as HFC buses. However, at the current state of battery performance, battery electric buses most likely cannot meet the daily operational time required, at an acceptable battery size.

The air quality improvement, and associated health benefits, related to the introduction of emission free HFC powered buses depends on the emissions of the conventional buses that are replaced. The overall health benefits in addition depend on the number of people exposed. In cities the conventional bus emissions have a relatively large health impact because of the combination of (1) the dense population and consequently large number of people exposed to exhaust gases and (2) the local conditions (limited wind, street canyons) causing limited dilution of exhaust gases and relatively high concentrations of pollutants. Consequently, from an air quality perspective the relative costly implementation of HFC buses is most (cost) effective in cities.

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[2] PM10 refers to all particles in the ambient air with a diameter less then10 micrometers

3.1.2 Scope and approach

The scope of this chapter is the achievable air quality improvement of replacing future (2025) diesel buses by HFC buses in European cities, as around 2025 HFC buses may be cost competitive, relative to conventional buses (Zaetta and Madden, 2010) This chapter focuses on particulate matter/soot (PM10), the key health threatening component, and nitrogen oxides (NOx).

As a second step, a rough indication is given of how the emission reductions by HFC buses relate to reduced mortality. These parameters can be quantified in so called DALY's (Disability Adjusted Lost Years of Life).

3.2 Improved air quality by HFC buses

3.2.1 Trends in emissions of conventional buses

The air quality benefits of hydrogen buses depend on the emission characteristics of the vehicles they replace. Over the last decade diesel powered vehicles have become much cleaner, due to the implementation of the increasingly tighter EURO-emission standards (see Figure 11).

The recently implemented Euro-5 emission standards ensure that current new vehicles emit substantially less than a decade ago: PM emissions limits for diesel buses are lower by about a factor 10, and NOx emission limits by about a factor 5. The future Euro-6 emission standard involves a further lowering of the emission limits for NOx and PM10.

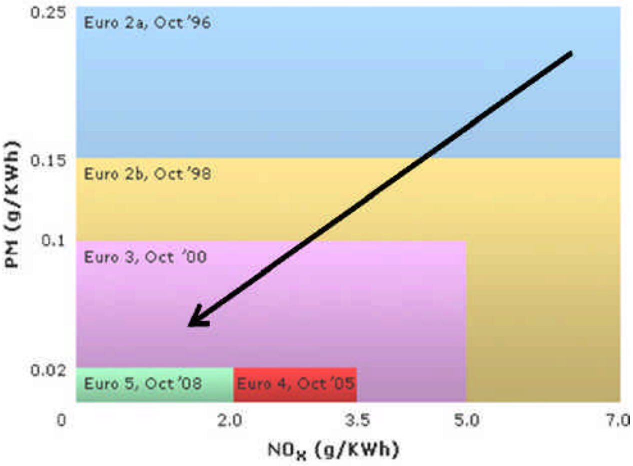

Figure 11 EU-emission standards for heavy duty diesel engines in g/kWh Source: www.dieselnet.com

Despite the growth in traffic, the increasingly stricter EU emission standards for buses and other vehicles have resulted in substantially lower traffic emissions of air polluting compounds in all member states. Although new vehicles are becoming increasingly cleaner, the emissions of the bus fleets lag behind by about a decade, since buses are kept in service for some 10 years before they are replaced. Consequently traffic emissions of pollutants are expected to continue to decrease over the next decade (see example Figure 12). Nevertheless, the emissions remaining around 2025 cannot be neglected. Despite the cleaner conventional bus fleet, the introduction of HFC powered buses will still involve substantial benefits for local air quality, especially in densely populated city centres (see details in Paragraph 3.3).

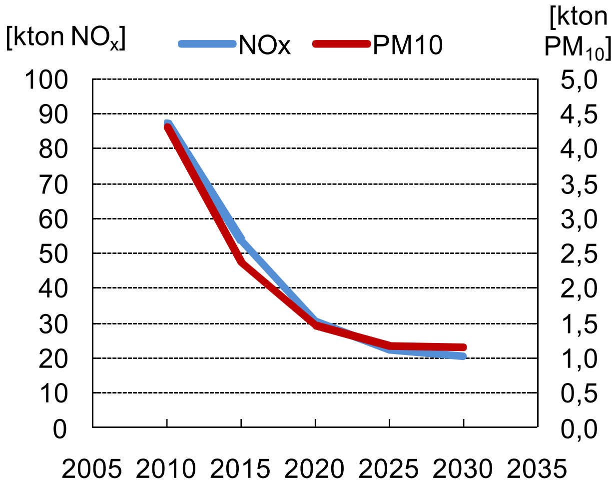

Figure 12 Expected direct emissions of road transport in the Netherlands, based on current transport policies: NOx (left) and PM10 (right); modified after Hanschke et al, 2009.

3.2.2 Emission standards current and future diesel buses

New city buses that are currently available on the market generally meet the European emission standards for an ‘enhanced environmentally friendly vehicle’ (EVV). EEV is a term used in the European emission standards for the definition of a ‘clean vehicle’ with emissions between the levels of Euro V and Euro VI. The Euro VI emissions standard will become effective from 2013 for new type approvals and from 2014 for all registrations. The Euro VI emission standard does also involve a particle number limit, in addition to the indicated particle mass limit in g/kWh. This particle number limit will prevent the possibility that the Euro VI PM mass standard will be met by using technologies that would enable a high number of ultra fine particles to pass (such as ‘open filters’).

3.2.3 Real life emissions

There are major differences between the type approval for buses and trucks and the ‘real life’ emissions, particularly for NOx during bus operation in urban areas (e.g. Ligterink et al, 2009). The Euro emission standards (expressed in gram pollutants per kWh), are not easily translated to real life driving conditions (with emissions expressed in gram pollutant per km driven). In the type approval test emissions are measured in an ESC and/or ETC cycle (see e.g. www.dieselnet.com for details). However, the ‘real life’ operating conditions of municipal buses differ from the test conditions, which may result in substantially higher emissions (Kadijk, 2008). In addition, conventional buses (both diesel and natural gas) show a relatively large variability in ‘real life’ emissions (Kadijk and Verbeek, 2007).

A compilation of several literature sources (Kadijk, 2008; Eichlseder and Rexeis, 2008; Nylund et al., 2007; Hausberger et al., 2007) indicate that the 'real life' emissions of advanced diesel city buses, that meet the EEV-standard (Enhanced Environmetally friendly Vehicle), are in the range of:

- 3-5 g/km for NOx (predominantly controlled by the efficiency of SCR catalyst)

- 0,02-0,03 g/km for particles (PM10)(predominantly controlled by the efficiency of the soot filter).

Note that the above emissions for the cleanest available diesel buses are comparable to the emissions of buses powered by natural gas engines, the main 'conventional' clean alternative (Kadijk (2008).

3.3 Results - air pollution prevented by HFC buses

The study considers the city of Amsterdam (currently approx. 750.000 inhabitants; and approximately 300 city buses in service) as a representative example, to evaluate the air quality benefits of HFC buses in (European) cities. However it should be kept in mind that in general health effects will be largest in cities with a high density of both people and buildings, because the health impact is related to: (1) the number of people exposed, with high municipal population density increasing overall health impacts; and (2) the dilution of exhaust gases, which is controlled by both meteorological conditions (wind) and the municipal building structure, with a high building density limiting the dilution of exhaust gases.

Following the Amsterdam approach, the impact of introducing HFC buses was also evaluated for London.

3.4 Amsterdam case study

3.4.1 Emission reduction potential

The air quality impact of substituting conventional municipal buses by HFCVs depends on the emissions of the advanced diesel buses replaced. For the city of Amsterdam the next section gives an assessment of the air quality improvement, based on following assumptions.

- Given the replacement time for buses of about 10 years, the buses that meet the EEV standard are assumed to reach full penetration in the bus fleet by 2025, with average city bus emissions assumed to be 4 g/km for NOx and 0,025 g/km for PM10.

- The Amsterdam municipal bus fleet drives about 22 million (10^6) km per year (Weijers en De Wilde, 2003; DIVV, 2010).

Following the above assumptions, the all EEV standard bus fleet, is expected to emit in Amsterdam around 2025:

- NOx: 88 x 10^6 g

- PM10: 0,55 x 10^6 g PM10 (predominantly in the form of ultra fine particles)

The complete substitution of diesel buses by HFC buses would result in the maximum of emissions prevented. Lower shares of HFC buses result in proportionally lower air quality benefits, as indicated in Figure 13.

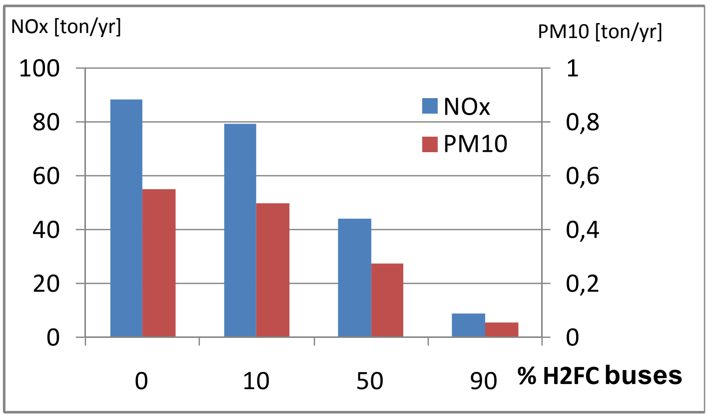

Figure 13 Prevented emissions of NOx and PM10 in 2025 as a function of the assumed fleet share of HFC buses in Amsterdam

3.4.2 Air Quality Improvement

For PM10, the most health relevant component, this value relates to a maximum reduction in the local atmospheric concentration in the order of 0,5 microgram per m^3, compared to an average annual concentration of about 30 microgram per m^3 (actualization of the estimate presented in Weijers en de Wilde, 2003). However, expressed in terms of health improvement, the relative gain may be larger given the small size and chemical composition of the diesel soot, to which stronger adverse impacts on health are attributed (see e.g. Hoek et al., 2002).

3.4.3 Indicative health impacts

Relating air quality improvement to health impact is based on statistical relationships, intrinsically involving large uncertainties. Several studies have shown that increased levels of traffic related air pollution, especially for PM, lead to increased mortality rates (e.g. Kunzli et al, 2000 and Hoek et al, 2002). Based on the number of inhabitants of Amsterdam (currently close to 0,75 million) the air quality improvements can be indicatively related to reduced loss of life. Following the approach of Kunzli (2000), the health benefits of substituting the complete municipal 2025 bus fleet of about 300 buses in Amsterdam, would roughly correspond to about a dozen of premature deaths prevented annually.

3.5 Other cities

3.5.1 London – emission reduction potential

The future emissions of advanced buses around Europe will be predominantly controlled by the EU emission standards. Consequently the buses in London in 2025 are assumed to have the same emission characteristics as buses in Amsterdam. Scaling of the Amsterdam bus fleet of close to 300 full day operated municipal buses to the London situation with about 6700 municipal buses in full day service, gives the emission reduction potential of HFC buses, relative to their fleet share (Figure 14).

The main factors controlling health impact (meteorology, population density, building structure) are quite comparable for Amsterdam and London. Consequently, the health impact in London is expected to be proportionally related to the number of buses, suggesting that a complete switch to clean hydrogen buses in London would roughly correspond to some hundreds of premature death prevented annually.

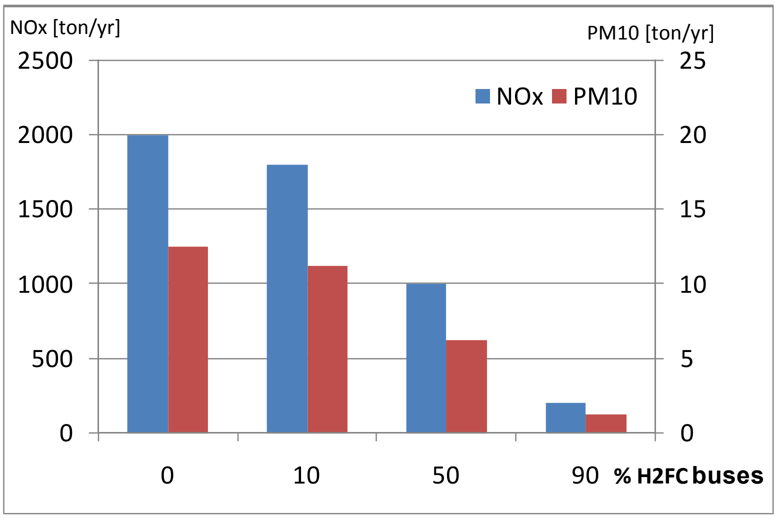

Figure 14 Prevented emissions of NOx and PM10 in 2025 as a function of the assumed fleet share of HFC buses in London

3.5.2 Scaling to other cities

The results could be scaled to other major European cities. Assuming similar emissions of advanced future diesel buses over Europe, the prevented emissions per city are linearly related to the total bus km covered by HFC buses. The impact of reduced bus emissions on local air quality (expressed in gram pollutant per cubic meter of air), will be comparable between most cities. However, this impact is also controlled by local conditions such as meteorology and building structure that effect the dilution of exhaust gases. Moreover, the overall health impact is linearly related to the number of people exposed. As a consequence, the air quality and health improvements for introducing HFC buses will be the largest in very compact and crowded cities like e.g. Genoa (I). On the contrary, the improvements will be lower in more widespread and less crowded cities like e.g. Munich (D).

3.5.3 Relative importance of HFC-vehicle related air quality benefits

Compared to other emission sources (such as industry and power plants), road transport is a major source of both NOx and PM10 emissions. For example, in the Netherlands the transport sector is responsible for about 60% of the total NOx emission, and about 30% of the total PM10 emission. Consequently, large scale substitution of conventional vehicles by advanced zero-emission HFC-vehicles would have a major positive impact on air quality.

Also this substitution would strongly facilitate member states in meeting the targets of both the EU directives on *Air Quality Directive* and *National Emission Ceilings*, which are currently difficult to meet for about half of the member states (EEA, 2010).

As already explained in paragraph 3.1.1., the health impact is not only determined by the amount of pollutants emitted, but also by the subsequent dispersion of pollutants and the number of people being exposed. As a consequence, substituting diesel buses by the HFC alternative is most (cost)effective in city-centres, where bus emissions, in the case of Amsterdam, constitute about 10% of total transport emissions (Weijers, 2010).

3.6 Conclusions

Substituting diesel by HFC-buses has the largest benefits on air quality and health in city centres, because of: (1) the dense population and consequently large number of people exposed; and (2) the municipal building structure, with “street canyons”, limiting dilution of exhaust gases, and associated relative high impact on the atmospheric concentration of pollutants.

The “clean” EEV standard diesel bus fleet in 2025 will still emit substantial amounts of NOx and PM that have a non-negligible impact on local air quality and related health impacts in city centres. Consequently the deployment of HFC-buses will improve air quality, and related health benefits:

In Amsterdam the maximum emission reduction potential, associated with a complete substitution of the 2025 advanced diesel buses by HFC buses would be: about 90 tons for NOx and about 0,55 ton for PM10. Lower substitution percentages of HFC buses would result in proportionally lower emission reductions.

In London the maximum emission reduction potential, associated with a complete substitution of the 2025 advanced diesel buses by H2FCHFC buses would be: about 2000 tons for NOx and about 12,5 tons for PM10.

For Amsterdam, the maximum emission reduction of PM10, the most health threatening component, would indicatively correspond to a maximum reduction of 0,5 microgram per m^3 in the local atmospheric concentration, relative to an average annual concentration of about 30 microgram per m^3. This air quality improvement roughly corresponds to about a dozen of premature death prevented annually.

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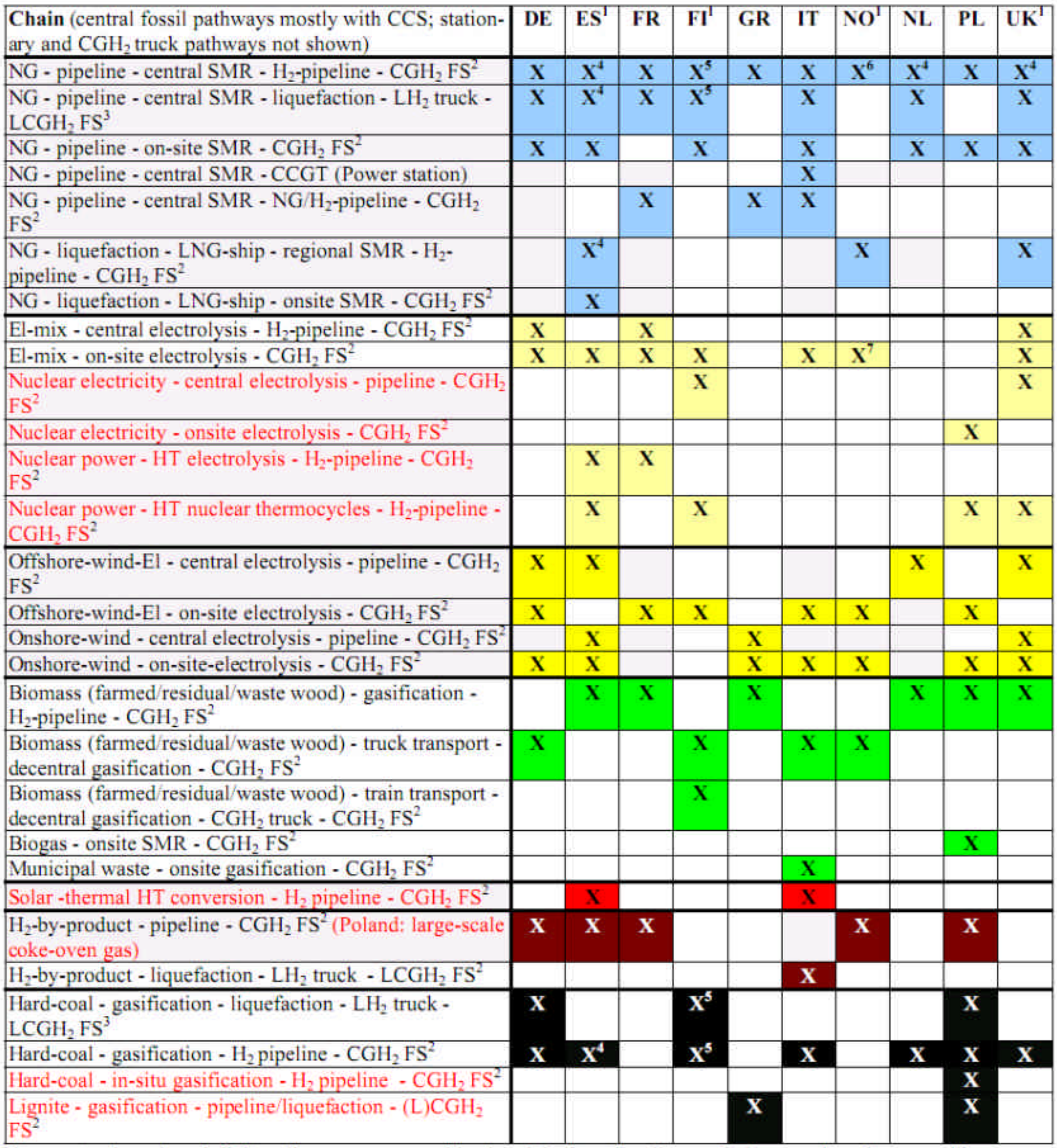
Annex A: Overview of hydrogen energy chains

The following hydrogen energy chains are retained from the project Hyways (Hyways, 2007). They include the expected configurations to bring hydrogen available to end-users, also in the transport sector. It can be observed that natural gas based chains are dominant over electrolysis (either supplied by renewable energy sources or by electricity from the network) and rather similar to gasification from coal and biomass chains.



Chain (central fossil pathways mostly with CCS; stationary and CGH_2 truck pathways not shown)	DE	ES[1]	FR	FI[1]	GR	IT	NO[1]	NL	PL	UK[1]
NG - pipeline - central SMR - H_2-pipeline - CGH_2 FS[2]	X	X[4]	X	X[5]	X	X	X[6]	X[4]	X	X[4]
NG - pipeline - central SMR - liquefaction - LH_2 truck - $LCGH_2$ FS[3]	X	X[4]	X	X[5]		X		X		X
NG - pipeline - on-site SMR - CGH_2 FS[2]	X	X		X		X		X	X	X
NG - pipeline - central SMR - CCGT (Power station)						X				
NG - pipeline - central SMR - NG/H_2-pipeline - CGH_2 FS[2]			X		X	X				
NG - liquefaction - LNG-ship - regional SMR - H_2-pipeline - CGH_2 FS[2]		X[4]					X			X
NG - liquefaction - LNG-ship - onsite SMR - CGH_2 FS[2]		X								
El-mix - central electrolysis - H_2-pipeline - CGH_2 FS[2]	X		X							X
El-mix - on-site electrolysis - CGH_2 FS[2]	X	X	X	X		X	X[7]			X
Nuclear electricity - central electrolysis - pipeline - CGH_2 FS[2]				X						X
Nuclear electricity - onsite electrolysis - CGH_2 FS[2]									X	
Nuclear power - HT electrolysis - H_2-pipeline - CGH_2 FS[2]		X	X							
Nuclear power - HT nuclear thermocycles - H_2-pipeline - CGH_2 FS[2]		X		X					X	X
Offshore-wind-El - central electrolysis - pipeline - CGH_2 FS[2]	X	X						X		X
Offshore-wind-El - on-site electrolysis - CGH_2 FS[2]	X		X	X		X	X		X	
Onshore-wind - central electrolysis - pipeline - CGH_2 FS[2]		X			X					X
Onshore-wind - on-site-electrolysis - CGH_2 FS[2]	X	X			X	X	X		X	X
Biomass (farmed/residual/waste wood) - gasification - H_2-pipeline - CGH_2 FS[2]		X	X		X			X	X	X
Biomass (farmed/residual/waste wood) - truck transport - decentral gasification - CGH_2 FS[2]	X			X		X	X			
Biomass (farmed/residual/waste wood) - train transport - decentral gasification - CGH_2 truck - CGH_2 FS[2]				X						
Biogas - onsite SMR - CGH_2 FS[2]									X	
Municipal waste - onsite gasification - CGH_2 FS[2]						X				
Solar -thermal HT conversion - H_2 pipeline - CGH_2 FS[2]		X				X				
H_2-by-product - pipeline - CGH_2 FS[2] (Poland: large-scale coke-oven gas)	X	X	X				X		X	
H_2-by-product - liquefaction - LH_2 truck - $LCGH_2$ FS[2]						X				
Hard-coal - gasification - liquefaction - LH_2 truck - $LCGH_2$ FS[3]	X			X[5]					X	
Hard-coal - gasification - H_2 pipeline - CGH_2 FS[2]	X	X[4]		X[5]		X		X	X	X
Hard-coal - in-situ gasification - H_2 pipeline - CGH_2 FS[2]									X	
Lignite - gasification - pipeline/liquefaction - (L)CGH_2 FS[2]					X				X	

blue - natural gas based; light yellow - non-renewable electricity based; yellow - wind energy based; green - biomass based; red - solar thermal (HT) based; brown - from by-product; black - coal based; chains added in Phase II marked in red

[1] ES, FI, NO and UK also use CGH_2 truck delivery pathways which are not shown here for simplicity.

[2] CGH_2 filling station: can refill ICE or FC cars and buses with CGH_2, can also be replaced by or combined with local micro-grid to supply stationary users such as fuel cells.

[3] $LCGH_2$ filling station: can refill ICE or FC cars and buses with LH_2 or CGH_2, also supply stationary users after gasification

[4] with and without CO_2 capture and storage [5] no CO_2 capture and storage (CCS)

[6] export energy chain by pipeline [7] electricity mix Nord Pool

Annex B: Electricity production routes

Hydrogen can be produced employing electrolysis. The exact energy balance and GHG emission accompanying the electrolysis process depend on the way the electricity is generated.

In the estimations presented in this report, WtT emissions from the European electricity mix are considered at a level of 237 g/MJ hydrogen. This value compared to the emissions of renewable energy technologies shows two orders of magnitude more emissions per energy unit. However, dedicated RES technologies to produce hydrogen are currently not competitive and unready to face a hydrogen demand of a large vehicle fleet. Hence, the easiest solution in the mid-term would be to produce hydrogen via electrolysis and supplied by the power from network.

At a country level, however, emissions could be more attractive from an emissions perspective. For example, Scandinavian countries with a high share of renewables could be able to produce hydrogen with lower emissions than other countries due to the low emissions in their power sector. France is another country low emission electricity supply due to the large nuclear park. In general, west European countries are strongly increasing the use of low carbon technologies in their electricity mix, which may render competitive and environmentally interesting to produce hydrogen on-site via electrolysis.

Other issues that may rise from electrolysis routes are water supply, cost of HRS, cost of hydrogen produced, central or decentralized production, etc.

Annex C: Bus emissions reduction

The following results are presented for less emission-wise relevant but equally likely scenarios for the bus sector. As a reminder, the abbreviations belong to:

No.	Energy Efficiency Improvement on ICE buses	Energy Efficiency Improvement on HFC buses	HFC bus penetration rate	Code
1	High (H)	Low to Moderate (L)	High (H)	H-L-H
2	Low to Moderate (L)	Low to Moderate (L)	High (H)	L-L-H
3	High (H)	Low to Moderate (L)	Low to Moderate (L)	H-L-L
4	High (H)	High (H)	Low to Moderate (L)	H-H-L
5	High (H)	High (H)	High (H)	H-H-H

- H L H: High technological improvement of ICE diesel buses, Low technological improvement and High penetration rate of hydrogen buses.

- L L H: Low technological improvement of ICE diesel buses, Low technological improvement and High penetration rate of hydrogen buses.

- H L L: High technological improvement of ICE diesel buses, Low technological improvement and Low penetration rate of hydrogen buses.

- H H L: High technological improvement of ICE diesel buses, High technological improvement and Low penetration rate of hydrogen buses.

- H H H: High technological improvement of ICE diesel buses, High technological improvement and penetration rate of hydrogen buses.

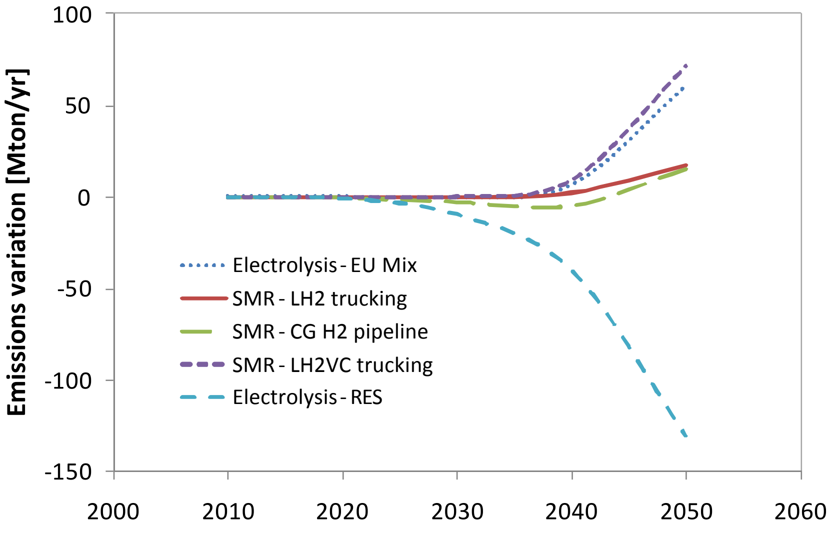


Figure 15 H-L-H emission variations for five WtT hydrogen routes

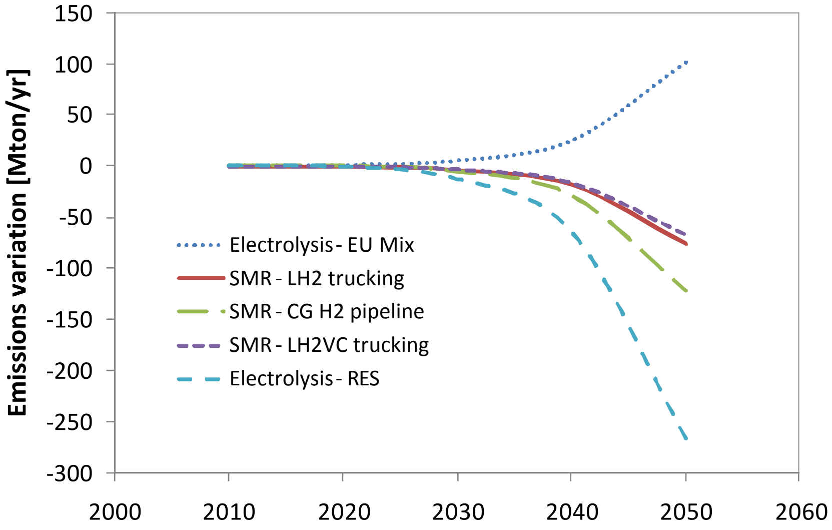


Figure 16 L-L-H emission variations for five WtT hydrogen routes

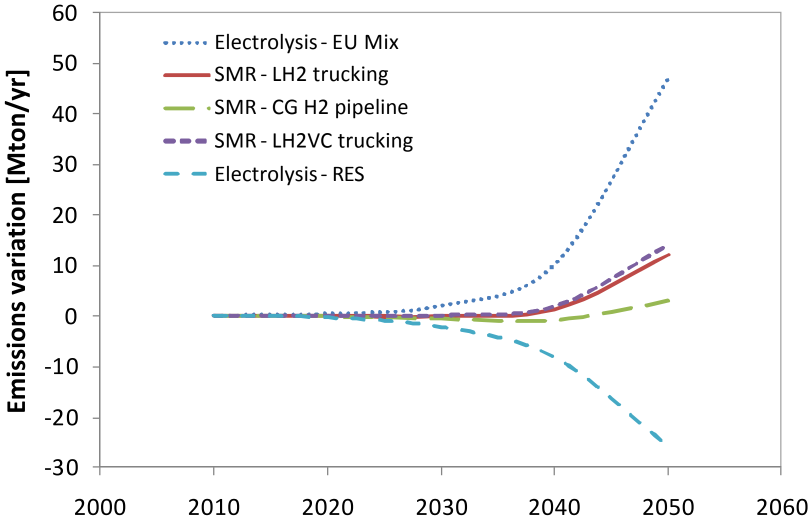


Figure 17 H-L-L emission variations for five WtT hydrogen routes

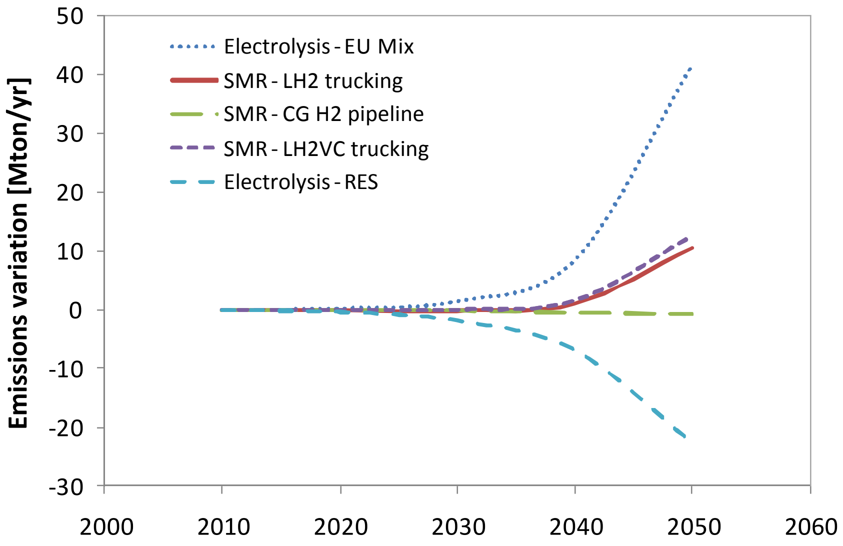


Figure 18 H-H-L emission variations for five WtT hydrogen routes

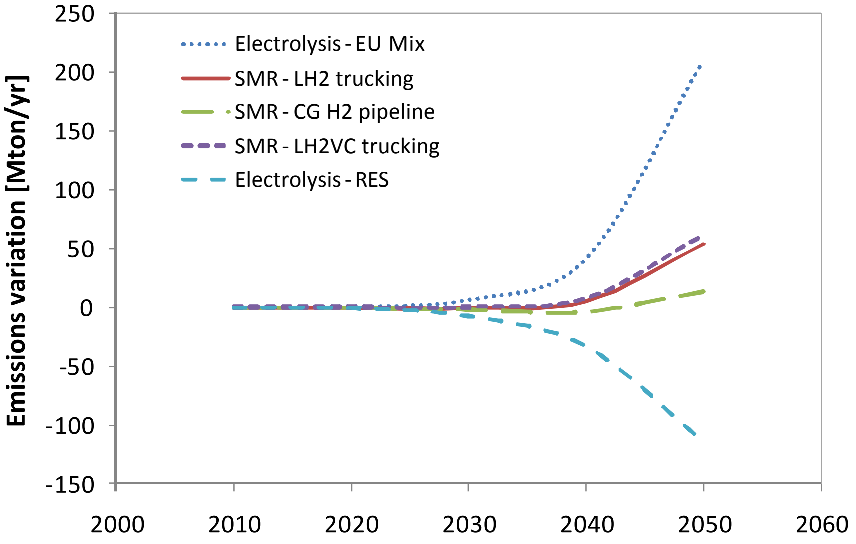


Figure 19 H-H-H emission variations for five WtT hydrogen routes