

Mixing and Transporting H₂ through the Natural Gas Network.

Impacts on Primary Energy Use and CO₂
Emissions for use of H₂ as Transport Fuel.

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This report is a result of a study into the impacts (on primary energy use and carbon dioxide emissions) of mixing and transporting hydrogen (for transport applications) using the existing natural gas network. The study has been executed within the framework of a European Union project – the NATURALHY (Contract No. 502661) which has been coordinated and managed by *GasUnie* Nederland BV and co-financed by the European Commission through the Sixth Framework Programme for Research and Technological Development. Within the NATURALHY project, Work Package 1 (WP1) presents the Life Cycle and Socio-Economic Assessment of mixing and transporting hydrogen using the existing natural gas grid, of which this report is an integral part.

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Abstract

Inadequacy of transport and distribution infrastructures is seen a barrier to the roll-out of hydrogen for both mobile (transport) and stationary applications. In most countries, the natural gas transport and distribution infrastructure is not only well-developed but extensively connected to many final consumers through dedicated networks. This existing, well-developed natural gas infrastructure could be used in the transport and distribution of hydrogen.

In the light of this, mixing and transporting hydrogen through the existing natural gas networks and further extracting of the hydrogen at the optimal part of the network for the end users is being considered as a possible short-term solution to this barrier. However, the impacts of this on the primary energy use and greenhouse gas emissions are still not generally known. Additionally, it is still generally not clear where to inject and where to extract the hydrogen, the capabilities of current separation technologies in handling this and the consequences this will have in the existing energy system. The objective of this study is therefore, to assess and analyse these impacts and to synthesise the optimal injection and extraction points as well as the systemic effects of this on the existing energy system.

For efficiently and effectively assessing the overall impacts- primary energy resource use and the total greenhouse gas emissions by this transport mode, a source-to-user model has been developed. The model identifies and characterises the complete chain of activities ranging from exploration of primary energy sources to end use of hydrogen as well as the optimal injection and extraction points of hydrogen in the natural gas network. Also using this model, the impacts on greenhouse gas emissions and primary energy resource consumption associated with injecting and transporting hydrogen through the natural gas grid has been evaluated.

As aforementioned, the mixing and transporting of hydrogen using the natural gas network may be seen as a short-term solution. Hence, in the long-term, a future complete hydrogen system consisting of transportation by either dedicated pipe networks or road tankers could be foreseen. Therefore, a comparison is made between the impacts of mixing and transporting hydrogen using the natural gas network and transporting through dedicated pipelines in gaseous form or transporting it via trucks in both liquid and compressed gaseous forms.

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Executive Summary

Hydrogen is a future energy carrier that has great potential for addressing many practical problems associated with attaining a sustainable, competitive and secure energy future for the European Union. Hydrogen can be produced from many different energy sources including fossil fuels with carbon capture and storage as well as renewables and nuclear power. The problem is how to deliver the required quantity cost-effectively in order to kick-start wider demand and application. This would involve, for example, the use of hydrogen in fuel cells and other technologies to meet transport needs without reliance on imported oil, whilst avoiding problems with air quality and depletion of primary energy resources. One of the delivery options that can be considered is the mixing and transporting of hydrogen using the extensively existing natural gas grids within the European Union (EU). In this regard, significant progress can be made by using the natural gas network as a transitional stage in the creation of the full Hydrogen energy economy. In order to do this, it is necessary to test all critical components of this transitional stage. Such testing is a central feature of the NATURALHY project (Contract No. 502661), which is being funded by the Directorate-General for Research under the 6th Framework Programme of the European Commission. Using a systematic and co-ordinated approach, the NATURALHY project contributes by "preparing for the hydrogen energy economy by using the existing natural gas system as a catalyst". The NATURALHY project involves a European consortium of 39 partners and consists of 8 Work Packages. Work Package 1 (WP1) concerns Life Cycle and Socio-Economic Assessment of mixing and transporting hydrogen using the existing natural gas grid, of which this report is an integral part.

For determining how efficiently and effectively the overall primary energy resource and the total greenhouse gas emissions are minimised by this delivery mode(s), a source-to-user model has been developed in WP1. The model identifies and characterises the complete chain of activities ranging from exploration of primary energy sources to end use of hydrogen. Using this model, the impacts on greenhouse gas emissions and primary energy resource consumption associated with injecting and transporting hydrogen through the natural gas grid have been evaluated and compared with other delivery options.

The other delivery options considered were using a dedicated pipeline for the compressed hydrogen delivery, using trucks in the delivery of hydrogen in compressed form and also using trucks in the delivery of hydrogen in liquid form. Also in the analysis, various hydrogen production routes were considered and included - natural gas with carbon capture and storage (CCS), coal with CCS, nuclear power, wind power and biomass energy. Apart from the production route, the mix of these routes also plays an important role in the primary energy use and emissions. In the light of this, different scenarios of production mix (adapted from the EU HyWays project on hydrogen road-mapping) were used in the analysis. The production mixes basically differ in the share of the renewables and/or fossil based production routes in the total EU hydrogen supply and were developed within the HyWays project.

The difference between the delivery options is that while others emphasise transportation using only hydrogen-dedicated systems, the NATURALHY project concerns injecting and transporting hydrogen, using the natural gas grid with the possibility of extracting it downstream. In this case, where to inject and where to extract the H₂ that will minimise primary energy use and emissions becomes an issue. In the analysis of the optimal injection and extraction points (which was conducted using the Dutch natural gas grid as a representative grid), it was concluded that the regional transport line is the optimal point for the injection and extraction of hydrogen. Various separation technologies – membranes, pressure swing absorption (PSA), etc., were considered for the extraction of the injected hydrogen. Based on an assessment of the separation technology, it is concluded that a system consisting of a state-of-the-art polymer membrane unit followed by a PSA unit shows the best outlook for extraction of hydrogen in terms of energy use. In any case, whichever separation technology is used, it is not possible to recover all the hydrogen contained in the natural gas/hydrogen mixture stream.

The overall impact of injecting and transporting hydrogen using the natural gas system on the primary energy use and greenhouse gas emissions not only varies by the choice of injection and extraction points, or the way the hydrogen is produced, but also by the penetration rate of H₂ end use application as well as the spatial and temporal domain being considered. The end-use application considered in the impact analysis is hydrogen fuel cell vehicles. In the analysis, assumed penetration rate was again adapted from the HyWays project, and a temporal domain spanning 2010 to 2050 was assumed with the spatial domain being the wider EU. Overall primary energy use and emission reductions associated with producing hydrogen (using a given production -mix), injecting and transporting (through the existing natural gas system as well as other transport modes) it to the consumers (for mobile end use application) is analysed.

The Well-to-Wheels (WtW)¹ primary energy use involved for the case of injecting and transporting hydrogen using the natural gas system is highest compared to the other transport modes. This can be explained from the fact that not all hydrogen can be extracted from the mixture. The remaining hydrogen is not counted as loss, as the calorific value of the hydrogen can still be used. However, the conversion losses associated with production of the remaining hydrogen would not have occurred if it was not necessary for the pure hydrogen to be extracted from the mixture. Therefore, the conversion losses, and all other upstream losses, are all attributed to the pure hydrogen extracted from the grid, thus leading to high overall primary energy use. A highest primary energy use increment of approximately 80% (relative to the reference case²) is reached in year 2050 for the case of transporting hydrogen using the existing natural gas grid.

At the same time, the results show that, notwithstanding its higher primary energy use, the case of using the existing natural grid in the transport of H₂ for mobile applications has the greatest emission reduction potential, and amounts to a WtW emission (equivalent carbon dioxide; eq. CO₂) reduction of approximately 85% compared to the reference scenario. Again, emission reduction potential can be explained from the fact that not all hydrogen can be extracted from the grid. The remaining part replaces natural gas as a fuel and will lead to CO₂ emission reduction for the natural gas application downstream in the grid, for example, in a residential boiler, at subsequently low CO₂ emission factors of the hydrogen. However, the CO₂ emission reduction for the natural gas application only materialises because it was necessary for the pure hydrogen to be extracted from the grid. Therefore, the CO₂ emission effect is attributed to the pure hydrogen stream that is used for the hydrogen vehicles. This may lead to great emission reduction potentials if hydrogen is largely produced from renewable sources.

Also, using the assumption that hydrogen vehicles would penetrate the EU-market substantially in the time frame 2020-2050, an alternative production-mix (*renewable path production mix*) was simulated. The result shows that the emission reduction and primary energy use are most sensitive to the production mix considered. With the most optimistic renewable hydrogen production mix, the results show a WtW greenhouse gas emission reduction (in eq. CO₂) of about 88% compared to the reference scenario in 2050. This represents a WtW eq. CO₂ reduction of about 3% by 2050, compared to the base case. Also, in terms of primary energy use, the alternative production mix (*renewable path production mix*) shows a 61% reduction of the primary energy use (in comparison to the base case) could be achieved in 2050 for the case of mixing and transporting H₂ using the existing natural grid.

¹ Well-to-Wheel analysis involves taking into account all activities connected with the production of energy from an original source through to its use in vehicles.

² The reference case here is the primary energy (WtW) for non H₂ vehicles, specifically diesel and gasoline

1. Introduction

It is necessary to introduce the general background and motivation for the use of natural gas network in transporting and distributing hydrogen for mobile and/or stationary applications. Hydrogen (H_2) is an alternative energy carrier and it has a possible role in guaranteeing energy security, energy diversity as well as its potential in reducing the burden often placed on the environment by the conventional carbon-intensive fuels. The lack of adequate H_2 infrastructure is a barrier to the widespread deployment of this new energy carrier. The mixing and transporting H_2 through natural gas network as a possible solution to the current absence of hydrogen infrastructure (transport and distribution) is explored and the relevant work in this area systematically reviewed.

1.1 Background and Motivation

The major challenges facing the current fossil fuel energy-based portfolio are un-guaranteed security of supply, greenhouse gas emissions and the allied problem of climate change, and environmental pollution. H_2 has attracted a significant amount of attention and research as an alternative energy carrier capable of addressing these challenges. By replacing (partly or completely), current hydrocarbon-based fuels and their associated greenhouse emissions, H_2 has shown potential at reducing or eliminating the pollution burdens often placed on the environments by the use of the traditional carbonised fuels. Apart from its decarbonising potential, by the use of H_2 in applications such as fuel cell vehicles, a new energy carrier is introduced which in one hand, increases the overall energy supply and security and, on the other hand, eliminates current fuel source-dependency.

The introduction of H_2 and H_2 end-use applications, however, faces the well-known “chicken and egg” problem. If the prospect for large-scale introduction of H_2 end-use applications is not clear, no dedicated H_2 infrastructure will be built. However, if there is no infrastructure available, the uptake of H_2 end-use application in the market place will be difficult. Clearly, the introduction of H_2 calls for a concerted action in the introduction of end-use applications and build-up of supporting infrastructure.

However, if technical prospects of end-use applications are good, there is still no guarantee that demand will develop. So development of dedicated infrastructure for transport and distribution of H_2 holds great economic risk. To overcome these risks, is it an option to use the existing natural gas network for transport and distribution of H_2 in the initial phase of a transition toward the large-scale use of H_2 as a fuel?

As currently there are no redundant pipelines, the concept would have to involve mixing of H_2 into the natural gas network at strategic locations and extracting H_2 from the network close to the end-user. In principle, adding extra H_2 to the network should be possible from a capacity perspective. Due to implementation of expected energy efficiency measures, especially in the domestic and commercial sector, decreasing natural gas demand could result in excess capacity for transport and distribution of H_2 in at least part of the network. Furthermore, capacity is available due to seasonal variation in the natural gas demand. In particular, during the summer, natural gas demand is much lower than in winter.

In several studies, it has been shown that the injection and transporting of a percentage range of H_2 using the natural gas network is technically possible (Polman et al. 2002; van Rosmalen et al. 2004). Identifying the feasibility and practicality of this option is the focal point of the NATURALHY project which is being funded by the Directorate-General for Research under the 6th Framework Programme of the European Commission.

1.2 Review of Related Programmes and Projects

A review of related projects, programmes and visions that envisage the use of the natural gas grid for transport of H₂ as a strategic option around the world has been conducted. The idea of mixing and transporting H₂ through the natural gas network is not entirely new. At the city level, in 1994, Munich initiated a project to determine the technical and economic feasibility of transporting and distributing H₂ through its extensive natural gas network. Though the technical feasibility of the project was reported (Ludwig-Bolkow, 1996), the implementation of the project was hindered due to lack of economic viability. At the national level, between 1999 and 2002, Denmark has initiated some projects, through the DGC-DONG-HNC and some Danish consortia, to ascertain the feasibility of mixing and transporting H₂ using their natural gas grid. Again, though, only economic rather than technical barriers were reported. This is also true in Norway, where such a project was initiated in 2000 by the Norwegian government. In January 2002, the Dutch Government through the VG² (“*ver-groening van gas*”) project introduced the concept of mixing and transporting H₂ via the natural gas network. In the United States, though substantial research and development (R&D) effort have been expended on the area of H₂ and its application by the US Department of Energy (DOE), the issue of mixing and transporting H₂ through the natural gas system is not as conspicuous as it is in Europe³. The DOE has started a substantial integrated R&D programme on all aspects of the H₂ chain which now includes an assessment of the potential of the existing natural gas infrastructure for H₂ delivery.

Apart from the NATURALHY project, the hallmark of other programmes and projects is that they take into account a particular city or nation, not taking into account the effects of other connecting corridors and/or nations on the entire proposed scheme especially from the perspective of economic viability. In 2003, GASTEC completed a study for the International Energy Agency (IEA) on the effects of reducing carbon dioxide (CO₂) emissions by adding H₂ to the natural gas system (Polman et.al, 2003). A more inclusive approach was adopted in this study by taking a wider European perspective; using the assumption that European natural gas grids can be generalized by combining the natural gas network features of the Netherlands, United Kingdom (UK) and France.

In 2004, the NATURALHY project was initiated that takes even more inclusive stance (EU level) in analysing the technical and economic feasibility of mixing and transporting H₂ through the natural gas network. Like the VG² project (Patil et.al., 2008), the NATURALHY project aims to investigate the conditions under which H₂ can be added and transported through the natural gas network with acceptable consequences for safety, durability and integrity of the system, H₂ separation, gas quality management, performance of end-use appliances, and life cycle and socio-economic assessment. In Table 1.1, the characteristics of these projects related to mixing and transporting hydrogen via the natural gas network are given.

³ Though the efforts and interests are not as conspicuous in the USA as in the EU, there seems to be increasing interests by the US DOE on the use of the existing natural gas grid in transporting H₂ (Florisson, 2009)

Table 1.1: Comparable projects Related to Mixing and Transporting H₂ via the Natural Gas Network

S/Nr	Project Name	Initiated by	Spatial Spread	Year Initiated	Year Completed	Mixture [% v/v]	Demixing [Yes/No]	Demixing Technology	End-use application	Statue & Remarks
City Level										
1	- ⁴	City of Munich	Munich	1994	?	Varies: 5-60/94-40	No	N.a.	Stationary	Was not implemented
3	-	GASTEC	Netherlands	?	?	17/83	No	N.a.	Stationary	No technical barrier
National Level										
4	-	DGC-DONG-HNC	Denmark	1999	2004	17/83	No	N.a.	stationary-CHP	?
5	-	Danish Consortium	Denmark	?	2002	?	?	?	?	?
6	-	Norwegian Government	Norway	2000	2003	?	?	?	?	?
7	VG2	Dutch	Netherlands	2001	2007	25/75	No	Na	Stationary	
Continental Level										
8	CO ₂ Reduction By adding H ₂ to NG	IEA	UK, France, Netherlands		2003	25/75	?	?	?	?
9	NATURALHY	European Commission	EU member states	2004	2009	25/75	Yes	PSA/Membrane	Mobile	In progress
10	-	JFE Engr. Corporation, Japan	EU/US ⁵	2004	2005		N.a.	N.a.	N.a.	See ⁶

⁴ Not mentioned in the references that reported these projects

⁵ The spatial spread as used here is has different connotation as it is just a review of the activities in the EU and USA in the area of mixing and transporting H₂ using the existing natural gas grid.

⁶ This was just a study on the current status of introducing H₂ using existing natural gas supply infrastructure in Europe and US initiated by JFE Engineering Corporation, Japan and conducted by the Institute of Energy Economics, Japan (IEEJ)

1.3 Structure of Report

In this report, an analysis of the possible impacts on primary energy use and CO₂ emissions resulting from injecting and transporting of H₂ using the natural gas grid is presented. The analysis is life cycle based since it not only considers the impacts of injecting H₂ into the natural gas network, its subsequent separation from the natural gas, and eventual utilisation either as pure H₂ or as a mixture with natural gas, but it also considers the impacts emanating from the various H₂ production routes (mix). The mixing and transporting of H₂ using the natural gas network may be seen as a short term solution. In the long term, future complete H₂ system consisting of H₂ transportation by either dedicated pipe networks or road tankers could be foreseen. Therefore, a comparison is made between the impacts of mixing and transporting H₂ using the natural gas system and transporting such using dedicated pipelines in gaseous form or transporting it via truck in both liquid and compressed gaseous forms.

The report presented here consists of 6 Sections. After the introduction in Section 1, the general methodology for the analysis of the impacts of transporting H₂ natural gas-mixture is presented in Section 2. In Section 3, general considerations regarding the transport of H₂ using the existing natural gas grid (where to optimally inject and extract the H₂, the energy use for injecting and extracting H₂, etc.) are given. In Section 4, the detailed results of the Well-to-Wheels (WtW) analysis is presented, while the analysis of the overall impacts this will have in the EU member states- in terms of primary energy use and emissions- if the H₂ injected and separated is used for mobile application in fuel cell cars - is discussed in Section 5. The conclusion and recommendations are presented in Section 6.

2. Methodology

This Section describes the general methodology used in the analysis. A detailed WtW approach has been taken, see Figure 2.1 and 2.2. Suffice it to say, considering the energy use and emissions associated with injecting H_2 into the natural gas grid as well in separating the H_2 from the H_2 / natural gas (NG) mixture adds an extra layer of activity to the WtW analysis. In line with this, the WtW chain has been decomposed into three distinct levels: the Well-to-Fuel (WtF), the Fuel-to-Tank (FtT) and the Tank-to-Wheel (TtW) activities. The injection and separation activity has been incorporated into the FtT (the transport and distribution) level of analysis.

The WtF analysis covers the emissions and primary energy associated with:

- Feedstock production
- Feedstock transport
- Fuel (H_2) production

For the purpose of this study, the FtT analysis covers the emissions and primary energy associated with:

- Fuel (H_2) injection into the existing natural gas grid
- Fuel (H_2) and/or fuel mixture transport
- Separation of the injected fuel (H_2) from the H_2 /NG mixture
- Fuel (H_2) dispensing (refuelling) to cars

Finally, the TtW analysis considers the emissions and primary energy use by H_2 vehicles (the end use application). The totality of these three distinct levels gives the complete WtW chain.

While the relevant data are available for WtF and TtW analysis, at the FtT level, no data exist for the energy use and emissions associated with the fuel (H_2) injection into the existing NG grid as well for the separation of the injected H_2 from the H_2 /NG mixture. Since these are needed for the complete WtW analysis, the first part of the analysis (see Section 3) has been dedicated to establishing these data using the relevant thermodynamic and emission models (see Appendix A).

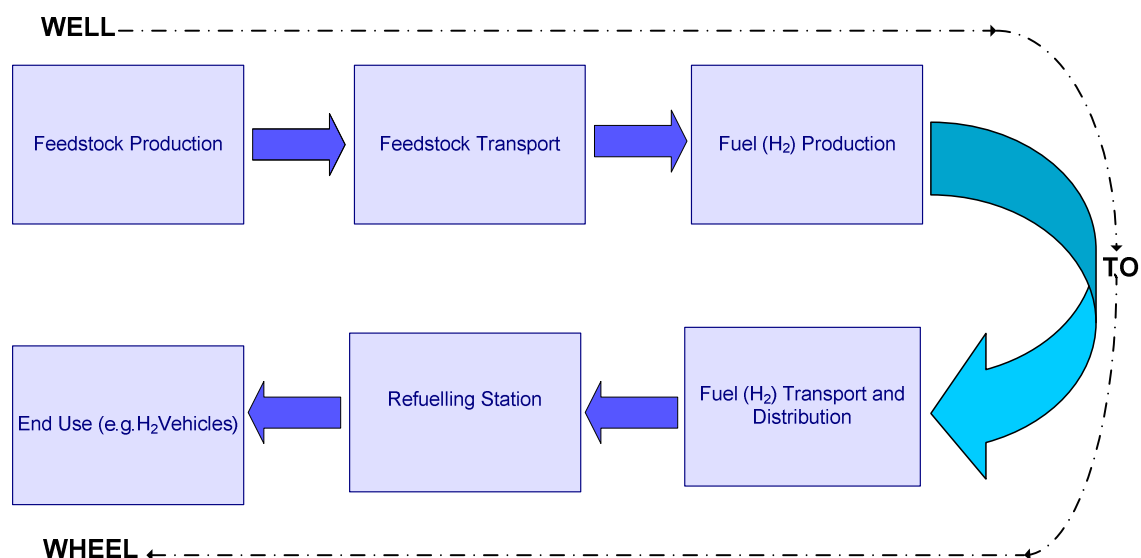


Figure 2.1: Block Diagram of WtW Chain Used in the Analysis

Table 2.1: Overview of the elements considered in the WtW analysis

	WTW Chains					
	Feed-stock Production ⁷	Feedstock Transport ⁸	Fuel (H ₂) Production route	Fuel (H ₂) Transport & Distribution	Fuel (H ₂) Dispensing	End use
Variants Considered	- Natural Gas - Coal - Biomass - Nuclear - Wind	- Ship - Train - Truck - Pipeline	- Reforming of NG without CCS - Reforming of NG with CCS - Gasification of Coal with CCS - Gasification of bio-mass-wood - Nuclear Power based electrolysis⁹ - Wind Energy based electrolysis	As: - Compressed gas mixed with natural gas and transported using the existent natural gas pipeline grid. - Compressed gas using dedicated H₂ pipeline - Compressed gas transported by truck: - Liquid transported by truck	- 880 bar gaseous H₂ dispensing unit	FC cars

Having established the energy use and emission data for the injection and separation of H₂ from the H₂/NG mixture, the overall WtW emissions and primary energy use is then estimated for each of the H₂ production routes as well as for each of the variants of the fuel transportation/distribution modes (see Table 2.1), using the model presented in Appendix A.

To determine the overall impact of injecting and transporting H₂ using the natural gas system on the primary energy use and greenhouse gas emissions, not only the choice of injection and extraction points and the way the H₂ is produced but also the production mix, the penetration rate of H₂ end use application, the spatial and temporal domain being considered, play a significant role in the analysis. In the HyWays project (HyWays, 2007,) various production mixes for the different EU member states as well as the penetration rate of H₂ vehicles have been projected. Applying the HyWays project production mix and the H₂ vehicle penetration rate, the overall primary energy use and emissions associated with producing H₂, injecting and transporting (through the existing natural gas system as well as other transport modes) it to the consumers (fuel cell car use) is thus calculated¹⁰ at different time scales (2010-2050).

⁷ The emissions and energy use in the construction of facilities for the exploration, extraction and processing of these feedstocks as well as the operations, maintenance and decommissioning of these facilities have been taken into consideration.

⁸ The emissions and energy use in the construction of transport media (e.g. pipeline) as well as their operations, maintenance and decommissioning have been taken into consideration.

⁹ Both the Nuclear Energy and Wind Energy routes produces electricity and then the water electrolysis technology is used to produce H₂.

¹⁰ Also using the model framework presented in Appendix A. The model has been implemented in a user-friendly MS Excel workbook.

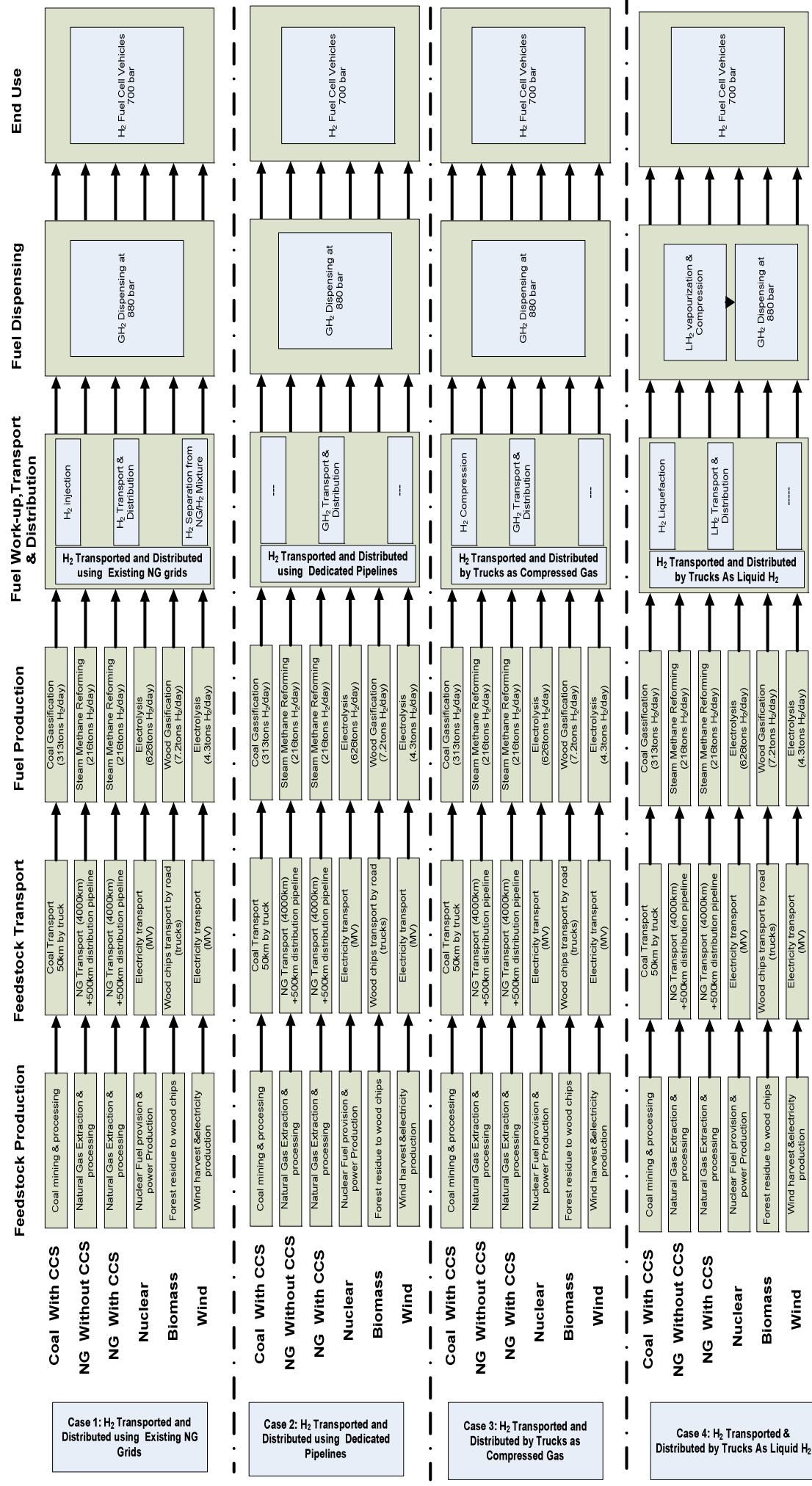


Figure 2.2: Overview of the Characteristics of the Chains and Transport Modes Analysed

3. System Description, Analysis of Injection and Extraction Points

The mixing and transporting of H₂ using the natural gas network may be seen as a short term solution to kick-start the use of H₂ as fuel in end-use applications, without the need to have a dedicated infrastructure for transport and distribution of H₂ in place. In the long term, a future complete H₂ system consisting of H₂ transportation by either dedicated pipe networks or road tankers could be foreseen. Therefore, a comparison is made between the impacts of mixing and transporting H₂ using the natural gas system and transporting such using dedicated pipelines in gaseous form or transporting it via the truck in both liquid and compressed gaseous forms.

The energy use and emissions involved in producing and transporting H₂ using dedicated pipelines in gaseous form or transporting it via the truck in both liquid and compressed gaseous forms is well documented. However, little or no data can be sourced for the energy use and emission inherent in mixing and transporting of H₂ using the natural gas network. Therefore, in this study, a calculation of the energy use for the injection and extraction process based on thermodynamic models, as well as associated emissions has been executed. In this Section, the basic assumptions, the selection and description of a generic system are determined. Additionally, the optimal injection and extraction points in the selected generic system as well as the primary energy use are synthesised.

3.1 Basic Assumptions

In the description and analysis of the system, some assumptions were made. For clarity and transparency, these assumptions are stated below:

- ◆ At the time of the analysis it was not yet clear what might be a practical or possible percentage of H₂ in the mix. For the purpose of assessing the impacts of using the natural gas grid for transport of hydrogen, a 10% H₂ by volume mixture has been assumed in the analysis.
- ◆ The initial H₂ content has been assumed constant (10%) for the impact analysis
- ◆ H₂/NG mixture behaves as an ideal gas
- ◆ The structure and characteristics of the Dutch regional and local natural gas distribution network has been selected as a representation case for the analysis¹¹. It is assumed that this structure is a good representation of regional and local distribution network in all member states, though the length of the national transmission grid may differ significantly due to differences in size of the member state and extent of the network.

3.2 Description of Dutch Natural Gas Network

The transmission of natural gas is carried out through a vast network made up of the main transmission line, the High-Pressure Transmission Line (HTL), and the sub-transmission line, the Regional Transmission Line (RTL). Both transmission lines consist of pipelines that extend over 11,000 kilometres in length (Gastransport-Services 2003), as well as equipment for compressing, blending, metering, and regulating different gas flows. The pipelines of the main transmission grid and much of the regional (sub-transmission) network are in the form of ring systems, allowing the gas to be rerouted if part of the system is out of service for some reason.

¹¹ This assumption can be corroborated by the IEA report on CO₂ reduction through the addition of natural gas into the gas grid (IEA, 2003), which speculated that the natural gas network of the Netherlands, France and UK can typically be combined to form a representative gas network that can be found any where in the world.

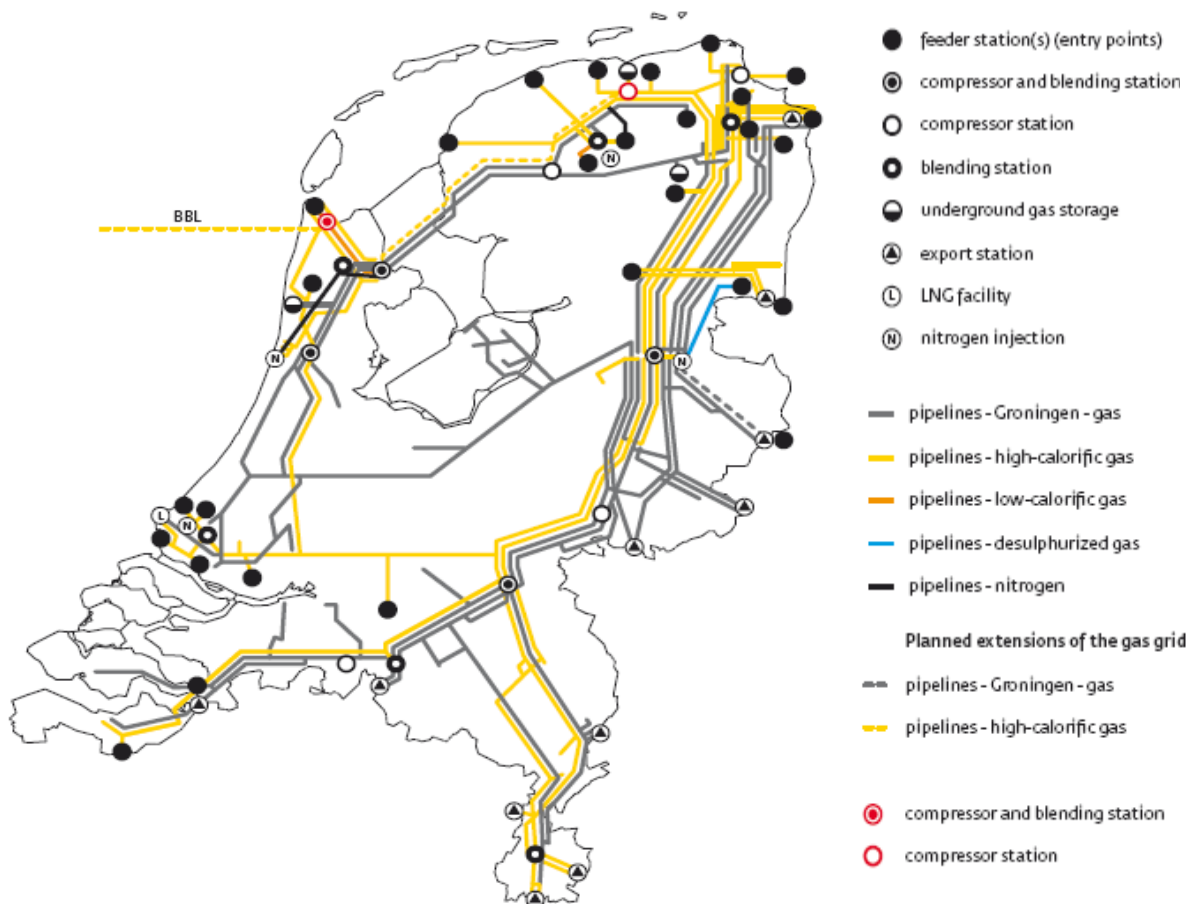


Figure 3.1: *The Dutch Natural Gas High-Pressure Transmission Network (Gasunie, 2005)*

Natural gas is supplied by the producers at a pressure range of approximately 46-67 bar. At this pressure, natural gas is transported through the main transmission pipelines to the major parts of the country. Figure 3.1 presents an overview of the Dutch HTL network. In summer, the gas in the main Groningen gas pipelines flows at a slow velocity, occasionally as low as 5 km/h (1.4 m/s). In winter, it is quite common for the speed to exceed 50 km/h (14 m/s).

When a high volume of gas has to be supplied, the drag of the pipe walls on the high velocity gas stream absorbs a considerable amount of energy and the transmission pressure drops. Therefore, located at various points in the network of pipelines are compressor stations which raise the pressure of the gas to the desired pressure level when it becomes too low due to transport losses.

From the HTL, the gas is routed to the Metering and Regulating (M&R) stations. At M&R stations, the pressure in the HTL system is reduced to an operating pressure of not more than 40 bar. Also at the M&R stations, the natural gas is given its characteristic smell through the injection of the chemical tetrahydrothiophene (THT). Natural gas as it comes out of the ground is virtually odour-free. Therefore, the odourisation alerts domestic consumer to leaks. M&R stations also supply measurement data relating to flow, which are vital for the control of gas in the network. In total, there are 75 Measuring and control stations (M&R stations) in the Dutch system.

Exiting the M&R station, the natural gas is routed to the RTL network. The RTL network has a total length of 6,000 km. The operating pressure generally ranges from 16 to 40 bar. The regional transmission lines transport the natural gas to the “*Gas Ontvangst Stations*”¹², the gas receiving stations.

¹² This literally means Gas Receiving stations. These are also called gas transfer stations or ‘city gate stations’ since these are local stations where the gas is transferred from the national or regional transmission grid to the urban or industrial grid.

stations (GOS). Figure 3.2 shows a schematic representation of the Dutch natural gas grid from the High-Pressure Transmission Line to the gas receiving stations.

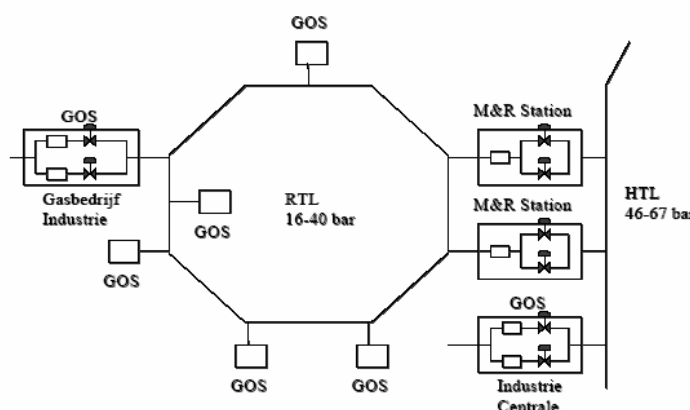


Figure 3.2: *Schematic of the Dutch Regional Transport Grid from a High-Pressure Transport Line to the Gas Receiving Stations*

At the GOS, totalling about 1,100 in number, the pressure of the gas as supplied by the RTL is further reduced to meet the pressure specification of the local distribution grid. The local distribution grid of the gas supply companies operate at pressures of 8 bar or lower. Also at the GOS, metering of the volume of gas supplied is carried out. Leaving the GOS, the natural gas is routed to the distribution grids – for industrial or residential customers. The distribution grid has an extensive network of about 120,000 km. About 700 of the GOS stations are linked to the local distribution grid for the supply of gas to residential areas. By the time the gas enters domestic gas pipes, the relative pressure is down to 25 millibar, the standard appliance pressure in the Netherlands. About 400 of the GOS stations are linked to the local distribution grid for the supply of gas to industrial users at somewhat higher pressure than the domestic.

3.3 Characterisation of the Dutch Natural Gas Grid

The Dutch pipeline system for transport of natural gas consists of the following elements:

Table 3.1: *Characteristics of the Dutch Natural Gas Grid*

S/nr	Network Type	Spatial Coverage	Pressure range [bar]	Length [km]
1	Transmission	National	46 – 67	5,000
2	Sub-Transmission	Regional	16 – 40	6,000
3	Distribution	Local - Industrial	1 – 8	35,000
4	Sub-Distribution	Local - Residential	0.03 - 0.15 ¹³	85,000
Other elements of the infrastructure				
	Name	Quantity[-]		
5	Compressor stations	9		
6	Blending stations	11		
7	Calibration stations	2		
8	Metering and Regulating Stations	75		
9	Gas Receiving Stations (GOS)	1,100		
10	Underground storage points	7		
11	Domestic productions points	43		
12	Entry points (feeder stations)	20 ¹⁴		
13	Exit stations	22		
	- boarder exit (Export) stations	10		

¹³ This is after local pressure reduction stations which reduces the distribution pressure (1-8 bar) to the pressure range suitable for the local and domestic consumption of natural gas.

¹⁴ About 14 feeder stations are used for the H-gas (43.5 – 44.4 MJ/m³ Wobbe range) while 6 feeder stations are used for the G-gas in the Wobbe band of 48 – 55 MJ/m³

In total, about 90 billion Nm³ of natural gas flow through the Dutch HTL grid annually. Nearly half of this quantity is exported to other countries. From the other 45 billion Nm³ of natural gas, about 8 billion Nm³ is supplied directly from the HTL grid to power stations. The remaining 37 billion Nm³ is supplied to the RTL grid via 75 M&R stations. The RTL grid supplies the gas to the distribution grid via about 1,100 GOS. About 700 of the GOS stations supply gas to residential areas (22 billion Nm³) and about 400 of the GOS supply gas to industrial users (15 billion Nm³).

The characteristics presented above lead to the following average values:

- Each M&R station receives in average about 500 million Nm³ of natural gas annually (~57,000 Nm³/h) and supplies the gas to 80 km of the RTL grid on which 15 GOS are connected. Of the total, 5 GOS supply gas to industrial users and 10 supply gas to residential areas.
- The throughput of an industrial GOS is in average about 37.5 million Nm³ per year (~ 4280 Nm³/h), while a GOS which supplies gas to residential areas has a throughput of about 31.3 million Nm³ per year (~ 3565 Nm³/h).

These average values are used for the cases and calculations presented in this study.

3.4 Place for Injection and Extraction of Hydrogen

Figure 3.1 shows schematically how the HTL network is laid-out in the Netherlands. Because most of these lines are interconnected to each other, H₂ injection at this level will cause this gas to be distributed all around the country and probably to other neighbouring countries to which natural gas is exported. Unless all H₂ injected at one point is entirely removed further in the network, injection of H₂ into the HTL will “contaminate” the international natural gas grid. Also the issue of volume is important as a very substantial amount of H₂ need to be produced and injected to achieve a percentage of 10% by volume. RTL networks are separated from each other and from the HTL network through M&R stations. Injection of H₂ into the RTL will not necessarily affect the rest of the natural gas grid all around the country¹⁵.

Another issue of importance, when choosing the possible location of injection and extraction points, is the pressure level of the grid at the injection point. A high-pressure level at that point means that the H₂ must be compressed to a higher pressure to be injected, otherwise there will be backflow. The pressure level in the HTL varies between approximately 46 to 67 bar. The pressure level in the RTL varies between approximately 40 to 16 bar. The pressure level of the RTL grid is more or less in line with product pressure of typical modern H₂ production processes.

One other issue that favours the choice of the RTL as the injection point is the fact that the H₂/NG mixture has a compressibility factor greater than 1. This means that the compression of H₂/NG mixture using the axial and/or centrifugal compressors originally designed for the natural gas compression will result in lower head pressures and lower capacities¹⁶. Using the HTL thus entails longer flow distance and, hence, compensation of the lost head pressure by the installation of the booster compressors or additional capacity. For the RTL, there might not be such booster stations as the flow distance is significantly lower.

The preferred place for extraction of H₂ is as close to the end-user as possible. Otherwise still specific infrastructure needs to be installed to transfer H₂ from the extraction point to the end-user, and this is exactly what the concept of the NATURALHY project would like to avoid. Nevertheless, also the

¹⁵ Also well corroborated by other researchers for instance, Haeseldonckx and D’haeseleer,(2008) who stated that the use of the RTL for transporting H₂ -natural gas mixtures is very logical for the transition from natural gas to H₂ .

¹⁶ Using H₂ in centrifugal compressors requires compression of a volume three times as large as when natural gas is used for the same LHV energy content. Furthermore, to obtain the same pressure ratio, the rotational velocity to compress H₂ must be 1.74 times higher than to compress natural gas. Unfortunately, this rotational velocity is limited by the material strength, which can cause problems when H₂ is sent through the existing pipeline infrastructure (Vanderoost et al, 2003).

Naturalhy concept requires specific infrastructure. The injection of H₂ will not be that difficult, but extraction requires separators that specifically need to be developed for this purpose.

Within the NATURALHY project, extraction is foreseen using membrane separators. Ideally, this should be membranes enabling one-step separation yielding fuel cell grade H₂ at minimal energy consumption. The driving force for separation is a difference in the partial pressures of gases that are separated between the permeate (product side) and the retentate (feed side) of the membrane. At the permeate side of the membrane, pure H₂ is separated at a minimum pressure of 1 bar. This is to avoid the risk of air leak in and the formation of combustible mixtures. Minimum pressure of 1 bar at the permeate side of the membrane also means H₂ pressure at the retentate side of the membrane of more than 1 bar is required; otherwise there will be no driving force. Use of sweep gas such as steam across the permeate side to reduce H₂ partial pressure in comparison with the H₂ partial pressure at the feed side—thus increasing driving force—, complicates the separation system and increases energy use and it therefore not considered at this point. If H₂ is present in the H₂/NG mixture at 10 % by volume, this means that the absolute pressure should be at least 10 bar. As a consequence of this, H₂ has to be separated and/or extracted from the RTL since the pressure level at the distribution grid is low (1-8) bar. At mixtures of 20 % by volume of H₂ or higher, separation could take place at absolute pressure of at least 5 bar, thus in principle enabling extraction to be carried out at the distribution side of the grid where the absolute pressure lies between 1-8 bar. This is illustrated in Table 3.2. The shaded and dotted area of the table indicates the area with positive, though still rather low driving force for the membrane separation at the distribution side of the grid. With this illustrative table, separation appears necessary in the RTL side of the grid unless the mixture is with volume of H₂ well above 20%, or even 30%.

Based on these arguments, it seems that injection of H₂ into the natural gas grid of the Netherlands is better to occur in the RTL network than into the HTL network. The analysis presented hereafter is based on this choice.

Table 3.2: *Optimal mixture % and partial pressures of H₂ necessary for effective separations*

Network type [-]	Network absolute pressure [bar]	H ₂ in the H ₂ /NG mixture [% by Volume]		
		10	20	30
		H ₂ partial pressure [bar]		
Distribution Grid	1	0.1	0.2	0.3
	2	0.2	0.4	0.6
	3	0.3	0.6	0.9
	4	0.4	0.8	1.2
	5	0.5	1.0	1.5
	6	0.6	1.2	1.8
	7	0.7	1.4	2.1
	8	0.8	1.6	2.4
RTL Grid	...	...	...	...
	16	1.6	3.2	4.8
	20	2.0	4.0	6.0
	24	2.4	4.8	7.2
	30	3.0	6.0	9.0
	40	4.0	8.0	12

3.5 Maximizing quantity of H₂ to be extracted

The amount of H₂ that can be extracted (recovered) from the H₂/NG mixture depends on the location where the H₂ is extracted. If H₂ is injected at the RTL-grid (after the M&R station) and subsequently extracted before the first GOS, all H₂ is still present in the RTL-grid and the maximum amount of H₂ can be recovered. Therefore, in order to maximise the quantity of H₂ to be separated from the H₂/NG mixture produced; ideally no users (GOS stations) are located between the H₂ injection and extraction points. Any other location of the injection and/or extraction points will lead to a lower pure H₂ stream extracted, because GOS stations will reduce the amount of mixture available for separation by consuming part of it (see Table 3.3). The deficiency of this configuration (that maximizes the quantity of

H₂ recovered) lies on relatively low maximum distance the unused H₂/NG mixture stream can be transported. In this configuration, a maximum transport distance of about 5 to 6 km unused H₂/NG mixture stream is only realizable for the Dutch natural gas grid (see Table 3.3).

The situation changes if mixtures with H₂ percentage of well over 20% are possible. This would enable separation after the GOS, in the distribution grid (see section 3.4 and Figure 3.4). In this case, the maximum H₂ recovery would still be similar to the recovery before the first GOS at low volume percentage mixtures, but larger transport distances are possible and separation will take place closer to the end-user.

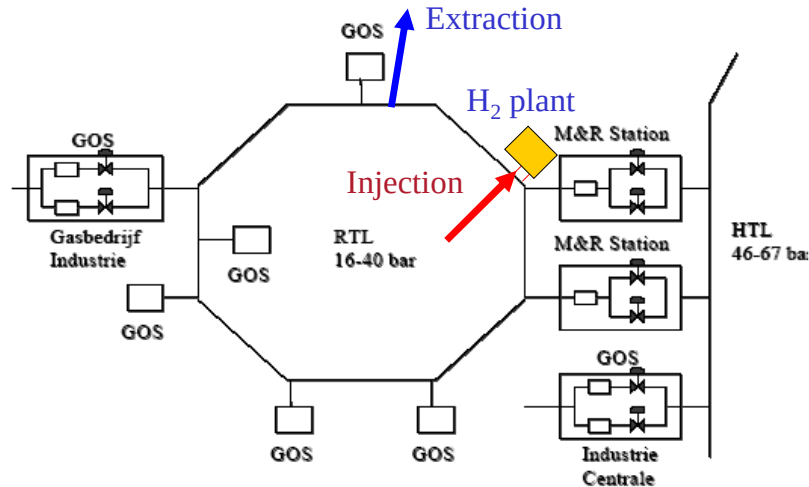


Figure 3.3: H₂ Injection and Extraction Points in the Dutch natural gas grid for a maximised quantity of H₂ to be extracted.

3.6 Maximising the Transport Distance after a M&R Station

In section 3.5, it is shown that the configuration that maximizes the amount of H₂ that can be extracted, on average, only leads to a transport distance of 5 to 6 km. The maximum transport distance through a branch of the RTL-grid is 80 km, on average. Upon increasing the transport distance the number of customers (GOS) between the point of H₂ injection and the point of H₂ extraction point will increase. Since at each GOS part of the H₂/NG mixture leaves the RTL-grid, the quantity of H₂ that can be extracted reduces with the number of GOS between the point of injection and the point of extraction (see Figure 3.4, Figure 3.5, and Table 3.3). Considering that 15 GOS are present between the injection and extraction points and assuming that each GOS consumes the same quantity of a H₂/NG mixture, after 14 GOS the H₂/NG mixture stream will be reduced to 1/15th of its original size. As a result, even if all H₂ contained in the H₂/NG mixture is extracted at that point, a maximum of 1/15th of the injected H₂ quantity can be extracted. The implication of maximizing the distance is that customers down stream of the H₂ extraction point will receive a H₂/NG mixture that differs from the mixture the customers get upstream of the extraction point. The stream downstream of an extraction point will be lower in H₂ content. This means the stream stays within the natural gas specifications, but that less H₂ will be available for recovery. This might be an important aspect, but is not considered further in this study.

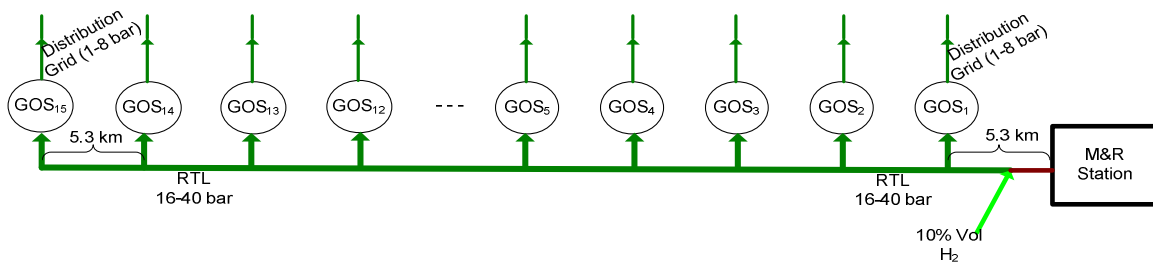


Figure 3.4: Illustration of the Linear Average Distance between Gas Receiving Stations

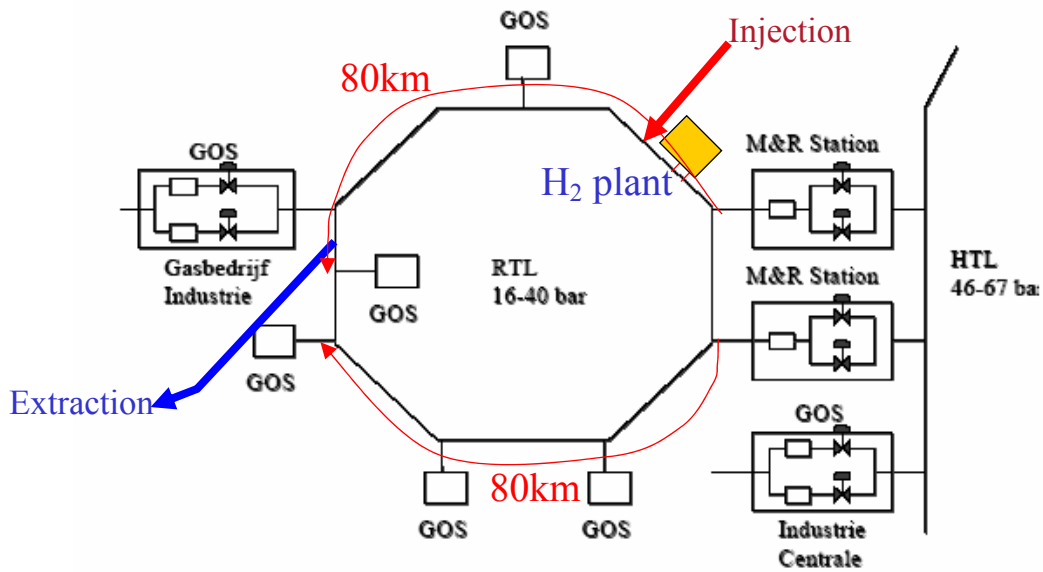


Figure 3.5: H_2 Injection and Extraction Points in the Dutch Natural Gas Grid for a maximised hydrogen transport distance.

Again the situation is somewhat different if mixtures with a hydrogen percentage of well over 20% are possible and extraction takes place after the GOS (see section 3.5). In that case the amount of H_2 extracted does not vary with the transport distance, but with the number of extraction points.

Table 3.3: H_2 available for recovery as a function of number of GOS between Injection & Separation
10 % Volume of H_2 in the H_2/NG Mixture

Separation before GOS Number	H_2 available for recovery [%]	Average transport distance [km]
1	100	5.3
2	93	10.7
3	87	16.0
4	80	21.3
5	73	26.7
6	67	32.0
7	60	37.3
8	53	42.7
9	47	48.0
10	40	53.3
11	33	58.7
12	27	64.0
13	20	69.3
14	13	74.7
15	7	80.0

3.7 Synthesis and Evaluation the H_2 Separation Systems

In this section, various system configurations for the separation of H_2 from the H_2/NG mixture have been synthesized. A conceptual design of a system for separating H_2/NG mixtures by Air Liquide, which is prepared for a French case study within the EU hydrogen roadmap project HyWays, is compared with two alternatives. The systems considered are described in details in section 3.7.1., and are:

- System proposed by Air Liquide as part of the HyWays project (CEA, 2006). This system is based on currently available technologies and consists of a polymer H₂ membrane unit, a compressor and a pressure swing absorption (PSA) purification unit configured in a closely integrated manner.
- A separator system consisting of PSA only. Typical PSA working pressure lies in the range between 20 to 25 bar.
- A separator system consisting of membrane units only. The membrane principle is based on pressure differentials. An optimum working point is found where the pressure difference between inflow and product (called permeate) is as large as possible. Palladium based membranes were considered for the separation as these are known to be highly selective towards H₂ (Kluiters, 2004) and thus might enable a one-step separation process.

3.7.1 Description and Evaluation of Energy Use of each H₂ Separation Systems

The various schemes for the extraction and/or separation of the H₂ from the H₂/NG mixture as outlined above have been synthesized and evaluated in relation to primary energy use. The primary energy use has been estimated using conventional thermodynamic models (see Appendix A).

Separator system consisting of a membrane unit coupled to a PSA

The results presented here were obtained in the before mentioned CEA study (CEA, 2006). A schematic diagram of this system is shown in Figure 3.6:

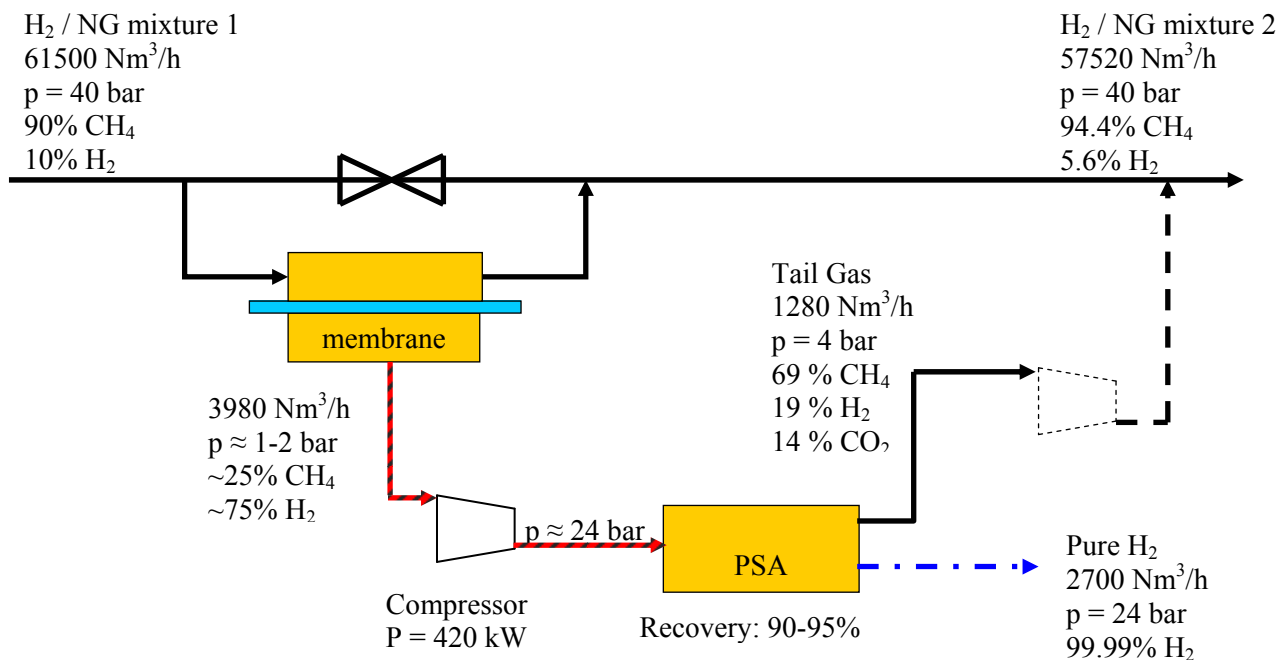


Figure 3.6: Separator system consisting of a combined Membrane and PSA Unit

The separator system is connected to the main H₂/NG mixture pipeline. A valve is depicted between the H₂/NG mixture 1 and H₂/NG mixture 2 streams to represent eventual by-pass. The system works as follows: Firstly, polymer H₂ selective membranes produce a H₂ enriched stream, with approximately 70 to 80% H₂ on a volume basis. Secondly, a PSA purification step provides pure H₂ after recompression of the H₂ enriched stream. Finally, the pure H₂ stream leaves the separator at a pressure of 24 bar. From the PSA unit, a tail gas stream containing the "impurities" leaves the separator at a pressure of about 4 bar and can be mixed in the low-pressure distribution network or injected into the RTL network after recompression. The separator's energy use originates from the compression power required before the PSA.

Considering a H₂/NG mixture 1 flow of 61500 Nm³/h at 10% H₂ content by volume, approximately 2700 Nm³/h of pure H₂ is recovered at the cost of an extra power compressor of about 420 kW. The energy use of this system is then characterised by a power consumption of about 0.05 kWh per kWh of delivered H₂. Note that the power required for the compressor connected to the tail gas stream leaving the PSA has not been taken into consideration. The study assumes that this stream would be mixed in the grid further downstream at pressure lower than the tail gas pressure.

Separator system consisting of only a PSA unit

A schematic diagram of this system is depicted in Figure 3.7. A system consisting of an expander, a PSA unit and a compressor is connected to the main H₂/NG mixture pipeline. The stream after the separator system (H₂/NG mixture 2) has different H₂ content than upstream the separator (H₂/NG mixture 1). In the scheme, a valve connects the H₂/NG mixture 1 and H₂/NG mixture 2 streams, symbolising a possible by-pass. The separator system is assumed connected to a H₂/NG mixture 1 stream flowing at approximately 40 bar pressure. Because of this and due to the optimum pressure at which a PSA system operates, an expander reduces the pressure to approximately a 20 bar level. The PSA system, produces H₂ stream at approximately 20 bar and a tail gas stream at approximately 4 bar. The tail gas stream is consequently pressurised up to the 40 bar level of the main pipeline producing the H₂/NG mixture 2 stream as depicted below.

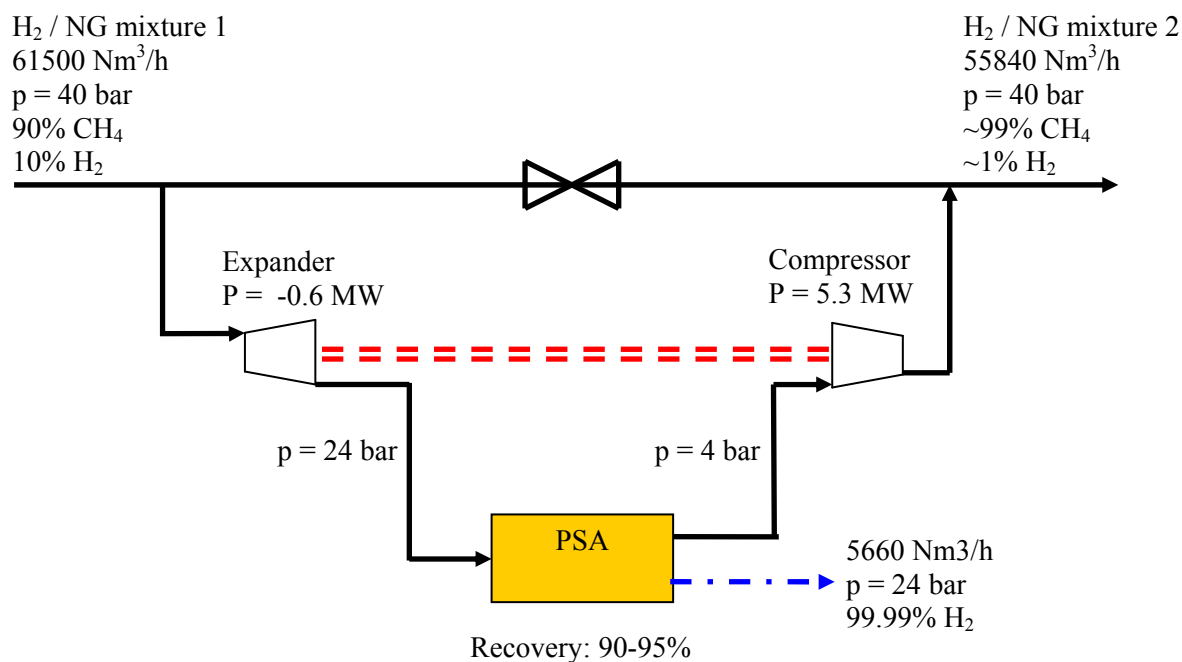


Figure 3.7: *Separator System Consisting of a PSA Unit Only*

In order to minimise the energy level required by the tail gas compressor, some work produced by the expander is passed through the compressor. Approximately 10% of the power required by the compressor is produced by the expander. Heat produced by the compressor is used to heat the incoming flow of the expander. It is assumed that no additional heating is needed. Considering a H₂/NG mixture 1 flow of 61500 Nm³/h at 10% H₂ content by volume and a PSA recovery of about 90%, approximately 5660 Nm³/h of pure H₂ is recovered at the cost of a nett extra power compressor of around 5 MW. The efficiency of this system is then characterised by a power consumption of about 0.28 kWh per kWh of delivered H₂.

Separator system consisting of a membrane unit only

A schematic diagram of this system is depicted in Figure 3.8. A system consisting of two heat exchangers, a heating system, a high temperature membrane unit and a compressor is connected to the main H₂/NG mixture pipeline.

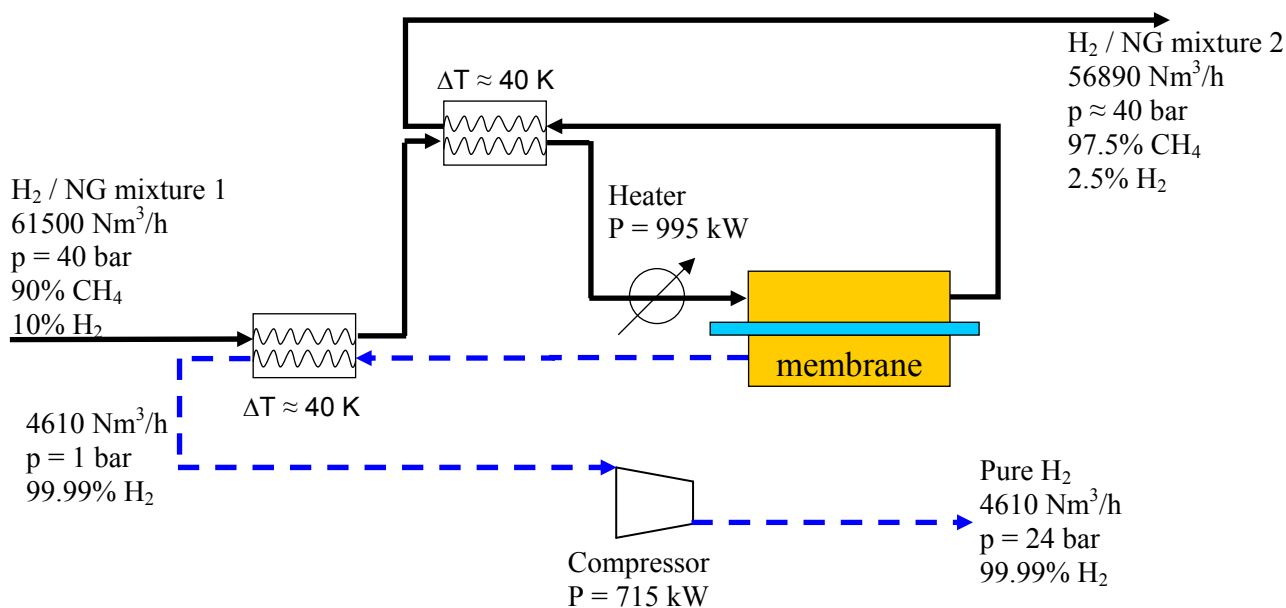


Figure 3.8: Separator System Consisting of a Membrane Unit only (ideal case)

A single-step membrane separator producing pure H₂ requires the use of highly selective, dense membranes, such as Palladium membranes. The optimum working temperature range of these membranes lies between 300 and 600°C. Therefore, a heating system is connected to the incoming flow entering the membrane. In order to minimise the power required to heat the incoming flow, two heat exchangers that pre-heat the incoming flow are included. Due to the working principle of a membrane system, the H₂ product stream (permeate) is obtained at a low pressure. To be compared to the other separators described above, a H₂ compressor is included. Considering a H₂/NG mixture 1 flow of 61500 Nm³/h at 10% H₂ content by volume and an ideally membrane system, approximately 4600 Nm³/h of pure H₂ is recovered. If the membrane operating temperature is assumed to be 300°C, and the temperature difference between incoming and outgoing heat exchanger flows is assumed to be 40 °C, the required heating power is approximately 1 MW. The power required by the H₂ compressor is estimated a little over 0.7 MW. As a result of this, the energy use of this system is estimated as about 0.05 kWh of electricity and about 0.07 kWh of heat per kWh of delivered H₂.

At a pressure of 40 bar and a mixture of 10% H₂ (4 bar H₂ partial pressure), the maximum recovery of H₂ is 75%, without using sweep gas at the membrane permeate side. In this case the H₂ partial pressure will be 1 bar both at the permeate as well as the retentate side of the membrane. However, the lower the partial pressure difference over the membrane, the lower the driving force for separation, and the larger the membrane surface area needed for the separation. In fact, 75% recovery in the above case is a theoretical case as it would require an infinitely large membrane surface area. Therefore, also a more realistic case is considered which produces the same amount of hydrogen as the system combining a polymer membrane unit and a PSA (see Figure 3.6). The more realistic case is represented by Figure 3.9 below. Calculations show that energy use in the form of electricity for compression of the pure hydrogen stream is constant at about 0.05 kWh per kWh of delivered H₂, but the specific energy use needed for heating increases to about 0.12 kWh per kWh of delivered H₂.

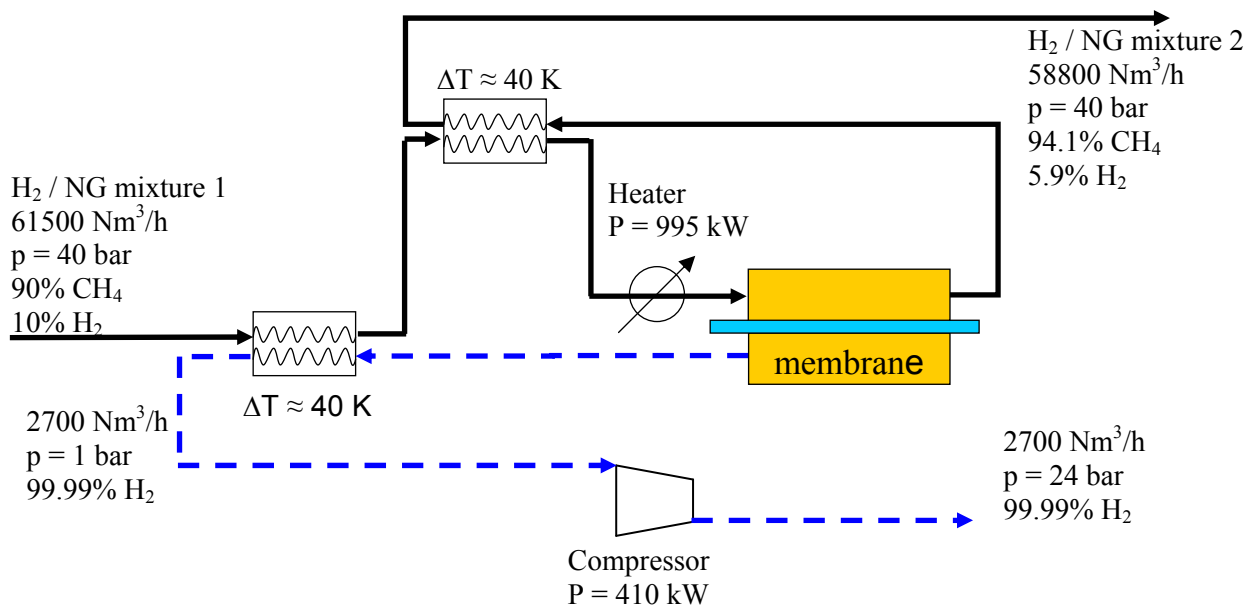


Figure 3.9: Separator System Consisting of a Membrane Unit only (Realistic Case).

Although highly selective dense palladium membranes can be considered as ideal membranes for H_2 separation, because they enable production of a pure hydrogen stream in a single process step¹⁷, the results show that ideal membranes do not necessarily lead to a separation system with the lowest energy use. The separator based on only PSA shows the highest energy use for separation. This system, also, is the only system that can separate almost all hydrogen from the mixture. The results of the three separator systems presented above show that the separator system consisting of a polymer membrane unit followed by a PSA unit, has the lowest energy use. Based on this result, this system has been selected for the energy chain analysis. Whichever separator system is used, it is not possible to recuperate all the H_2 contained in the NG/ H_2 mixture stream in an efficient way.

3.7.2 Transport and Recovery of H_2 for How Many Hydrogen Vehicles?

The number of H_2 vehicles (HV) that can be serviced depends on factors such as the total flow rate, the H_2 volume in the mixture, the number of GOS between H_2 injection and extraction, the extraction efficiency of the separation system as well as the efficiency and annual mileage of the HV. Using the parameters in Table 3.4, Table 3.5 presents order of magnitude estimates for the number of cars that can be serviced, depending on where separation of hydrogen takes place in the RTL-grid.

Table 3.4: Parameters for Estimating the Potential H_2 Vehicles Serviced per GOS

Parameter	Unit	Quantity
Number of M&R station	[-]	75
Number of Gas Receiving Stations (GOS)	[-]	1100
Number of GOS per M&R station	[-]	15
Amount of gas at each M&R station	[Million Nm ³ /yr]	500
H_2	[vol%]	10/20/30
Extraction efficiency	[%]	50
HV efficiency	[kWh/km]	0.2325
Energy content of H_2 (LHV)	[kWh/Nm ³]	3
Annual HV mileage	[km]	15000

¹⁷ In reality it is questionable whether fuel cell grade hydrogen, 99,999%, can be produced in a single step. This would require membranes with a selectivity of around 10,000 or more. This could possibly only be achieved with relatively thick Palladium membranes with a low flux, or alternatively an after treatment step is necessary.

The results indicate that the number of HVs that can be supplied with hydrogen, which is transported as 10% mixture via the natural gas network, ranges from 1500 to about, 21000, depending on whether a separator is located before the 15th or 1st GOS, respectively. In addition, the amount of cars that can be serviced is proportional to the hydrogen volume percentage of the mixture; if the hydrogen volume percentage doubles, then also the amount of cars doubles that can be supplied with hydrogen.

Figure 3.6 shows that H₂ recovery by the membrane part of the combined polymer membrane and PSA separator system is about 48%. This means that the partial pressure of hydrogen in the incoming flow should at least be 2.1 bar. Table 3.2 then shows that a mixture of 30% by volume of hydrogen could just be enough to enable separation to take place in the 1 to 8 bar distribution grid after the GOS. In that case, the results in Table 3.5 indicate that each separator could yield enough hydrogen to supply about 4,400 cars with hydrogen. Currently, there are about 8.2 million light duty vehicles in the Netherlands, with a total of 1,100 GOS in the Netherlands, this translates to about 7,450 vehicles per GOS, on average. By taking the ratio of these two figures, the conclusion could be that if the RTL and local distribution grid can handle a mixture of 30% by volume of H₂, the NATURALHY option for transport of hydrogen could support a hydrogen vehicle penetration level of about 60%.

However, it is questionable whether this penetration is indeed feasible because of the fluctuations in the natural gas demand which invariably means that the effective amount of H₂ that could be extracted will also fluctuate. Combined industrial, commercial and residential demand for natural gas varies widely between summer and winter period. This does not match with the demand profile of fuel at retail stations which is rather constant throughout the year. Besides the mismatch in supply and demand profiles, the fluctuations also introduce challenges with respect to finding the right dimensions for the hydrogen production process(es) and separation unit(s), to maintain a certain volume percentage of hydrogen in the mixture and to enable efficient separation of hydrogen from the mixture.

The above mentioned issues are not further addressed and quantified in this report. For the purpose of the analysis in this paragraph, the assumption is that it is possible to effectively extract the amount of H₂ (the fluctuations not withstanding) as presented in Table 3.5, thus supporting a hydrogen vehicle penetration level of about 60%.

Table 3.5: Potential H₂ vehicles serviced as a function of Injection and Extraction points

Separation before GOS Number	Potential H ₂ Vehicles to be served per year		
	10 % H ₂ Volume	20% H ₂ Volume	30 % H ₂ Volume
1	21,505	43,011	64,516
2	10,750	21,505	33,255
3	7,169	14,337	21,506
4	5,376	10,753	16,129
5	4,301	8,602	12,903
6	3,584	7,169	10,753
7	3,072	6,144	9,216
8	2,688	5,376	8,064
9	2,389	4,779	7,168
10	2,151	4,301	6,452
11	1,955	3,910	5,865
12	1,792	3,584	5,376
13	1,654	3,309	4,963
14	1,536	3,072	4,608
15	1,466	2,932	4,398

4. Well-to-Wheels Analysis

In this Section, the primary energy use (relevant and contributory to energy resource depletion) as well as total greenhouse gas emissions for the production routes and transport modes (the injection and extraction process inclusive) considered is presented. The primary energy use for the mobile applications is given in terms of energy use per kilometre that is driven by a HV. Total greenhouse gas emissions (CO₂ and other prominent greenhouse gas emissions associated with global climate change) are translated and given in terms of grams equivalent CO₂¹⁸ per kilometre that is driven by a HV.

4.1 Basis of Analysis

The production routes (and mix) considered are basically the H₂ production routes and mix that have been generated by H₂ experts from EU-member states that participated in the EU hydrogen roadmap project HyWays (Hyways, 2007). The production routes include coal with carbon capture and storage (CCS), natural gas without CCS, natural gas with CCS, nuclear power, electricity grid¹⁹, wind power and biomass energy. The analysis presented in this report only considered the case where H₂ extraction is executed before the GOS. In Figure 2.2, the total chain analyzed is presented while the chain and their respective characteristics are discussed in details in Appendix C.

As an illustration, the natural gas with CCS chain is used here. The natural gas is assumed to be extracted and processed in Russia and transported into the EU gas network (at an average distance of 4000 km) and then further distributed to production plants (500 km distance, on average). A Steam Methane Reformer (SMR) located at that point produces H₂, which becomes subsequently distributed to the filling stations. Also at the SMR plant, the CO₂ emission produced are separated, transported (50 km distance, on average) and subsequently stored in an old gas/oil field, or an aquifer. The H₂ produced through SMR technology (at an output pressure of at least 30 bar) can be transported to the filling station using any of the four H₂ transport modes or routes as depicted in Figure 4.1 and described below, i.e. mixing and transporting it using the existing natural gas grid-*NATURALHY mode*, through dedicated pipeline, trucking it as compressed H₂ (CGH₂) and trucking it as liquefied H₂ (LH₂).

For the *NATURALHY transport mode*, the H₂ (available at 30 bar) is further compressed to a pressure well above 40 bar to create an effective driving force for successful injection into the RTL grid. The compressed H₂ at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80 km, before being separated (see chapter 3). After the separation, H₂ at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H₂ vehicles. On-board pressure in the car is 700 bar. The higher filling pressure is needed to create enough driving force to enable fast filling within technical boundary conditions of the filling system.

For the case of *dedicated pipelines*, the pressure of the H₂ produced at the SMR of about 30 bar is considered sufficient for distribution through a H₂ pipeline over a distance of up to 80 km, without addi-

¹⁸ Equivalent CO₂ is a measure for describing how much global warming a given type and amount of a greenhouse gas may cause, using the functionally equivalent amount or concentration of carbon dioxide (CO₂) as the reference point. Other greenhouse gases are converted to equivalent CO₂ by means of the relevant Global Warming Potential (GWP).

¹⁹ Though all production routes that supply electricity (e.g. wind energy) are connected to the electricity network, this might not be enough and as such electricity from the grid might still be needed. "Grid" is therefore used here as a "pseudo-production-route" to account for the electricity demand and production changes that will be introduced in the power sector due to the electricity-based H₂ production processes. In case of an increase in electricity demand (due to these electricity-based H₂ production processes), it is expected that the system will build in additional capacity necessary to meet the additional demand. The impact on emissions and energy use resulting from the introduction of H₂ into the energy system is therefore determined by the emissions and energy use originating from the power sector, needed to meet the additional demand.

tional compression energy. Making for transmission pressure loss, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression before being dispensed to the H_2 vehicles.

And for the case of transport through the *trucking of the compressed H_2* to the refueling station, the H_2 from the SMR at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H_2 can then be transported by truck via the road in high pressure cylinders. There is also energy included here (in the form of diesel) for the operation of the road truck. The truck delivers the compressed H_2 to the filling station for further compression before being dispensed to the H_2 vehicles.

Finally, for the case of transport through the *trucking of liquefied H_2* to the refueling station, the H_2 from the SMR at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. At the station liquid hydrogen is pumped to the required pressure of 880 bar using a cryogenic pump. Pressure build-up arises from vaporization of the liquid in a confined volume during pumping. This operation is less energy-intensive than first evaporating liquid hydrogen and then compressing the gaseous hydrogen using a compressor. The pumped and vaporized H_2 is then dispensed to H_2 vehicles.

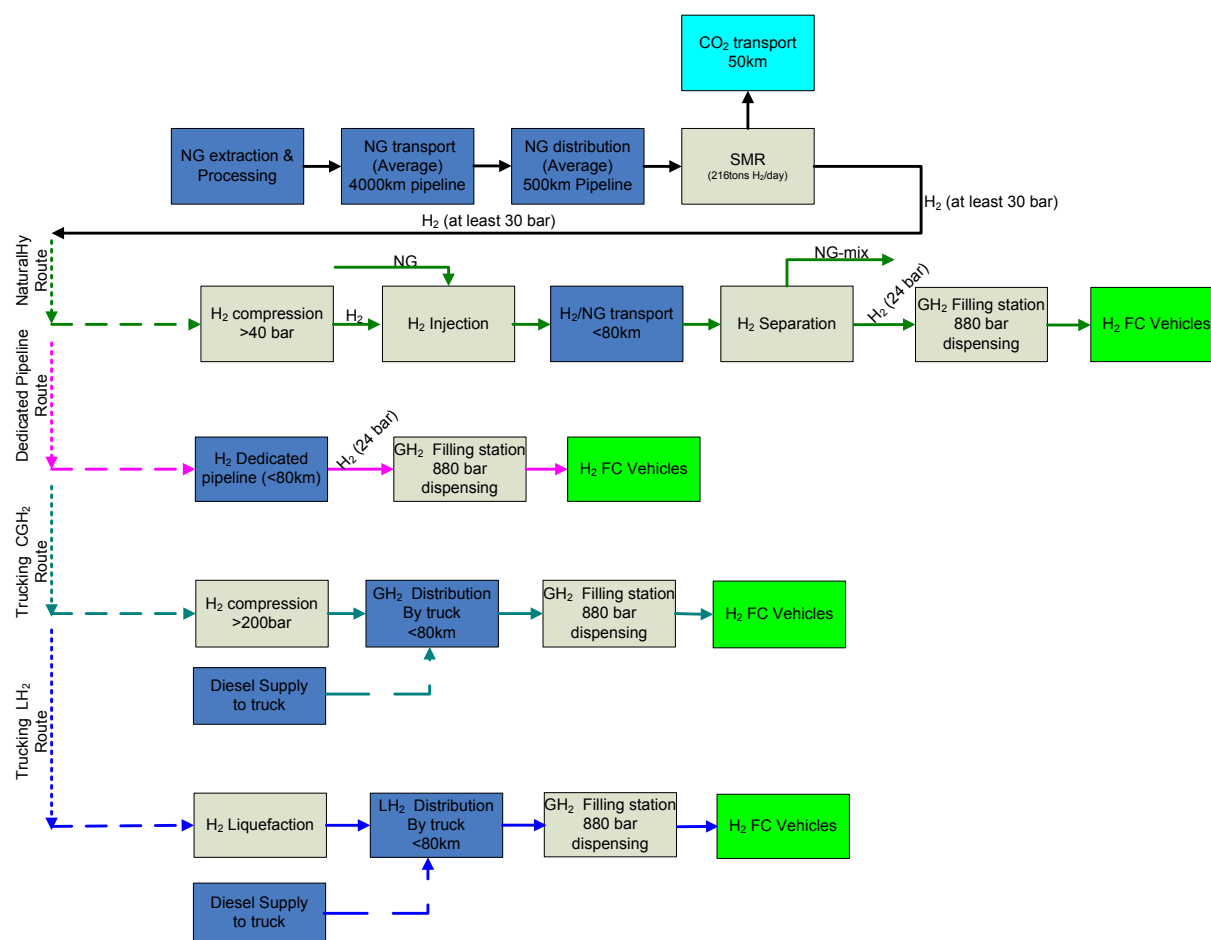


Figure 4.1: Illustration of the Natural Gas with CCS Chain

The WtW analysis (primary energy use and emissions) of each of the transport routes for the case of the natural gas with CCS chain as well as the reference scenario (WtW analysis of conventional diesel and gasoline fuels) are illustrated in Figure 4.2 and figure 4.3. From Figure 4.2, the case of transporting the H_2 produced from natural gas with CCS using the existing natural gas pipeline consumes more primary energy especially at the fuel production part of the WtW chain. This is attributable to the con-

version losses during production of the hydrogen that cannot be extracted from the mixture. The H₂ that cannot be extracted is not counted as loss as its calorific value can still be used.

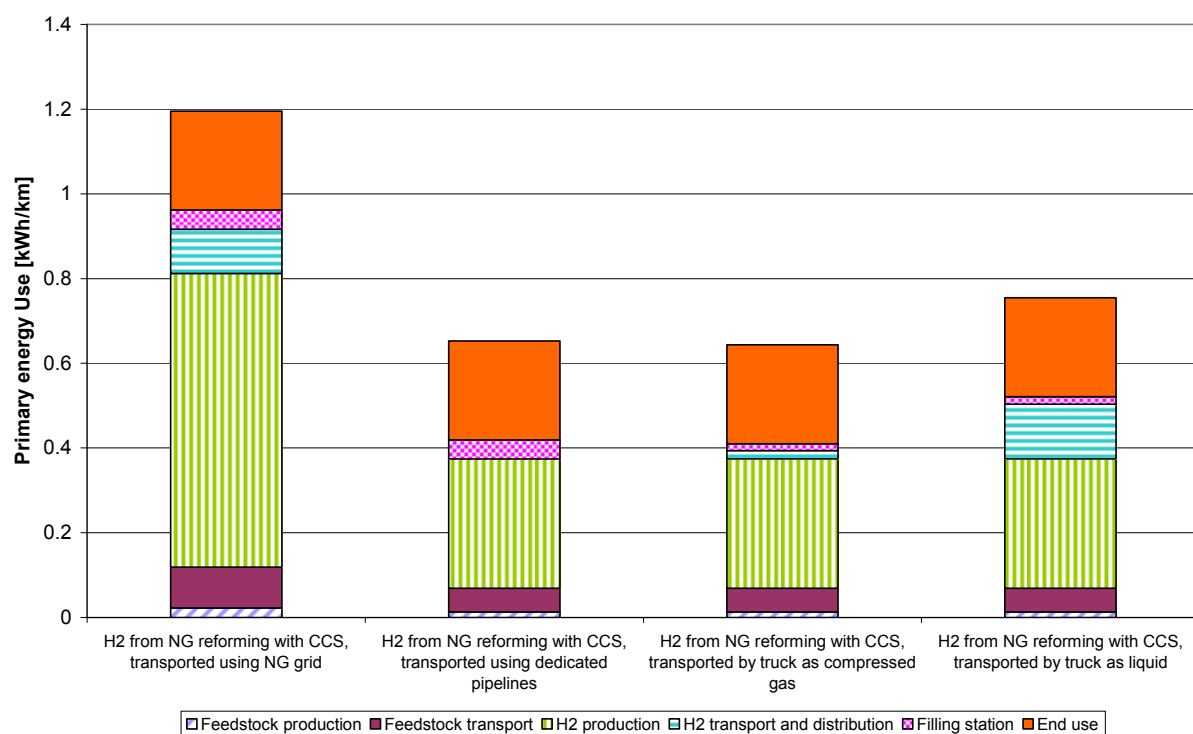


Figure 4.2: Illustration of WtW Primary Energy Use for Natural Gas with CCS Chain

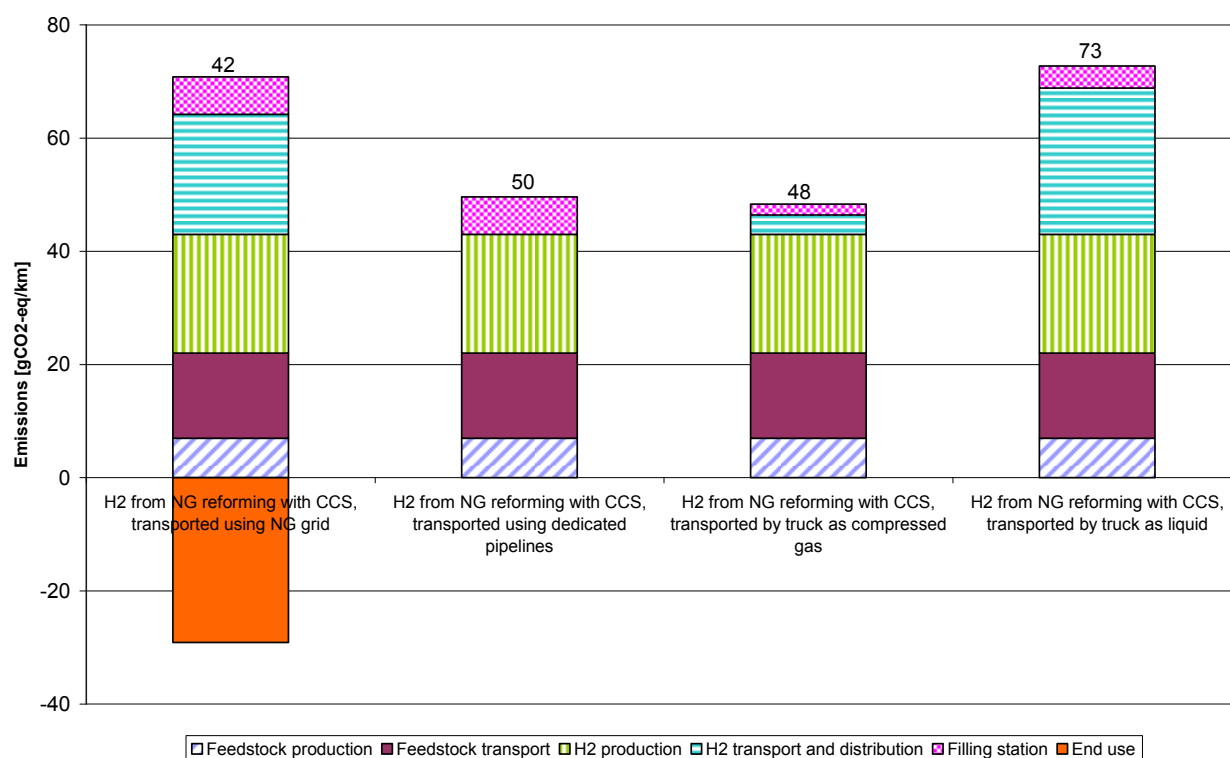


Figure 4.3: Illustration of the WtW Total Greenhouse Gas Emissions for Natural Gas with CCS Chain

However, the emissions associated with this are lower in comparison with both the other transport routes as well as the reference scenario (Figure 4.3). It shows clearly that the end use emission is nega-

tive for the cases where H_2 is produced from natural gas and injected into, transporting it through and then separated from the existing natural gas network. The negative values mean that total greenhouse gas emission is avoided. The cause of this is discussed in details in the sections that follow.

An indication of the various contributions of the parts of the WtW chain to total primary energy use and greenhouse gas emissions are given in Figure 4.4 through Figure 4.11. Unlike Figure 4.2 and Figure 4.3, where the effect of different transport modes was illustrated for hydrogen originating from the same feedstock (hydrogen from natural gas by reforming with CCS), in Figure 4.4 to Figure 4.11 all feedstocks are plotted in the same graph per transport mode. Figure 4.4 to Figure 4.7 show the results for primary energy use and Figure 4.8 to Figure 4.11 show the result for greenhouse gas emissions.

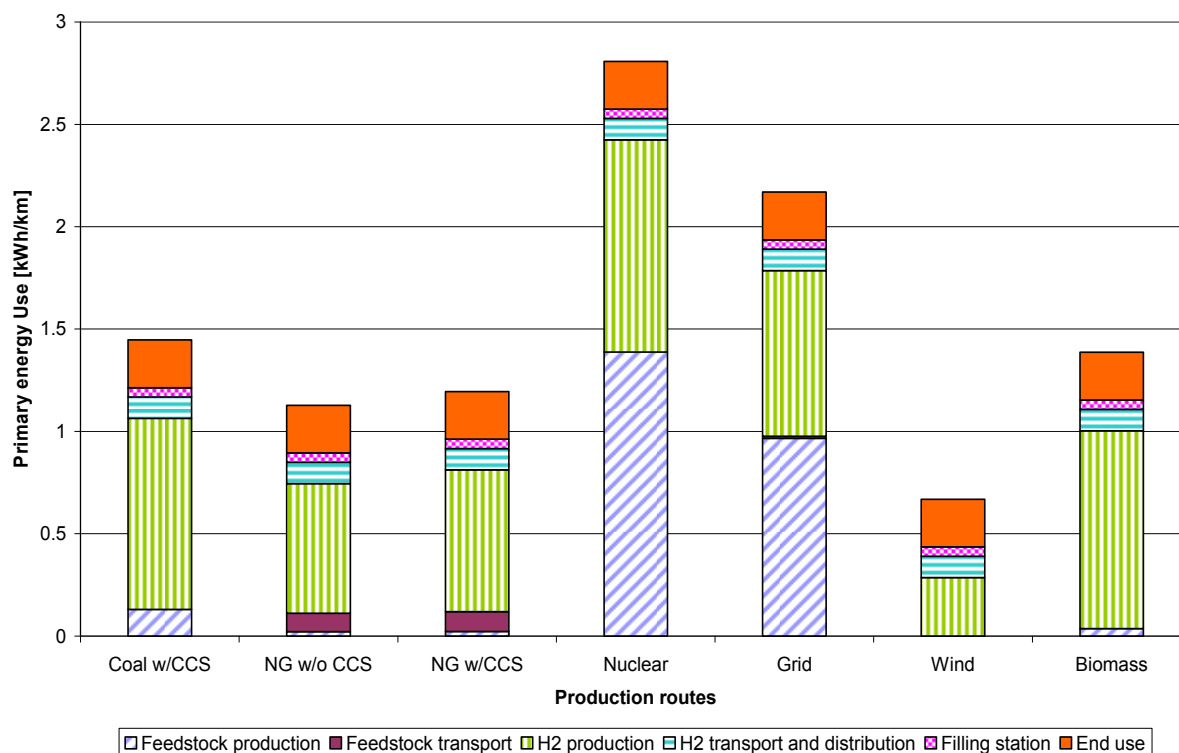


Figure 4.4: *WtW Primary Energy Use for Various H_2 Production Routes for NATURALHY Project Option*

At the feedstock production level (Figure 4.4 to Figure 4.7), using the nuclear power route to produce H_2 consumes relatively more primary energy than the other production means because of the feedstock uranium. This is because uranium exploration is energy intensive. This is also true at the fuel production level where the nuclear power route also consumes relatively, more primary energy than the other routes. This can be accounted for the fact that the use of nuclear in producing H_2 has relatively lower efficiency compared to other routes.

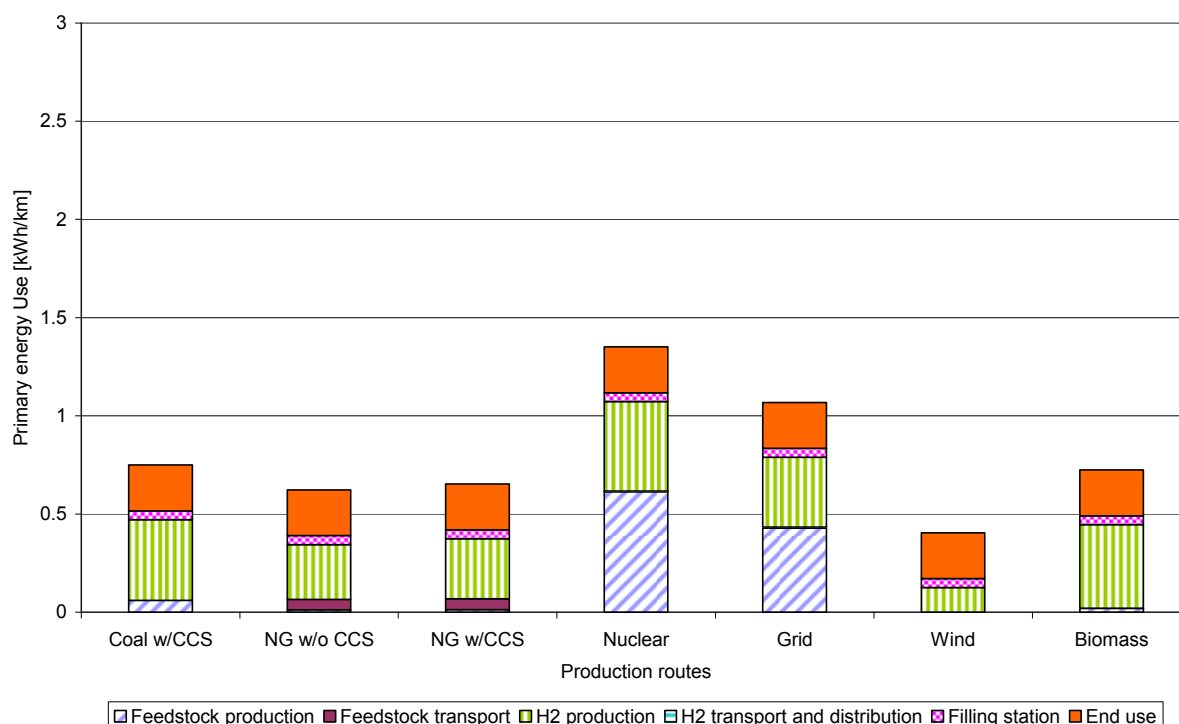


Figure 4.5: *WtW Primary Energy Use for Various H₂ Production Routes for the Dedicated Pipeline Option*

In Figure 4.4, it can be observed that hydrogen production consumes the highest amount of primary energy amongst the chains and for the different production routes²⁰. This could be explained by the fact that the H₂ production process is the lowest efficiency link in the WtW chain.

In the light of Figure 4.4, since using the nuclear power route in producing H₂ is more energy intensive and relatively of lower efficiency than the other routes, it there means that the primary energy use is highest in the nuclear route. This line of reasoning also holds true in the remaining parts of the production routes. The primary energy use of the HVs is same in all and has been assumed to be 0.232kWh/km.

Comparatively, the WtW primary energy use for the various H₂ production routes for the NATURALHY option (Figure 4.4) is relatively higher than the other transport modes (Figure 4.5 to Figure 4.7) due to conversion losses resulting from the low H₂ extraction efficiency in the H₂ /NG mixture of the NATURALHY option. Since only 44% of the hydrogen injected is extracted, therefore, more primary energy use results from extra conversion losses, as more H₂ has to be produced per unit of H₂. Also more primary energy use is also required for extra production and transport of feedstock needed to produce the extra unit of H₂.

In any case, for the NATURALHY option, the non-extracted H₂ is not lost but will replace a specific volume of natural gas in the downstream NG/H₂ mixture. Consequently, the primary energy that would have been used in producing such quantity of natural gas that has been replaced by H₂ is equally taken into consideration - compensated - (weighed out with the primary energy use in producing the un-extracted H₂). Unfortunately, the net compensation is rather a penalty (except for H₂ production from wind) as the well-to-fuel primary energy use in producing the un-extracted H₂ is far greater than the primary energy use in producing the natural gas the un-extracted hydrogen replaces (see Table C. 3 in the appendix).

²⁰ In Table C.2 and Table C.3 in Appendix C, more quantitative results are presented.

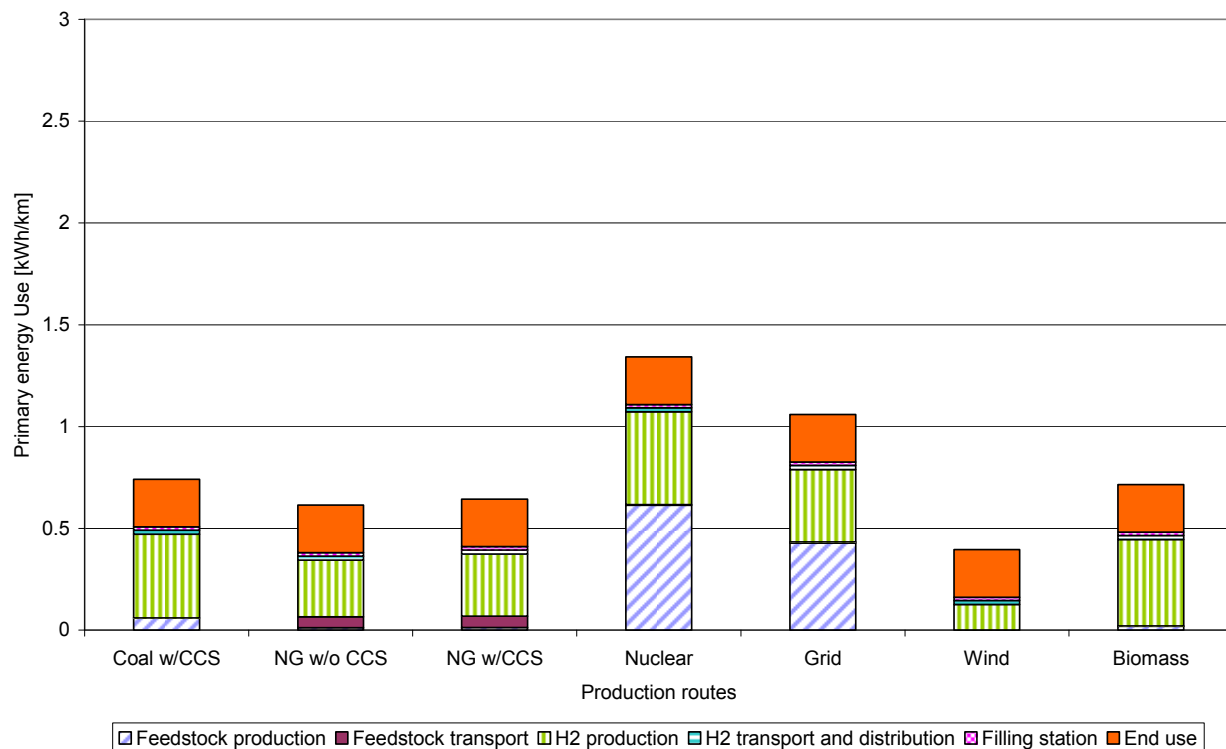


Figure 4.6: *WtW Primary Energy Use for Various H₂ Production Routes for the Compressed Hydrogen Truck Option*

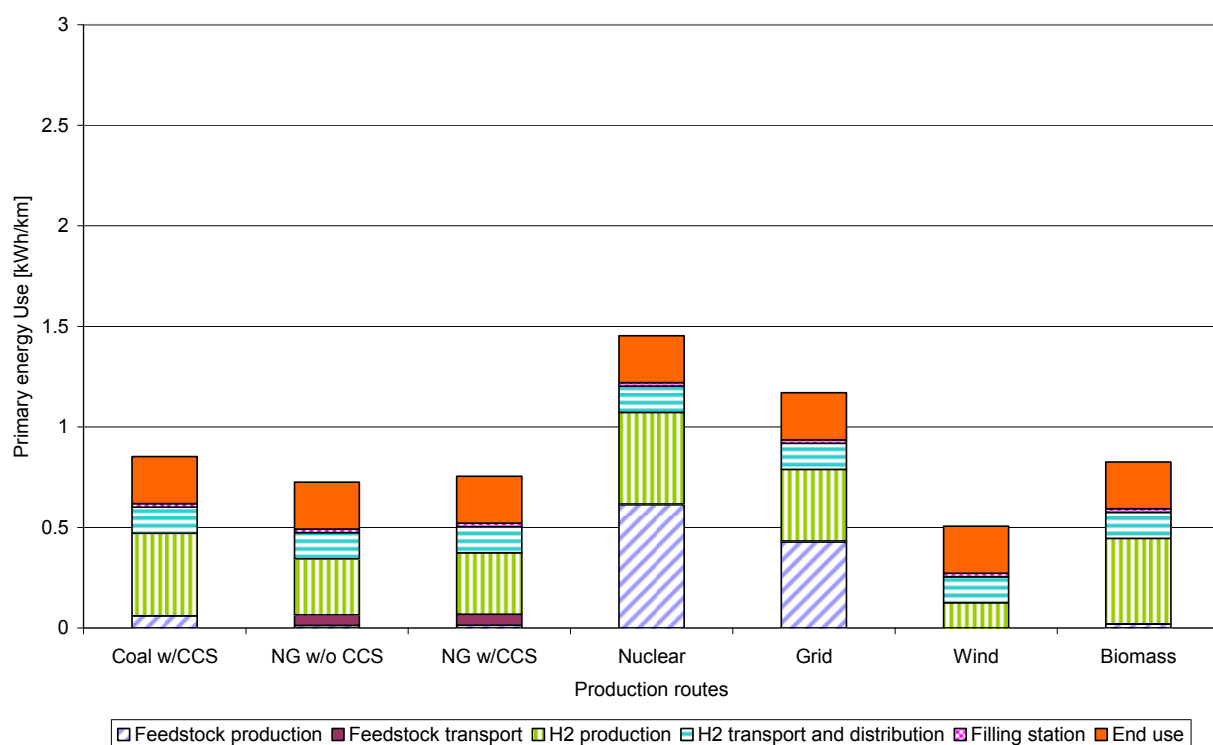


Figure 4.7: *WtW Primary Energy Use for Various H₂ Production Routes for the Liquid Hydrogen Truck Option*

Figure 4.8 to Figure 4.11 depict the total greenhouse gas emissions given in terms of grams of equivalent CO₂ per kilometre that is driven by a HV. At the feedstock production level, in all the

transport options, the emissions associated with the grid electricity is the highest. Though the emissions resulting from the grid electrolytic hydrogen production is extremely low or zero as electrolysis itself does not generate emissions, the resulting high emissions is attributable to the electricity production (from mixed sources- mineral oil, nuclear, waste, coal, NG) which in this case is considered as the feedstock.

At the end use level, most of the emissions are negative for the NATURALHY option. For this transport option, the non-extracted H_2 is not lost but will replace a specific volume of natural gas in the downstream NG/ H_2 mixture. Consequently, the green house emissions that would have been associated with the production of such quantity of natural gas that has been replaced by H_2 is equally taken into consideration - compensated - (weighed out with the emissions associated the production of the un-extracted H_2). If the amount of green house emissions associated with the production of the un-extracted hydrogen is lower than that associated with the production of the natural gas it replaces, then there will be a net reduction in the emissions due to the replacement and vice versa. Here, the net compensation is rather rewarding in most cases as the emissions associated with producing the natural gas the un-extracted hydrogen replaces far out-weighs the emissions associated with producing the un-extracted H_2 (see Table C. 3 in the appendix). The net reduction or increment in the emission has been allocated to the end use part of the chain. The total greenhouse gases emitted in the end use segment is negative²¹ for the coal with CCS, natural gas with CCS, nuclear power, wind power and biomass energy routes. However, in the case of the NG without CCS chain as well as the grid, the emission factor for producing the un-extracted H_2 is greater than the emission factor of the NG it replaces. Therefore, there is net emission increment due to this replacement which results in the emission at the vehicle and/or end use application being positive.

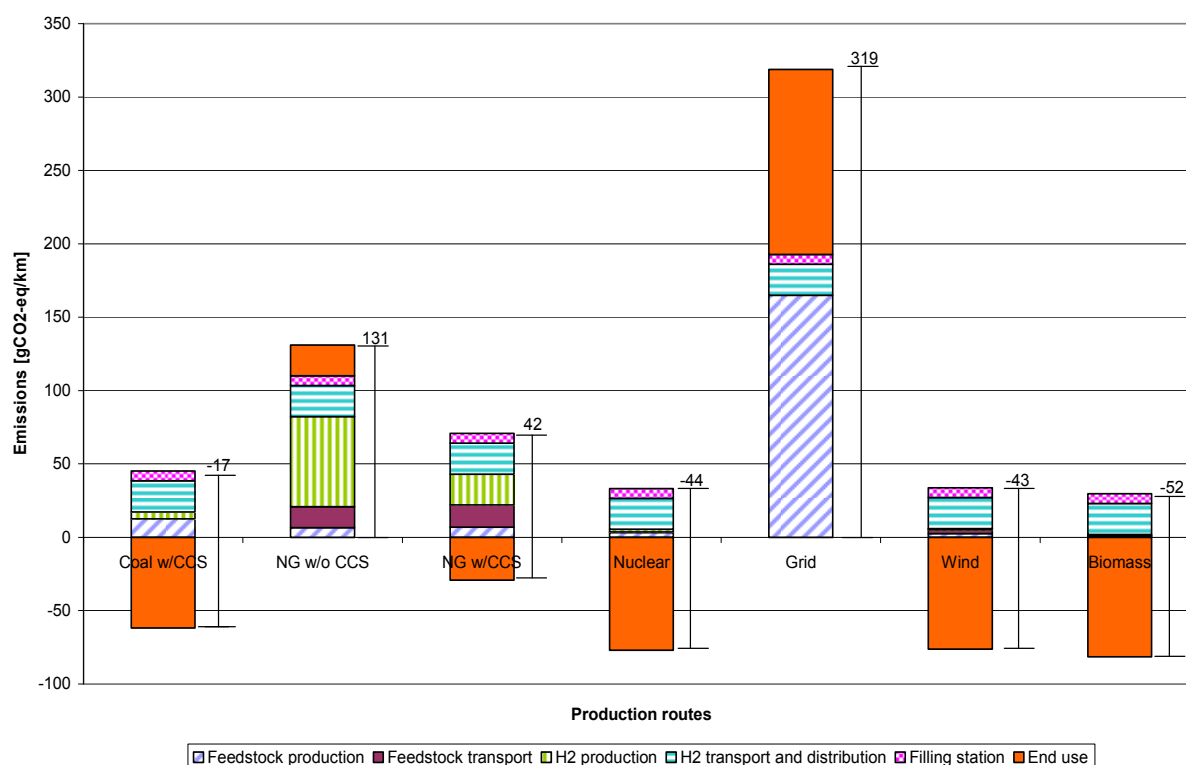


Figure 4.8: *WtW Total Greenhouse Gas Emissions for Various H_2 Production Routes for the NATURALHY Option*

In the case of nuclear, wind, biomass and coal with CSS routes, the overall emission is negative. In the case of NG without CCS, NG with CCS, and the grid, the overall emission is still positive. At the

²¹ Generally, if the overall emission factor associated with the production of H_2 is less than the emission factor for production of NG, then net emissions decreases. This decrease is however, attributed to the use of pure H_2 by the end use application. As this is zero for the mobile (HV) end use, the emissions then become negative.

feedstock production level, the total greenhouse gas emissions are highest for the electricity grid and coal without CCS of all the production routes. This may be mainly attributed to emissions associated with coal combustion. Generally, the lower the extraction efficiency, the more H_2 that will remain in the mix and the better the emissions for these routes with overall negative emission. This suggests that the more we drive with H_2 from these routes the more GHG emission we save. However, regarding many unresolved issues (additional infrastructure, limited transport distance etc) it may be better to consider the option of greening the gas for stationary applications.

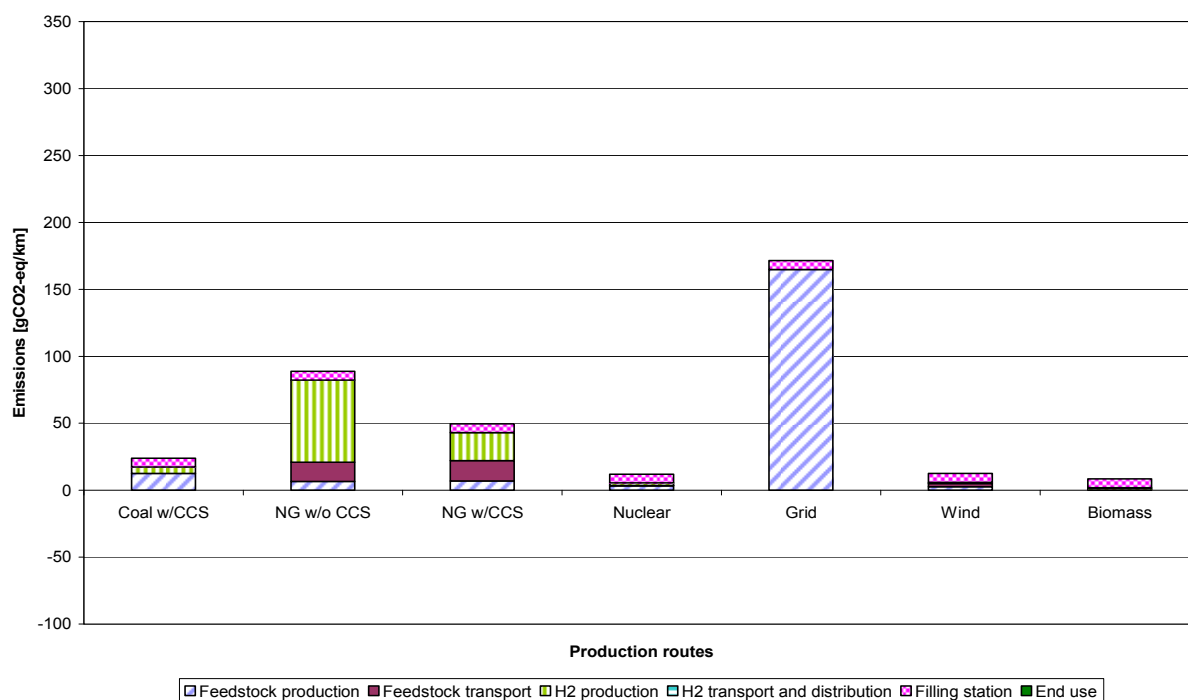


Figure 4.9: *WtW Total Greenhouse Gas Emissions for Various H_2 Production Routes for the Dedicated Pipeline Option*

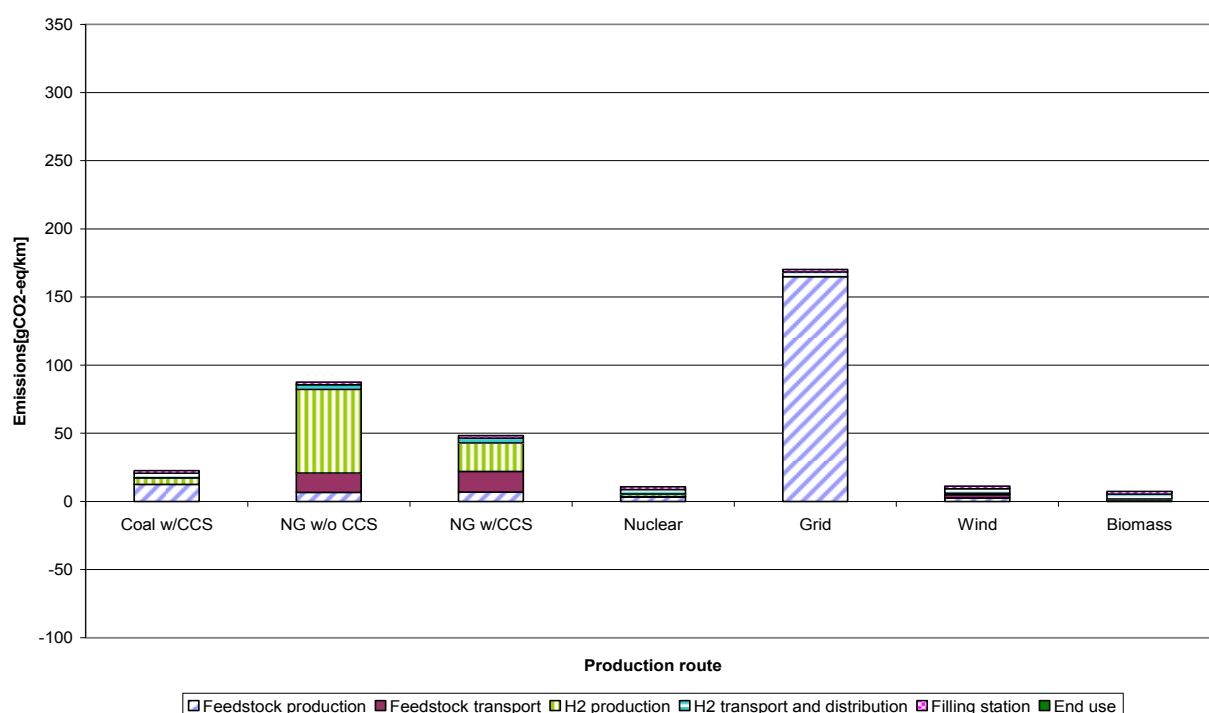


Figure 4.10: *WtW Total Greenhouse Gas Emissions for Various H_2 Production Routes for the Compressed Hydrogen Truck Option*

At the fuel production level, the total greenhouse gas emissions in the cases where natural gas is used as feedstock (without CCS) is the highest and are largely determined by the emissions from the methane reforming process and the absence of the carbon capture and storage systems in these chains. For the other transport scenarios, the total greenhouse gas emissions emanating from the transport and distribution of the H₂ produced are positive and, thus, contribute to the overall global warming. Comparatively, the compressed H₂ truck transport option has less total greenhouse gas emissions than the liquid hydrogen truck-in transport option. This difference can be explained by the emissions resulting from the energy-intensive liquefaction process.

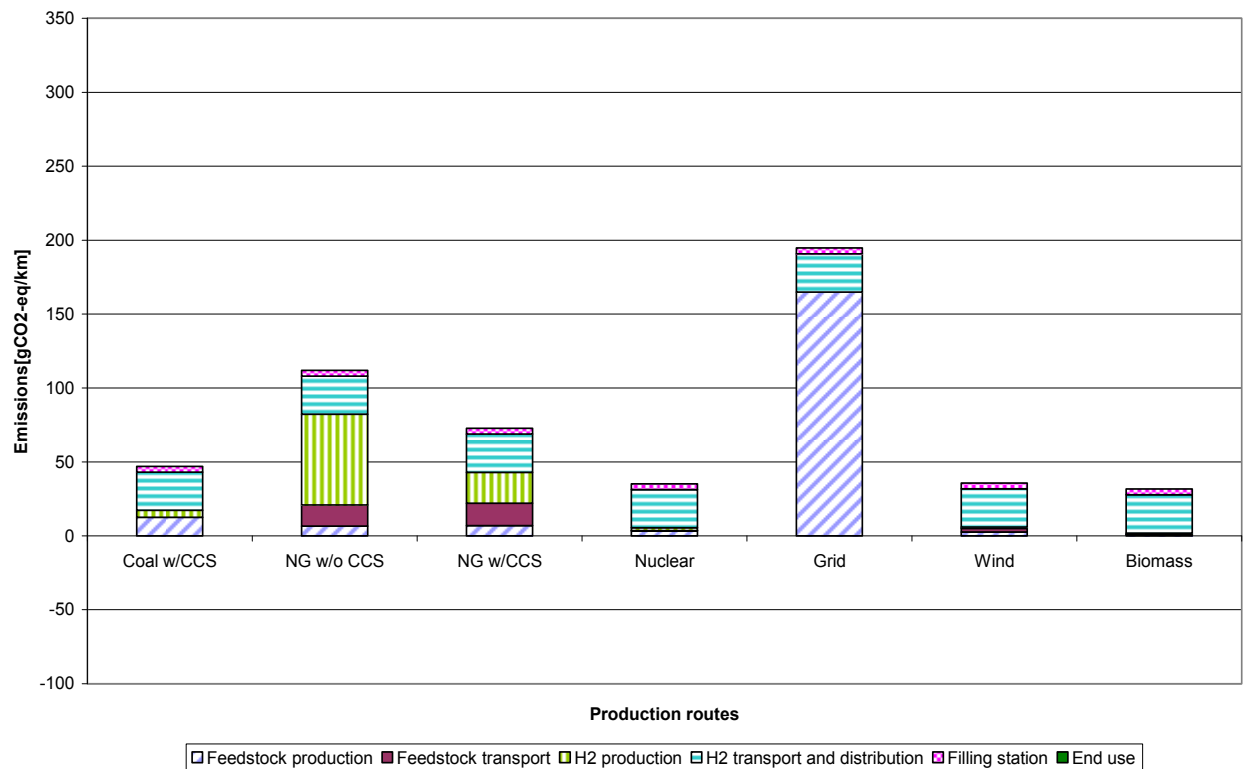


Figure 4.11: *WtW Total Greenhouse Gas Emissions for Various Hydrogen Production Routes for the Liquid Hydrogen Truck Option*

4.2 Impacts of Different Production Routes & Transport Options.

Figure 4.12 shows the total primary energy use for the selected WTT energy chains, production routes and transport options.

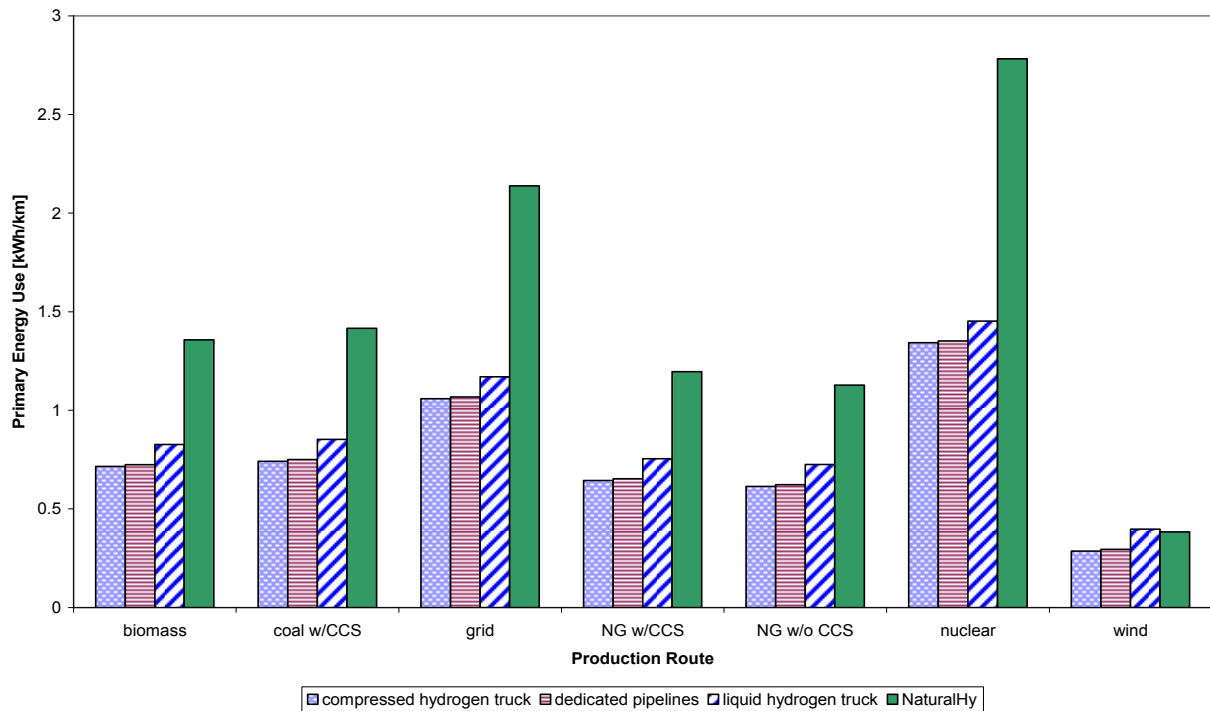


Figure 4.12: *WtW Primary Energy Use for Various Hydrogen Production Routes and Transport Options*

In all the transport routes, mixing and transporting H_2 using the natural gas grid and separating it downstream of the grid (the NATURALHY option) have the highest primary energy consumption. This can be explained by the primary energy expended in separating H_2 from the H_2 / NG mixture and the additional conversion losses of the H_2 that can not be extracted from the H_2 /NG mix. Next to the NATURALHY option, in terms of primary energy consumption, is the transport of H_2 by means of liquid hydrogen trucks. The transport and distribution of liquefied H_2 result in a slight increase of primary energy use compared to transport and distribution of compressed H_2 . This is due to the higher energy associated with the liquefaction process. Irrespectively of the production process, the transport and distribution of H_2 using either the dedicated pipeline or compressed hydrogen truck has, more or less, the same primary energy consumption.

Producing H_2 by the wind-based electrolysis of water (wind chain) shows the greatest potential in primary energy utilization minimisation for all the transport options. The primary energy use in producing H_2 from reforming of natural gas with CCS is relatively larger than producing H_2 from natural gas reforming without CCS. This is explained by energy use associated with CCS operation. In any case, the primary energy use involved in producing H_2 from natural gas reforming (with or without CCS) and the production of H_2 from biomass do not show any statistically remarkable difference for all the transport options. Figure 4.13 presents the total greenhouse gases emitted with the different H_2 production routes and transport options. It shows clearly that these emissions are negative for the cases where H_2 is produced from renewable energy sources (nuclear, biomass energy and wind power), and injected into, transporting it through and then separated from the existing natural gas network. The negative values mean that total greenhouse gases are avoided in these cases. This trend is quite in line with literature (IEA, 2003; Bose, 2006; Ajah et al., 2007). Also total greenhouse gas emissions are negative in the case of producing H_2 using nuclear power and then using the existing natural gas network for transportation. It should be borne in mind that though there is a reduction in total greenhouse gas emission in the nuclear power chain, the primary energy use associated with this chain is comparatively high.

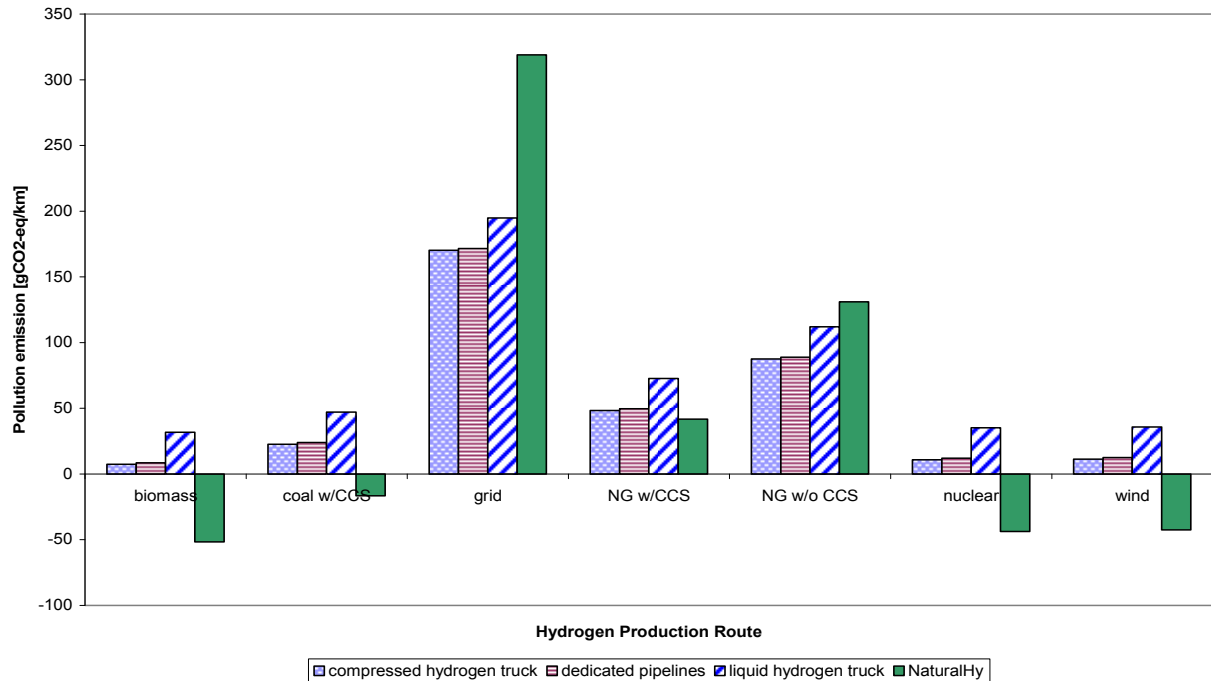


Figure 4.13: *WtW Total Greenhouse Gas Emissions for Various Hydrogen Production Routes and Transport Options*

In Figure 4.14, the primary energy use (coloured circles) vs. the GHG emissions (coloured rectangles) for the various hydrogen production routes and transport options are shown. It can be seen that though the nuclear route is relatively unfavourable in terms of primary energy use, it has one of the best performances in terms of GHG emissions. Obviously, the wind and biomass route have the best performances in terms of both primary energy use and GHG emissions while the producing hydrogen through the grid electricity is an unfavourable option in terms of both primary energy use and GHG emissions.

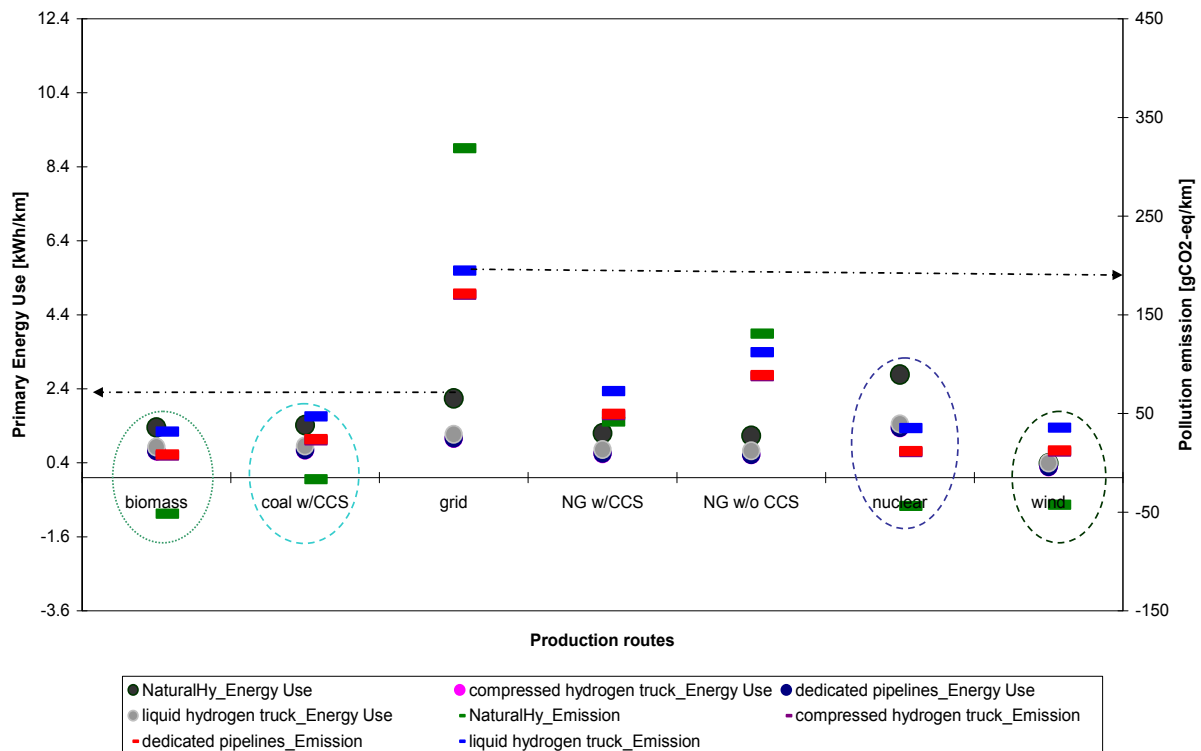


Figure 4.14: *Primary Energy Use vs WtW Total GHG Emissions for Various Hydrogen Production Routes and Transport Options.*

5. Overall Impacts of the Various EU Transport Scenarios: primary energy use and emissions.

The impact of injecting and transporting H₂ using the existing natural gas network on the primary energy use and total greenhouse gas emissions is determined by the choice of injection and extraction points, the way the H₂ is produced, the penetration rate of H₂ end-use applications, the spatial and temporal domain being considered, etc. In this section, taking the EU as the spatial domain, the impact (primary energy use and total greenhouse gas emissions) of injecting and transporting H₂ using the existing natural gas network on the wider EU is analysed.

Basic Assumptions:

- ◆ Large-scale use of H₂ as fuel is mainly anticipated for the transport sector. Since the transport sector is dominated by cars, the impact analysis is carried out assuming cars as the end-use application for H₂.
- ◆ The penetration of the HVs within EU member states is approximated using the penetration curve resulting from “high policy support” and “fast technology learning” as developed within the framework of the HyWays Project.
- ◆ The use of different sources of H₂ production has been assumed, thus leading to an array of H₂ production mix in the EU member states. The H₂ production mix within a given member states is approximated by the H₂ production mixes as established in the HyWays Project.
- ◆ Timescales considered are 2010 to 2050 with a time interval of 10 years

With the assumed penetration rate, the overall impact on primary energy use and total greenhouse gas emissions associated with producing H₂ (using a given production mix), injecting and transporting (through the existing natural gas network as well as other transport options) it to the consumers (for mobile end-use applications) is analysed in this Section.

Figure 5.1 reveals that the WtW primary energy use involved for the case of injecting and transporting hydrogen using the existing natural gas system is the highest compared to the other transport options. This can be explained by the primary energy required²² in conversion losses and in extracting H₂. All the transport options considered here show increasing primary energy use from 2020. This could be explained by a combination of projected non-hydrogen vehicles growth in Europe as well as the HV projections adapted from the HyWays Project. A peak primary energy use of approximately 13.7GJ is reached in year 2050 for the case of transporting H₂ using the existing natural gas network. This represents a primary energy use increment of approximately 80% (relative to the reference case) in year 2050.

However, as discussed in Appendix B.2, part of this gap may have been caused by the use of the HyWays diesel and gasoline data which considered only the operational aspect of lifecycle as the reference in comparing the NATURALHY data where more detailed lifecycle approach (operational as well as maintenance and decommissioning of the system) has been taken.

The implication of using the HyWays reference diesel and gasoline data is that a rather lower primary energy use for the reference scenario (because of not accounting for the maintenance and decommissioning aspects of the lifecycle) may have resulted. This bias may have contributed in widening the gap between the energy use of the NATURALHY option when compared with the HyWays diesel and gasoline reference scenario.

²² Primary energy use results from additional conversion losses, as more H₂ has to be produced per unit of H₂ and from separation of H₂ from the H₂/NG mixture. Primary energy use is also required for extra production and transport of feedstock needed to produce the extra H₂.

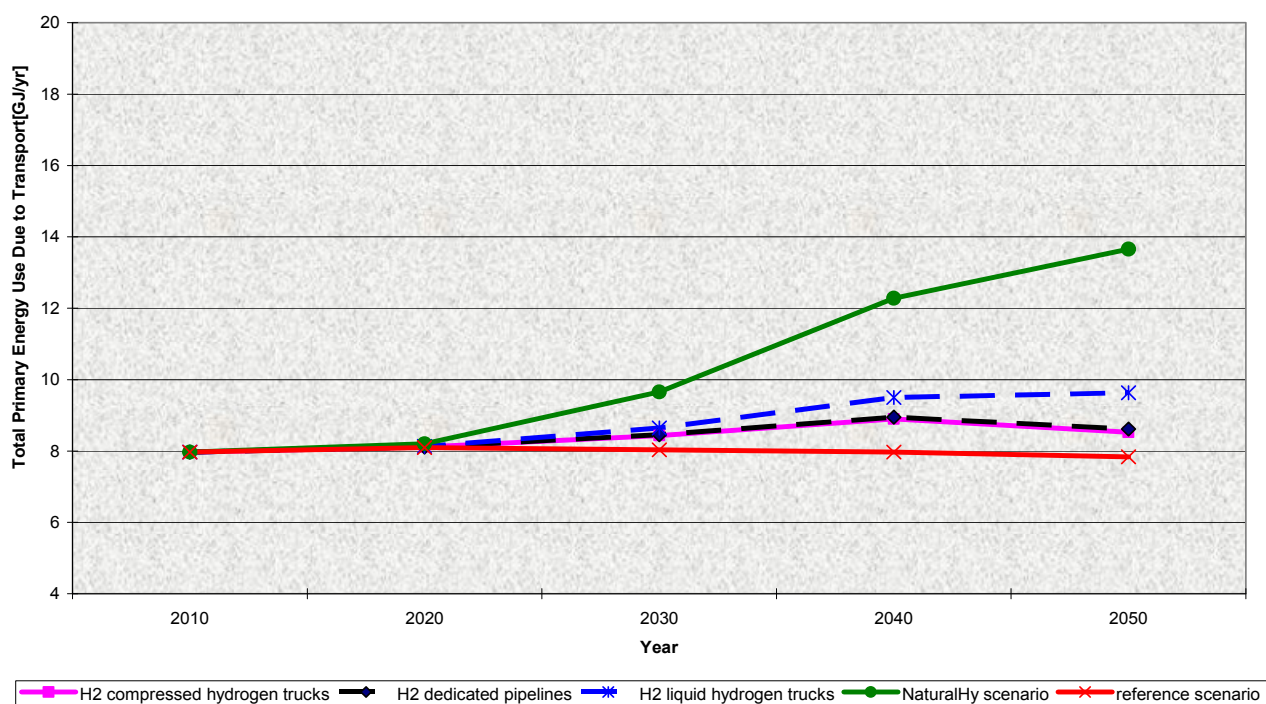


Figure 5.1: Total EU Primary Energy Use Assuming a Mix of All Hydrogen Production Routes

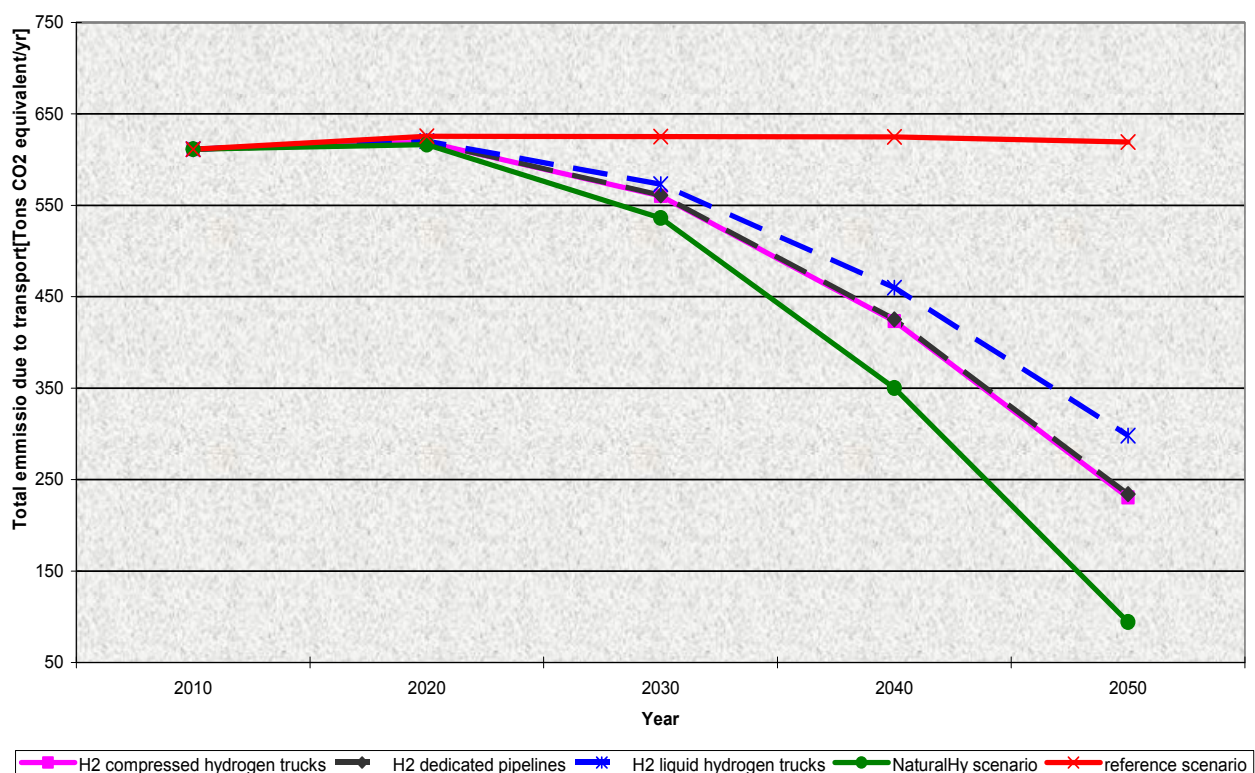


Figure 5.2: Total EU Greenhouse Gas Emissions Assuming a Mix of All Hydrogen Production Routes

From Figure 5.2, it can be seen that the use of the existing natural gas network for the transport of H₂ for mobile end-use applications (the NaturalHy scenario) amount to a WtW total greenhouse gas emissions reduction of approximately 85% (or approximately a reduction 525 million tonnes of equivalent

CO₂ per year by 2050) compared to the reference scenario. Transporting H₂ either through a dedicated pipeline or trucking it to the desired demand points in compressed form has slightly less potential for total greenhouse gas emissions reduction. Within the assumptions made in this analysis, a reduction of about 385 million tonnes of equivalent CO₂ per year by 2050 is possible using these two transport modes. This amounts to a total reduction of about 62% by year 2050 in comparison to the reference case. In the case of trucking in H₂ in liquid form to areas where they are needed, an approximate reduction of 321 million tonnes of equivalent CO₂ per year can be achieved by 2050 compared with the reference scenario. This is a total reduction of about 52% by year 2050.

Again, as discussed in Appendix B.2, the use of the HyWays diesel and gasoline data which considered only the operational aspect of lifecycle as the reference in comparing the NATURALHY data where more detailed lifecycle approach (operational as well as maintenance and decommissioning of the system) may have introduced some bias into the analysis.

The implication of using the HyWays reference diesel and gasoline data is that a rather lower greenhouse emission for the reference scenario (because of not accounting for the maintenance and decommissioning aspects of the lifecycle) may have resulted. If this bias is considered, then there may even be slightly higher emission reductions compared to the ones afore-mentioned.

5.1 Sensitivity of the Impact Analysis to Model Parameters

In this Section, the sensitivity of the impacts to the factors or parameters used in this analysis are determined, with major focus (necessitated by the various unresolved issues), however, on the production mix factor.

5.1.1 EU H₂ Production Mix

The results presented in the preceding Sections have been simulated with the base case EU H₂ production mix where the share of renewables of about one-third by 2050 was assumed (HyWays, 2007). The assumption in this production mix is that fossil fuel-based sources (natural gas and coal with CCS) and, after 2030, nuclear sources of H₂ production (see Appendix B), will play significant role. In order to check the effect of this assumed production mix on primary energy use and total greenhouse gas emissions, an alternative scenario- the “renewable pathway scenario”- has been synthesised (see also Appendix B).

Renewable pathway production mix Scenario

The relatively higher share enjoyed by the fossil-based sources (coal and natural gas) in the base case scenario is partly due to the understanding that CCS technology will be used to offset the environmental burdens of these routes. In reality though, there are still a lot of uncertainty about CCS technology. In the event that this technology is not implemented commercially, and assuming that (a) fossil fuel prices continue to rise; and (b) greenhouse gas emission legislation becomes stringent, then emphasis will be shifted from the fossil fuel sources to the renewable energy sources. Therefore, in the alternative production mix scenarios-the “renewable pathway scenario”- the share of H₂ production from renewable sources plays the major role (almost 90% of the mix), with the wind power making the largest contribution (62%) of the renewable energy supply. The share of nuclear power remains substantially lower (from one-third to one-tenth) compared to the base case while the shares of natural gas and coal are very low at about 2%.

5.1.2 Sensitivity of primary energy use to EU H₂ Production Mix

In this section, the sensitivity of primary energy use to the renewable pathway production mix scenario as explained in section 5.1.1 is analysed.

In general, compared to the base case, the “renewable pathway scenario” consumes less primary energy. This can be explained by the fact that, in this scenario, much of contributions to H₂ production have shifted substantially from natural gas and coal as well as biomass energy to wind power.

Transporting H₂ by other options (except by using the existing natural gas network) appears to consume less primary energy on a cumulative basis than the reference scenario (non-hydrogen vehicles). There is not a clear differentiation between transporting H₂ in a dedicated pipeline or trucking it in a compressed form. These two forms of transport, however, consume the least primary energy but the economic cost as well as total greenhouse gas emission is envisaged to be higher.

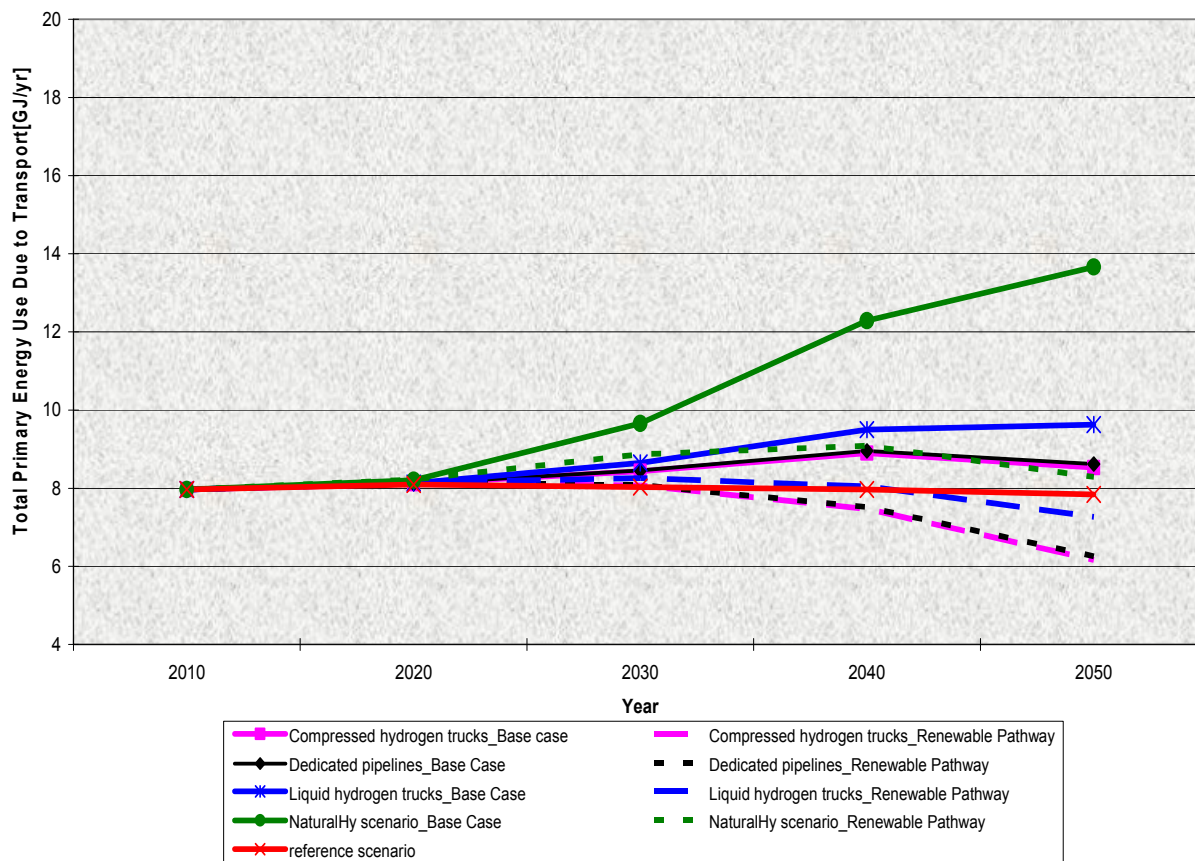


Figure 5.3: Sensitivity of Primary Energy Use to the “Renewable Pathway Scenario” Production Mix

From Figure 5.3, it can be deduced that for the “renewable pathway scenario”, a 61% reduction of the primary energy use, in comparison to the base case could be achieved in 2050 for the case of mixing and transporting H₂ using the existing natural gas network. This more or less, equals the primary energy use of the reference case. This can be explained by the fact that this production mix assumes that CCS will not play any significant role and that greater part of the mix will be from renewable sources. Therefore, the primary energy use associated with CCS and energy-intensive fossil fuel sources would have been eliminated, culminating to the drastic reduction in primary energy use.

5.1.3 Sensitivity of CO₂ Equivalent emissions to EU H₂ production mix

The sensitivity of the amount of greenhouse gas emission (in CO₂-equivalent) to the renewable pathway production mix as explained in section 5.1.1 is analysed in this section.

Also, compared to the base case, the “renewable pathway scenario” shows a higher potential for total greenhouse gas emissions reduction.

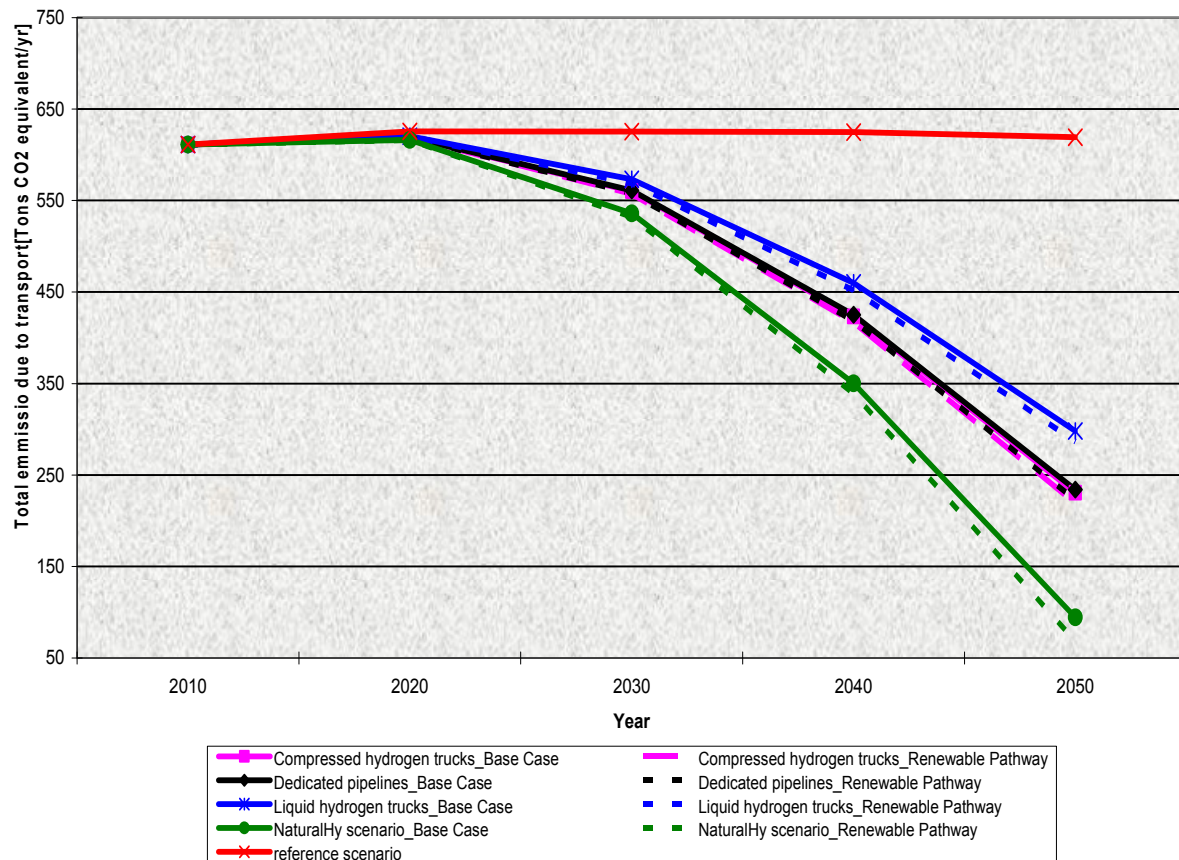


Figure 5.4: Sensitivity greenhouse gas due to transport to the “Renewable Path” production-mix

As shown in Figure 5.4, the use of the existing natural gas network for the transport of H_2 for mobile end-use applications results in a WtW total greenhouse gas emissions reduction of approximately 88% (about 551 million tonnes of equivalent CO_2 per year in absolute terms by 2050). This is a 3% improvement compared to the base case production mix reduction of 85% (or approximately a reduction 525 million tonnes of equivalent CO_2 per year by 2050). However, this is quite insignificant compared to the percentage reduction in the primary energy use of 61% associated with the same renewable portfolio.

One deduction can be made here, that the choice of the renewable mix can be tuned in such a way that one or both the primary energy use and GHG emissions can be reduced at the same time.

6. Conclusions and Outlook

6.1 Conclusions

An analysis of the possible impacts on primary energy use and total greenhouse gas emissions resulting from transporting H_2 using the natural gas network has been presented. The analysis is life cycle based since it not only considers the impacts of injecting H_2 into the natural gas network, its subsequent separation from the natural gas, and its eventual utilisation either as pure H_2 or as a mixture with natural gas but also those of the H_2 production routes. In this Section, conclusions are drawn based on the results of this analysis.

Injecting and transporting Hydrogen using the existing natural gas network:

It can be concluded that the medium pressure (16-40 bar) transport grid and not the high pressure (46-67 bar) transport grid is the optimal place for injecting hydrogen into the existing natural gas network. Therefore, the mixing and transporting of H_2 through the regional natural gas network (RTL side of the grid) for pure H_2 applications (fuel cells) seems the most attractive given the volume of H_2 to be injected and extracted, as well other technical issues. Injecting in the high pressure transport network means that hydrogen will end up everywhere in the national network or even to the corridor networks. Furthermore, large amount of hydrogen needs to be produced for significant volume fraction of hydrogen.

Extracting hydrogen from the H_2 /NG mixture:

For extracting H_2 from the H_2 /NG mixture: a) the pressure in hydrogen system should be greater than ambient pressure b) a difference in the partial pressure of gas that is separated between the permeate (product side - H_2) and its partial pressure in the retentate (feed side - H_2 /NG) of the membrane is a necessity to create the driving force for the membrane separation.

The contributions of these boundary conditions as well as the current structure and pressure levels in the natural gas grid require high volume fraction of H_2 to enable extraction at the low pressure (1-8 bar) side (distribution side) of the grid. A minimal volume fraction of hydrogen of the order of 25-30% is necessary to enable separation at this low pressure side of the grid. Otherwise separation ought to be executed in the same part of the network (RTL) where the H_2 is injected. This seriously limits the transport capability and given the fact that the optimal point for extraction of H_2 is the point as close to the end-user as possible, specific infrastructure may still need to be installed to transfer the H_2 from the extraction point to the end-user. This may after all negate the essence of the transport process.

Impacts on primary energy use and green house gas emission:

From the impact analysis conducted, it has been clearly shown that the primary energy use and total greenhouse gas emissions associated with the complete life cycle of H_2 production from different sources can vary substantially.

Generally, the mixing and transporting of H_2 using the natural gas network shows a tendency for higher primary energy use compared to the other H_2 transport options considered here.

On the other hand, mixing and transporting of H_2 using the natural gas network shows a potential in total greenhouse gas emissions reduction compared to the other H_2 transport options considered here. This reduction is largely due to the contribution of the un-extracted hydrogen in the H_2 /NG mixture which is used in stationary applications as “green gas”. Green gas only and only if the emission factor associated with H_2 production is less than the emission factor associated with the production of natural gas.

At lower extraction efficiency, more hydrogen will remain in the mix thus bettering the emission reduction for the routes with overall negative emission. In other words, effectively supplying H_2 fuelled vehicles with H_2 transported through the NG grid, we are also greening the natural gas grid because only part of the H_2 added to the grid can be extracted. This by-effect (the greening of the grid) causes a change in emissions. This suggests that the more we drive with H_2 from these routes the more

GHG emission we save. However, in view of the many unresolved issues (additional infrastructure, limited transport distance etc) it may be worthwhile to consider the option of *greening the gas* for stationary applications.

Sensitivity Analysis:

Sensitivity analysis conducted shows that total EU primary energy use and total greenhouse gas emissions reductions that may result from the use of H₂ produced and transported using the existing natural gas network, for transport applications are highly sensitive to the H₂ production mix within EU member states. Having a production mix that favors “low carbon” sources available in indigenous energy supply in the EU significantly reduces the total greenhouse gas emissions from transport in 2050.

6.2 Outlook

On a general level, mixing and transporting H₂ using the existing natural gas network for pure H₂ applications and/or for the “greening of natural gas” (which is based on the direct use of H₂ / NG mixtures) looks like an attractive concept. However, the concept is affected by some important efficiency, effectiveness and general issues, as discussed below.

Limitations in the H₂ Production Routes

The analysis shows that, on average, about 15-20 MW H₂ production capacity will be required and this seems to place a limitation on the options for hydrogen production. On one hand, for coal and biomass gasification, this might seem too small a scale. On the other hand, for biomass fermentation, this may be too large a scale. For natural gas reforming, this might be relatively too small scale for applying CCS and may still need some necessary infrastructure. And for electrolysis, it might not be regarded as a sensible use of a high grade fuel if H₂ is burnt for low grade heat or turned into electricity again for households or industry.

Fluctuations and Network Capacity

An issue that calls for attention is the fluctuations in the natural gas demand which invariably means that the amount of H₂ that can be effectively supplied to end users will also fluctuate. This raises the question of whether H₂ end users will be able to cope with this problem? One of the central aims of the NATURALHY project is to act as a catalyst for kick-starting and stimulating the transition towards a “hydrogen economy” by gradually building up H₂ demand through the use of the existing natural gas networks for mixing and transporting H₂. However, the limitations in the capacity of existing natural gas networks and the daily and seasonal fluctuations pose a serious concern with respect to flexibility of this transition. Finally the issue related to the improvement of separation or extraction efficiency need also to be resolved.

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Appendix A: Model Framework

In this section, all the model used in estimating the emission and primary energy use due to injection and extraction of H₂, as well as the total primary energy use and total greenhouse gas emission due to EU Transport Scenarios are described.

Let λ_{ijk} be well to wheel greenhouse gas emission of production route i in the total H₂ production mix in year j for scenario k and π_{ijk} be the Well-to-Wheel energy use of production route i in the total H₂ production mix in year j for scenario k ; and μ_{ijk} be the tank to wheel share of production route i in the total H₂ production mix in year j for scenario k and

$$i = \left\{ \begin{array}{l} \text{Coal w/CCS} \\ \text{NG w/o CCS} \\ \text{NG w/CCS} \\ \text{Nuclear} \\ \text{Grid} \\ \text{Wind} \\ \text{Biomass} \end{array} \right\}; \quad j = \left\{ \begin{array}{l} 2010 \\ 2020 \\ 2030 \\ 2040 \\ 2050 \end{array} \right\}; \quad k = \left\{ \begin{array}{l} \text{Refence Scenario} \\ \text{NaturalHY} \\ \text{Dedicated H2 Pipeline} \\ \text{Compressed H2 truck} \\ \text{Liquid H2 truck} \end{array} \right\}$$

$$w = \left\{ \begin{array}{l} \text{Feedstock production} \\ \text{Feedstock transport} \\ \text{Fuel (H2) production} \\ \text{Fuel (H2)transport \& Distribution} \\ \text{Refuelling \& Dispensing} \\ \text{End Use} \end{array} \right\}$$

The well to wheel greenhouse gas emission (PE) of production route i , in year j for scenario k , is a summation of all the greenhouse gas emitted during:

- Feedstock production
- Feedstock transport
- Fuel (H₂) production
- Fuel (H₂) transport and distribution
- Refuelling station energy use
- End use energy use(by the vehicles)

That is:

$$\lambda_{ijk} = \sum_{w=1}^W PE_{ijk} \quad \text{A1. 1}$$

Where w is a well to wheel activity and W is the totality of all the activities involved in producing and using H₂.

The greenhouse gas emission data used for each scenario (except for the emission due to the injection and extraction of the H₂) were all obtained from the NATURALHY Library of Results of work package 1 as well as the EUCAR-CONCAWE-JRC Well to wheel Report (EUCAR-CONCAWE, 2007).

Therefore the total greenhouse gas emission (expressed in equivalent CO₂) in year j for scenario k (η_{jk}) has been modeled as:

$$\eta_{jk} = \sum_{i=1}^I \mu_{ijk} \lambda_{ijk} \quad A1.2$$

Combining equations A1.1 and A1.2 we obtain:

$$\eta_{jk} = \sum_{i=1}^I \sum_{w=1}^W \mu_{ijk} PE_{ijk} \quad A1.3$$

In the same way, the well to wheel energy use (EU) of production route i , in year j for scenario k , is a summation of the all the greenhouse gas emitted during:

- Feedstock production
- Feedstock transport
- Fuel (H₂) production
- Fuel (H₂) transport and distribution
- Refuelling station energy use
- End use energy use(by the vehicles)

That is:

$$\pi_{ijk} = \sum_{w=1}^W EU_{ijk} \quad A1.4$$

Where w is a well to wheel activity and W is the totality of all the activities involved in producing and using H₂.

Also, the energy use data used for each production route and scenario (except for that due to the injection and extraction of the H₂) were all obtained from the NATURALHY Library of Results of work package 1 as well as the EUCAR-CONCAWE-JRC Well to wheel Report (EUCAR-CONCAWE-JRC, 2007).

And the Primary energy use due to transport averaged over the H₂ chain in year j and scenario k has been modelled as:

$$\delta_{jk} = \sum_{i=1}^I \mu_{ijk} \pi_{ijk} \quad A1.5$$

Combining equations A1.4 and A1.5 we obtain:

$$\delta_{jk} = \sum_{i=1}^I \sum_{w=1}^W \mu_{ijk} EU_{ijk} \quad A1.6$$

Estimating the Emission and Primary Energy Use Due to Injection and Extraction of H₂

The injection and extraction of H₂ into and out of the natural gas grid, was subsumed into the Fuel (H₂) transport and distribution activity of the well to wheel.

Since the injection and transportation of H₂ using the natural gas grid is relatively new, there is no documented data on both the energy use and emissions associated with it. Therefore, in the project, a calculation of the energy use for the injection and extraction process, based on thermodynamic models, was carried out (see Table C.2 for the snapshot of a sample MS Excel spreadsheet).

The primary energy use in MJ energy expended/ MJ H₂ is estimated as:

$$\frac{\text{Actual Power Consumption}}{\text{H}_2 \text{ Flow rate} * \text{H}_2 \text{ Lower Heating Value}} \quad A1.7$$

And Actual Power consumption is modelled as:

$$\frac{\text{Theoretical Power Consumption}}{\text{Efficiency}} \quad \text{A1. 8}$$

And the theoretical power consumption is modelled as:

$$P_1 V \left(\frac{\varepsilon}{\varepsilon - 1} \right) \left\{ \left(\frac{P_2}{P_1} \right)^{\left(\frac{\varepsilon - 1}{\varepsilon} \right)} - 1 \right\} \quad \text{A1. 9}$$

Where P_1 , P_2 are the inlet (suction) and outlet (discharge) pressure respectively, V is the volume throughput and ε is the adiabatic exponent. Thus the theoretical power requirement is equal to the product of the adiabatic head and the volumetric gas flow rate at the inlet of the compressor.

Also, the greenhouse gas emission arising from the injection and extraction of the H_2 could be estimated depending on whether the turbine for the compressor uses electricity(el) or natural gas (th). For each, the emission has been modeled as follows:

Let the :

Ratio of the energy use for injection or extraction to the total electricity or natural gas production be R and the CO_2 equivalent emission due to electricity or natural gas production be C . Then :

$$\text{Equivalent } CO_2 \text{ emission due to injection or extraction} = \frac{R * C}{\text{efficiency}} \quad \text{A1. 10}$$

Also, in the Greenhouse gas emission and primary energy use estimation, the fact that not all the H_2 injected is totally extracted is taken into account. Therefore, total energy use due to injection and extraction is a summation of the energy due to injection, energy due extraction, energy used in producing the non-extracted H_2 minus the compensation for the natural gas replaced by the non-extracted H_2 (in energy use equivalent).

Total primary Energy use (TPEU) Due to EU Transport Scenarios:

Let:

Number of vehicle in year j , scenario $k = \alpha_{jk}$

Total annual mileage of vehicles in year j , scenario $k = \beta_{jk}$

H_2 Penetration in year j scenario $k = \gamma_{jk}$

Share of gasoline PISI hybrid in the share of non- H_2 vehicles in year j , scenario $k = \chi_{jk}$

WTW energy use gasoline PISI hybrid in year j , scenario k [in MJ/km] = ϕ_{jk}

WTW CO_2 -emission gasoline PISI hybrid [g CO_2 eq/km], year j , scenario $k = \tau_{jk}$

Share of Diesel DISI hybrid in the share of non- H_2 vehicles in year j , scenario $k = \zeta_{jk}$

WTW energy use diesel DISI hybrid DPF in year j , scenario k [in MJ/km] = ν_{jk}

WTW CO_2 -emission gasoline PISI hybrid in year j scenario k [g CO_2 eq/km] = ρ_{jk}

Then total primary energy use (TPEU) due to transport in year j , scenario k is modelled as:

$$TPEU_{jk} = \alpha_{jk} \beta_{jk} \left(\gamma_{jk} \delta_{jk} + (1 - \gamma_{jk}) \{ \chi_{jk} \phi_{jk} + \zeta_{jk} \nu_{jk} \} \right) \quad \text{A1. 11}$$

Total greenhouse gas emission (TPE) due to transport in year j , scenario k is modelled as:

$$TPE_{jk} = \alpha_{jk} \beta_{jk} \left(\gamma_{jk} \eta_{jk} + (1 - \gamma_{jk}) \{ \chi_{jk} \tau_{jk} + \zeta_{jk} \rho_{jk} \} \right) \quad \text{A1. 12}$$

Appendix B: Model Parameters

B.1 Parameters

1. Number of vehicles (non H₂) in the EU member states. The Eurostat vehicle stock data of 2007 was used see table B.1.
2. Projected penetration of HV along a considered temporal scale. The HyWays Penetration scenario was used (see last row of Table B. 1)
3. Average car mileage in the EU member states. 2000km/vehicle/year was taken, also based on HyWays results
4. Reference Vehicles (Gasoline and Diesel)

Gasoline

- TTW share gasoline PISI hybrid [gasoline hybrid/E total non-H₂]: 0.6
- TTW energy use gasoline PISI hybrid [MJ/km] :1.62
- WTW CO₂-emission gasoline PISI hybrid [gCO₂eq/km] : 141
- WTW energy use gasoline PISI hybrid [MJ/km] : 1.84

Diesel

- TTW end use share diesel DISI hybrid DPF [diesel hybrid/total non-H₂]: 0.4
- TTW energy use diesel DISI hybrid DPF [MJ/km] : 1.46
- WTW CO₂-emission diesel DISI hybrid DPF [gCO₂eq/km] : 129
- WTW energy use diesel DISI hybrid DPF [MJ/km] : 1.69

Table B. 1: *Parameters for the Base Line Simulation*

Parameter	Unit	2010	2020	2030	2040	2050
Non H ₂ Vehicles (nHV) ²³	x10 ⁶ [-]	224	227	226	224	220
HV fuel economy	[kWh/km]	0.2325	0.2325	0.2325	0.2325	0.2325
Fuel economy gasoline PISI hybrid	[kWh/km]	0.45	0.45	0.45	0.45	0.45
Share (ratio) of gasoline PISI hybrid	[-]	0.60	0.60	0.60	0.60	0.60
Fuel economy diesel DISI hybrid	[kWh/km]	0.40	0.40	0.40	0.40	0.40
Share (ratio) of diesel DISI hybrid	[-]	0.40	0.40	0.40	0.40	0.40
Averaged travelled distance	[km/yr]	20000	20000	20000	20000	20000
HV cumulative penetration	[%]	0	1.2	11.9	35.9	69.4

A peak is reached in year 2020 and then a downward trend sets in. The number of vehicles [millions] presented in Table B. 1 is for the EU-25 plus (Liechtenstein, Iceland, Norway, Switzerland)

²³ The total number of vehicles for the EU25+Iceland+Liechtenstein+Norway+Switzerland was obtained from the (Euro-Stat Vehicle Stock). However, an earlier report (Well-to-wheels analysis of future automotive fuels and power-trains in the European context WTW report) have projected the vehicle growth for six EU states- Denmark, France, Greece, Italy, Netherlands and Norway. Therefore, the ratio of these two categories of stock was taken and used in the correction of the projection to EU25+Iceland+Liechtenstein+Norway+Switzerland.

B.2 Validation of the NATURALHY set of data

The basic data for the analysis were developed in-house in WP1 of the NATURALHY project based on the lifecycle of the various considered chains. In this section, these data are compared with HyWays data (Herman and Weeda, 2006) for selected equivalent chains. In Figure B. 1 and Figure B. 2 respectively, the comparisons of the primary energy use data and the greenhouse gas emissions data used in both the NATURALHY and HyWays are presented. The naming scheme of each of the chain is meant to reflect the source (HyWays or NATURALHY), then the feedstock from which H₂ is produced (natural gas-NG or biomass), the production technology (SMR or gasification etc), and the transport option (trucking H₂ in as compressed gaseous form-CGH₂ or as liquefied hydrogen -LH₂). For instance the scheme *NaturalHy_NG/SMR/CCS/CGH₂* means that the data set is from NATURALHY, where H₂ is produced from NG using the steam methane reforming process with the associated carbon capture and storage and the produced H₂ is transported as compressed gaseous H₂ using a truck.

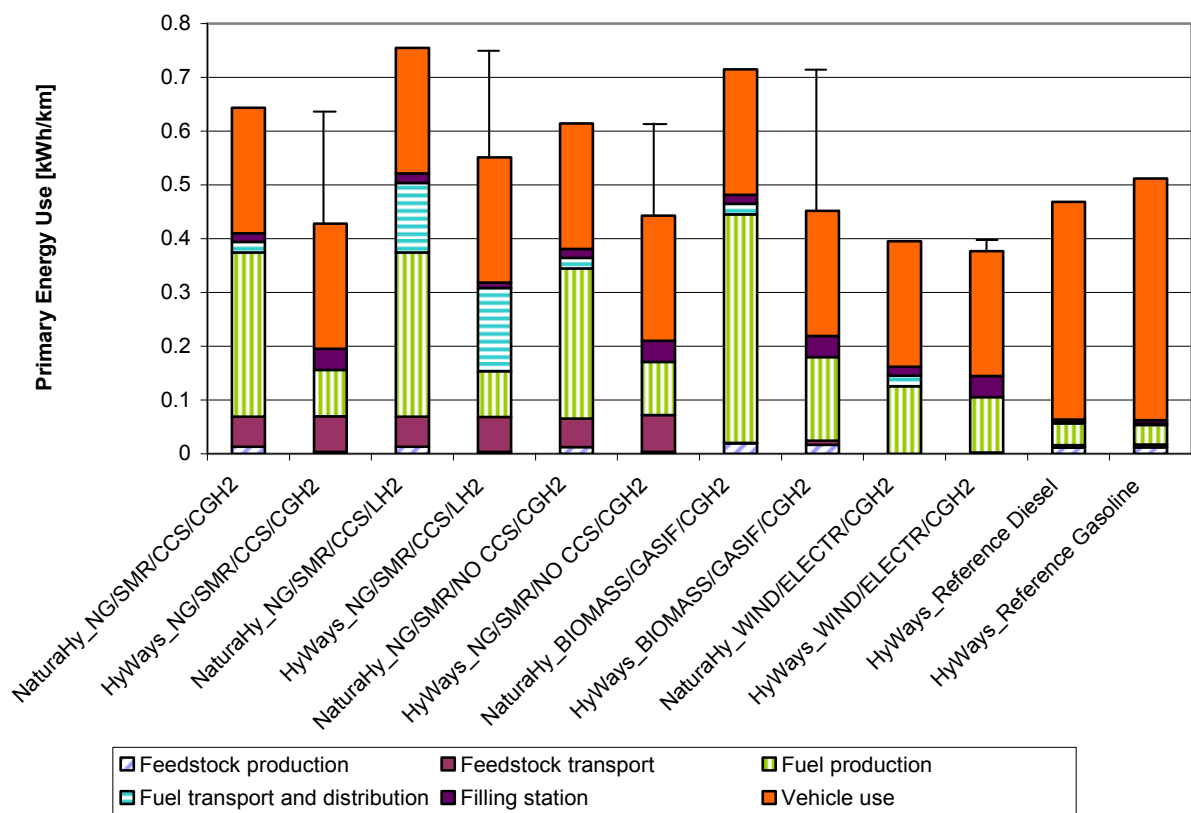


Figure B. 1: Comparison of Primary Energy Use Data of NaturalHy and HyWays

Figure B. 1 shows that in general, the primary energy use for the NATURALHY chains are higher than that of the HyWays. This can be explained by the rather more detailed lifecycle approach taken in the NATURALHY case as compared to the HyWays case. In the HyWays, only the operational aspect of the system is considered while in the NATURALHY case, not only the operational but also the energy use in the maintenance as well as the decommissioning of the system has been taken into account. For the reference diesel and gasoline energy sources, the HyWays data as presented above have been adapted for the analysis as no detailed study of the reference diesel and gasoline chain was executed in the NATURALHY. The implication of using the HyWays reference diesel and gasoline data is that a rather lower primary energy use (because of not accounting for the maintenance and decommissioning aspects of the lifecycle) may have resulted. This may widen the gap between the energy use as ob-

tained from the NATURALHY data when compared with that obtained using the Hyways reference diesel and gasoline case.

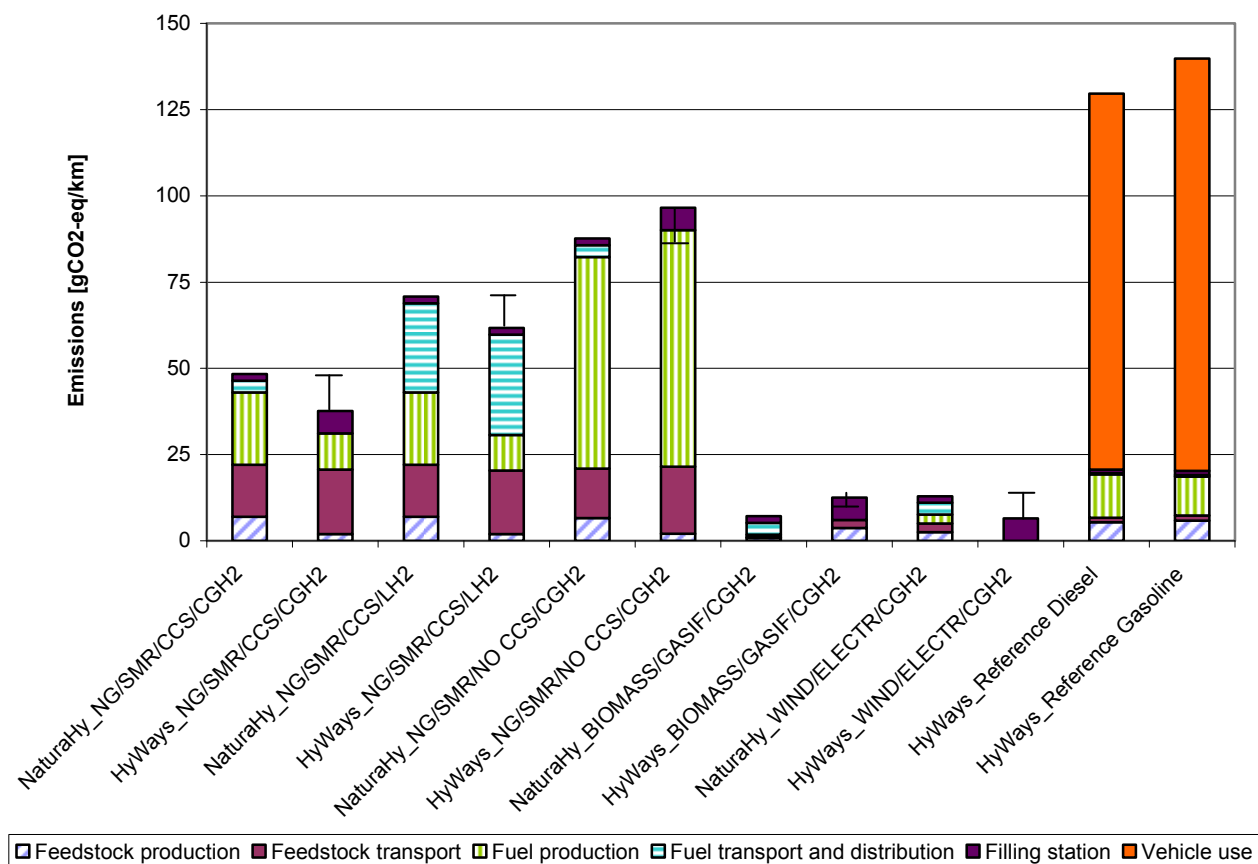


Figure B. 2: Comparison of Greenhouse Gas Emissions Data of NaturalHy and HyWays

Also Figure B. 2 shows that the greenhouse gas emissions data for the NATURALHY case are in some cases higher than that of the HyWays data. This can also be explained by the rather more detailed life cycle approach taken in the NATURALHY case as compared to the HyWays case.

Again, the implication of using the greenhouse gas emissions data from the HyWays reference case is that a rather lower emission from the reference diesel and gasoline (because of not accounting for the maintenance and decommissioning aspects of the lifecycle) may have resulted.

Generally, the greenhouse gas emissions data between the HyWays and the NATURALHY have less deviation compared to the primary energy use. The higher deviations in the primary energy use as obtained from the NATURALHY in comparison to the greenhouse emissions could be explained by the fact that though maintenance and decommissioning exercise seem to be more energy intensive, they generally are low in greenhouse gas emissions.

B.3 EU H₂ Production Mix Scenarios

The production of H₂ can be achieved through many renewable routes such as biomass, wind etc. Among the EU member states, the various routes that can potentially play a role in the renewable production of H₂ have been synthesized and the mix and shares of these routes at different temporal scales quantified (HyWays, 2007). In Table B. 2, and Table B. 3, a projection of the percentage shares of these routes in H₂ production is given for both the base and the alternative scenarios.

Base Case: Fossil intensive path scenario

The assumption in this production mix scenario is that fossil based sources- natural gas, coal with CCS and after 2030, nuclear sources of H₂ production (Table B. 2), will play significant role in the H₂ production mix. In this scenario, the fossil based sources-coal and natural gas (mainly equipped with CCS technology) takes up about 67% of the production mix in 2030. This decreases to about 40% in 2050.

Table B. 2: *Projected EU H₂ Production Mix- “Base Case Scenario”*

Production Route	Year				
	2010	2020	2030	2040	2050
Projected EU H₂-Production Mix [%]					
By-Product	0	31	4	2	1
Coal +Natural Gas	0	34	66	47	39
Nuclear	0	0	1	7	10
Grid	0	0	0	0	0
Wind	0	0	1	3	15
Biomass	0	34	29	41	29
Solar HT	0	0	0	0	7

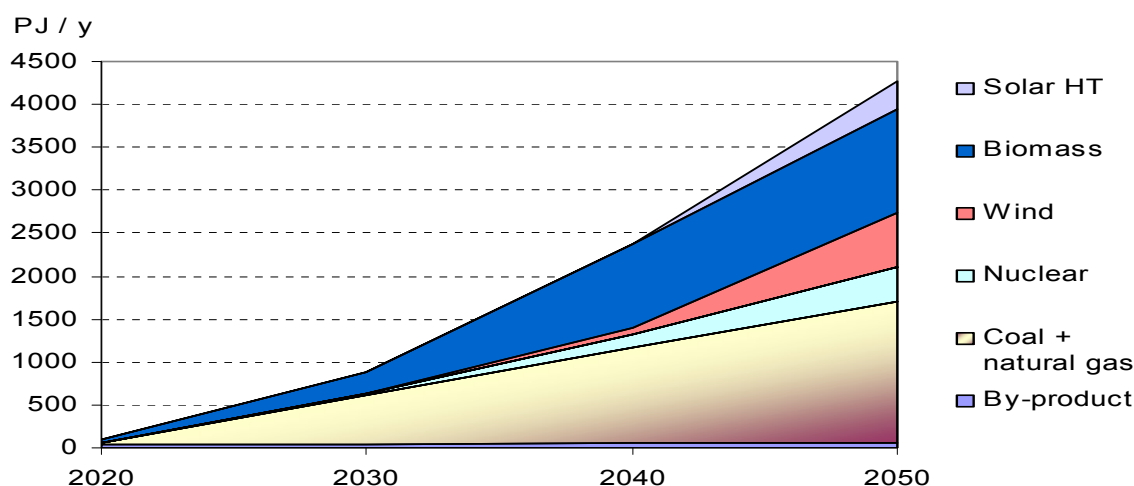


Figure B. 3: *EU H₂ Production Mix “Base Case Scenario” [Adapted from HyWays]*

Alternative Scenario: *Renewable pathway Scenario*

The relatively higher share enjoyed by the fossil-based sources (coal and natural gas) in the base case is partly based on the understanding that CCS technology will be used to offset the environmental burdens of these routes. In reality though, there are still a lot of uncertain clouds hovering around the CCS technology. In the event that the technology do not make it to the full blow commercial stage, and assuming that: 1) fossil fuel prices continues to rise 2) the emission legislations become stringent, then emphasis will be shifted from the fossil sources to the renewable pathways. Therefore, in the al-

ternative production mix scenarios-the renewable pathway, the share of the H₂ production from renewable sources plays the major role (almost 90% of the mix), with the wind energy taking the lion share (62%) of the renewables. The share of nuclear remains substantially lower (from one-third to one-tenth) compared to the base case while the shares of natural gas and coal stands very low at about 2%.

Table B. 3: *Projected EU H₂ Production Mix- “Renewable Pathway Scenario”*

Production Route	Year				
	2010	2020	2030	2040	2050
	Projected EU H₂-Production Mix [%]				
By-Product	0	9	5	2	1
Coal +Natural Gas	0	23	23	9	2
Nuclear	0	1	11	10	10
Grid	0	0	0	0	0
Wind	0	9	13	42	62
Biomass	0	59	36	26	18
Solar HT	0	0	12	11	8

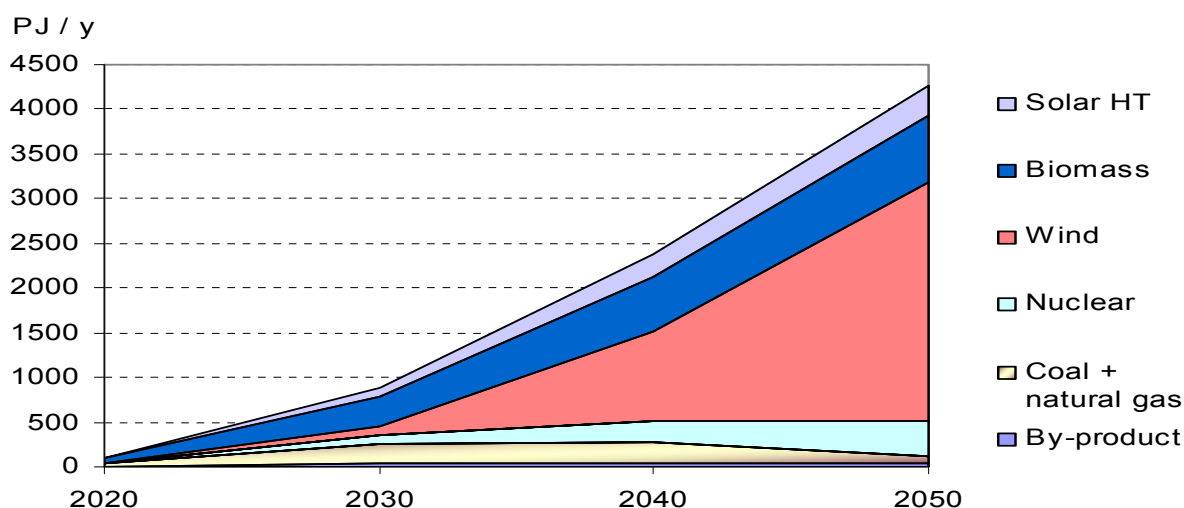


Figure B. 4: *EU H₂ Production Mix “Renewable Pathway Scenario” [Adapted from HyWays]*

Appendix C : Chain Selection and Description

The possible well to wheels chain for H₂ has been selected based on the feedstock for producing H₂ as well as the application and/or involvement of Carbon Capture and Storage (CCS) in the production process. Based on the feedstock the following chains have been described in this section: natural gas without CCS chain; natural gas with CCS chain; coal with CCS chain; biomass chain; wind chain; nuclear chain. Each of these chains basically differs in how the feedstock is processed and transported to the H₂ production plant. For the purpose of the analysis, the H₂ produced can be transported through any of the four modes or routes (NATURALHY-mixing & transporting H₂ using the existing NG grid, dedicated pipeline, trucking it as CGH₂ and trucking it as LH₂). These transport routes are shown as dotted green (NATURALHY), pink (dedicated pipeline), aqua (trucking in as compressed H₂) and blue (trucking in as liquid H₂). Depending on the transport mode or route, the H₂ could be worked up to suit the transport mode to be applied. For instance, in transporting the produced H₂ by truck (trucking it as CGH₂), H₂ is compressed to about 200 bar before being transported to the filling stations by a dedicated tube trailer, which is also a diesel-fuelled vehicle.

Natural Gas without CCS chain

The Natural gas is assumed to be extracted and processed in Russia and transported into the EU gas network (at an average distance of 4000 km distance) and then further distributed to production plants (500 km distance, on average). A SMR located at that point produces H₂, which becomes subsequently distributed to the filling stations. At the SMR plant, the produced CO₂ are not captured and sequestered. The H₂ produced through SMR technology (at an output pressure of at least 30 bar) can be transported to the filling station using any of the four H₂ transport modes or routes (NATURALHY, dedicated pipeline, trucking it as CGH₂ and trucking it as LH₂).

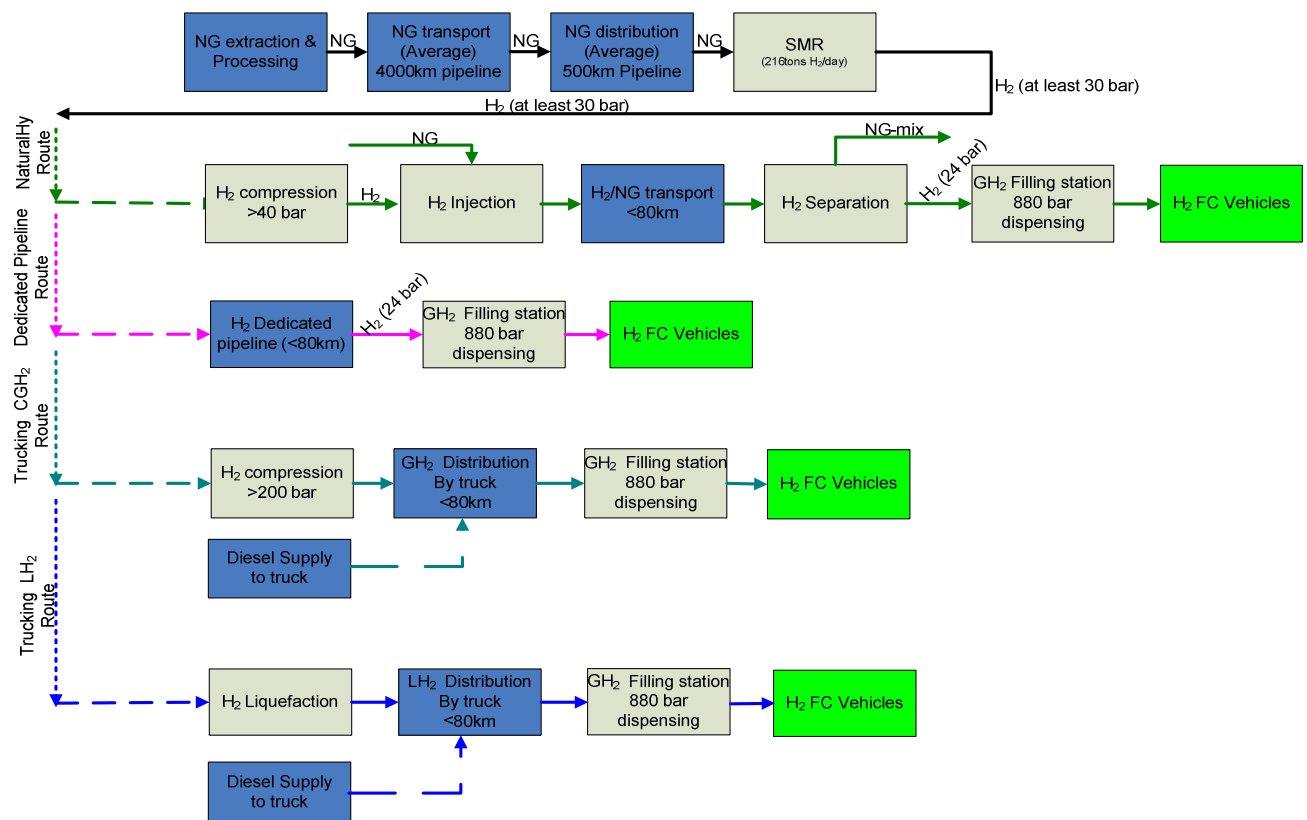


Figure C. 1: Modeled NG without CCS Chain

For the *NATURALHY transport option*, the H_2 (available at 30 bar) is further compressed to a pressure well above 40 bar (to create an effective driving force for successful injection into the RTL grid). The compressed H_2 at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80km, before being separated (see chapter 3). This is considered sufficient for distribution through the RTL-grid over a distance of up to 80 km, without additional compression energy. After the separation, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

For the case of *dedicated pipelines*, the pressure of the H_2 produced at the SMR of about 30 bar is considered sufficient for distribution through the RTL-grid over a distance of up to 80km, without additional compression energy. Making for transmission pressure loss, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

And for the case of transporting H_2 through the *trucking of the compressed H_2* to the refueling station, the H_2 from the SMR at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H_2 can then be transported by truck via the road in high pressure cylinders. There is also energy included here (in the form of diesel) for the operation of the road truck. The truck delivers the compressed H_2 to the filling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

Finally, for the case of transporting H_2 through the *trucking of liquefied H_2* to the refueling station, the H_2 from the SMR at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. Though H_2 delivered in liquid form to the refuelling station may have to be vaporised and compressed if the vehicles require compressed H_2 , this operation is subsumed into the operation of the filling station as this process is less energy-intensive than compression of gaseous H_2 - the liquid can be pumped to the required pressure before vaporization. The vaporized and compressed H_2 is then dispensed to H_2 vehicles.

Natural Gas with CCS chain

The Natural gas is assumed to be extracted and processed²⁴ in Russia and transported²⁵ into the EU gas network (at an average distance of 4000 km distance) and then further distributed to production plants (500 km distance, on average). A Steam Methane Reformer (SMR) located at that point produces H₂, which becomes subsequently distributed to the filling stations using any of the four transport modes or routes.

Also at the SMR plant, the produced CO₂ are separated²⁶, transported (50 km distance, on average) and subsequently stored in old gas/oil fields.

The H₂ produced through SMR technology (at an output pressure of at least 30 bar) can be transported to the filling station using any of the four H₂ transport modes or routes (NATURALHY, dedicated pipeline, trucking it as CGH₂ and trucking it as LH₂) as discussed below.

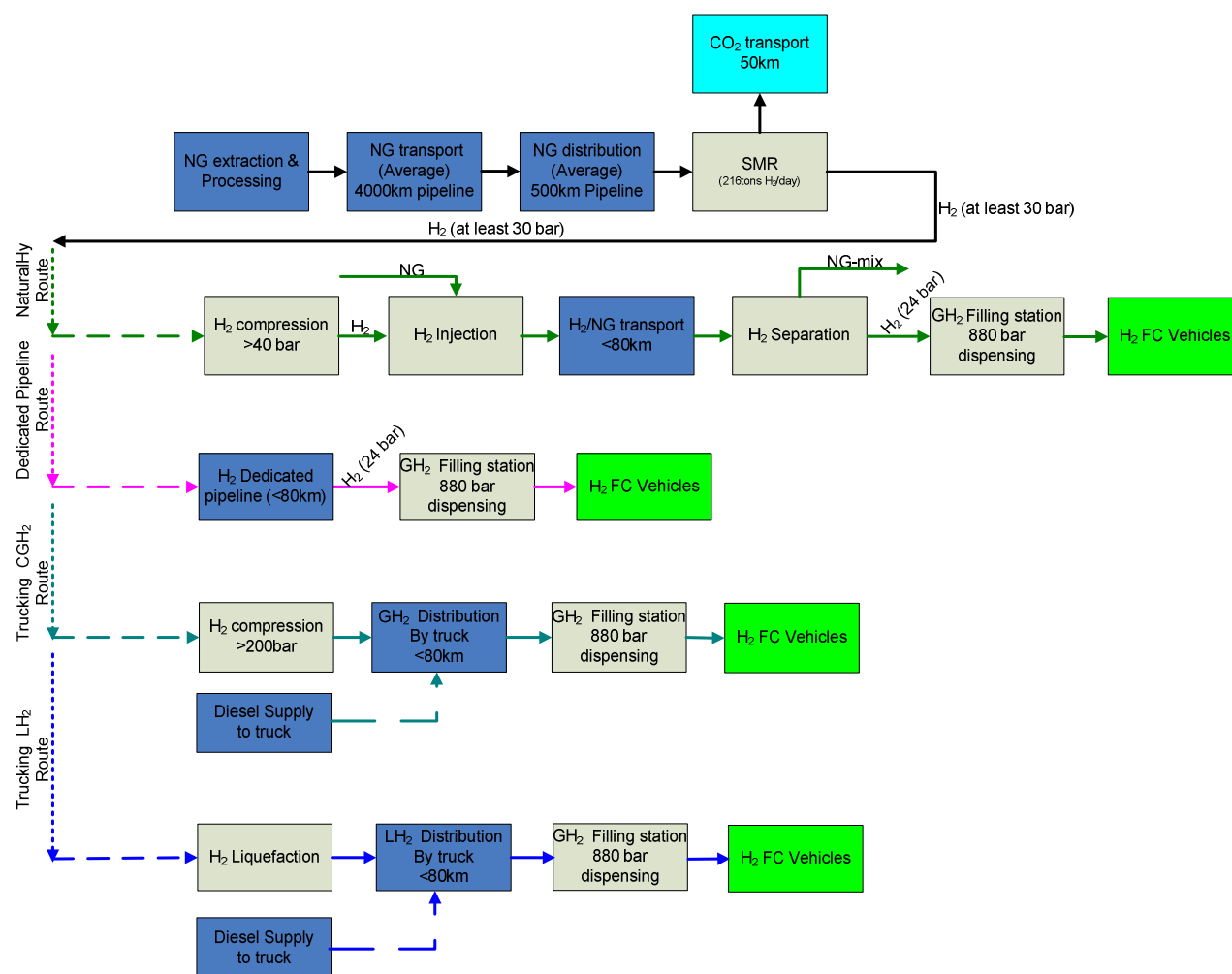


Figure C. 2: Modelled NG with CCS Chain

For the *NATURALHY* transport option, the H₂ (available at 30 bar) is further compressed to a pressure well above 40 bar (to create an effective driving force for successful injection into the RTL grid). The

²⁴ To be used, natural gas (NG) 1422 tons/hr must be extracted, processed. Processing is required because heavier hydrocarbons and contaminants such as H₂S must be removed. The extraction and processing processes require electricity and some additional heat, which can be provided by burning some NG in a heating plant.

²⁵ NG is imported through the EU natural gas mix transport pipeline. Thereafter it is distributed via the national, regional and local natural gas high-pressure pipeline grids.

²⁶ CO₂ capture is carried out via scrubbing process using AMDEA (Activated Methyl Di-ethanol Amine) units.

compressed H_2 at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80km, before being separated (see Section 3). After the separation, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

For the case of *dedicated pipelines*, the pressure of the H_2 produced at the SMR of about 30 bar is considered sufficient for distribution through the RTL-grid over a distance of up to 80km, without additional compression energy. Making for transmission pressure loss, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

And for the case of transporting H_2 through the *trucking of the compressed H_2* to the refueling station, the H_2 from the SMR at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H_2 can then be transported by truck via the road in high pressure cylinders. There is also energy included here (in the form of diesel) for the operation of the road truck. The truck delivers the compressed H_2 to the filling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

Finally, for the case of transporting H_2 through the *trucking of liquefied H_2* to the refueling station, the H_2 from the SMR at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. Though H_2 delivered in liquid form to the refuelling station may have to be vaporised and compressed if the vehicles require compressed H_2 , this operation is subsumed into the operation of the filling station as this process is less energy-intensive than compression of gaseous H_2 - the liquid can be pumped to the required pressure before vaporization. The vaporized and compressed H_2 is then dispensed to H_2 vehicles.

Coal with CCS chain

In this H₂ chain, coal is extracted (mined and processed) within the EU member states. Therefore, the characteristics of the hard coal used are derived from the EU hard coal mix. It is also assumed that a coal mine methane mitigation method (CMM) is applied during the mining and processing. The extracted coal is transported (at an average distance of 50 km) via truck to the coal gasification plant (313 tons H₂/day capacity), where H₂ is produced through the gasification of the hard coal with the associated CO₂ capture and sequestration. The pressure of the H₂ produced through coal gasification is also assumed to be at least 30 bar. Again, the produced H₂ can be transported to the filling station using any of the four H₂ transport modes or routes (NaturalHy, dedicated pipeline, trucking it as CGH₂ and trucking it as LH₂).

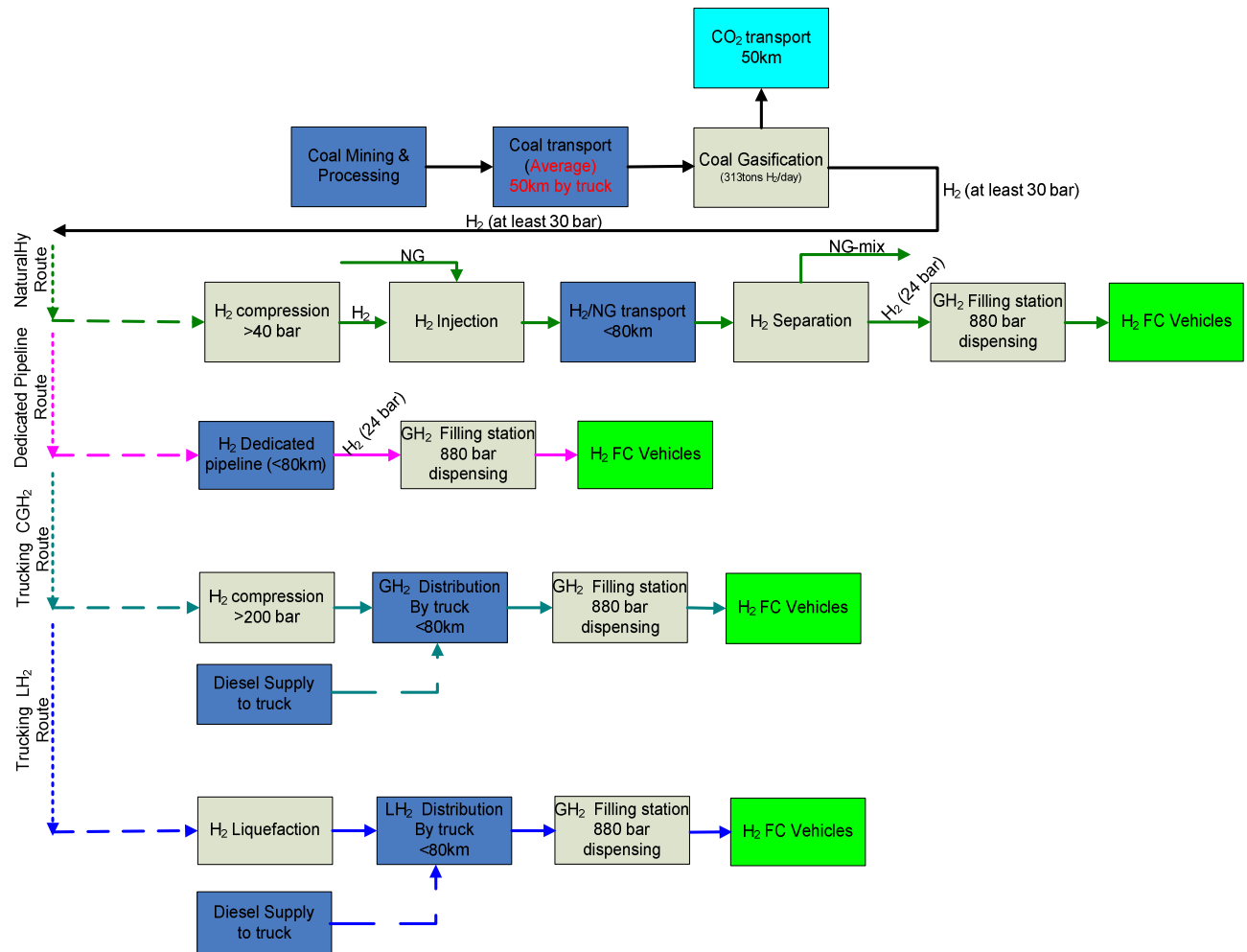


Figure C. 3: Modeled Coal with CCS Chain

For the *NATURALHY* transport option, the H₂ produced through coal gasification (available at 30 bar) is further compressed to a pressure well above 40 bar (to create an effective driving force for successful injection into the RTL grid). The compressed H₂ at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80km, before being separated (see chapter 3). After the separation, H₂ at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H₂ vehicles.

For the case of *dedicated pipelines*, the pressure of the H₂ produced at the coal gasification plant of about 30 bar is considered sufficient for distribution through the RTL-grid over a distance of up to 80km, without additional compression energy. Making for transmission pressure loss, H₂ at a pressure

of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H₂ vehicles.

And for the case of transporting H₂ through the *trucking of the compressed H₂* to the refueling station, the H₂ from the coal gasification plant at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H₂ can then be transported by truck via the road in high pressure cylinders. There is also energy included here (in the form of diesel) for the operation of the road truck. The truck delivers the compressed H₂ to the filling station for further compression of up to 880 bar before being dispensed to the H₂ vehicles.

Finally, for the case of transporting H₂ through the *trucking of liquefied H₂* to the refueling station, the H₂ from the coal gasification plant at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. Though H₂ delivered in liquid form to the refuelling station may have to be vaporised and compressed if the vehicles require compressed H₂ this operation is subsumed into the operation of the filling station as this process is less energy-intensive than compression of gaseous H₂ - the liquid can be pumped to the required pressure before vaporization. The vaporized and compressed H₂ is then dispensed to H₂ vehicles.

Biomass Energy Chain

In this chain, forest residue²⁷ is collected and chipped. The chipping machine is assumed to be run by diesel. The wood chip is assumed to be collected from the surroundings of the gasifier (approximately 50 km) and transported by diesel-fuelled trucks and then converted to H₂ in a relative small-scale gasifier (7.2tonsH₂/day). The pressure of the H₂ produced through biomass (wood) gasification is also assumed to be at least 30 bar. The H₂ can be transported in four different modes or routes (NaturalHy, Dedicated pipeline, Trucking it as CGH₂ and Trucking it as LH₂) as discussed below.

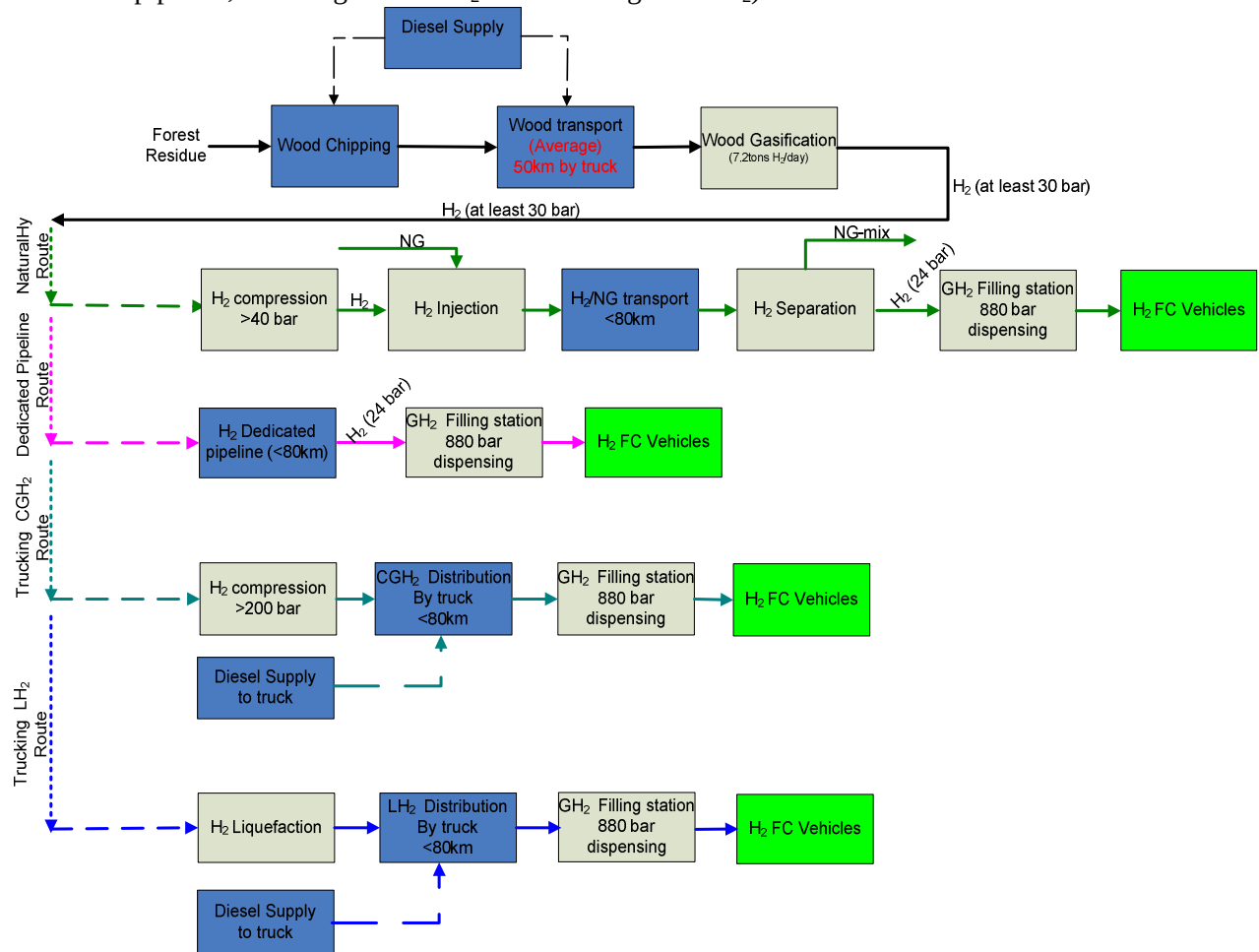


Figure C. 4: Modelled Biomass Energy Chain

For the *NATURALHY* transport option, the H₂ produced through biomass (wood) gasification (available at 30 bar) is further compressed to a pressure well above 40 bar (to create an effective driving force for successful injection into the RTL grid). The compressed H₂ at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80km, before being separated (see chapter 3). After the separation, H₂ at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H₂ vehicles.

For the case of *dedicated pipelines*, the pressure of the H₂ produced at the biomass (wood) gasification plant of about 30 bar is considered sufficient for distribution through the RTL grid over a distance of up to 80km, without additional compression energy. Making for transmission pressure loss, H₂ at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H₂ vehicles.

²⁷ Wood residues are generated in the process of timber harvesting and of thinning after reforestation, in the timber processing industry (carpentry shops, furniture producers etc.) and as wood waste e.g. from used furniture. The wood is chipped at the source and then transported to the gasification plant by truck.

And for the case of transporting H_2 through the *trucking of the compressed H_2* to the refueling station, the H_2 from the biomass (wood) gasification plant at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H_2 can then be transported by truck via the road in high pressure cylinders. There is also energy included here (in the form of diesel) for the operation of the road truck. The truck delivers the compressed H_2 to the filling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

Finally, for the case of transporting H_2 through the *trucking of liquefied H_2* to the refueling station, the H_2 from the biomass (wood) gasification plant at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. Though H_2 delivered in liquid form to the filling station may have to be vaporized and compressed if the vehicles require compressed H_2 , this operation is subsumed into the operation of the filling station as this process is less energy-intensive than compression of gaseous H_2 - the liquid can be pumped to the required pressure before vaporization. The vaporized and compressed H_2 is then dispensed to H_2 vehicles.

Wind Energy Chain

In this chain wind harvested using the wind turbine generates electricity generated. The electricity is distributed (using the medium voltage grid; 10-20kV) to an electrolysis plant where H_2 in a relative small-scale (4.3tons H_2 /day) is produced in the alkaline atmospheric electrolyser. The pressure of the H_2 produced at the electrolyser is also assumed to be at least 30 bar. Also, the gaseous H_2 produced by this plant feed the CGH $_2$ filling station using any of the four H_2 transport modes or routes (NATURALHY, dedicated pipeline, trucking it as CGH $_2$ and trucking it as LH $_2$) as discussed below.

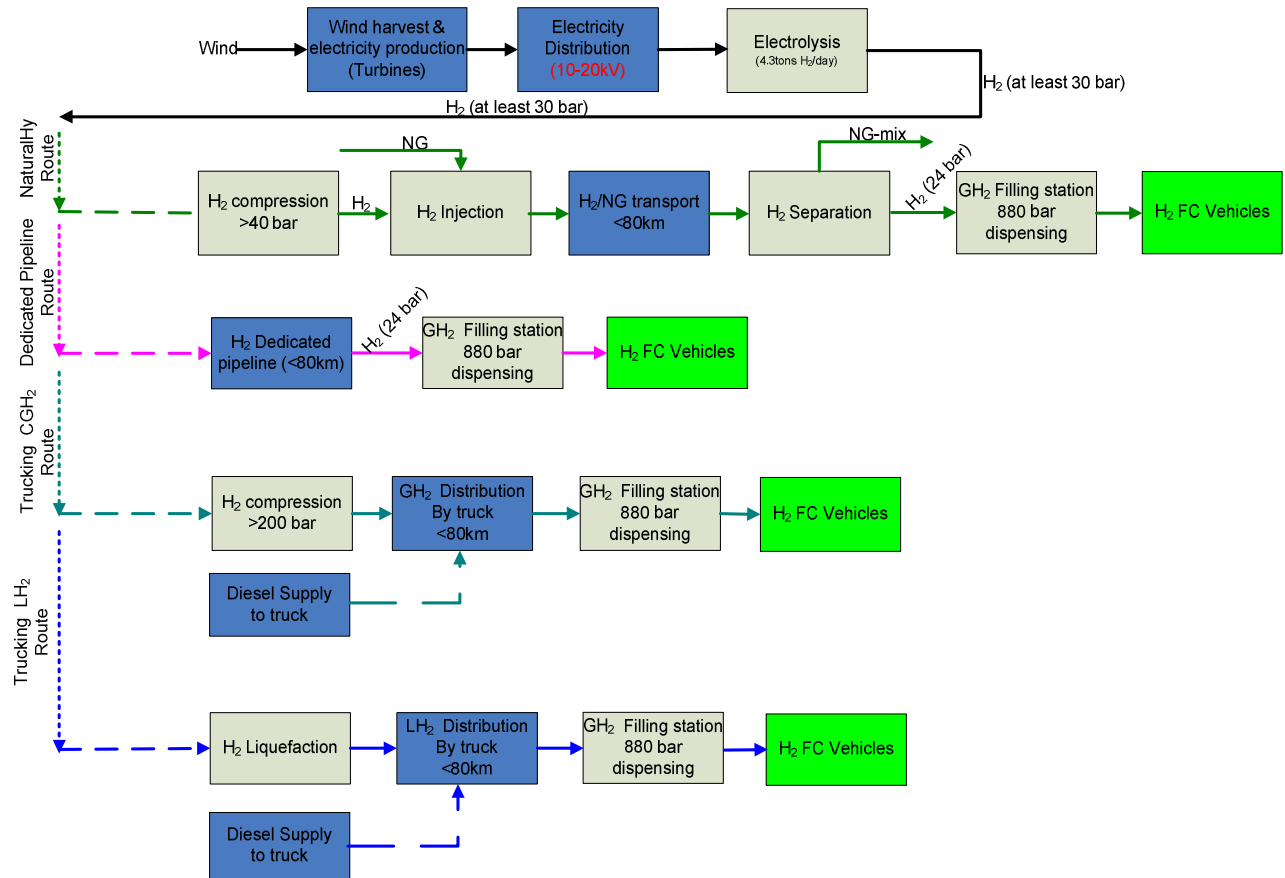


Figure C. 5: *Modelled Wind Energy Chain*

For the *NATURALHY* transport option, the H_2 produced by the electrolyser (available at 30 bar) is further compressed to a pressure well above 40 bar (to create an effective driving force for successful injection into the RTL grid). The compressed H_2 at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80km, before being separated (see chapter 3). After the separation, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

For the case of *dedicated pipelines*, the pressure of the H_2 produced at the electrolyser of about 30 bar is considered sufficient for distribution through the RTL-grid over a distance of up to 80km, without additional compression energy. Making for transmission pressure loss, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

And for the case of transporting H_2 through the *trucking of the compressed H_2* to the refueling station, the H_2 from the electrolyser at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H_2 can then be transported by truck via the road in high pressure cylinders. There is also energy included here (in the form of diesel) for the operation of the road truck. The truck deliv-

ers the compressed H_2 to the filling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

Finally, for the case of transporting H_2 through the *trucking of liquefied H_2* to the refueling station, the H_2 from the electrolyser at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. Though H_2 delivered in liquid form to the refuelling station may have to be vaporized and compressed if the vehicles require compressed H_2 , this operation is subsumed into the operation of the filling station as this process is less energy-intensive than compression of gaseous H_2 - the liquid can be pumped to the required pressure before vaporization. The vaporized and compressed H_2 is then dispensed to H_2 vehicles.

Nuclear Power Chain

In this the nuclear fuel extracted and processed is used as input in a Nuclear power plant (capacity of 1450 MW, an efficiency of 34% and a lifetime of 30 years) for producing electricity. The electricity is distributed (using the medium voltage grid; 10-20kV) to an electrolysis plant where H_2 (626 tons H_2 /day) is produced in a series of alkaline atmospheric electrolyzers.

Also, the gaseous H_2 produced by this plant feed the CGH₂ filling station using any of the four H_2 transport modes or routes (NATURALHY, dedicated pipeline, trucking it as CGH₂ and trucking it as LH₂).

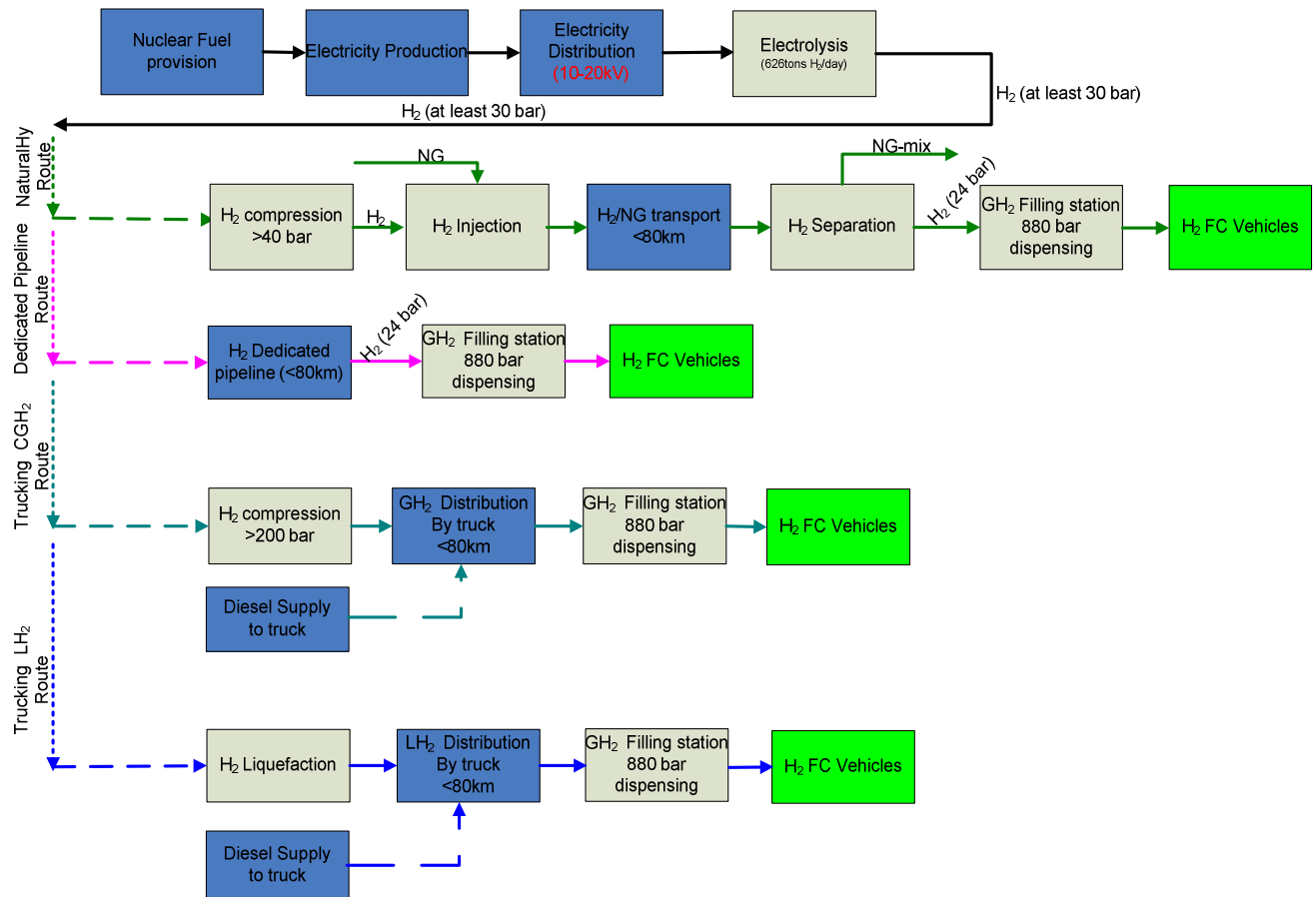


Figure C. 6: *Modelled Nuclear Power Chain*

For the *NATURALHY* transport option, the H_2 produced by the electrolyser (available at 30 bar) is further compressed to a pressure well above 40 bar (to create an effective driving force for successful injection into the RTL grid). The compressed H_2 at a pressure in excess of 40 bar is then injected into the RTL grid and thus transported over a distance of up to 80km, before being separated (see chapter 3). After the separation, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

For the case of *dedicated pipelines*, the pressure of the H_2 produced at the electrolyser of about 30 bar is considered sufficient for distribution through the RTL-grid over a distance of up to 80km, without additional compression energy. Making for transmission pressure loss, H_2 at a pressure of between 20-24 bar is routed to the refilling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

And for the case of transporting H_2 through the *trucking of the compressed H_2* to the refueling station, the H_2 from the electrolyser at a pressure of about 30 bar is further compressed to about 200 bar. The compressed gaseous H_2 can then be transported by truck via the road in high pressure cylinders. There

is also energy included here (in the form of diesel) for the operation of the road truck. The truck delivers the compressed H_2 to the filling station for further compression of up to 880 bar before being dispensed to the H_2 vehicles.

Finally, for the case of transporting H_2 through the *trucking of liquefied H_2* to the refueling station, the H_2 from the electrolyser at a pressure of about 30 bar is liquefied and transported by truck also via road to the filling station. Though H_2 delivered in liquid form to the refuelling station may have to be vaporized and compressed if the vehicles require compressed H_2 , this operation is subsumed into the operation of the filling station as this process is less energy-intensive than compression of gaseous H_2 - the liquid can be pumped to the required pressure before vaporization. The vaporized and compressed H_2 is then dispensed to H_2 vehicles.

Table C. 1: Primary Energy Use (kWh/km) For All Chain Types and Delivery Options

Delivery Option	WtW Chain	Chain Type						
		Coal w/CCS	NG w/o CCS	NG w/CCS	Nuclear	Grid	Wind	Biomass
NaturalHy	Feedstock production	0.130	0.021	0.022	1.388	0.966	-0.007	0.037
	Feedstock transport	-0.031	0.090	0.096	-0.026	0.011	-0.279	-0.029
	H ₂ production	0.933	0.633	0.693	1.037	0.810	0.286	0.966
	H ₂ transport and distribution	0.104	0.104	0.104	0.104	0.104	0.104	0.104
	Filling station	0.045	0.045	0.045	0.045	0.045	0.045	0.045
	End use	0.233	0.233	0.233	0.233	0.233	0.233	0.233
	Total	1.416	1.128	1.195	2.782	2.169	0.383	1.357
Dedicated Pipeline	Feedstock production	0.061	0.012	0.013	0.614	0.428	0.000	0.019
	Feedstock transport	0.000	0.053	0.056	0.002	0.005	-0.109	0.001
	H ₂ production	0.411	0.279	0.305	0.456	0.356	0.126	0.425
	H ₂ transport and distribution	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Filling station	0.045	0.045	0.045	0.045	0.045	0.045	0.045
	End use	0.233	0.233	0.233	0.233	0.233	0.233	0.233
	Total	0.750	0.623	0.653	1.351	1.068	0.295	0.724
CGH ₂ Truck	Feedstock production	0.061	0.012	0.013	0.614	0.428	0.000	0.019
	Feedstock transport	0.000	0.053	0.056	0.002	0.005	-0.109	0.001
	H ₂ production	0.411	0.279	0.305	0.456	0.356	0.126	0.425
	H ₂ transport and distribution	0.020	0.020	0.020	0.020	0.020	0.020	0.020
	Filling station	0.017	0.017	0.017	0.017	0.017	0.017	0.017
	End use	0.233	0.233	0.233	0.233	0.233	0.233	0.233
	Total	0.741	0.614	0.644	1.342	1.059	0.286	0.715
LH ₂ Truck	Feedstock production	0.061	0.012	0.013	0.614	0.428	0.000	0.019
	Feedstock transport	0.000	0.053	0.056	0.002	0.005	-0.109	0.001
	H ₂ production	0.411	0.279	0.305	0.456	0.356	0.126	0.425
	H ₂ transport and distribution	0.130	0.130	0.130	0.130	0.130	0.130	0.130
	Filling station	0.018	0.018	0.018	0.018	0.018	0.018	0.018
	End use	0.233	0.233	0.233	0.233	0.233	0.233	0.233
	Total	0.852	0.725	0.755	1.453	1.170	0.397	0.826

Table C. 3: *Net Compensations of the primary energy and emissions for the NATURALHY transport option*

	Primary Energy Use [MJ expended/MJ H ₂ produced]					
	Coal w/CCS	NGw/oCCS	NGw/CCS	Nuclear	Grid	Biomass
WtF_extra H ₂ produced	2.57	1.88	2.04	5.85	4.30	2.43
WtF_Compensation_NG_Replaced	-0.16	-0.16	-0.16	-0.16	-0.16	-0.16
Net	2.41	1.72	1.88	5.69	4.14	2.27

	GHG Emissions [gCO ₂ eq/MJ H ₂ produced]					
	Coal w/CCS	NGw/oCCS	NGw/CCS	Nuclear	Grid	Biomass
WtF_extra H ₂ produced	26.25	124.64	65.14	8.18	249.90	2.92
WtF_Compensation_NG_Replaced	-99.80	-99.80	-99.80	-99.80	-99.80	-99.80
Net	-73.55	24.84	-34.66	-91.62	150.10	-96.88

	Primary Energy Use [kWh/Km]					
	Coal w/CCS	NGw/oCCS	NGw/CCS	Nuclear	Grid	Biomass
WtF_extra H ₂ produced	0.60	0.44	0.48	1.36	1.00	0.57
WtF_Compensation_NG_Replaced	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
Net	0.56	0.40	0.44	1.33	0.97	0.53

	GHG Emissions [gCO ₂ eq/km]					
	Coal w/CCS	NGw/oCCS	NGw/CCS	Nuclear	Grid	Biomass
WtF_extra H ₂ produced	22.05	104.70	54.72	6.87	209.92	2.45
WtF_Compensation_NG_Replaced	-83.83	-83.83	-83.83	-83.83	-83.83	-83.83
Net	-61.78	20.86	-29.12	-76.96	126.08	-81.38

SEPARATION USING MEMBRANE ONLY (theoretical maximum size)

Flow 1

Main flow	61,500 [Nm3/h]
Pressure main flow	40 [bar]
hydrogen content	10%
metahne content	90%
hydrogen flow, main	6,150 [Nm3/h]
Std hydrogen density	0.085 [kg/m3]
Std methane density	0.68 [kg/m3]
Cp hydrogen	14.199 [kJ/(kg*K)]
Cp methane	2.1816 [kJ/(kg*K)]
Massa hydrogen in flow	523 [kg/h]
Massa methane in flow	37,638 [kg/h]
Reqd temperature increase	40 C
Heat reqd for hydrogen	296,901 [kJ]
Heat reqd for metahne	3,284,442 [kJ]
Total heat required	3,581,344 [kJ]
equivalent to	995 [kW/h/h]

Flow 2

Membrane recovery	77%
Pure hydrogen flow	4,736 [Nm3/h]
Energy in hydrogen	14,188 [kW/h/h]
Hydrogen pressure	1 [bar]
Desired output pressure	24 [bar]

Flow 3

Hydrogen in retentate	1,415 [Nm3/h]
Methane in tail gas	55,350 [Nm3/h]
Total flow 3	56,765 [Nm3/h]
Pressure retentate	40 [bar]
hydrogen content	2.5%

Compression of flow 3

Isentropic H2 Compressor

1 stage, no cooling

Flow	4,736 [Nm3/h]	E-flow	13,416 [kW/h/h]
Inlet pressure	1.31541667 [Nm3/s]		
Compression factor	1 [-]		
Actual flow	1.31541667 [m3/s]		
Outlet pressure	24 [bar]		
Isentropic Coeff	1.41 [-]		
Mechanic efficiency	0.96 [-]	0.95	
Compressor efficiency	96% [-]	0.758	
Total efficiency	96% [-]		
Isentropic druk	5 [bar]		
Required power	716 [kW]		
Electric efficiency	1 [-]		
Reqd electric power	716 [kW/h/h]	0.93	

Energy ratio compression	0.0534 [kWh/kWh_H2]
Energy ratio heating	0.0701 [kWh/kWh_H2]
Total Required power	1,711 [kW/h/h]
Energy ratio total	0.1235 [kWh/kWh_H2]

Inflow

CH4					
H2					
Mixed flow					
	[% vol]	Volume [Nm3/h]	Std. Dens [kg/m3]	Mass [kg/h]	Energy [kWh/kg]
	0%	0	0.68	0	0
	100%	4,736	0.085	403	13,416
	100%	4,736	0.085	403	13,416

P [bar]	Hydrogen	F @ 0C
1	1	1
17	17	1.0109
30	30	1.0192
40	40	29.0124
50	50	1.0320
60	60	19.0295
70	70	50.0231
80	80	1.0518
100	100	1.0650
120	120	1.0782
150	150	1.0980
200	200	1.1320
250	250	1.1660
300	300	1.2010
350	350	1.2360
400	400	1.2720
450	450	1.3080
500	500	1.3440
550	550	1.3800
600	600	1.4160
650	650	1.4525
700	700	1.4890
750	750	1.5245
800	800	1.5600
850	850	1.5960
900	900	1.6320
950	950	1.6670
1000	1000	1.7020

Figure C. 7: Snapshot of Developed MS Excel Thermodynamic model for the H₂ Separation Process (Target Case)