Integrated design for demonstration of efficient liquefaction of hydrogen (IDEALHY)

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)

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Publishable summary

Hydrogen is expected to be an important future clean transport fuel. In the absence of a pipeline network, liquid hydrogen is the most effective way to supply larger refuelling stations in the medium term. However, at present hydrogen liquefaction is expensive, energy-intensive and limited in capacity.

The IDEALHY project investigates the different steps in the liquefaction process in detail, using innovations and greater integration in an effort to reduce specific energy consumption by 50 % compared to the state of the art, and simultaneously minimise the total costs (both CAPEX and OPEX).

This report defines the pathways for hydrogen generation, conditioning, liquefaction, distribution and end use which will be analysed and compared in the life cycle and economic assessment.

These pathways start with the initial source of energy that provides the hydrogen. For the analysis, they are divided into three steps:

- From the energy source via hydrogen generation and conditioning up to entry into the liquefaction plant
- Hydrogen liquefaction
- From the liquefaction plant to utilisation, including transportation by ship (applicable to some pathways) and road tanker, storage at the refuelling station, pressurisation and gasification and refuelling, and finally utilisation in fuel cell powered buses and cars.

The benchmark cases are petrol and diesel, being the standard fuels for road vehicles today. They are introduced in “Baseline Results Report” of this project (Ref. 1). The Baseline Results Report also outlines the life cycle assessment methodology to be employed.

As an alternative to liquid transportation of hydrogen (and further benchmark), gaseous distribution by road trailers is considered as well.

Two types of pathways can be distinguished with respect to size and energy source:

- Liquefaction at intermediate scale (about 50 tonnes per day) when hydrogen generation and liquefaction take place in the demand country or region;
- Liquefaction at large scale (about 500 tonnes per day) when the resource region is distant from the demand country/region, and hydrogen transportation by ship is required.

Energy sources considered for hydrogen generation for the former are surplus wind electricity, and reformation of compressed[1] and of liquefied natural gas (with and without carbon capture and storage; CCS). For the latter, brown coal and compressed natural gas are investigated (including CCS in both cases) as well as concentrated solar power.

Key words

Pathways for hydrogen generation, liquefaction, distribution and usage

Life cycle assessment of road passenger transport

[1] In this report, the term “compressed natural gas” stands for gaseous natural gas transported in pipelines.

Abbreviations

CAPEX	CAPital EXpenditure
GH_2	(compressed) Gaseous Hydrogen
LCA	Life Cycle Assessment
LCEA	Life Cycle and Economic Assessment
LH_2	Liquid Hydrogen / Liquefied Hydrogen
LNG	Liquefied Natural Gas
NG	Natural Gas
OPEX	OPerational EXpenditure
tpd	tonnes per day
WP	Work Package

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1 Introduction

1.1 IDEALHY Project Objectives

Hydrogen is expected to be an important future clean transport fuel. In the absence of a pipeline network, liquid hydrogen is the most effective way to supply larger refuelling stations in the medium term. However, at present hydrogen liquefaction is expensive, energy-intensive and limited in capacity.

The IDEALHY project investigates the different steps in the liquefaction process in detail, using innovations and greater integration in an effort to reduce specific energy consumption by 50 % compared to the state of the art, and simultaneously minimise the total costs (both CAPEX and OPEX). The project brings together world experts to develop a generic process design and plan for a large-scale demonstration of efficient hydrogen liquefaction in the range of up to 200 tonnes per day (tpd). This represents a substantial scale-up compared to existing and proposed plants worldwide.

1.2 Work Package Scope and Objectives

This report is compiled as part of work package 3 (WP3) "Whole Chain Assessment" of IDEALHY. This WP consists of three tasks:

- Scenario Development for liquid hydrogen (LH_2)
- Safety
- Life Cycle and Economic Assessment (LCEA)

The overall objective of WP3 is to determine the impact of supplying and distributing significant volumes of liquid hydrogen to a refuelling infrastructure. Starting point was the collection of existing scenarios of liquefied hydrogen energy chains developed in the European study for hydrogen vehicles (Ref. 2).

1.3 Deliverable Objective in relation to the WP

The objectives of the LCEA of the IDEALHY project are to evaluate and compare the environmental (primary energy and prominent greenhouse gas emissions) and economic costs and benefits of all relevant pathways for the supply and utilisation of (liquid) hydrogen. Details of the methodology applied and the steps to be taken are provided in the Baseline Results Report (Ref. 1). The Baseline Results Report also outlines the spreadsheet workbooks to be employed for the LCEA work.

In order to carry out the LCEA work, the specific hydrogen pathways had first to be defined. It particular, it was necessary to determine the individual elements along the chain of processes in sufficient detail with respect to the production of hydrogen, its liquefaction, tanker transport, re-gasification at the filling station, and its utilisation by cars and buses.

The decision-making was mainly based on the Scenario Development task of WP3. This report documents the outcomes of this procedure.

The final concept of the demonstration plant to be established towards the end of the IDEALHY project and to be realised in a subsequent project will not only be based on the trade-off between capital and operational expenditure on the one hand and the efficiency of the process on the other hand. The impact on overall energy use and on CO_2 emissions along the pathways will also be an input on decisions in this area.

1.4 Scope of the Deliverable Report and approach

The key question to be answered by the LCEA work of the IDEALHY project is whether liquid hydrogen supply can be competitive with the benchmark cases in terms of greenhouse gas emissions and costs along the well-to-wheel chain.

The benchmarks are conventional petrol/diesel on the one hand and gaseous hydrogen supply on the other. Compressed gaseous hydrogen distribution today and in the future is considered in parallel with the LH_2 cases in the following chapter.

Petrol and diesel are the standard fuels for private cars and public buses at present and can be expected to remain so for a considerable period into the future. They are discussed in Baseline Results Report of this project (Ref. 1) and illustrated in Figure 1.

A crucial point with respect to the competitiveness of LH_2 is the level of efficiency that "advanced hydrogen liquefaction" as being developed in this project can accomplish. However, the feedstock that constitutes the basis for hydrogen generation and the transportation effort along the pathway can also be expected to play a prominent role.

The time frame considered in selecting specific pathways was roughly the period 2018 – 2030. In 2018, the demonstration plant based on the results of the IDEALHY project could be operational. By 2030, commercial plants can be expected to be in service. On the other hand, hydrogen pipeline networks are rather unlikely to become reality within this time frame. Therefore, hydrogen transportation by pipeline does not fall into the scope of the IDEALHY project LCEA work.

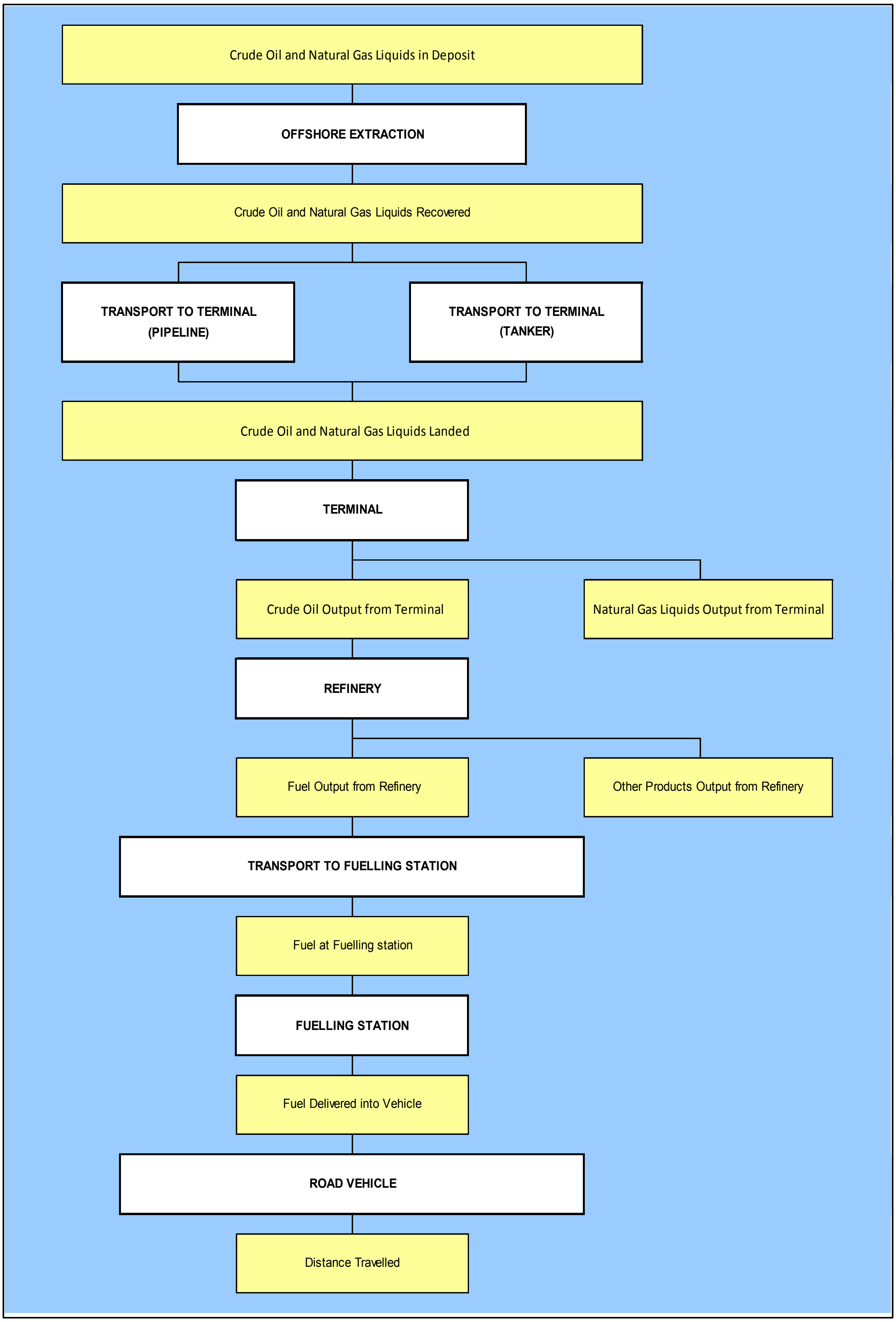

Figure 1: Baseline Case consisting of current road passenger transport fuelled by petrol or diesel derived from crude oil (from Ref. 1).

2 Hydrogen Pathways Selected

The hydrogen pathways, starting with the initial source of energy for providing hydrogen, are divided into three steps for the analysis:

- From the energy source via hydrogen generation and conditioning up to entry into the liquefaction plant
- Hydrogen liquefaction
- From the liquefaction plant to utilisation, including transportation by ship (applicable to some pathways) and road tanker, storage at the refuelling station, pressurisation and gasification and refuelling, and finally utilisation in fuel cell powered buses and cars.

As an alternative to liquid transportation of hydrogen and as a benchmark, gaseous distribution by road trailers is considered, as mentioned. See section 2.3 for detail.

Two types of pathways are distinguished with respect to size of the liquefaction plant and energy origin:

- Liquefaction at intermediate scale, about 50 tpd, when hydrogen generation and liquefaction take place in the demand country or region;
- Liquefaction at large scale, about 500 tpd, when the resource region is rather far from demand the country/region and hydrogen transportation by ship is foreseen.

The plant sizes of about 50 tpd for demand country liquefaction and 500 tpd for resource country liquefaction are based on the assumption that 50 tpd is the maximum size for a vacuum insulated cold box (for accomplishing temperatures below 80 K) that can be transported by road (Ref. 3). While other components of a liquefaction plant can be assembled on the site, the cold box must be delivered in one piece. For the 500 tpd liquefaction plant it is assumed that 10 separate cold boxes are used. A final figure for the maximum size for of the cold box will be established in the course of the IDEALHY project.

2.1 From energy source to hydrogen liquefaction plant

Energy sources considered for hydrogen generation and liquefaction taking place in the demand country/region are:

- Electrolysis with surplus wind electricity;
- Reformation of compressed[2] and of liquefied natural gas (with and without carbon capture and storage; CCS).

Energy sources considered for hydrogen generation and liquefaction far away from the region of utilisation are:

- Electrolysis with electricity from concentrated solar power;
- Gasification of brown coal with CCS;
- Reformation of compressed natural gas with CCS.

[2] In this report, the term “compressed natural gas” stands for gaseous natural gas transported in pipelines.

2.1.1 Hydrogen liquefaction at intermediate scale: Demand country production with local use

2.1.1.1 Electrolysis with (surplus) wind electricity

The pathway is illustrated in Figure 2. It is of relevance for countries with a strong potential for wind energy usage.

Although the electricity could come from either offshore or onshore farms, the analysis will focus on offshore, because of the higher number of full load hours that can be expected for the wind turbines and thus, for the electrolysis. Hydrogen generation and liquefaction could be located at points where the offshore cable (high voltage DC line if the farm is far offshore) connects with the mainland grid.

The electrolysis is likely to be sized larger than liquefaction capacity and accompanied by large-scale storage, such as a salt cavern, to bridge periods of no wind energy surplus because fuel demand is more or less continuous and constant. Sizes for electrolysis plants currently discussed in Germany lie in the range of 500 MW installed electrical power, which is equivalent to about 250 tonnes of hydrogen generated per day.

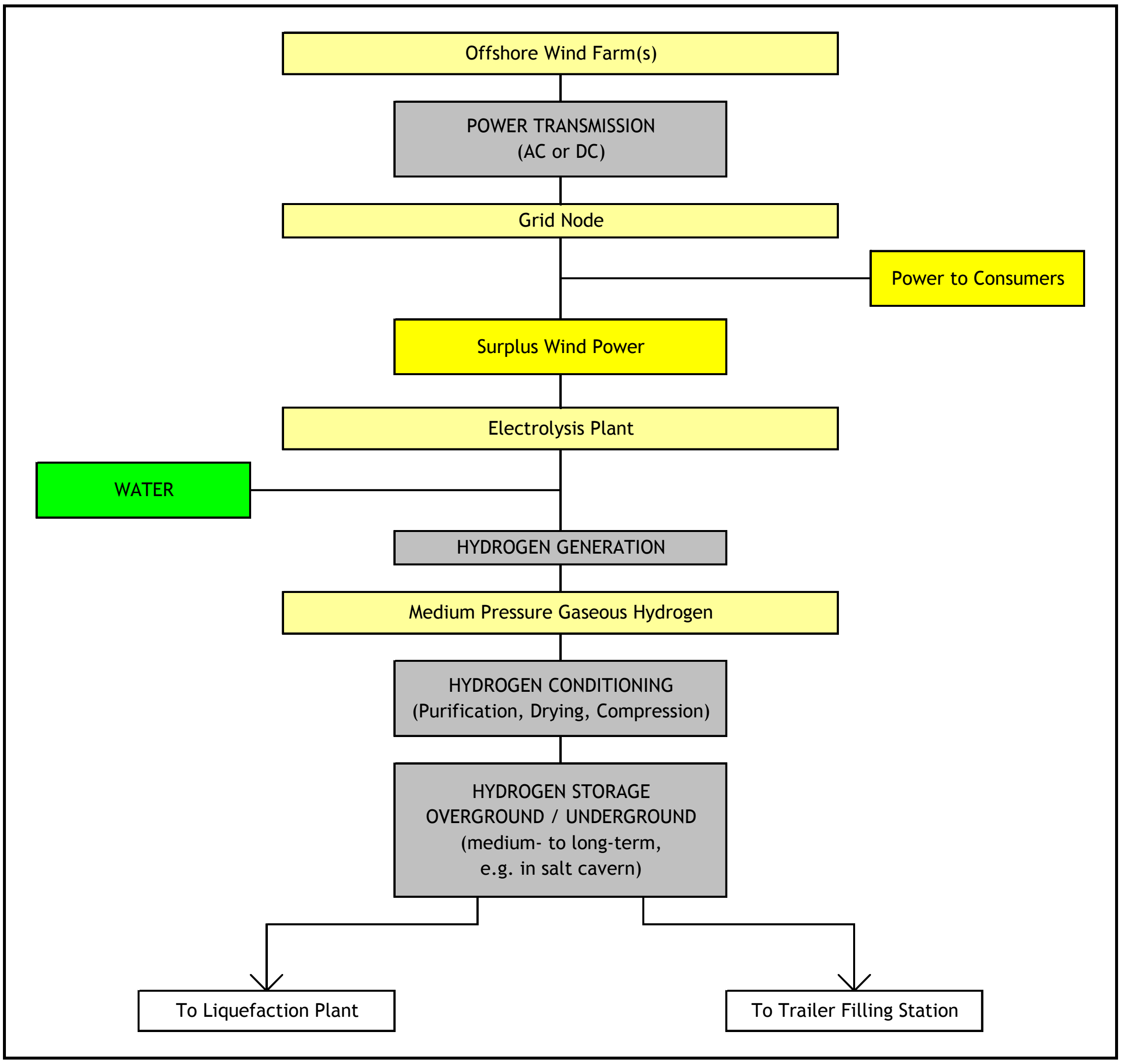

Figure 2: Pathway "Electrolysis with surplus wind electricity", up to stationary storage before liquefaction or distribution by trailer in gaseous state.

2.1.1.2 Reformation of compressed / liquefied natural gas with and without carbon capture and storage

The pathway is illustrated in Figure 3. The reformation plant is assumed to be in the range of 200 tonnes daily hydrogen generation capacity of which 150 tpd are used for other purposes. This scale of the reformer enables the addition of CCS.

When LNG is employed as feed, hydrogen cooling through cold from re-gasification of LNG can optionally be made use of in the hydrogen liquefaction process to improve efficiency.

2.1.2 Hydrogen generation at large scale: Resource country production with transport to demand country

2.1.2.1 Electrolysis with electricity from concentrated solar power

The pathway is illustrated in Figure 4. It is likely to be of relevance in southern Europe and Northern Africa, for example. The electricity generation capacity of the solar plant could be higher than the equivalent of 500 tpd hydrogen. Sufficient supply of water may be a crucial factor.

2.1.2.2 Gasification of brown coal with CCS

The pathway is illustrated in Figure 5. It is of interest in particular with respect to considerable resources of brown coal in Australia and an expected demand for hydrogen in Japan.

2.1.2.3 Reformation of compressed natural gas with CCS

The pathway is illustrated in Figure 6.

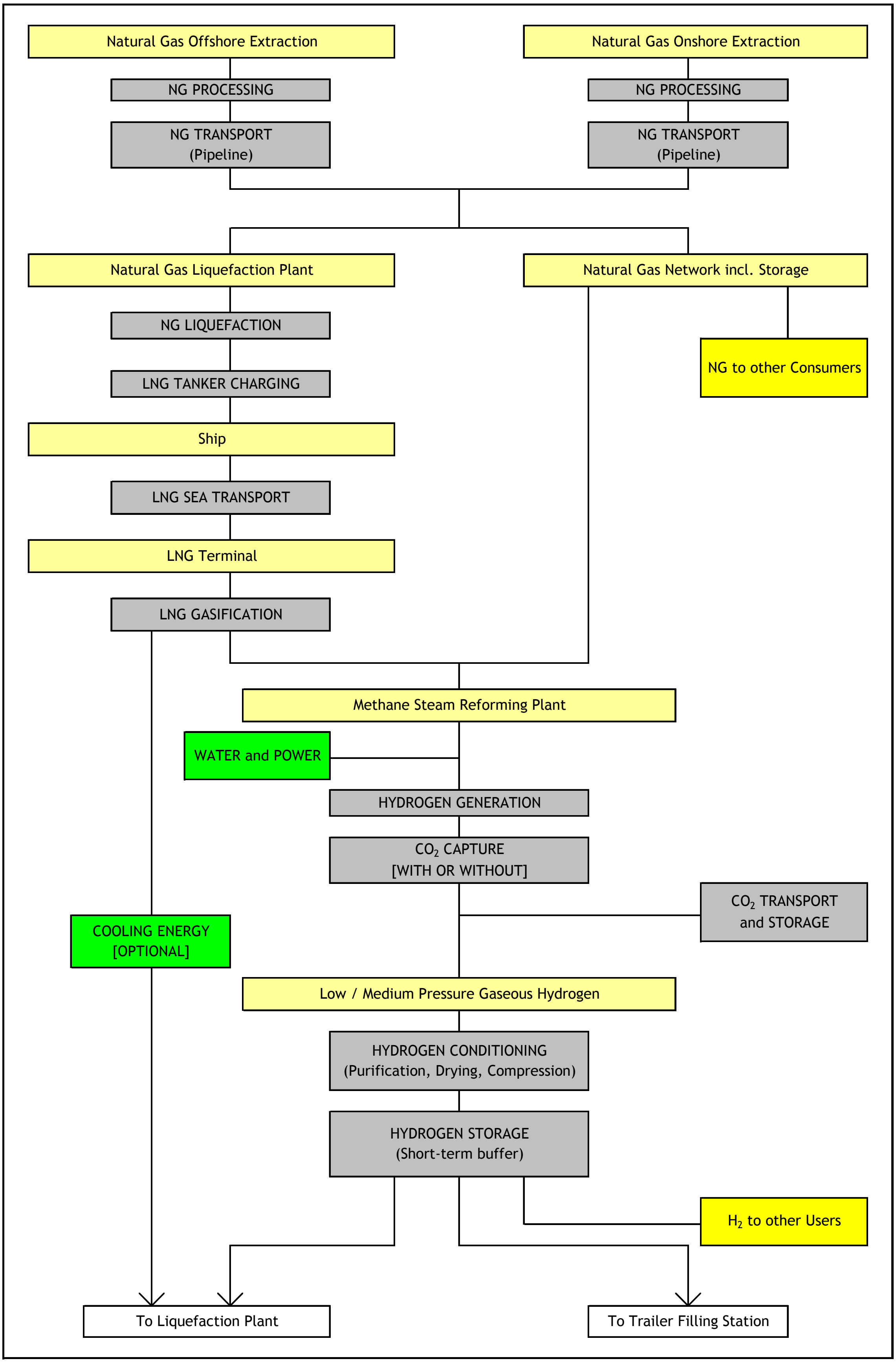

Figure 3: Pathway "Reformation of compressed / liquefied natural gas", up to stationary storage before liquefaction or distribution by trailer in gaseous state.

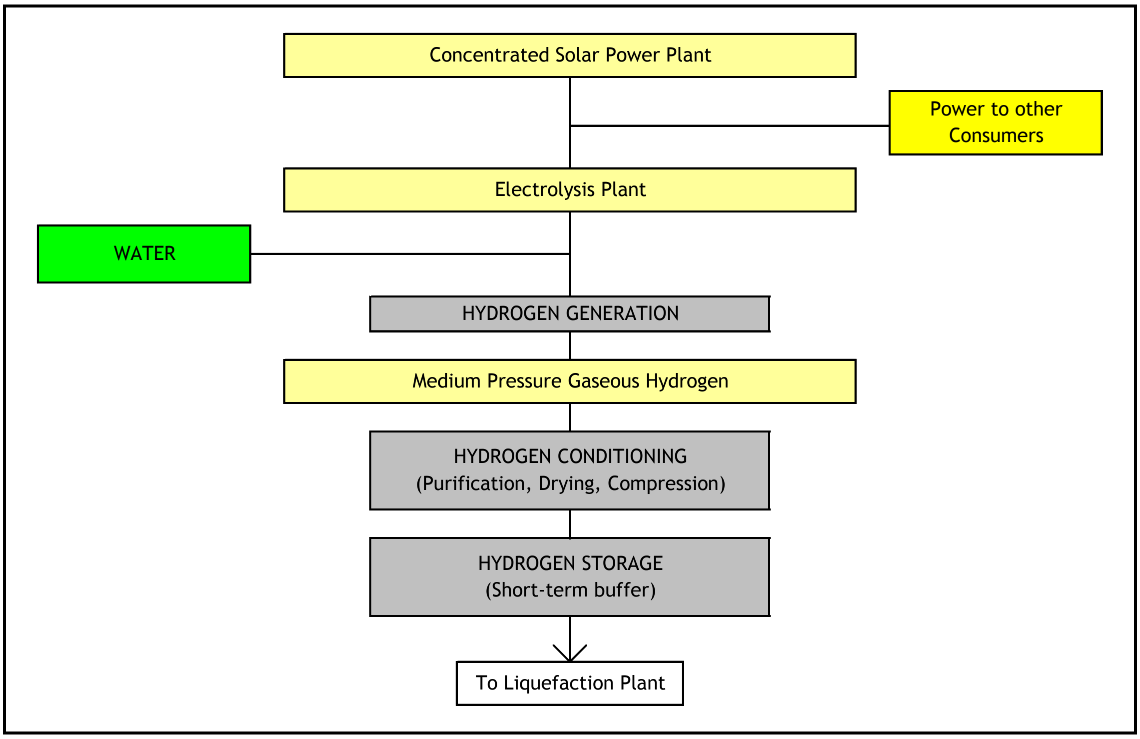

Figure 4: Pathway "Electrolysis with electricity from concentrated solar power", up to stationary storage before liquefaction.

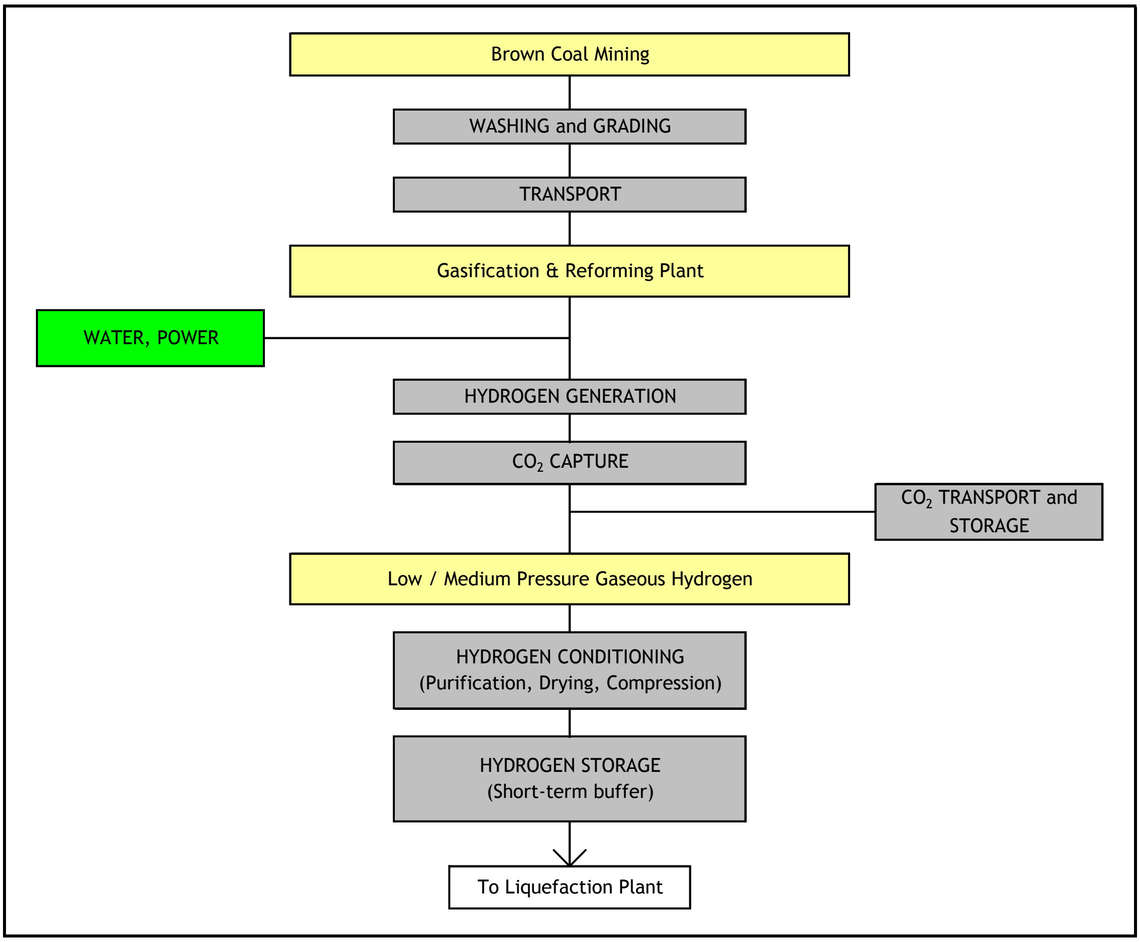

Figure 5: Pathway "Gasification of brown coal with CCS", up to stationary storage before liquefaction.

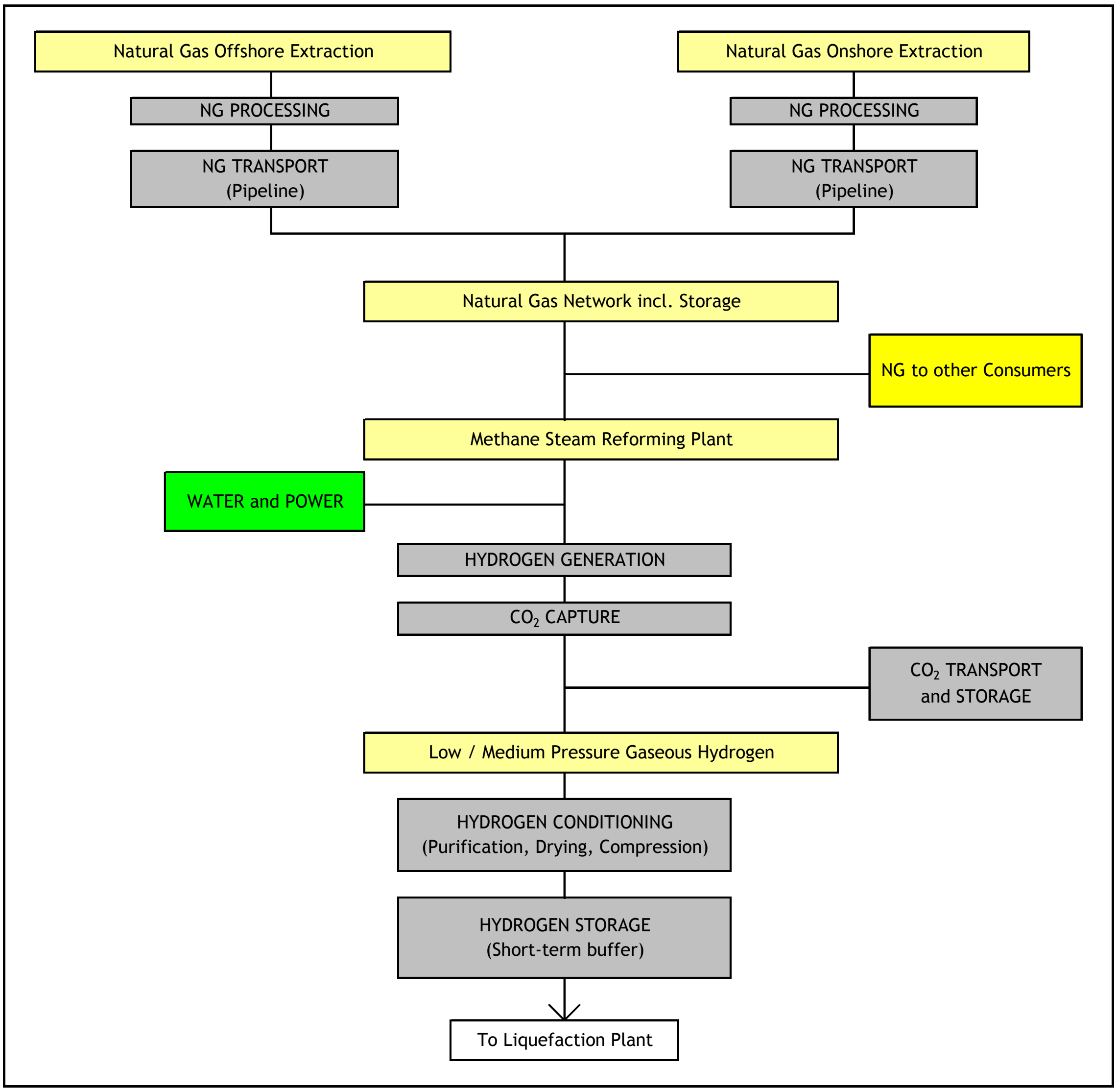

Figure 6: Pathway "Reformation of compressed natural gas with CCS", up to stationary storage before liquefaction.

2.2 Hydrogen liquefaction

This element of the pathways is illustrated in Figure 7. Hydrogen pressure and purity are decisive factors for the specific energy demand of the liquefaction process. A default input pressure of 20 bar is assumed for the time being. Lower pressures upstream or a high level of impurities will increase specific consumption of the plant.

Both "conventional" liquefaction (state-of-the-art today) and "advanced" liquefaction (based on the outcomes of the IDEALHY work) will be considered for comparison and benchmarking.

As explained, (advanced) liquefaction in the demand country will have a capacity of 50 tpd. Liquefaction in a resource country context will be 500 tpd in size, with 10 cold boxes working in parallel and the other components tailored around them.

Utilising cooling energy from LNG re-gasification is an option to be studied. For some pathways there may also be interaction between the liquefaction and the production/ conditioning processes (for example, the use of tail gas from liquefaction to purge the pressure swing adsorption in an upstream hydrogen clean-up unit; this option is not visualised in Figure 7).

Apart from this, power will be the only input and process efficiency the key parameter.

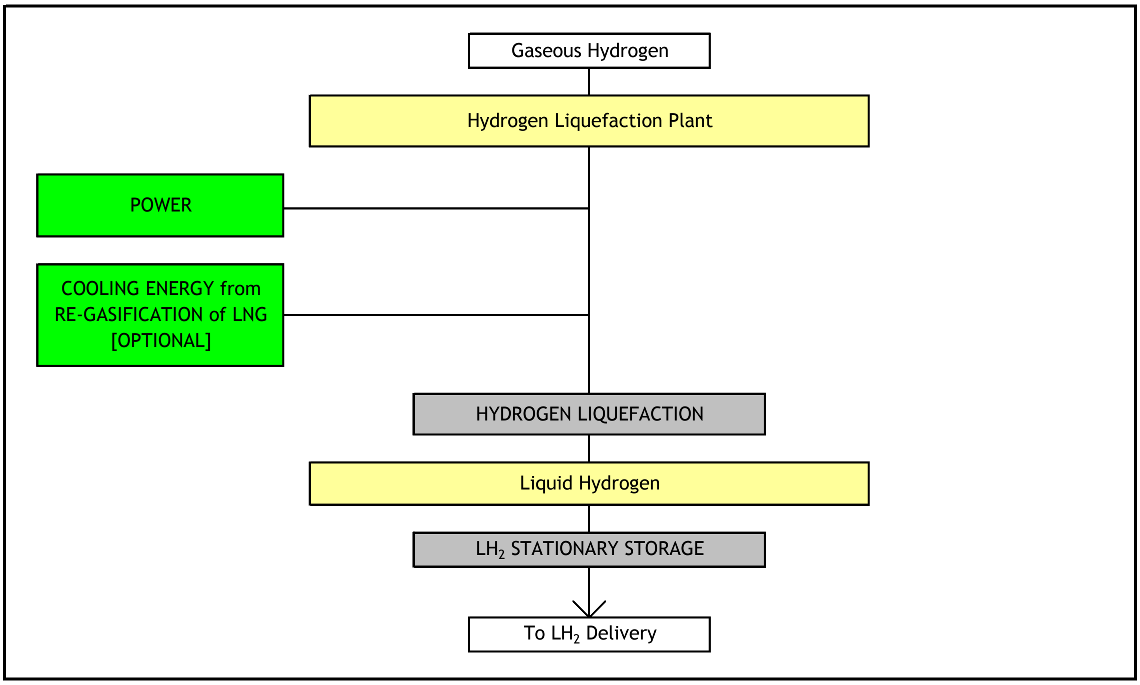

Figure 7: Hydrogen liquefaction.

2.3 Distribution of hydrogen and its utilisation in mobility

2.3.1 Liquid hydrogen

This distribution pathway is outlined in Figure 8. In the case that the resource country is far from the demand country, LH_2 will be first be transported by ship in vessels similar to those for LNG.

The hydrogen is delivered to refuelling station by road tanker where it is stored in a stationary vessel. Pressurisation to and above the rated pressure of the vehicle tank (buses: 350 bar, cars: 700 bar) and evaporation take place on demand, i.e. when a vehicle is refuelled. Up to 4000 kg can be transported per cryogenic road trailer, today and in the future.

2.3.2 Gaseous hydrogen

This distribution pathway is outlined in Figure 9.

Trailer pressure today typically is 200 bar (sometimes 300 bar) and 400 to 600 kg hydrogen can be transported in steel vessels.

For the future, 500 bar vessels made from composite materials and containing around 1,000 kg hydrogen will be considered.

As mentioned, hydrogen pipeline networks are unlikely to become reality in the timeframe up to 2030. They are therefore not considered in the IDEALHY project.

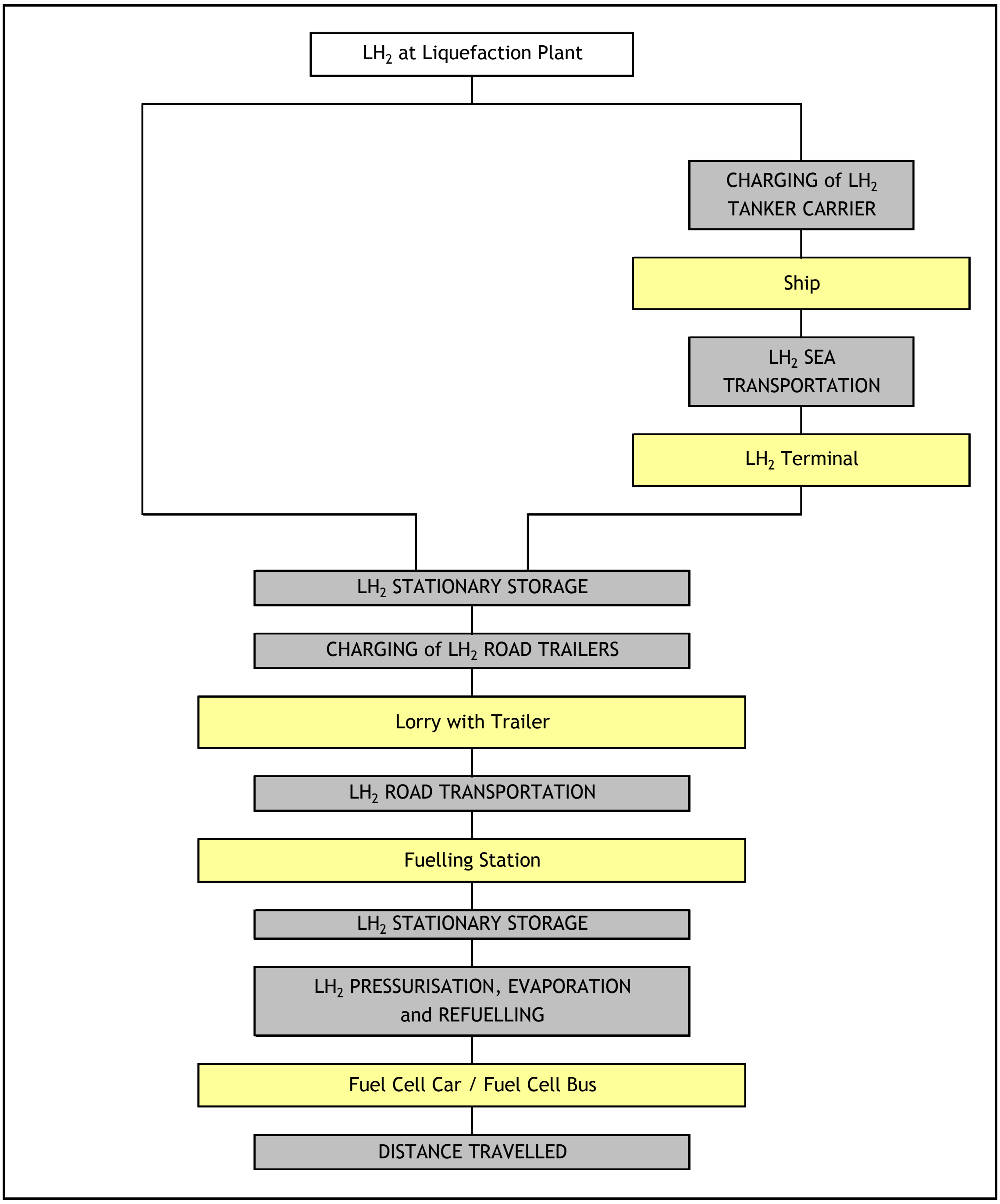

Figure 8: Distribution of liquid hydrogen up to gaseous hydrogen refuelling and utilisation.

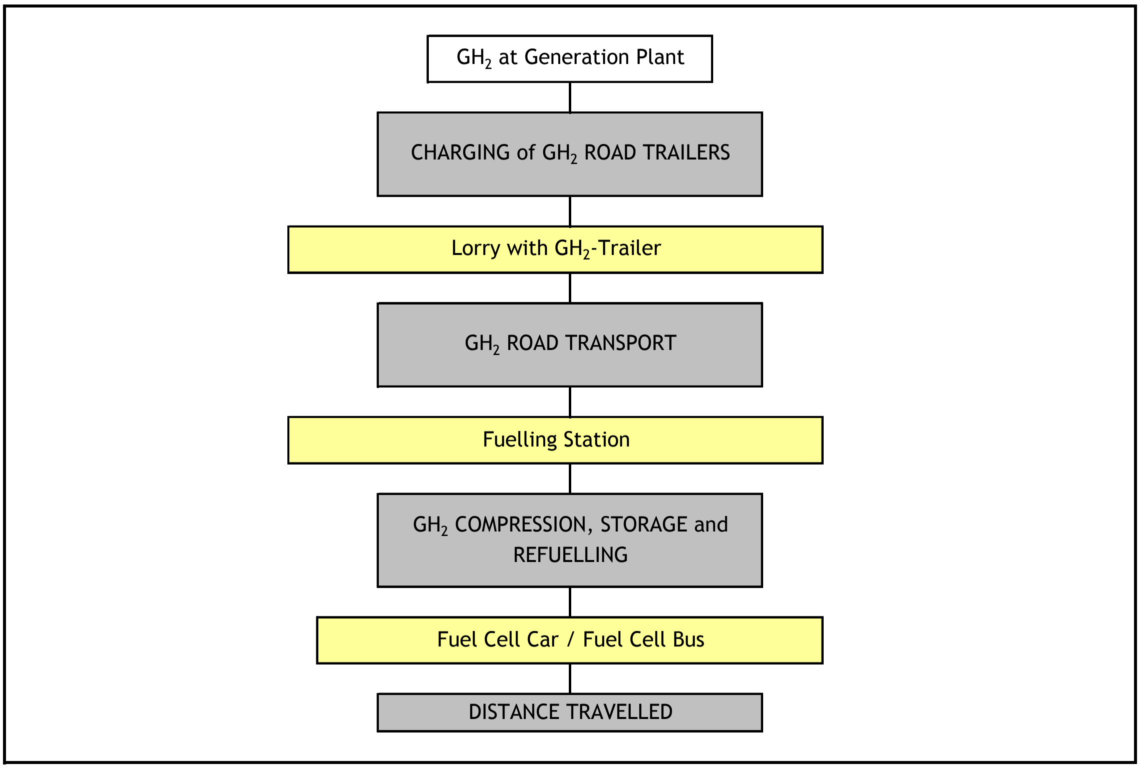

Figure 9: Distribution of gaseous hydrogen up to refuelling and utilisation.

3 Impact of results on WP objectives and overall project

The pathways defined in this report form a basis for the forthcoming life cycle and economic assessment work throughout the IDEALHY project.

The report also is the starting point for gathering information on the individual elements of the process chains along the pathways. Information will be collected from the partners in the project consortium as well as from external sources.

4 Conclusions

The report provides the necessary clarification and agreement for the needs of the IDEALHY project with respect to various pathways of hydrogen generation, conditioning, liquefaction, transportation and, finally, utilisation in mobility.

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