HyWays

"Hydrogen supply chains for Spain"

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1. Introduction

Within the framework of the HyWays project, work packages WP1 and WP2 present the energy chains selected for the timeframe 2020, 2030 and 2050 by the ten involved member states: Finland, France, Greece, Germany, Italy, Norway, the Netherlands, Poland, Spain and the United Kingdom. In this report, the selected chains for Spain are elaborated.

The WP1/WP2 objectives are:
- To propose a set of chains for each country whose data and hypothesis will be transmitted to the WP3,
- To calculate for each chain the energy efficiencies, the GHG emissions and the levelized costs.

The selection of these chains (H_2 production, infrastructure of supply and end use technologies) were performed according to:
- The considered timeframe,
- The specificities of each country (politic, geographic,…), and
- The available and projected technologies and infrastructure.

This report:
- Presents the selected chains for Spain, described by means of schemes including the processes used and their links,
- Provides the results obtained from the calculations of these chains. For comparison purposes, the presentation of results has been lied out graphically.

The simulation of the chains was performed using the E3-database tool developed by L-B-Systemtechnik (LBST, Germany). Most of the data used in the tool has been issued from the EUCAR/CONCAWE/JRC study and the GEMIS database. Part of the data has been adapted or created to represent the specific infrastructure of Spain. To ensure uniformity within the different Member States, all defined production processes within the database have remained unchanged.

2. Methodology

During several workshops organized in Spain, where experts from the industry and research institutes attended, a number of hydrogen production (and utilization) chains were selected. This selection took place based on the specific infrastructure and natural resources of this Member State.

The selected chains were subsequently modelled using the E3-database tool of LBST. With this tool the GHG emissions, the energy requirements and the costs of the supply of transportation fuel, electricity and heat were estimated.

As a time horizon, the years 2020, 2030 and 2050 were selected. Reason of doing so is that it can be expected that in 2020 fuel cell vehicles as well as the different hydrogen generation technologies will be commercially available. The years 2030 and 2050 were added for long term processes not available in 2020.

The basis of the database is a common file created from the interview of the industrial partners and the member state representatives. This data was incorporated into the database after being validated. The processes used in E3-database for the calculation of the hydrogen energy pathways are also available in a spreadsheet bearing the name of "technology fact sheet". This is an EXCEL-based spreadsheet where all inputs and outputs of the database are presented, including the used references to come to these values.

All calculations performed within the E3-database are based on the lower heating value (LHV) of the main sources. Most of the processes already have been used in the CONCAWE/EUCAR/JRC study. Newly introduced processes are:

- Processes where CO_2 capture and storage is embodied,
- Processes which describe stationary hydrogen fuelled fuel cells, and
- Gas engines and gas turbines.

For the Hydrogen pathways selected in Spain, the following new processes were introduced:

- GH2 / Hard Coal / FW no CCS (gasification of coal with the Foster Wheeler process and with no CO2 sequestration),
- GH2 / Solar / Thermo chemical cycles (Sulphur-Iodine),
- Power Station / Mix Spain 2020 (Electric mix in Spain).

The calculation rules used within the E3-database are presented in 7.

3. Chains Selection

3.1. Possible chains

There are many ways of grouping possible hydrogen production and utilization chains. A first approach is performed with the used feedstock as a basis. Next, depending on the location of a production plant (central or de-central) on the production process and end users, a large matrix of possible hydrogen pathways could be created. From here, if the possibility of capturing Carbon as an abatement technique is also considered, the number of possible chains almost double.
In this study the following approach was used:

Firstly, the possible chains were grouped by feedstock. As possible feedstock's were identified:

- Natural gas
- Oil residues
- Coal
- Electricity
- Nuclear, solar and wind power
- Hydroelectric power
- Biomass
- Other

Under category "Other" are included: waste, hydrogen as by-product and imported liquefied hydrogen. Although "hydrogen as by-product" is not a feedstock as such, but in fact a production process, it is included as a feedstock because it can be treated as a "ready-for-use" product.

Secondly, the hydrogen production chains were grouped by the used production process with a distinction between central and de-central processes. The identified production processes were Steam Methane Reforming (SMR), gasification and electrolysis. Some other feedstock depending processes as High Temperature Thermo-chemical, Photo-biological and fermentation are also possible, although still under development.

Thirdly, two types of hydrogen usage were identified: a filling station (FS) for all kind of vehicles and the stationary use of hydrogen (STU), the last one being either domestic or industrial.
Finally, the way hydrogen could be delivered was included: compressed gas (CGH_2) or liquefied (LH_2).

Based on these subsystems, a selection of most probable hydrogen supply chains can be performed, depending on the specific Member State infrastructure and availability of main resources.

3.2. Chain Selection for Spain

There are two kinds of parameters that may affect the calculation of a specific hydrogen chain for a Member State: Infrastructure distances and Member State related costs of main resources. Moreover, depending on the considered chain, transport means and distances may vary.

Most probable hydrogen production and consumption chains were selected for the main fuel sources of natural gas, biomass, coal, solar and electricity (Spain mix, dedicated reactor and wind power). This selection was performed during a couple of workshops held between field experts, energy utilities and researchers. The choice was based on availability of a natural gas (NG) infrastructure, availability of other (renewable) resources and specific national infrastructure distances. Table 1 compiles all developed chains for Spain.

Table 1. Overview of the hydrogen chains considered

Feedstock	NG	×
	Coal	×
	Oil residues	-
	Electricity [1]	×
	Biomass	×
	Waste	-
	By-product	×
Distribution	Filling-station (FC or ICE)	×
	Filling station (liquid H_2)	×
	CHP (FC)	×
	CHP (ICE)	×
	Heating boiler	-
	Combination CHP (FC) and heating boiler	×
	CCGT	-

For Spain, eight hydrogen chains were selected. It leads to 27 sub-chains, 24 for mobile applications and 3 for stationary applications. The selected chains are presented inTable 2.

[1] Both electricity from wind power and the Spanish mix electricity are considered.

Table 2. Selected Spanish Chains for the Hydrogen pathway

N°		Feedstock	Production Process	Transport	CO_2 seq.	Gas / Liquid	Application
1	a	Biomass	Central Gasification	GH_2 pipeline	No	Gas	Car FS
2	a1	NG (pipeline)	Central SMR	GH_2 pipeline	No	Gas	Car FS
	a2	NG (ship)	Central SMR	GH_2 pipeline	No	Gas	Car FS
	b1	NG (pipeline)	Central SMR	CGH_2 truck	No	Gas	Car FS
	b2	NG (ship)	Central SMR	CGH_2 truck	No	Gas	Car FS
	c1	NG (pipeline)	Central SMR	LH_2 truck	No	Liquid	Car FS
	c2	NG (ship)	Central SMR	LH_2 truck	No	Liquid	Car FS
	d1	NG (pipeline)	Central SMR	GH_2 pipeline	Yes	Gas	Car FS
	d2	NG (ship)	Central SMR	GH_2 pipeline	Yes	Gas	Car FS
	e1	NG (pipeline)	On Site SMR	GH_2 pipeline	No	Gas	Car FS
	e2	NG (ship)	On Site SMR	GH_2 pipeline	No	Gas	Car FS
3	a1	Coal	Gasification	GH_2 pipeline	No	Gas	Car FS
	a2	Coal	Gasification	GH_2 pipeline	No	Gas	Domestic use
	b	Coal	Gasification	CGH_2 truck	No	Gas	Car FS
	c1	Coal	Gasification	GH_2 pipeline	Yes	Gas	Car FS
	c2	Coal	Gasification	GH_2 pipeline	Yes	Gas	Domestic use
4	a	On shore Wind Power	On Site Electrolysis	GH_2 pipeline	No	Gas	Domestic use
	b	On shore Wind Power	Central Electrolysis	GH_2 pipeline	No	Gas	Car FS
	c	On shore Wind Power	Central Electrolysis	CGH_2 truck	No	Gas	Car FS
	d	Off-shore Wind Power	Central Electrolysis	GH_2 pipeline	No	Gas	Car FS
	e	Off-shore Wind Power	Central Electrolysis	CGH_2 truck	No	Gas	Car FS
5	a	Solar	Thermal conversion	GH_2 pipeline	No	Gas	Car FS
	b	Solar	Thermal conversion	CGH_2 truck	No	Gas	Car FS
6	a	Mix Electricity	On Site Electrolysis	GH_2 pipeline	No	Gas	Car FS
7	a	By-product		CGH_2 truck	No	Gas	Car FS
8	a	HT Nuclear Heat	HT Electrolysis	GH_2 pipeline	No	Gas	Car FS
	b	HT Nuclear Heat	TC Cycles	GH_2 pipeline	No	Gas	Car FS

In the following section, these hydrogen production and utilization chains are presented one by one.

4. Selected Chains

In the following paragraphs, the eight selected hydrogen chains for Spain and their variants are presented. The chains presented are all chains as stated in Table 2.
First, all hydrogen chains for mobile applications are developed, ordered by the feedstock used. All hydrogen chains for stationary use follow there after.

4.1. Chain 1.a. Biomass, Central Gasification, no CCS; use: car filling station

Description
Spanish residual wood is chipped and transported by a 40 tons truck over 50 km to the gasification plant. The electricity needed in the gasification plant is provided by a biomass power plant located near the gasification plant. Once the biomass has been gasified and the gaseous hydrogen has been separated from the syngas, the CGH_2 is transported to the filling stations through a pipeline grid consisting in large pipelines (50 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.
The wood chipping process uses also diesel fuel for the conversion of energy into mechanical work.

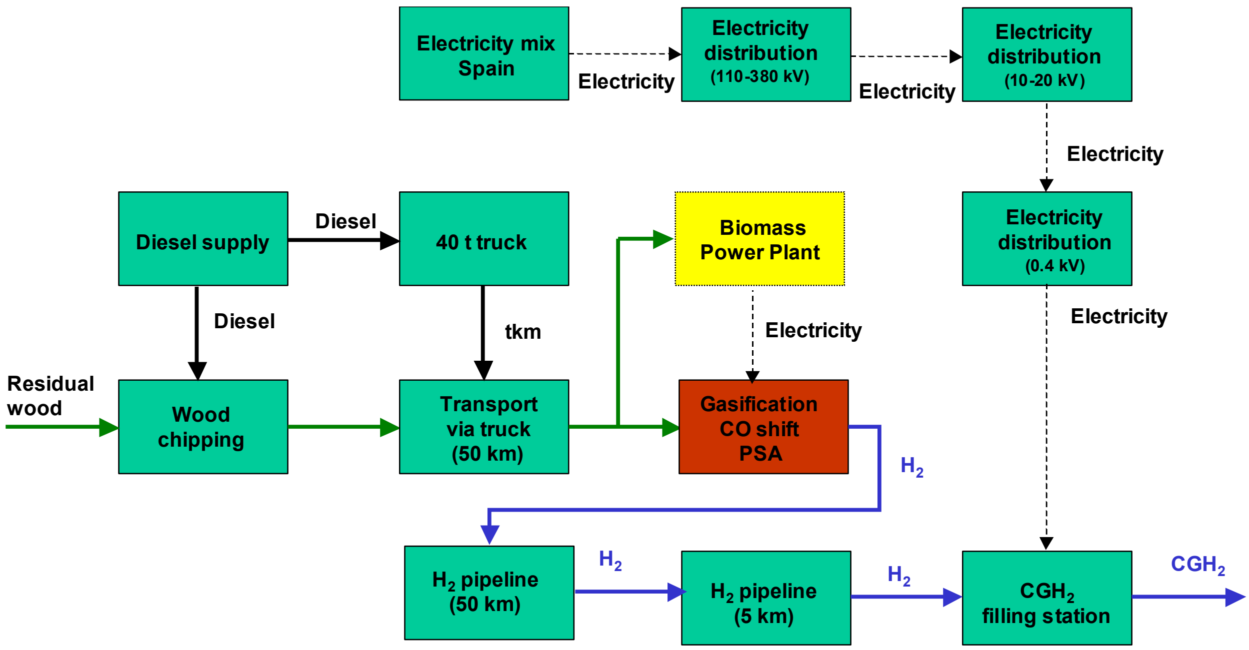

Figure 1. Modelled hydrogen chain for Biomass gasification, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Biomass provision A.1
- Biomass chipping A.6
- Biomass transport A.2
- Electricity provision A.1
- Electricity transport A.2
- Hydrogen production from biomass A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5
- Biomass power plant A.6

4.2. Chain 2.a1. Natural Gas (pipeline), Central SMR, no CCS, GH_2 pipelines; use: car filling station

Description

Natural gas extracted and processed in NG producer countries is transported into the Spanish gas network (1000 km distance) and becomes distributed to a central point (250 km distance, on average). A SMR located at that point produces hydrogen, which becomes subsequently distributed to the filling stations. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.
The excess electricity produced by the Linde SMR is sold to the grid (credit).
The filling station requires electricity, which comes from the Spanish mix.

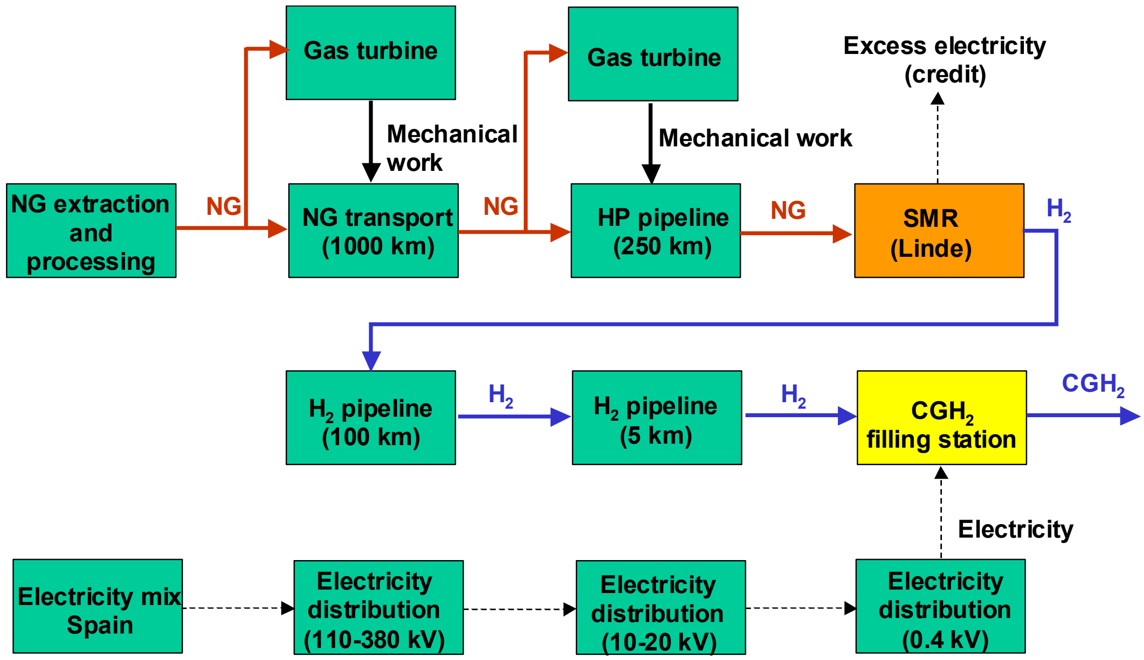

Figure 2. Modelled hydrogen chain for NG (pipeline) with central SMR and no CCS, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport pipelines A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas (including CCS) A.3
- Hydrogen transport A.4
- Filling station A.5

4.3. Chain 2.a2. Natural Gas (ship), Central SMR, no CCS, GH_2 pipelines; use: car filling station

Description

Natural gas extracted in NG producer countries is liquefied nearby the NG field. The data for the natural gas liquefaction has been derived from the Snohvit LNG Project [Snohvit 2003].
The LNG is transported to Spain via a LNG carrier (distance: 2,000 km).
At the terminal the LNG is vaporized and fed into a steam methane reformer where the natural gas is converted to hydrogen without CO_2 capture and storage. The produced hydrogen is subsequently distributed to the filling stations. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

The heat for the vaporization is derived from the combustion of natural gas. Therefore approximately 0.019 kWh natural gas per kWh of gaseous natural gas is required. Further about 0.004 kWh mechanical work per kWh of gaseous natural gas is required. The mechanical work is generated by a diesel engine (efficiency: 30%).
The excess electricity produced by the Linde SMR is sold to the grid (credit).
The filling station requires electricity, which comes from the Spanish mix.

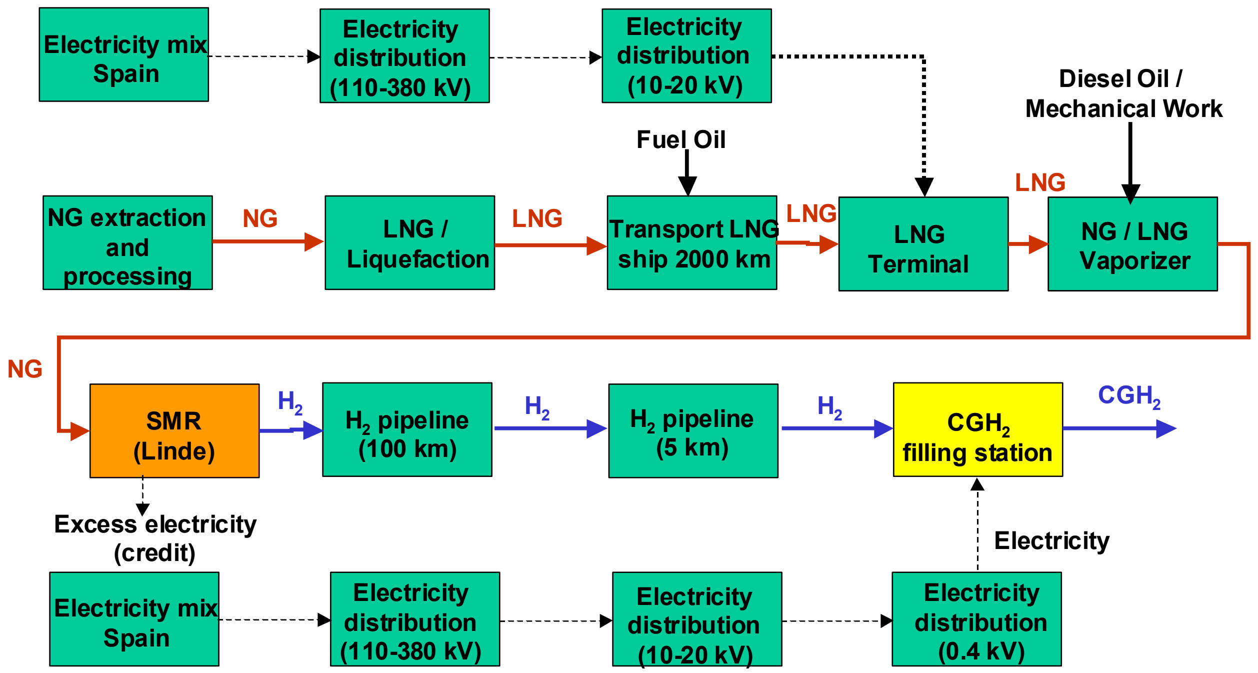

Figure 3. Modelled hydrogen chain for NG (ship) with central SMR and no CCS, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas A.3
- Hydrogen transport A.4
- Filling station A.5

4.4. Chain 2.b1. Natural Gas (pipeline), Central SMR, no CCS, CGH_2 trucks; use: car filling station

Description
Natural gas extracted and processed in NG producer countries is transported into the Spanish gas network (1000 km distance) and becomes distributed to a central point (250 km distance, on average). A SMR located at that point produces hydrogen, which becomes subsequently distributed to the filling stations.
Therefore, the hydrogen is compressed and then transported by a CGH_2 truck on 50 km.

The excess electricity produced by the Linde SMR is sold to the grid (credit).
The filling station requires electricity, which comes from the Spanish mix.

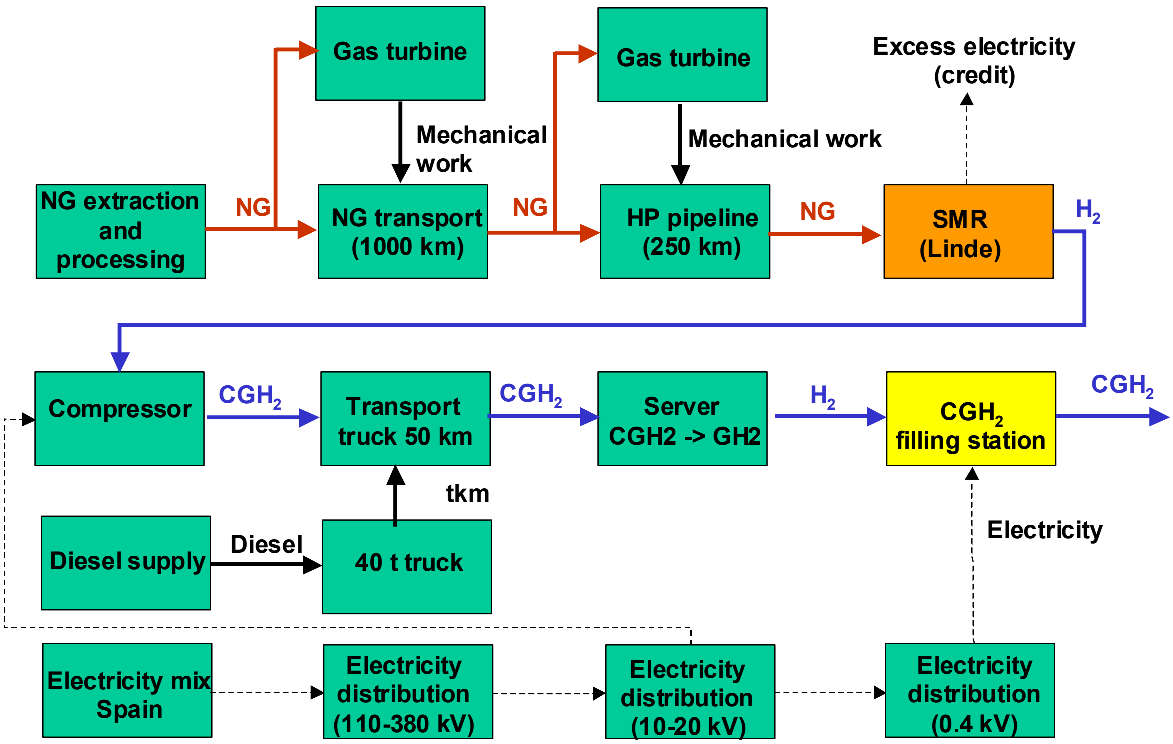

Figure 4. Modelled hydrogen chain for NG (pipeline) with central SMR and no CCS, CGH_2 truck, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport pipelines A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas (including CCS) A.3
- Hydrogen transport A.4
- Filling station A.5

4.5. Chain 2.b2. Natural Gas (ship), Central SMR, no CCS, CGH_2 trucks; use: car filling station

Description

Natural gas extracted in NG producer countries is liquefied nearby the NG field. The data for the natural gas liquefaction has been derived from the Snohvit LNG Project [Snohvit 2003].
The LNG is transported to Spain via a LNG carrier (distance: 2,000 km).
At the terminal the LNG is vaporized and fed into a steam methane reformer where the natural gas is converted to hydrogen without CO_2 capture and storage. The produced hydrogen is subsequently distributed to the filling stations.
Therefore, the hydrogen is compressed and then transported by a CGH_2 truck on 50 km.

The heat for the vaporization is derived from the combustion of natural gas. Therefore approximately 0.019 kWh natural gas per kWh of gaseous natural gas is required. Further about 0.004 kWh mechanical work per kWh of gaseous natural gas is required. The mechanical work is generated by a diesel engine (efficiency: 30%).
The excess electricity produced by the Linde SMR is sold to the grid (credit).
The filling station requires electricity, which comes from the Spanish mix.

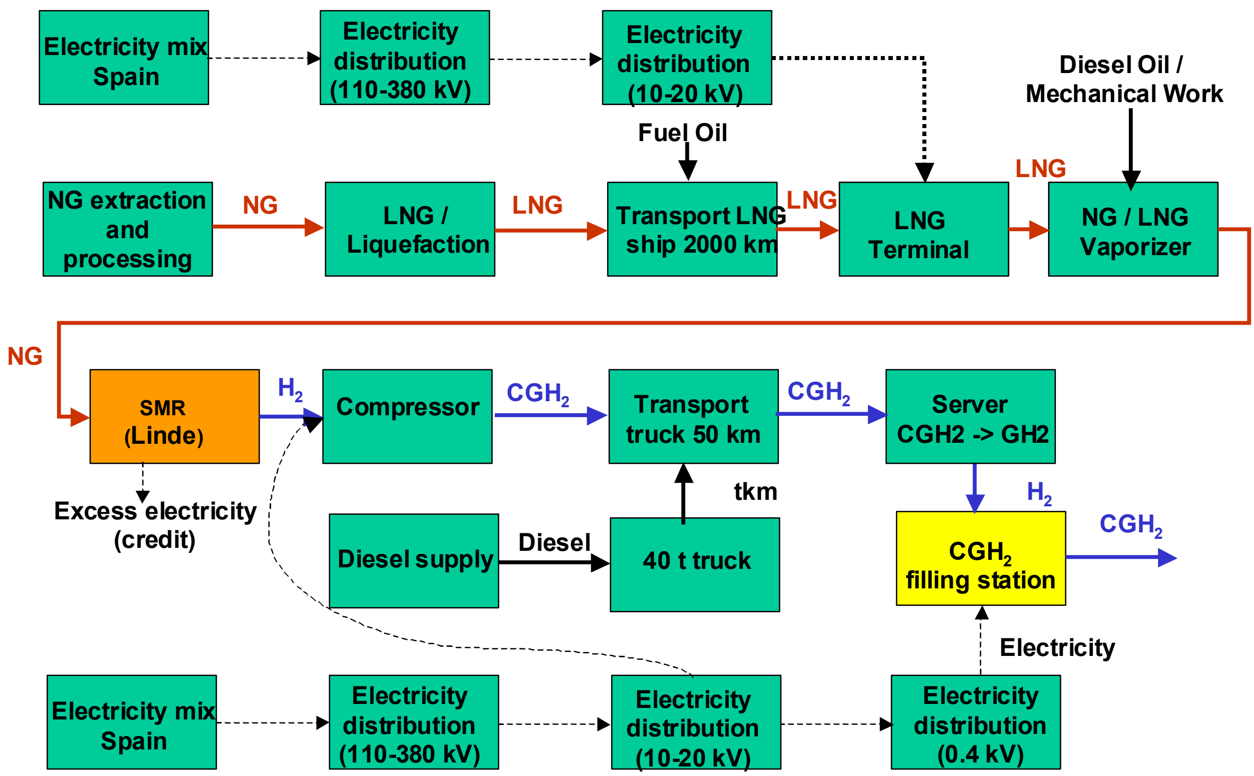

Figure 5. Modelled hydrogen chain for NG (ship) with central SMR and no CCS, CGH_2 truck, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport ship A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas (including CCS) A.3
- Hydrogen transport A.4
- Filling station A.5

4.6. Chain 2.c1. Natural Gas (pipeline), Central SMR, no CCS, LH_2 trucks; use: car filling station

Description

Natural gas extracted and processed in NG producer countries is transported into the Spanish gas network (1000 km distance) and becomes distributed to a central point (250 km distance, on average). A SMR located at that point produces hydrogen, which becomes subsequently distributed to the filling stations.
Gaseous hydrogen produced by this plant is liquefied and then transported by truck on 150 km.

The excess electricity produced by the Linde SMR is sold to the grid (credit).
Electricity required at the liquefaction plant is obtained from Spanish mix at a high-voltage level, whereas electricity required at the filling station is required at low-voltage level.

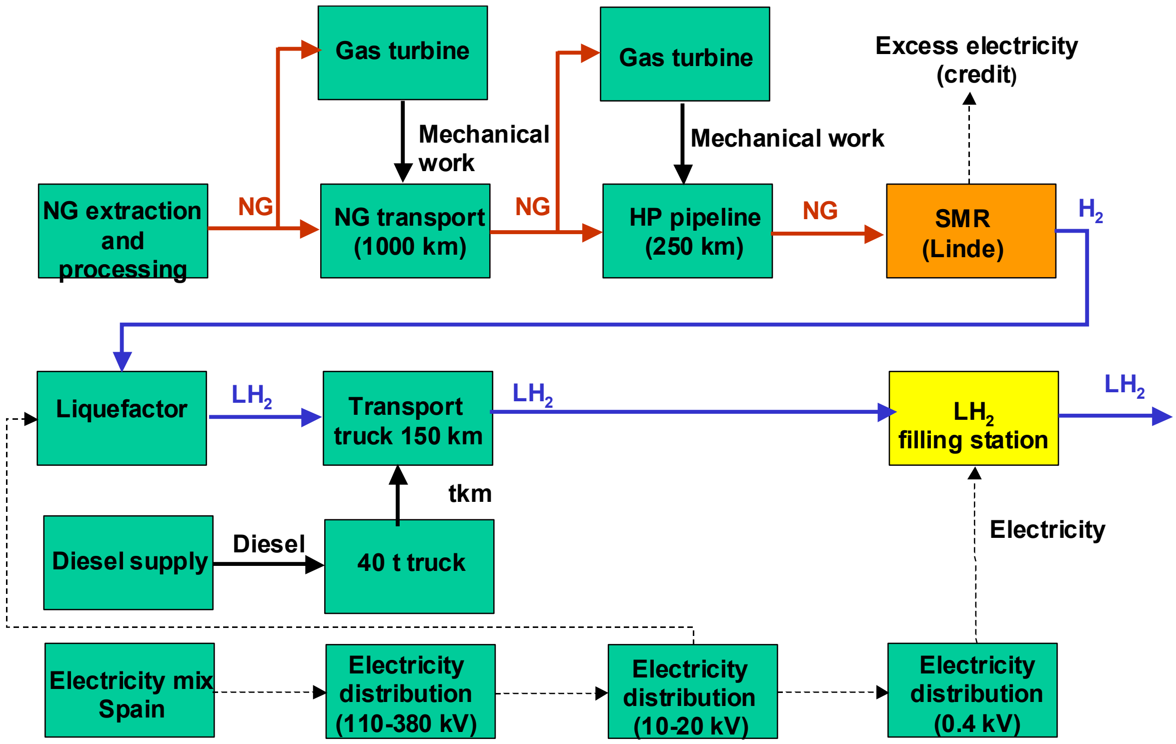

Figure 6. Modelled hydrogen chain for NG (pipeline) with central SMR and no CCS, LH_2 truck, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport pipelines A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas A.3
- Hydrogen transport A.4
- Filling station A.5
- Liquefaction of hydrogen A.3
- Transport of liquefied hydrogen A.4

4.7. Chain 2.c2. Natural Gas (ship), Central SMR, no CCS, LH_2 trucks; use: car filling station

Description

Natural gas extracted in NG producer countries is liquefied nearby the NG field. The data for the natural gas liquefaction has been derived from the Snohvit LNG Project [Snohvit 2003].
The LNG is transported to Spain via a LNG carrier (distance: 2,000 km).
At the terminal the LNG is vaporized and fed into a steam methane reformer where the natural gas is converted to hydrogen without CO_2 capture and storage.
Gaseous hydrogen produced by this plant is liquefied and then transported by truck on 150 km to the filling stations.

The heat for the vaporization is derived from the combustion of natural gas. Therefore approximately 0.019 kWh natural gas per kWh of gaseous natural gas is required. Further about 0.004 kWh mechanical work per kWh of gaseous natural gas is required. The mechanical work is generated by a diesel engine (efficiency: 30%).
The excess electricity produced by the Linde SMR is sold to the grid (credit).
Electricity required at the liquefaction plant is obtained from Spanish mix at a high-voltage level, whereas electricity required at the filling station is required at low-voltage level.

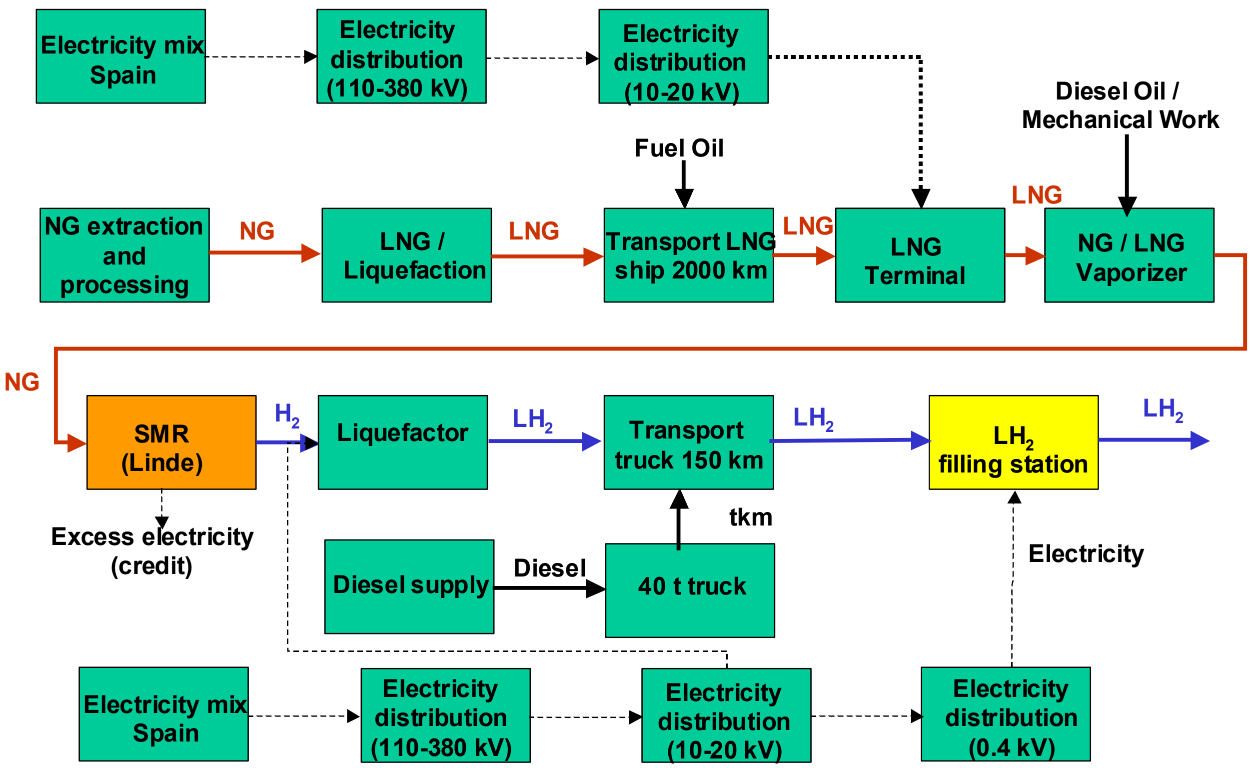

Figure 7. Modelled hydrogen chain for NG (ship) with central SMR and no CCS, LH_2 truck, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction	A.1
- Natural gas transport	A.2
- Electricity production	A.1
- Electricity transport	A.2
- Hydrogen production from natural gas	A.3
- Hydrogen transport	A.4
- Filling station	A.5
- Liquefaction of hydrogen	A.3
- Transport of liquefied hydrogen	A.4

4.8. Chain 2.d1. Natural Gas (pipeline), Central SMR with CCS, GH_2 pipelines; use: car filling station

Description

Natural gas extracted and processed in NG producer countries is transported into the Spanish gas network (1000 km distance) and becomes distributed to a central point (250 km distance, on average). A SMR located at that point produces hydrogen, which becomes subsequently distributed to the filling stations. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

The central SMR separates the produced CO_2, which becomes subsequently stored in old gas/oil fields after transport (50 km distance, on average).

The filling station requires electricity, which comes from the Spanish mix.

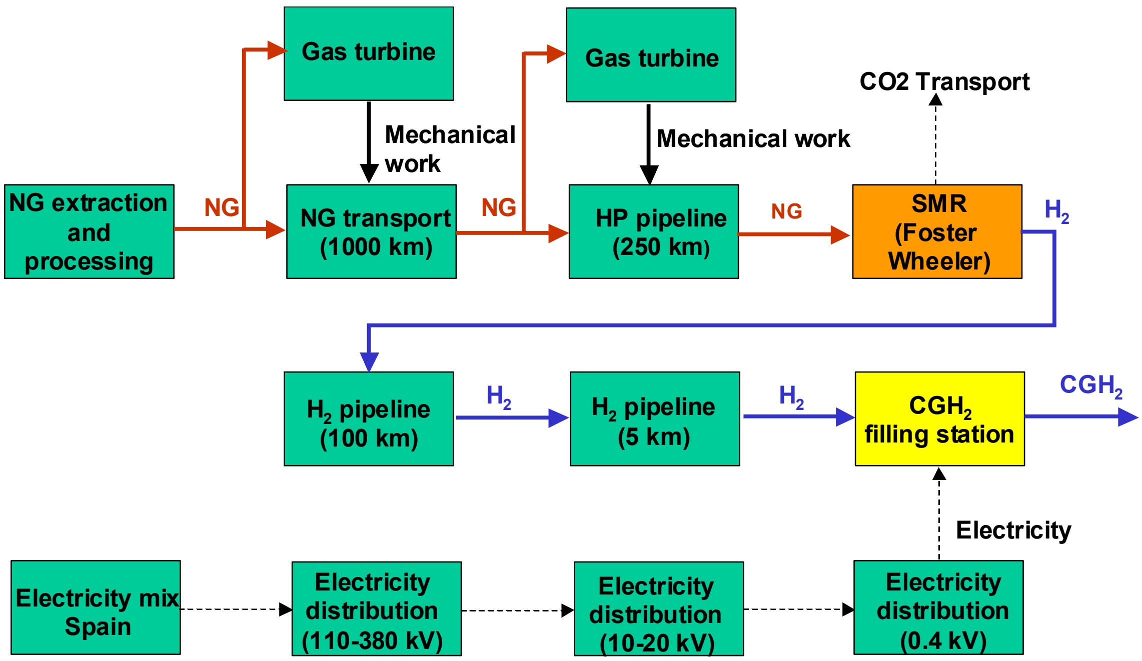

Figure 8. Modelled hydrogen chain for NG (pipeline) with central SMR with CCS, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport pipelines A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas (including CCS) A.3
- Hydrogen transport A.4
- Filling station A.5

4.9. Chain 2.d2. Natural Gas (ship), Central SMR with CCS, GH_2 pipelines; use: car filling station

Description

Natural gas extracted in NG producer countries is liquefied nearby the NG field. The data for the natural gas liquefaction has been derived from the Snohvit LNG Project [Snohvit 2003].
The LNG is transported to Spain via a LNG carrier (distance: 2,000 km).
At the terminal the LNG is vaporized and fed into a steam methane reformer where the natural gas is converted to hydrogen with CO_2 capture and storage in old gas/oil fields after transport (50 km distance, on average).
Gaseous hydrogen produced by this plant is transported to the filling stations.
Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

The heat for the vaporization is derived from the combustion of natural gas. Therefore approximately 0.019 kWh natural gas per kWh of gaseous natural gas is required. Further about 0.004 kWh mechanical work per kWh of gaseous natural gas is required. The mechanical work is generated by a diesel engine (efficiency: 30%).
Electricity required at the liquefaction plant is obtained from Spanish mix at a high-voltage level, whereas electricity required at the filling station is required at low-voltage level.

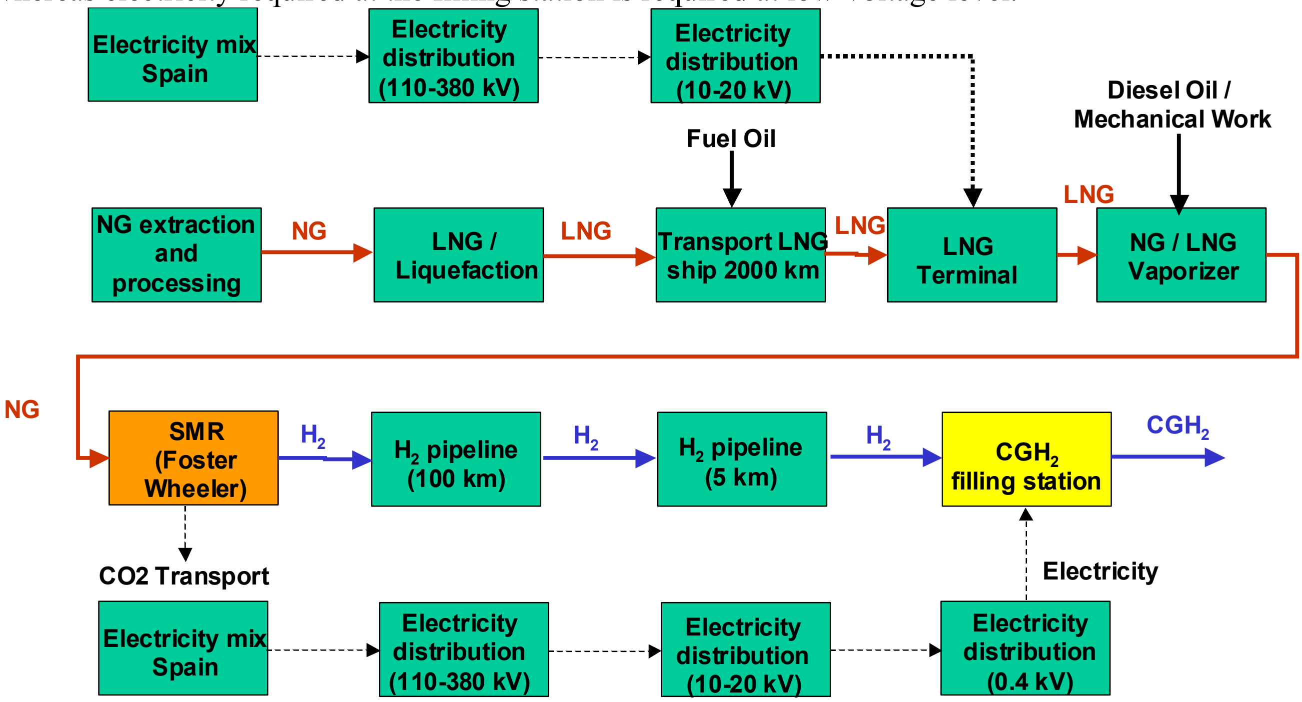

Figure 9. Modelled hydrogen chain for NG (ship) with central SMR with CCS, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas (including CCS) A.3
- Hydrogen transport A.4
- Filling station A.5

4.10. Chain 2.e1. Natural Gas (pipeline), On-site SMR, no CCS, GH_2 pipelines; use: car filling station

Description

Natural gas extracted and processed in NG producer countries is transported into the Spanish gas network (1000 km distance) and becomes distributed to an on-site SMR (250 km distance, on average). The produced hydrogen becomes subsequently distributed to the filling station with a small pipeline (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

Electricity required at the SMR plant is obtained from Spanish mix at a high-voltage level, whereas electricity required at the filling station is required at low-voltage level.

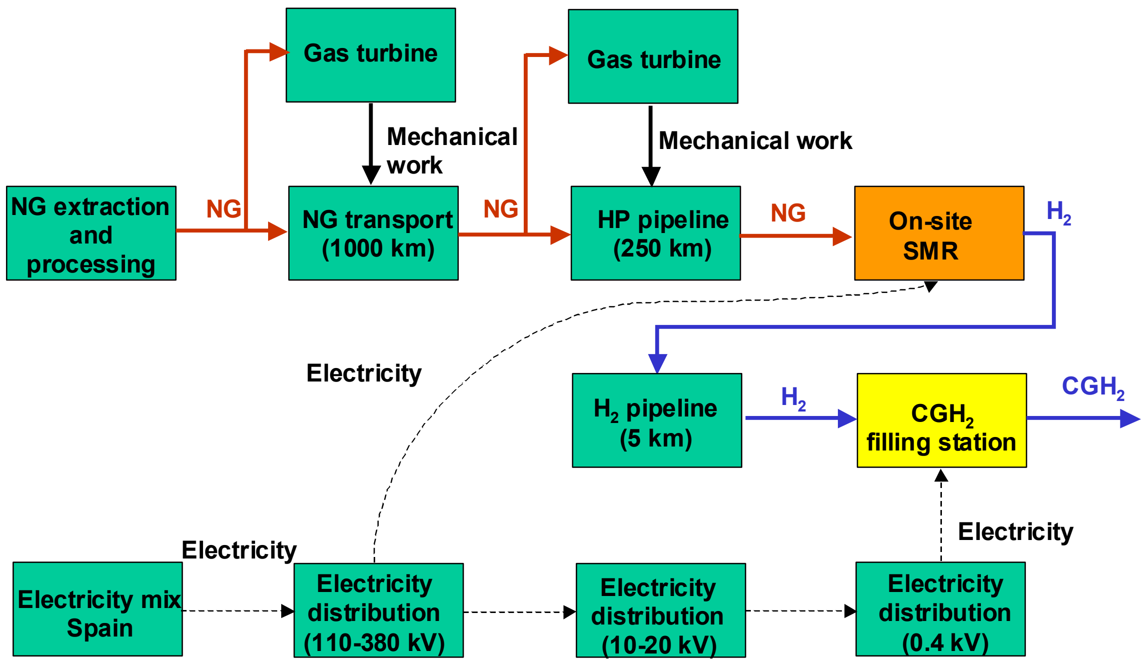

Figure 10. Modelled hydrogen chain for NG (pipeline) with on-site SMR and no CCS, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport pipelines A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas A.3
- Hydrogen transport A.4
- Filling station A.5

4.11. Chain 2.e2. Natural Gas (ship), On-site SMR, no CCS, GH_2 pipelines; use: car filling station

Description

Natural gas extracted in NG producer countries is liquefied nearby the NG field. The data for the natural gas liquefaction has been derived from the Snohvit LNG Project [Snohvit 2003].
The LNG is transported to Spain via a LNG carrier (distance: 2,000 km).
At the terminal the LNG is vaporized and fed into a steam methane reformer where the natural gas is converted to hydrogen without CO_2 capture and storage.
The produced hydrogen becomes subsequently distributed to the filling station with a small pipeline (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

The heat for the vaporization is derived from the combustion of natural gas. Therefore approximately 0.019 kWh natural gas per kWh of gaseous natural gas is required. Further about 0.004 kWh mechanical work per kWh of gaseous natural gas is required. The mechanical work is generated by a diesel engine (efficiency: 30%).
Electricity required at the liquefaction plant and the SMR plant is obtained from Spanish mix at a high-voltage level, whereas electricity required at the filling station is required at low-voltage level.

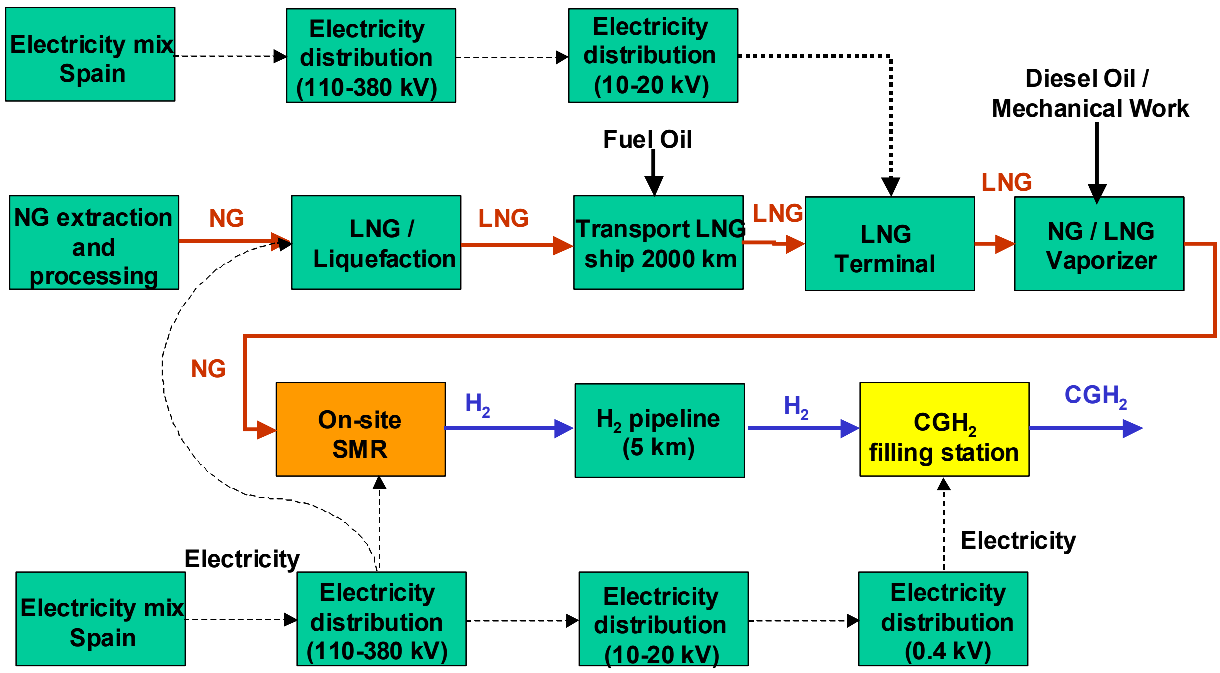

Figure 11. Modelled hydrogen chain for NG (ship) with on-site SMR and no CCS, for use in FS

For description of the processes used for the model of this chain, see sections indicated below:

- Natural gas processing and extraction A.1
- Natural gas transport A.2
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from natural gas A.3
- Hydrogen transport A.4
- Filling station A.5

4.12. Chain 3.a1. Hard Coal, Gasification, no CCS, GH_2 pipeline; use: car filling station

Description

In this hydrogen chain, hydrogen is generated via gasification of hard coal without CO_2 capture and sequestration. The characteristics of the hard coal used are derived from the EU hard coal mix.

The supply of CGH_2 to the filling stations is performed through a hydrogen pipeline grid. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

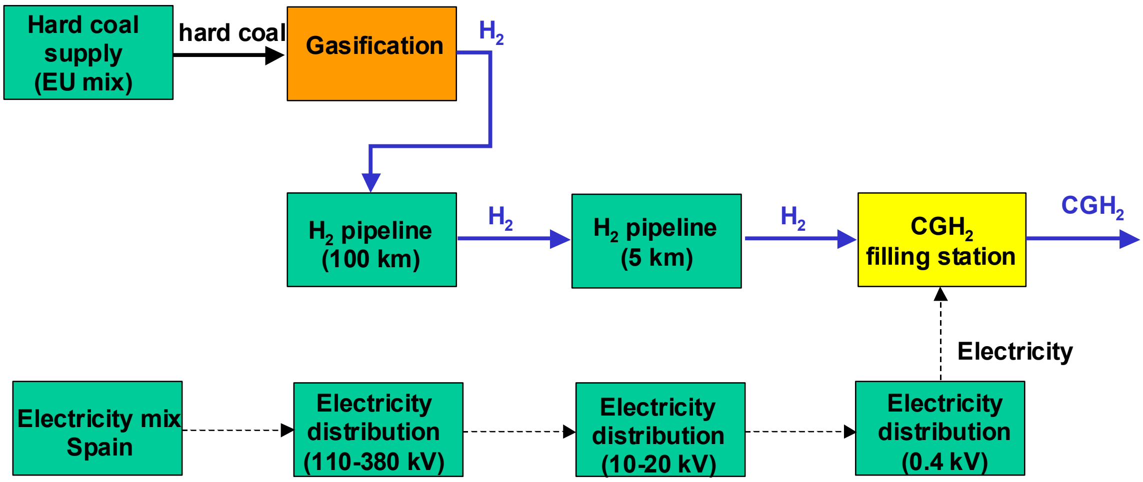

Figure 12. Modelled hydrogen chain for coal gasification without CCS, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Coal provision A.1
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from coal A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5

4.13. Chain 3.b. Hard Coal, Gasification, no CCS, CGH_2 truck; use: car filling station

Description

In this hydrogen chain, hydrogen is generated via gasification of hard coal without CO_2 capture and sequestration. The characteristics of the hard coal used are derived from the EU hard coal mix.

The produced hydrogen is compressed and then transported by a CGH_2 truck on 50 km.

Electricity required at the compressor is obtained from Spanish mix at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

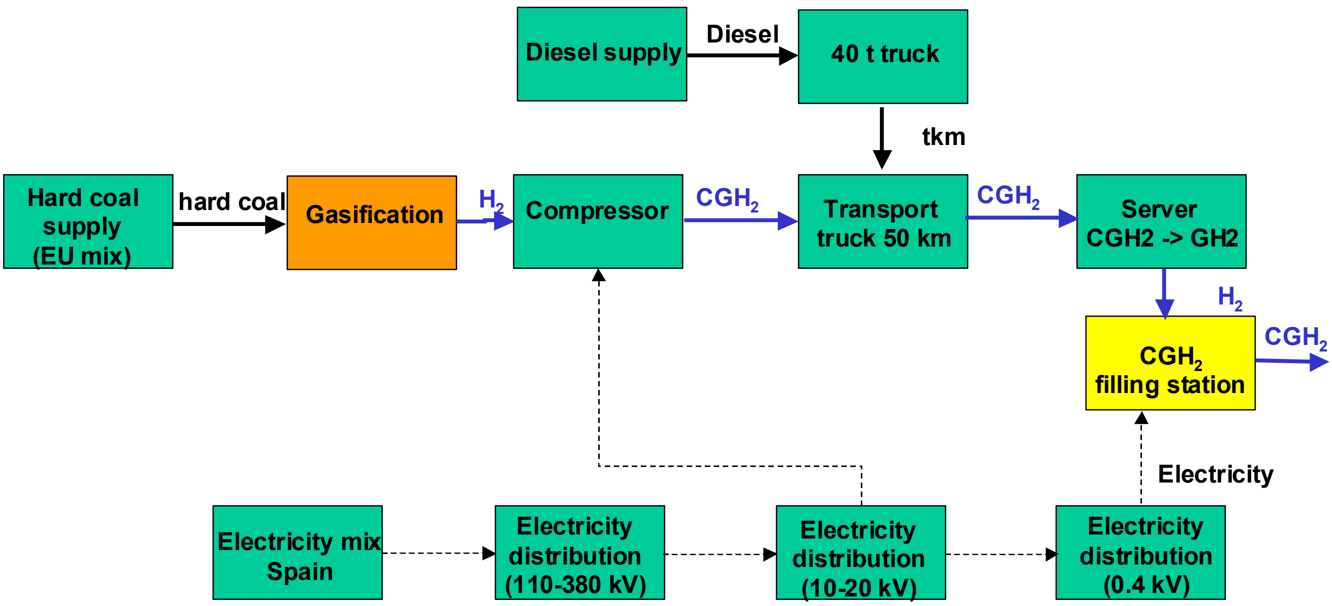

Figure 13. Modelled hydrogen chain for coal gasification without CCS, CGH_2 truck, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Coal provision A.1
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from coal A.3
- Hydrogen transport A.4
- Filling station A.5

4.14. Chain 3.c1. Hard Coal, Gasification with CCS, GH_2 pipeline; use: car filling station

Description

In this hydrogen chain, hydrogen is generated via gasification of hard coal with CO_2 capture and sequestration. The characteristics of the hard coal used are derived from the EU hard coal mix. The supply of CGH_2 to the filling stations is performed through a hydrogen pipeline grid. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

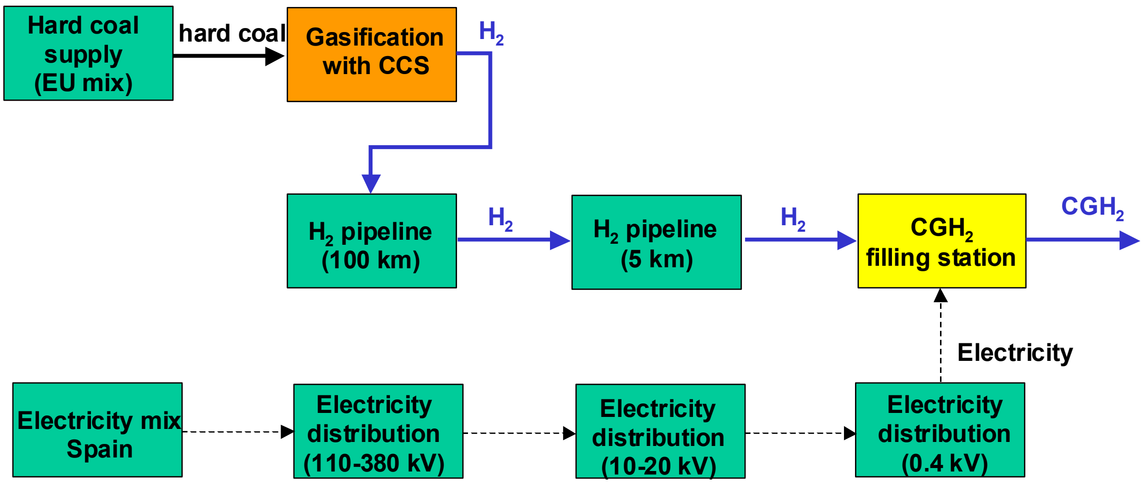

Figure 14. Modelled hydrogen chain for coal gasification with CCS, GH_2 pipeline ,for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Coal provision A.1
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from coal A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5

4.15. Chain 4.b. On shore wind power, central electrolysis, GH_2 pipeline; use: car filling station

Description

Electricity generated by on-shore wind turbines is distributed to a central electrolysis plant.
The supply of CGH_2 to the filling stations is performed through a hydrogen pipeline grid. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

Electricity required at the electrolysis plant is obtained from electricity at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

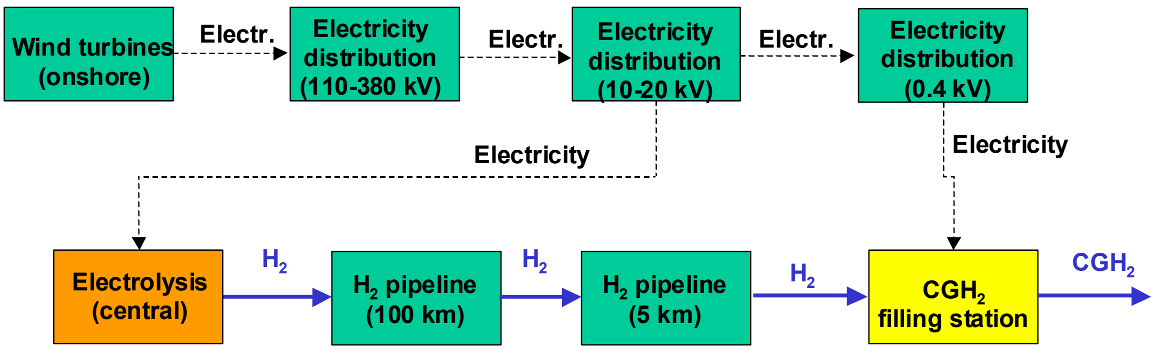

Figure 15. Modelled hydrogen chain for central electrolysis with on-shore wind turbines, GH_2 pipeline, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5

4.16. Chain 4.c. On shore wind power, central electrolysis, CGH_2 truck; use: car filling station

Description

Electricity generated by on-shore wind turbines is distributed to a central electrolysis plant. The produced hydrogen is compressed and then transported by a CGH_2 truck on 50 km.

Electricity required at the electrolysis plant is obtained from electricity at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

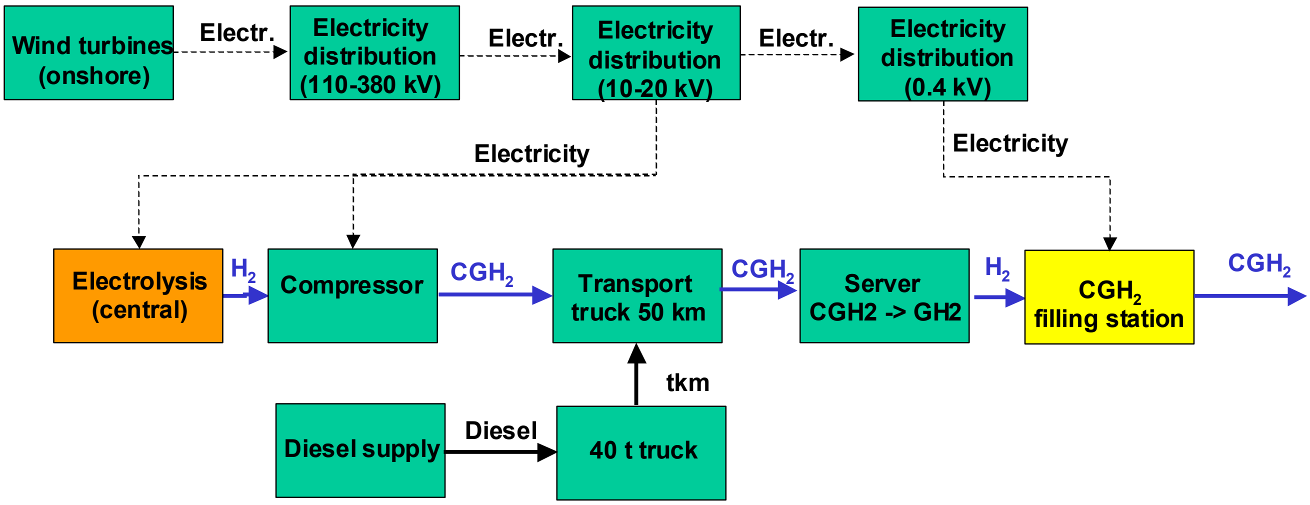

Figure 16. Modelled hydrogen chain for central electrolysis with on-shore wind turbines, CGH_2 truck, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport A.4
- Filling station A.5

4.17. Chain 4.d. Off shore wind power, central electrolysis, GH_2 pipeline; use: car filling station

Description

Electricity generated by off-shore wind turbines is distributed to a central electrolysis plant. The supply of CGH_2 to the filling stations is performed through a hydrogen pipeline grid. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

Electricity required at the electrolysis plant is obtained from electricity at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

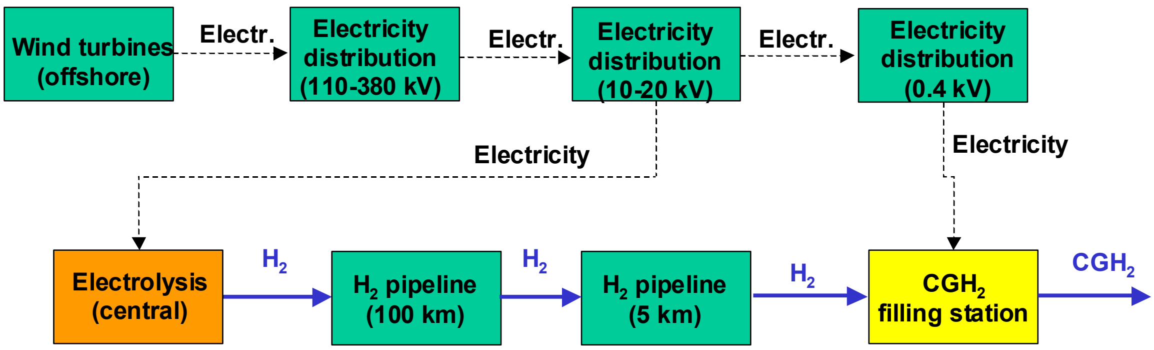

Figure 17. Modelled hydrogen chain for central electrolysis with off-shore wind turbines, GH_2 pipeline, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5

4.18. Chain 4.e. Off shore wind power, central electrolysis, CGH_2 truck; use: car filling station

Description

Electricity generated by off-shore wind turbines is distributed to a central electrolysis plant. The produced hydrogen is compressed and then transported by a CGH_2 truck on 50 km.

Electricity required at the electrolysis plant and the compressor is obtained from electricity at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

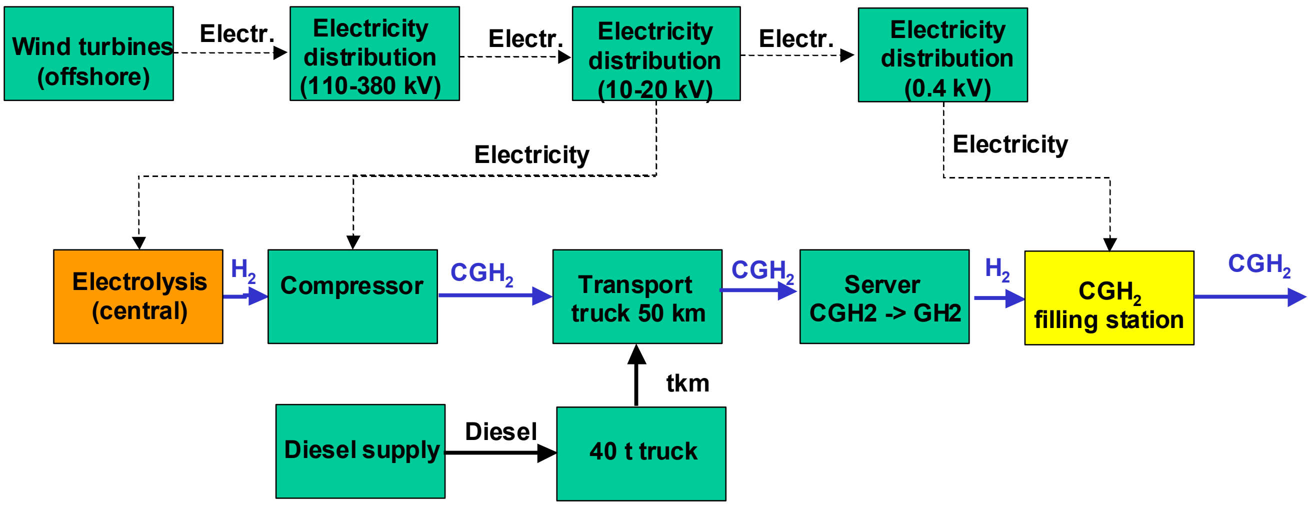

Figure 18. Modelled hydrogen chain for central electrolysis with off-shore wind turbines, CGH_2 truck, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production	A.1
- Electricity transport	A.2
- Hydrogen production	A.3
- Hydrogen transport	A.4
- Filling station	A.5

4.19. Chain 5.a. Solar thermal, thermo chemical cycles (mixed ferrites), GH_2 pipeline; use: car filling station

Description

The Thermal power is converted into heat which is used to decompose $ZnFe_2O_4$ to produce GH_2 (mixed ferrites cycle).

The supply of CGH_2 to the filling stations is performed through a hydrogen pipeline grid. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

Electricity required at the filling station is obtained from Spanish mix at low-voltage level.

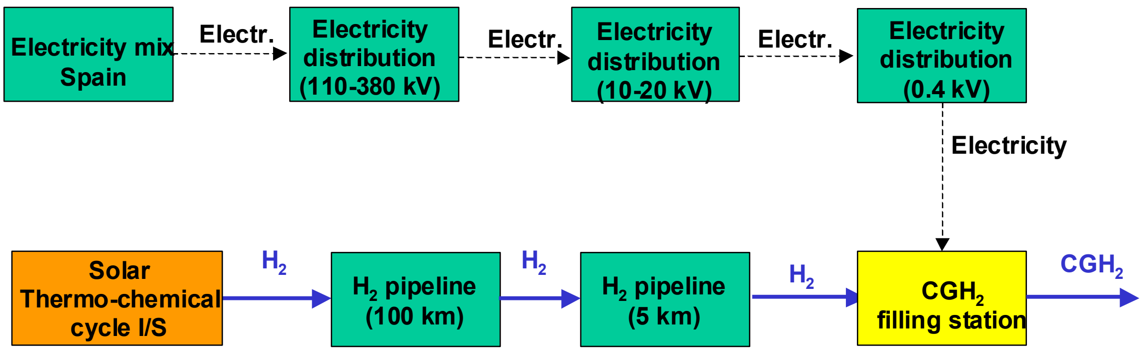

Figure 19. Modelled hydrogen chain for solar thermal, thermo chemical cycles mixed ferrites, GH_2 pipeline, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5

4.20. Chain 5.b. Solar thermal, thermo chemical cycles (mixed ferrites), CGH_2 truck; use: car filling station

Description

The Thermal power is converted into heat which is used to decompose $ZnFe_2O_4$ to produce GH_2 (mixed ferrites cycle).

The produced hydrogen is compressed and then transported by a CGH_2 truck on 50 km to the filling stations.

Electricity required at the compressor is obtained from Spanish mix at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

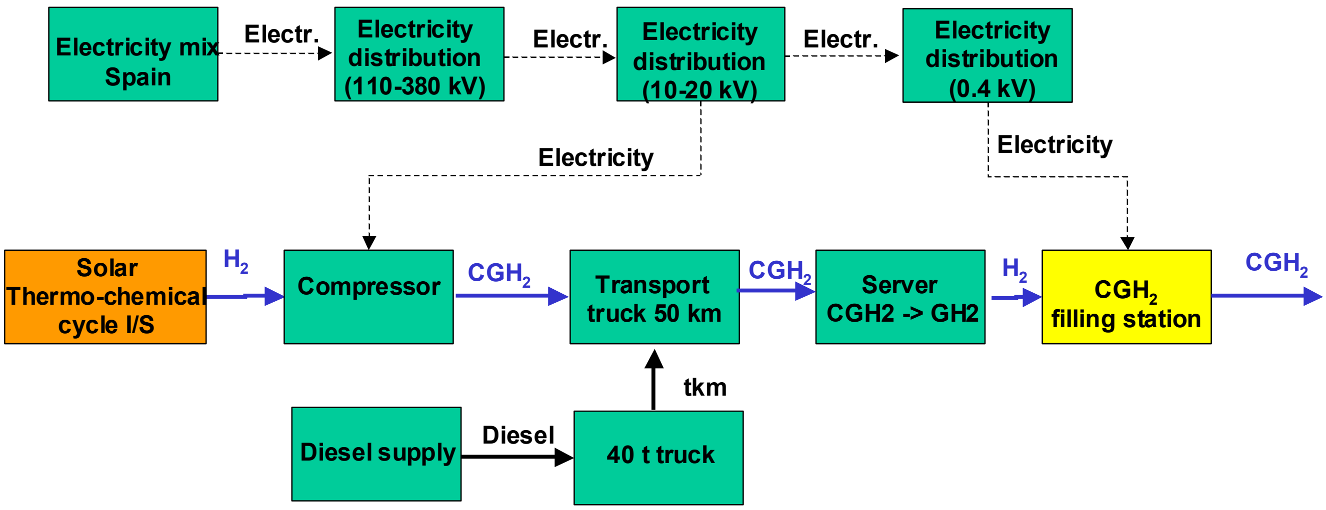

Figure 20. Modelled hydrogen chain for solar thermal, thermo chemical cycles mixed ferrites, CGH_2 truck, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport A.4
- Filling station A.5

4.21. Chain 6.a. Spanish Mix Electricity, On Site Electrolysis, GH_2 pipeline; use: car filling station

Description

Electricity coming from the Spanish mix is distributed to an on site electrolysis plant. Gaseous hydrogen produced by this plant feed the CGH_2 filling station.

Electricity required at the electrolysis plant is obtained from Spanish mix at a medium-voltage level whereas electricity required at the filling stations is obtained from Spanish mix at a low-voltage level.

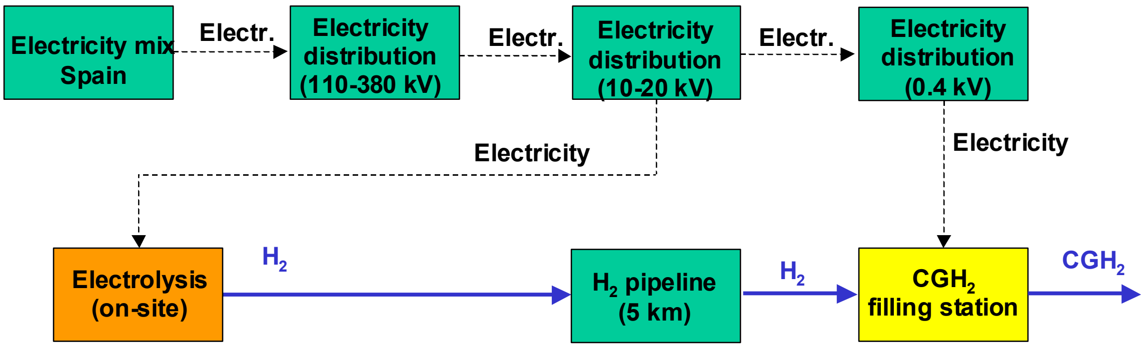

Figure 21. Modelled hydrogen chain for Spanish Mix Electricity, On site electrolysis, GH_2 pipeline, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production through electrolysis A.3
- Hydrogen transport A.4
- Filling station A.5

4.22. Chain 7.a. By-product, CGH_2 truck; use: car filling station

Description

By-product hydrogen is generated by various types of industrial processes e.g. in refineries. Today the by-product hydrogen is used as fuel for the supply of process heat within the industry. If the by-product is exported as product e.g. for hydrogen vehicles within the industry additional natural gas will be required for the supply of process heat. Therefore the generation of by-product hydrogen can be considered as a process with natural gas as input and hydrogen as output and a conversion efficiency of 100%.

The produced hydrogen is compressed and then transported by a CGH_2 truck on 50 km to the filling stations.

Electricity required at the compressor is obtained from Spanish mix at a medium-voltage level, whereas electricity required at the filling station is required at low-voltage level.

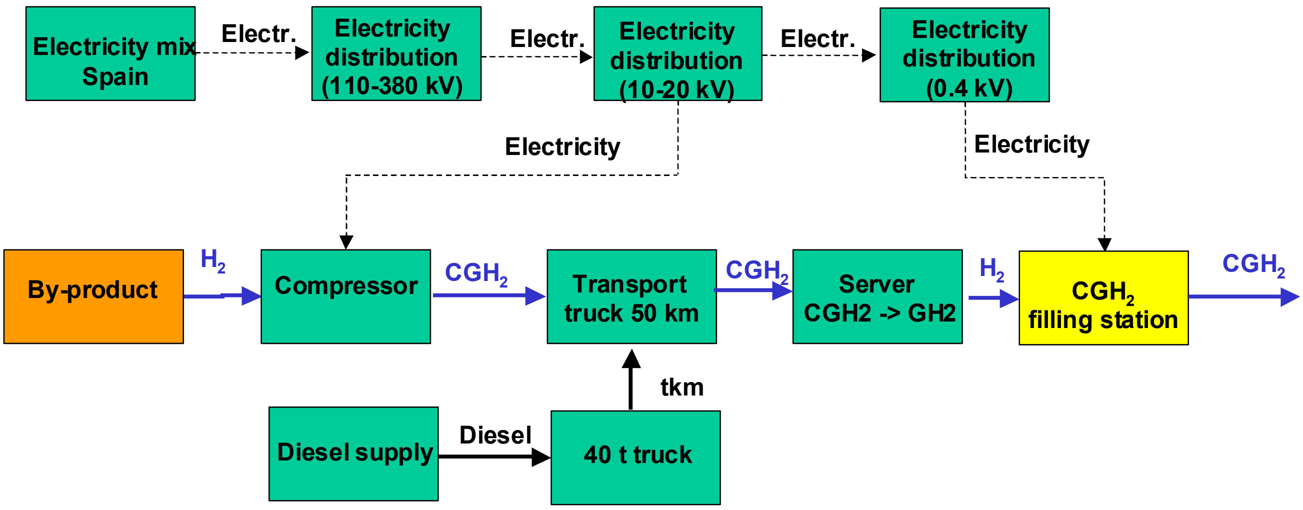

Figure 22. Modelled hydrogen chain for by-product, for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity provision A.1
- Electricity transport A.2
- Hydrogen transport A.4
- Filling station A.5

4.23. Chain 8.a. Dedicated nuclear reactor, Central High Temperature Electrolysis, GH_2 pipeline; use: car filling station

Description

The heat produced by the nuclear reaction in the EPR reactor is divided in two parts. The first one is used in the turbines to produced the electricity needed in the high temperature electrolysis plant (HTE) whereas the second one is transported on 10 km to HTE. Gaseous hydrogen (CGH_2) produced by this plant is subsequently distributed to the filling stations. Therefore, the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

Electricity required at the compressor is obtained from Spanish mix at low-voltage level.

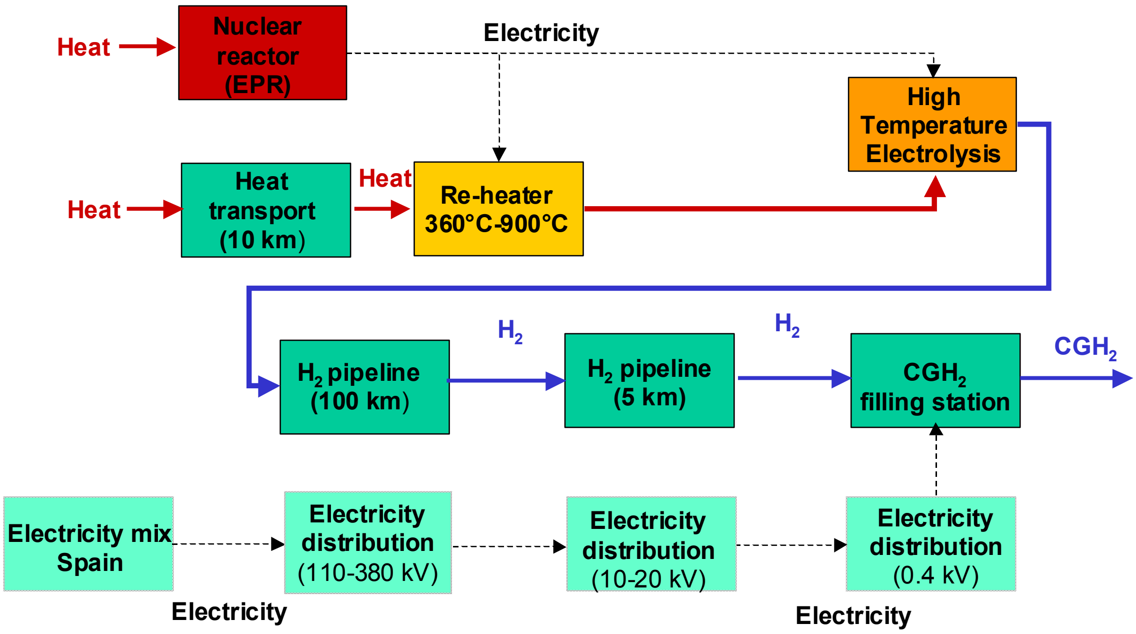

Figure 23. Modelled hydrogen chain for central HT electrolysis, electricity from dedicated nuclear reactor (EPR), for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity provision A.1
- Electricity transport A.2
- Hydrogen production through HT electrolysis A.3
- Hydrogen transport A.4
- Filling station A.5

4.24. Chain 8.b. Dedicated nuclear reactor, Thermo-chemical cycle (S/I), GH_2 pipeline; use: car filling station

<u>Description</u>
The heat produced by the nuclear reactor is used to decompose H_2SO_4 to produce GH_2 (sulphur iodine cycle).
Gaseous hydrogen (GH_2) produced by this plant is subsequently distributed to the filling stations. Therefore, the hydrogen grid consists of a large pipeline (50 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

Electricity required at the compressor is obtained from Spanish mix at low-voltage level.

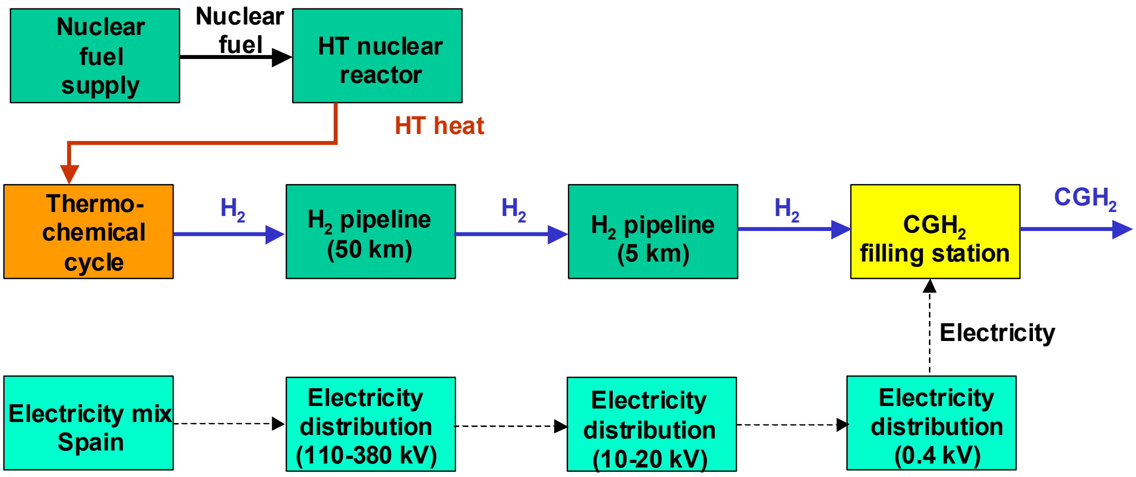

Figure 24. Modelled hydrogen chain for thermo-chemical cycle (S/I), for use in filling stations

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity provision A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport A.4
- Filling station A.5

4.25. Chain 3.a2. Hard Coal, Gasification, no CCS, GH_2 pipeline; use: stationary

Description

In this hydrogen chain, hydrogen is generated via gasification of hard coal without CO_2 capture and sequestration. The characteristics of the hard coal used are derived from the EU hard coal mix.

The supply of CGH_2 to the end users (domestic appliances) is performed through a hydrogen pipeline grid (the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year).

The gasification plant produces gaseous hydrogen at 880 bar. The CGH_2 distributed is used in combined fuel cells (FC CHP) that follow the heat demand of the users. In the case that the heat demand is covered, more electricity will on average be produced that the users require. At those moments, some electricity generation elsewhere will be avoided. This process is accounted in the model as "credit".

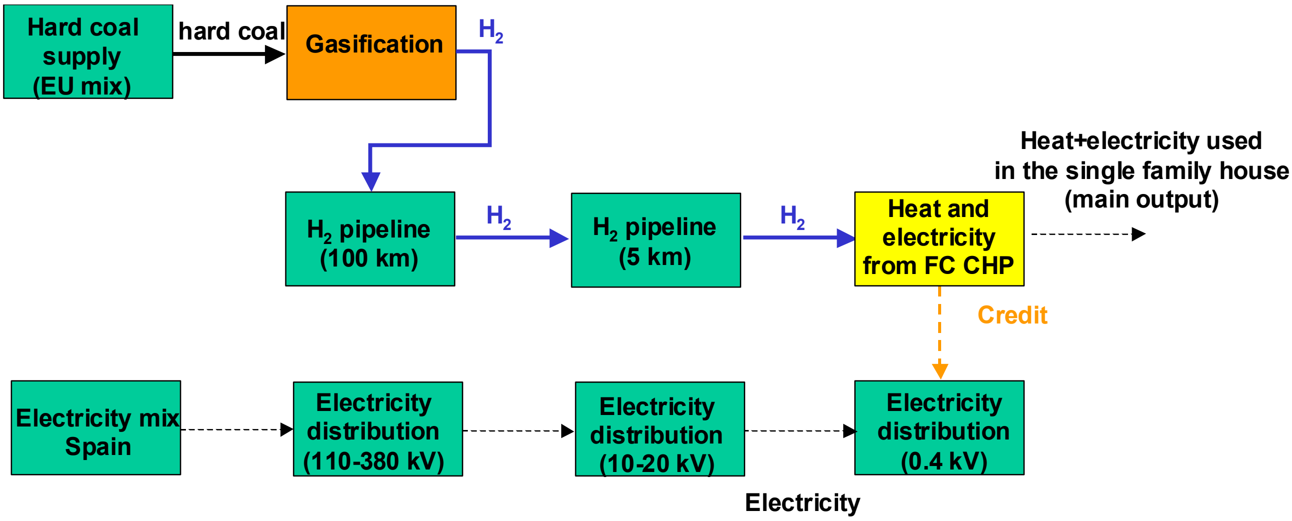

Figure 25. Modelled hydrogen chain for coal gasification without CCS, for use in FC CHP

For description of the processes used for the model of this chain, see sections indicated below:

- Coal provision A.1
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from coal A.3
- Hydrogen transport by pipeline A.4
- FC CHP A.5

4.26. Chain 3.c2. Hard Coal, Gasification with CCS, GH_2 pipeline; use: stationary

Description

In this hydrogen chain, hydrogen is generated via gasification of hard coal with CO_2 capture and sequestration. The characteristics of the hard coal used are derived from the EU hard coal mix.
The supply of CGH_2 to the end users (domestic appliances) is performed through a hydrogen pipeline grid (the hydrogen grid consists of a large pipeline (100 km) with a throughput of 240 GWh H_2 per pipeline and year and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year).
The gasification plant produces gaseous hydrogen at 880 bar. The CGH_2 distributed is used in combined fuel cells (FC CHP) that follow the heat demand of the users. In the case that the heat demand is covered, more electricity will on average be produced that the users require. At those moments, some electricity generation elsewhere will be avoided. This process is accounted in the model as "credit".

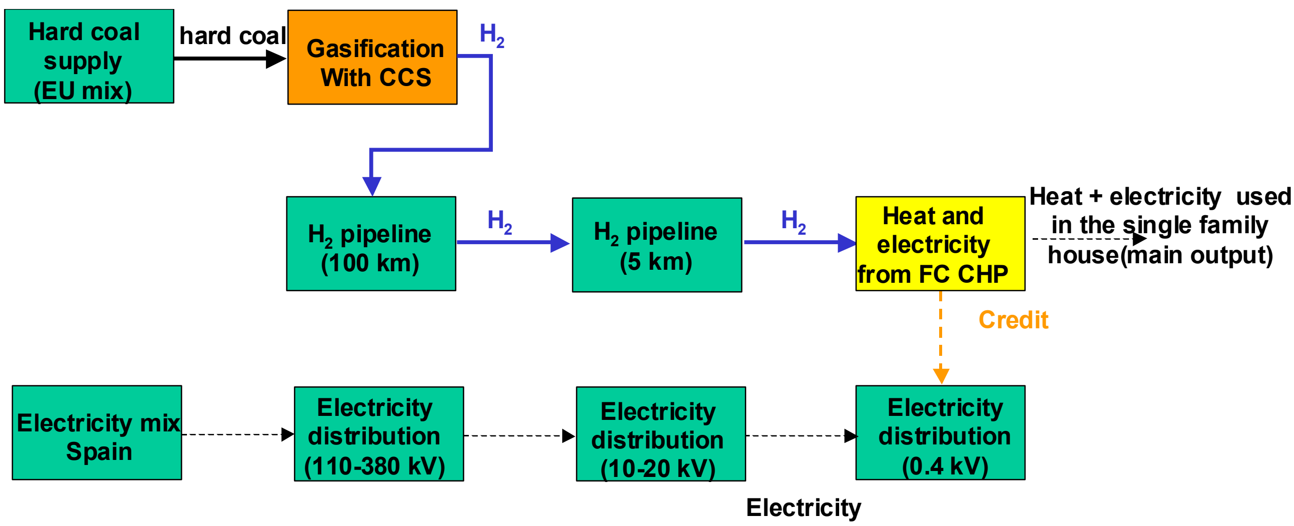

Figure 26. Modelled hydrogen chain for coal gasification with CCS, for use in FC CHP

For description of the processes used for the model of this chain, see sections indicated below:

- Coal provision A.1
- Electricity production A.1
- Electricity transport A.2
- Hydrogen production from coal A.3
- Hydrogen transport by pipeline A.4
- FC CHP A.5

4.27. Chain 4.a. On shore wind power, on site electrolysis, GH_2 pipeline; use: stationary

Description

Electricity generated by on-shore wind turbines is distributed to an on site electrolysis plant. The CGH_2 distributed is used in combined fuel cells (FC CHP) that follow the heat demand of the users. In the case that the heat demand is covered, more electricity will on average be produced than the users require. At those moments, some electricity generation elsewhere will be avoided. This process is accounted in the model as "credit".

Electricity required at the electrolysis plant is obtained from electricity at a medium-voltage level.

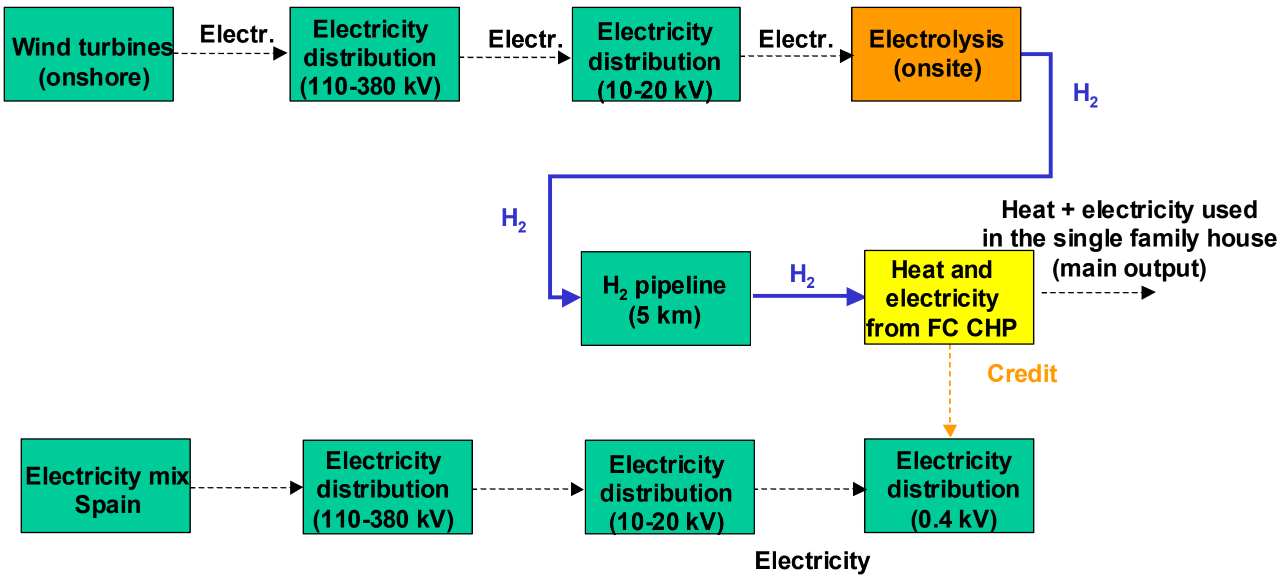

Figure 27. Modelled hydrogen chain for on-site electrolysis with on-shore wind turbines, for use in FC CHP

For description of the processes used for the model of this chain, see sections indicated below:

- Electricity production A.1
- Electricity transport A.2
- Hydrogen production A.3
- Hydrogen transport by pipeline A.4
- FC CHP A.5

5. Results

5.1. Hypothesis required for calculations

The calculated costs (kWh of hydrogen for mobile applications or kWh of heat + electricity for stationary applications) are levelized for the years 2020, 2030 and 2050 according to the calculation rules presented in 7. For Spain, a discount rate of 6% has been used.

In the following paragraphs, the results for mobile and stationary applications are given for 1 provided kWh. For mobile applications, well-to-tank (WTT) analyses have been performed. For stationary use, the analyses are of the type well-to-stationary-use (WTStU).

5.2. Efficiencies: WTT and WTStU

The following figures show the efficiencies of all selected hydrogen supply chains in accordance to the following list:

Description of mobile supply chains

Chain 1.a. Biomass, Central Gasification, no CCS (2020, 2030, 2050)
Chain 2.a1. Natural Gas (pipeline), Central SMR, no CCS, GH_2 pipelines; (2020, 2030)
Chain 2.a2. Natural Gas (ship), Central SMR, no CCS, GH_2 pipelines; (2020, 2030)
Chain 2.b1. Natural Gas (pipeline), Central SMR, no CCS, CGH_2 trucks; (2020, 2030)
Chain 2.b2. Natural Gas (ship), Central SMR, no CCS, CGH_2 trucks; (2020, 2030)
Chain 2.c1. Natural Gas (pipeline), Central SMR, no CCS, LH_2 trucks; (2020, 2030)
Chain 2.c2. Natural Gas (ship), Central SMR, no CCS, LH_2 trucks; (2020, 2030)
Chain 2.d1. Natural Gas (pipeline), Central SMR with CCS, GH_2 pipelines; (2030, 2050)
Chain 2.d2. Natural Gas (ship), Central SMR with CCS, GH_2 pipelines; (2030, 2050)
Chain 2.e1. Natural Gas (pipeline), On-site SMR, no CCS, GH_2 pipelines; (2020, 2030, 2050)
Chain 2.e2. Natural Gas (ship), On-site SMR, no CCS, GH_2 pipelines; (2020, 2030, 2050)
Chain 3.a1. Hard Coal, Gasification, no CCS, GH_2 pipeline; (2020, 2030)
Chain 3.b. Hard Coal, Gasification, no CCS, CGH_2 truck; (2020)
Chain 3.c1. Hard Coal, Gasification with CCS, GH_2 pipeline; (2030, 2050)
Chain 4.b. On shore wind power, central electrolysis, GH_2 pipeline; (2020, 2030, 2050)
Chain 4.c. On shore wind power, central electrolysis, CGH_2 truck; (2020, 2030, 2050)
Chain 4.d. Off shore wind power, central electrolysis, GH_2 pipeline; (2030, 2050)
Chain 4.e. Off shore wind power, central electrolysis, CGH_2 truck; (2030, 2050)
Chain 5.a. Solar thermal, thermo chemical cycles (mixed ferrites), GH_2 pipeline; (2050)
Chain 5.b. Solar thermal, thermo chemical cycles (mixed ferrites), CGH_2 truck; (2030, 2050)
Chain 6.a. Spanish Mix Electricity, On Site Electrolysis, GH_2 pipeline; (2030, 2050)
Chain 7.a. By-product, CGH_2 truck; (2020)
Chain 8.a. Dedicated nuclear reactor, Central High Temperature Electrolysis, GH_2 pipeline; (2050)
Chain 8.b. Dedicated nuclear reactor, Thermo-chemical cycle (S/I), GH_2 pipeline; (2050)

Description of stationary use of hydrogen supply chains

Chain 3.a2. Hard Coal, Gasification, no CCS, GH_2 pipeline; (2020, 2030)
Chain 3.c2. Hard Coal, Gasification with CCS, GH_2 pipeline; (2030, 2050)
Chain 4.a. On shore wind power, on site electrolysis, GH_2 pipeline; (2020, 2030, 2050)

Figure 28 shows the efficiencies of the selected chains for the provision of hydrogen for mobile end users.

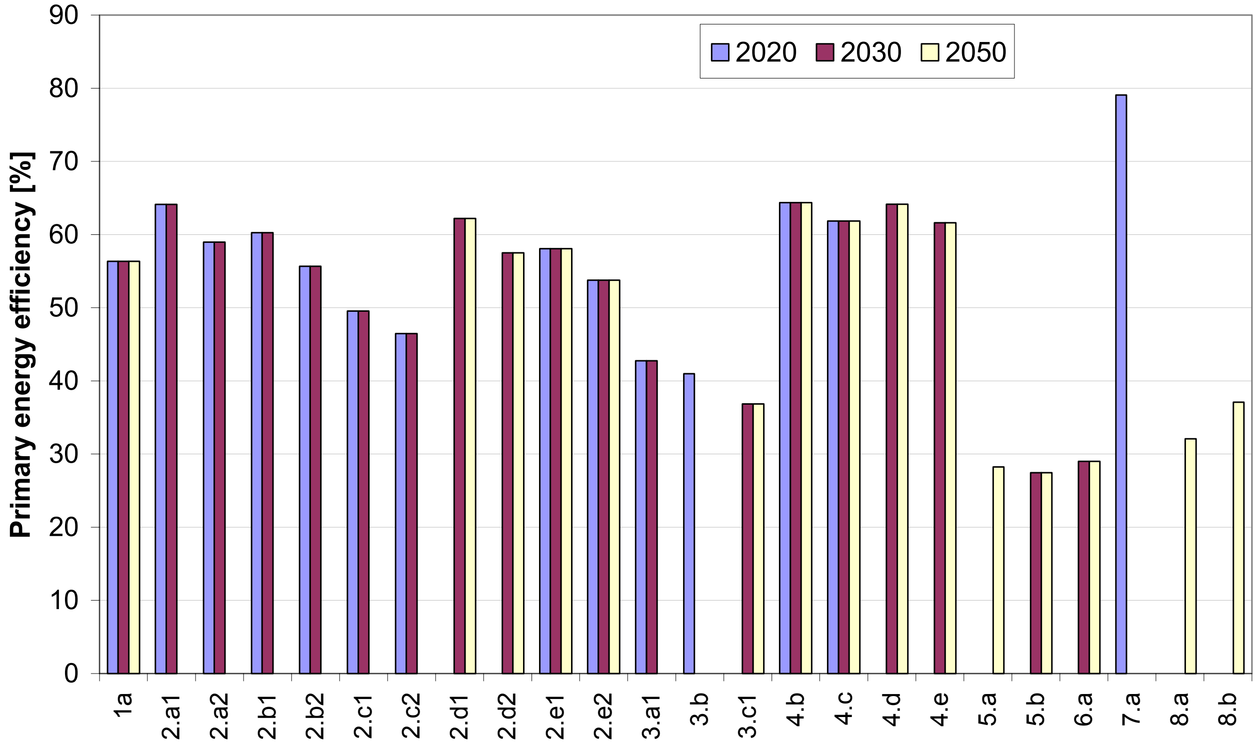

Figure 28. Efficiencies of selected mobile H2 supply chains

Figure 29 shows the efficiencies of the selected chains for the provision of hydrogen for stationary end users.

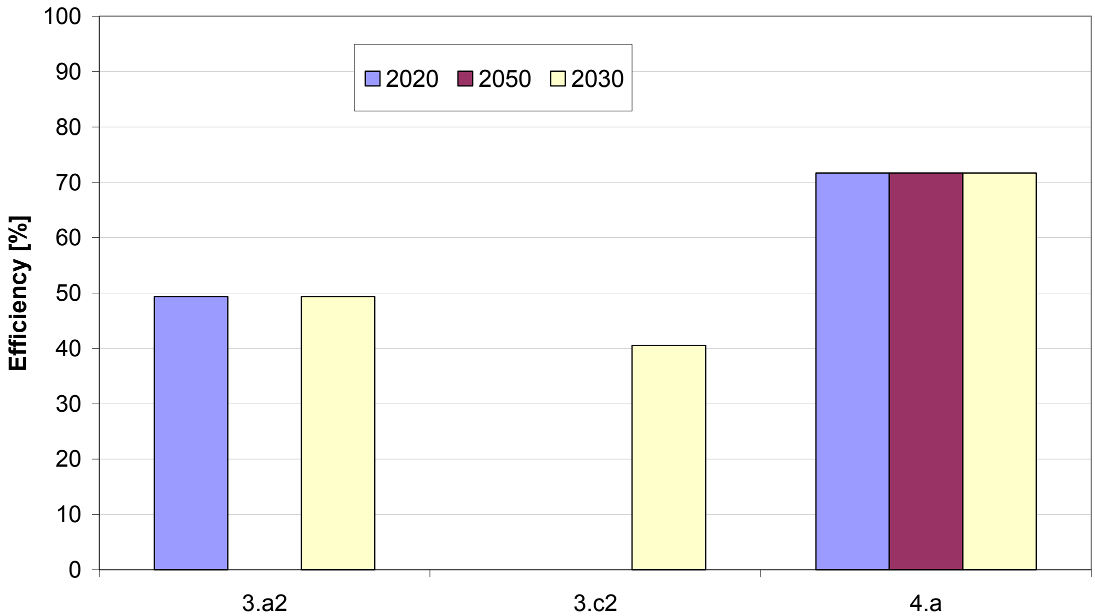

Figure 29. Efficiencies of selected H_2 supply chains for stationary use

5.3. Greenhouse Gas Emissions: WTT and WTStU

In 2020 there are five ways to produce hydrogen for the mobile applications : Biomass gasification, Steam Methane Reforming (without CCS), Coal gasification (without CCS), Wind Power electrolysis (on-shore) and by-product. Figure 30 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

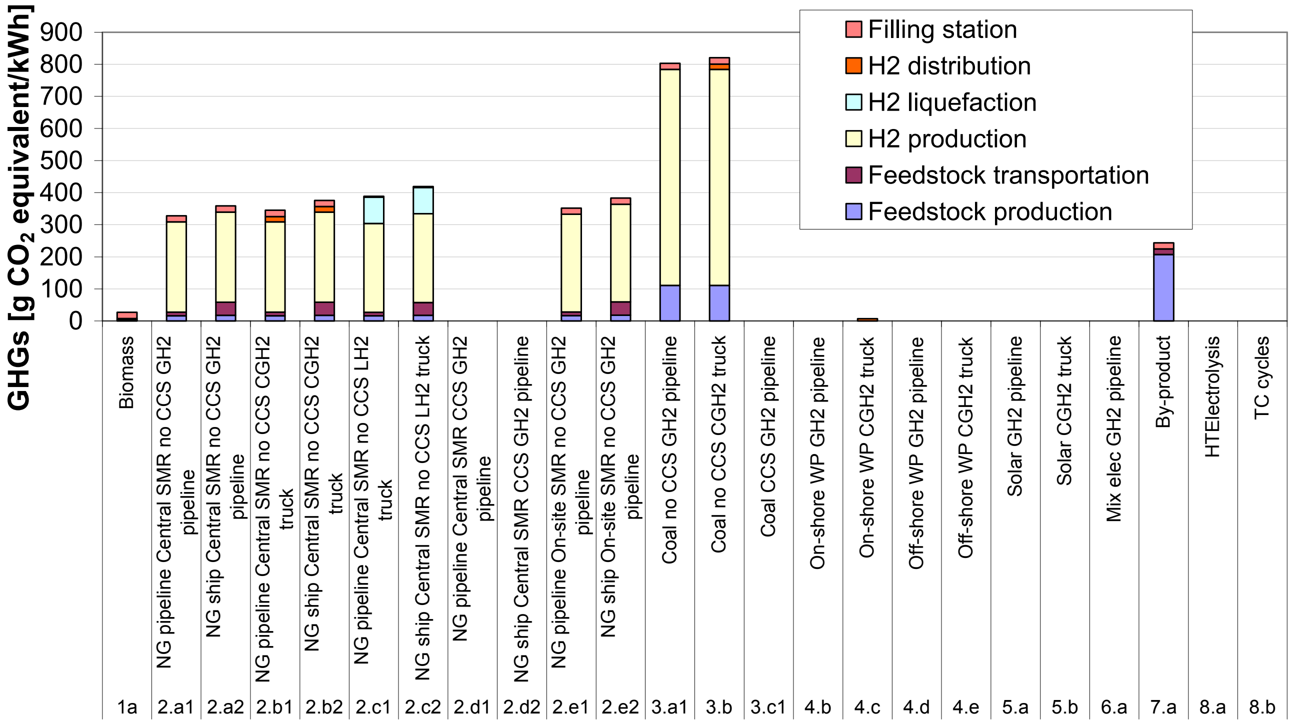

Figure 30. CO_2-equivalent emissions of mobile H_2 supply chains in 2020

In 2020, we assumed that there is no carbon capture and sequestration (CCS), that is why there are many GHG emissions when using a SMR (chains 2.) or a coal gasification plant (chains 3.). In these two cases, the GHG emissions are mainly due to the hydrogen production. The second cause of GHG emissions is the hydrogen liquefaction which needs electricity from the Spanish mix.

Using by-product (chain 7.) leads to more emissions than using biomass (chain 1.) and on-shore electrolysis (chains 4.b and 4.c).

In 2030 there are six ways to produce hydrogen for the mobile applications : Biomass gasification, Steam Methane Reforming (with and without CCS), Coal gasification (with and without CCS), Wind Power electrolysis (on-shore and off-shore), Solar thermal Cycles S/I and central electrolysis with electricity mix. Figure 31 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

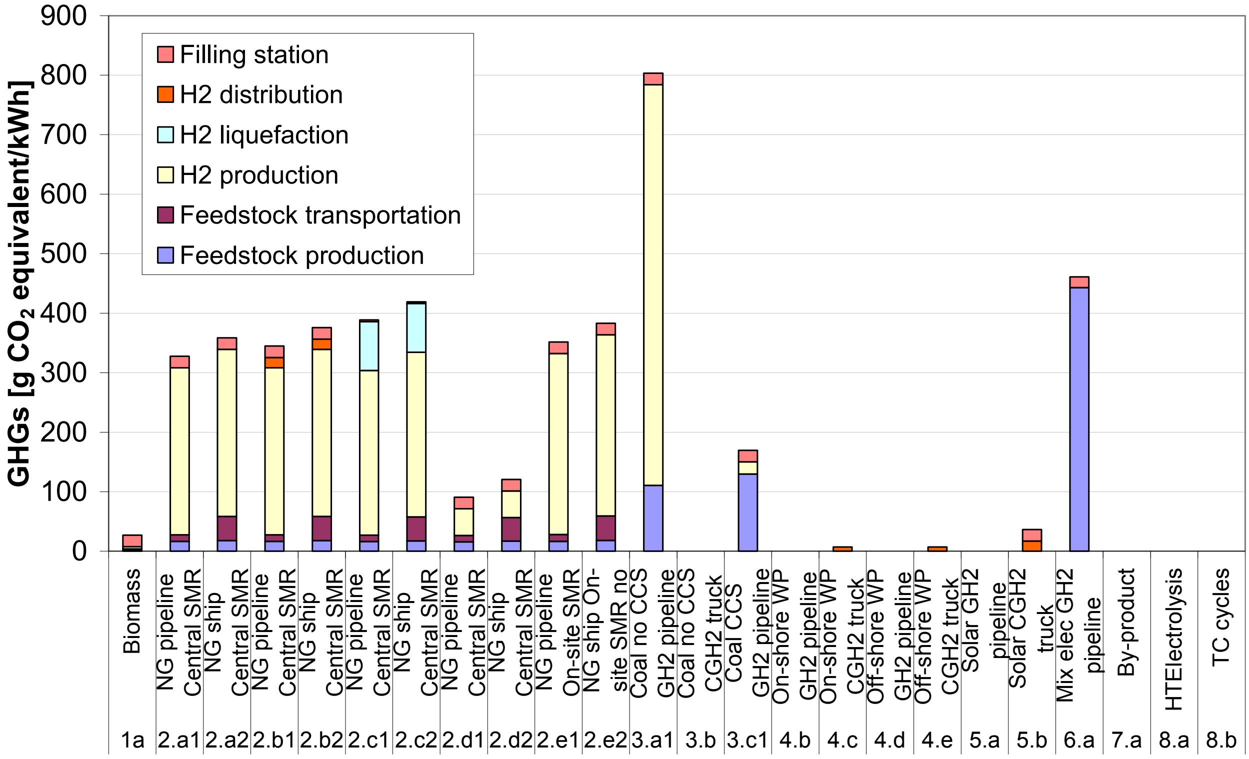

Figure 31. CO_2-equivalent emissions of mobile H_2 supply chains in 2030

In 2030, we assumed that the CCS is feasible. It can be observed with SMR (chain 2.d) and with coal gasification (chain 3.c). However, we don't assumed CCS for the production of electricity which explain the high emissions for water electrolysis since the Spanish mix produces many GHG (due the high part of coal and NG in the mix).

In 2050 there are eight ways to produce hydrogen for the mobile applications : Biomass gasification, Steam Methane Reforming (Central with CC and On-site without CCS), Coal gasification (with CCS), Wind Power electrolysis (on-shore and off-shore), Solar thermal Cycles S/I, Central electrolysis with electricity mix, High temperature electrolysis and Nuclear TC cycle S/I. Figure 32 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

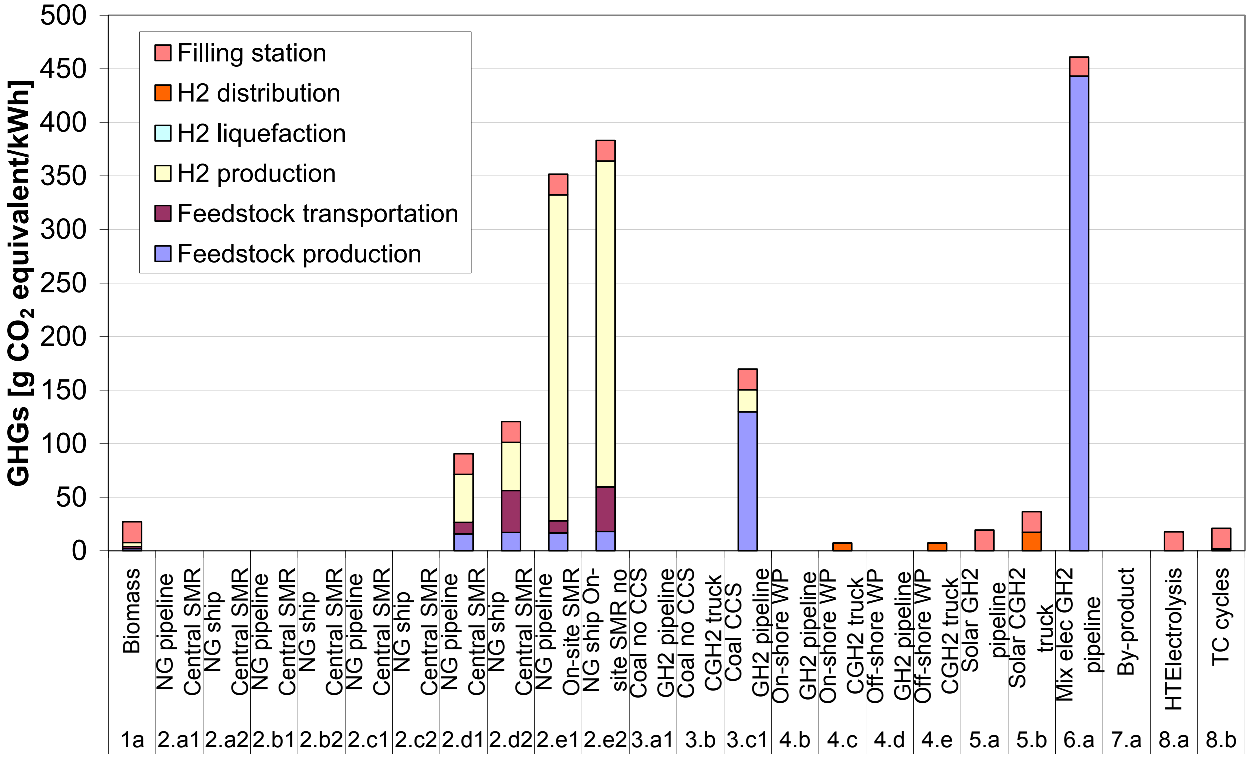

Figure 32. CO_2-equivalent emissions of mobile H_2 supply chains in 2050

Since we don't assumed CCS for the production of electricity, the production of hydrogen by water electrolysis is the bigger GHG producer. Then we find On-site SMR (no CCS). The other ways have few emissions thanks to CCS.

There are three ways to produce hydrogen for the stationary applications : Coal gasification without CCS (2020, 2030), Coal gasification with CCS (2030) and On-shore wind power electrolysis (2020,2030,2050). Figure 33 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

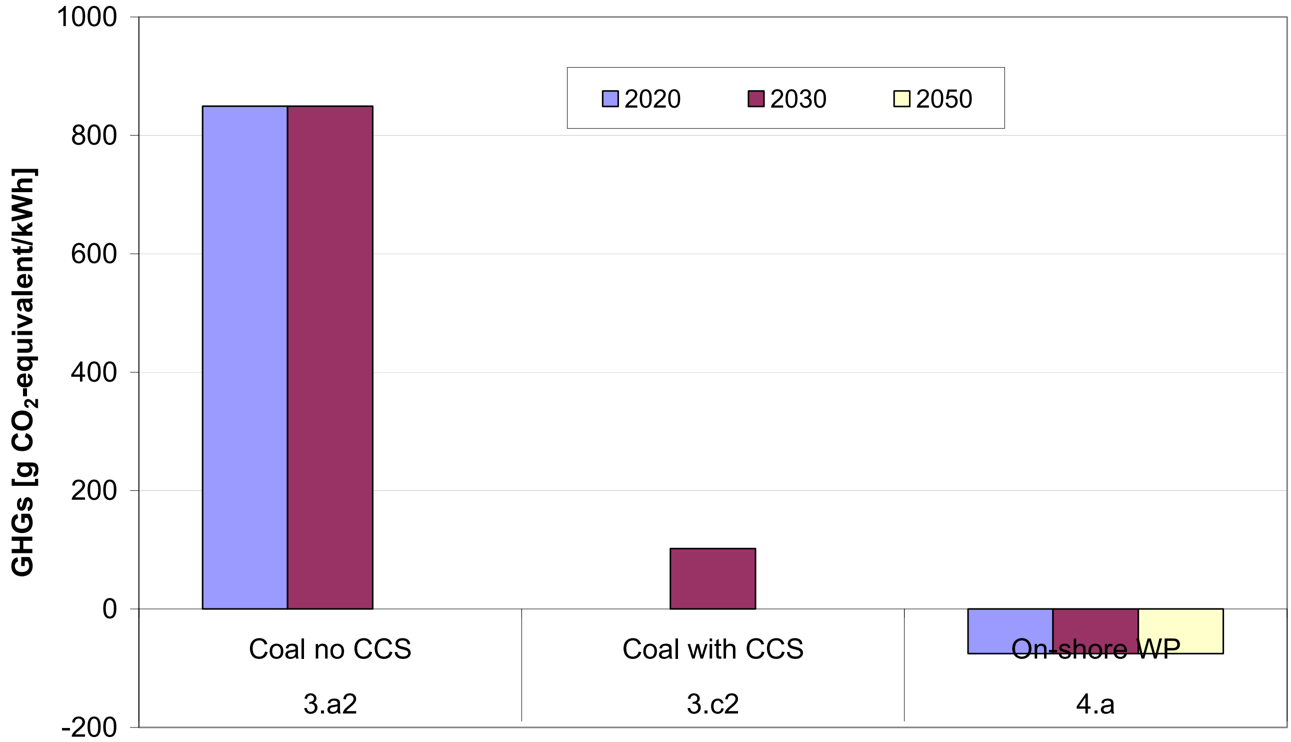

Figure 33. CO_2-equivalent emissions of stationary use of H_2 supply chains

Obviously, the coal gasification without CCS is the main GHG producer.
The negative GHG in the case of on-shore wind power can be explain by the fact that wind power produces no GHG and the FC produces some electricity sold to the grid as a credit, which avoids some GHG due to the mix.

5.4. Costs: WTT and WTStU

In Figure 34 and Figure 35, the given costs are calculated in [€/kWh] hydrogen, delivered at 880 bar to provide a full pressure of 700 bar to the vehicle tank for mobile applications and heat + electricity for stationary applications.

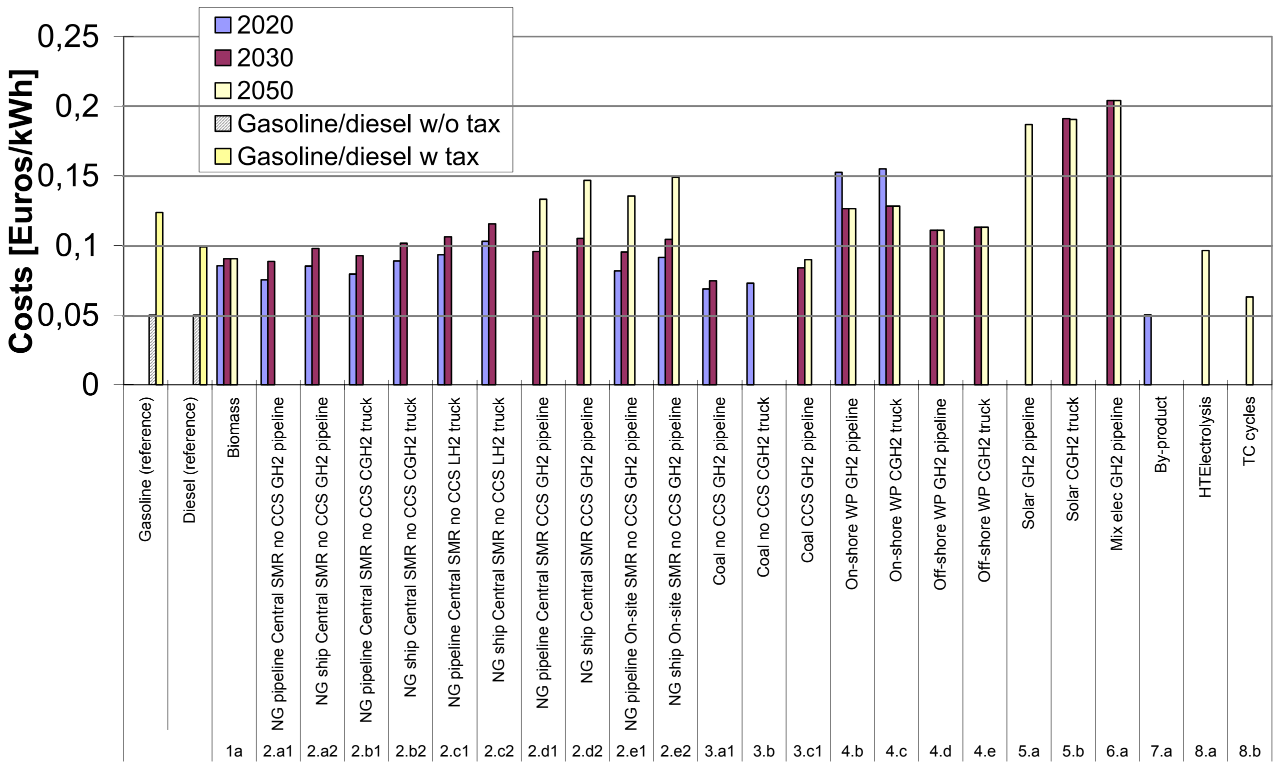

Figure 34. Costs of selected mobile hydrogen supply chains.

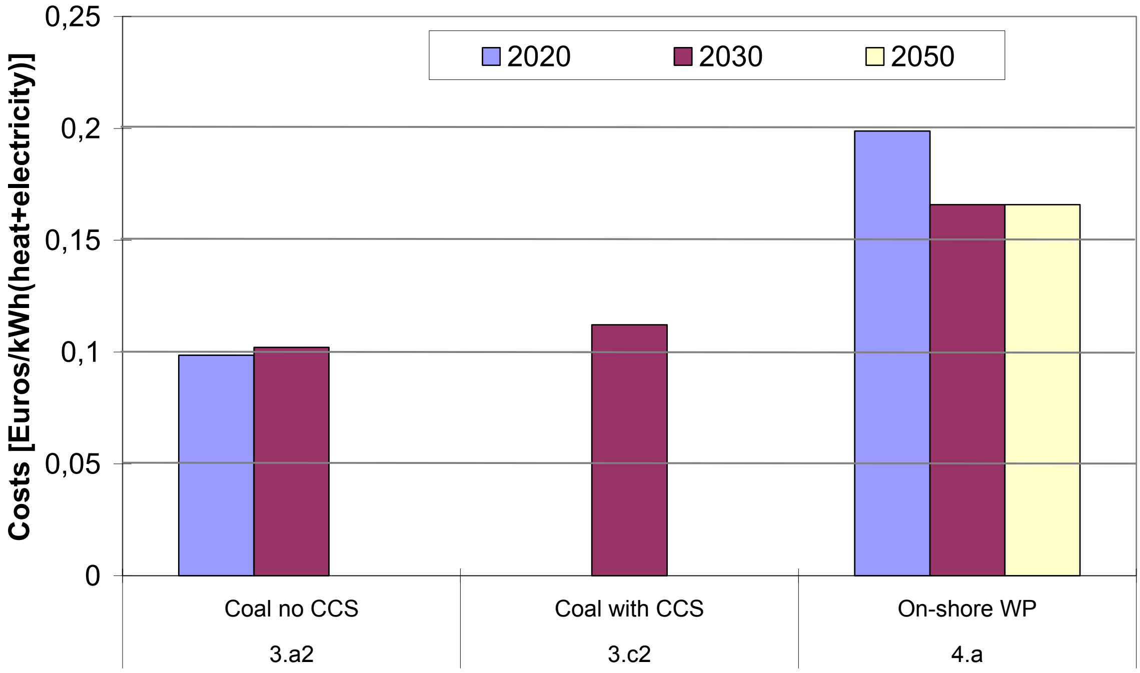

Figure 35. Costs of selected stationary use hydrogen supply chains.

The use of by-product is the cheapest way.
We can clearly see the increase of NG price from 2020 to 2050. In 2030, wind power is competitive with SMR.
HT processes (HTE and TC cycles) appears to be cheaper than Coal gasification with CCS, whereas Solar thermal is very expensive (quite as expensive as electrolysis with the Spanish mix).

6. Remarks

In this report a synthesis of the selected chains and data for Spain has been performed. The tables presented allow a synthetically overview of the choices made.

7. Calculation rules

- **Conversion factors for Greenhouse Gas Equivalents**

For the conversion of the different greenhouse gases (GHG) to CO_2-equivalents, the following conversion factors have been used:

Table 3. Conversion factors [IPCC 2001]

Emission	g CO_2 equivalent per g
CO_2	1
CH_4	23
N_2O	296

- **Learning curves**

Economic learning curves have been applied to technologies that will be produced at large numbers of units e.g. hydrogen filling stations, onsite electrolysers and onsite steam reformers. The learning curve is defined by the following formula:

$$I = a \cdot N^{-b}$$

where:

I	=	Investment of the N^{th} unit
a	=	Investment of the 1^{st} unit
N	=	Number of units
b	=	Parameter

The parameter b ranges between 0.1 and 0.3. In some literature the so-called progress ratio (PR) is indicated. The progress ratio is used to express the progress of cost reductions for different technologies. The cost reduction is (1-PR) for each doubling of cumulative production. The progress ratio can be calculated by

$$PR = 2^{-b}$$

If the progress ratio (PR) is given, the investment of the N^{th} unit can be calculated by

$$I = a \cdot N^{\frac{\ln(PR)}{\ln(2)}}$$

For the calculation of the fuel supply costs for the average investment per unit has to be considered. This means that e.g. if 10,000 hydrogen filling stations will be installed the investment of the 1st filling station as well as the investment of the last filling stations influences the fuel supply costs. Therefore for the cost calculation in E3 database the average investment has been used. The average investment can be calculated by integration of the formula for the learning curve:

$$A = \frac{a}{N} \cdot \int_1^N N^{-b} dN = \frac{a}{N} \cdot \left[\frac{1}{1-b} \cdot \left(N^{1-b} - 1 \right) + 1 \right]$$

where A = average investment of one unit. As a result, the average investment is always higher than the investment of the N^{th} unit.

- **Scaling by size**

The investment for volume related technologies (in contrast to surface related technologies e.g. photovoltaics) like coal power stations but also steam reforming plants and hydrogen liquefaction plants do not increase linearly with the size of the plants. The investment of a plant with a size required here can be calculated by

$$I_2 = I_1 \cdot \left(\frac{C_2}{C_1} \right)^{0.7}$$

where

I_1	=	Investment of the plant with capacity C_1
I_2	=	Investment of the plant with capacity C_2
C_1	=	Capacity of plant 1
C_2	=	Capacity of plant 2

- **Levelized costs**
  - *Cost calculation for phase T1 (construction of the plant)*

In this phase of the life cycle only capital expenditures are considered. It is assumed that a plant is built needing capital expenditures during its construction time T1.

$$C_{C(T1)} = C_{T1} = (Invest_{plant} \cdot r) \cdot T1 \cdot 0.5 \qquad [€]$$

where

$C_{C(T1)}$ =	Capital costs during construction of the plant
$Invest_{plant}$ =	Investment for the plant
r =	Interest rate
T1 =	Construction period in years

- *Cost calculation for phase T2 (operation of the plant)*

Capital costs

The capital costs are levelized by assuming equal capital expenditures for every year t in the period T2.

$$C_{DI(t)} = \frac{r}{1-(1+r)^{-T2}} \cdot Invest_{plant} \qquad [€/yr]$$

where
$C_{DI(t)}$ = Captial expenditure in every year t
r = Interest rate
T2 = Economic lifetime of the plant in years
$Invest_{plant}$ = Investment for the plant

Overhead costs

$$C_{OH(t)} = Invest_{plant} \cdot OH \qquad [€/yr]$$

where
$Invest_{plant}$ = Investment for the plant
OH = Overhead coefficient.

Operating and maintenance costs

The operating and maintenance expenditures in the year t are

$$C_{OM(t)} = Invest_{plant} \cdot OM + C_{Lab} \qquad [€/yr]$$

where
$C_{OM(t)}$ = Operatin and maintenance costs
$Invest_{plant}$ = Investment for the plant
OM = Maintenance coefficient
C_{Lab} = Labor costs in € per year

Energy and material costs

The processes are connected with upstream processes which supply the inputs. The costs of the inputs for a process are

$$C_{E(t)} = \sum_i Input_i \cdot IC_i \cdot P \cdot AFLH_t \qquad [€/yr]$$

where
$Input_i$ = Input of type i (e.g. natural gas, coal, etc.)
IC_i = Consumption of input of type i (e.g. kWh/kWh, kWh/kg, kg/kWh, kg/kg, tkm/kWh)
P = Process scale (e.g. in kWh/h, kg/h, tkm/h)

$AFLH_t$ Equivalent full load period (annual full load hours)

Levelized annual costs in period T_2

$$C_{T2(t)} = C_{DI(t)} + C_{OH(t)} + C_{OM(t)} + C_{E(t)} \qquad [€/yr]$$

$$C_{T2} = C_{T2(t)} \cdot T2 \qquad [€]$$

- *Cost calculation for phase T3 (dismantling of the plant)*

For the costs for the dismantling a fixed amount can be defined:

C_{T3} [€]

- *Levelized Costs*

Then the levelized costs per unit are

$$LEC = \frac{C_{T1} + C_{T2} + C_{T3}}{T2 \cdot AFLH_t \cdot P} \qquad [€/kWh], [€/kg], [€/tkm]$$

where:
LEC = Levelized costs

- *Use of specific costs for "processes" / plants*

There are situations where it seems preferable to directly input specific costs for a process instead of calculating the costs using the detailed cost input information as described above.

Possible reasons are:

- The detailed economic data are not available.
- It seems preferable to use market prices for certain energies / materials /services e.g. the market price for crude oil based gasoline and diesel
- The process scale of the process is some order of magnitude bigger than the process scale needed in the supply chain for the "Supply Scenario".

E3database also allows the direct input of specific costs for a process as "total variable costs" (e.g. electricity costs: 0.03 €/kWh).

8. Description of processes

In this section all processes used in the modelling of the hydrogen supply chains using the E3-database are presented. The processes are grouped as follows:

- Extraction of feedstock's
- Transport of feedstock's to production facilities
- Hydrogen production
- Hydrogen transport
- Hydrogen usage

There are also other processes used that do not directly match into the groups above. Example of such a process is the required mechanical work used to compensate the energy losses during pipeline transport. All these processes are grouped under the name 'auxiliary'.

In the following paragraphs, only the processes used into the selected Spanish chains are described.

A.1 Availability of Feedstock's

In this section the following feedstock's are considered:

- Natural gas
- Biomass
- Electricity
- Diesel
- Coal

Electricity is not a feedstock as such. Nevertheless, it is included here because it is used as a feedstock from which hydrogen can be produced through electrolysis.

- *Provision of Natural Gas*

To be used, natural gas (NG) must be extracted, processed and transported. 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.

Processing is required because heavier hydrocarbons and contaminants such as H_2S 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.

The cost of the supply of natural gas has been assumed to be 0.0284 €/kWh $_{NG}$ in 2020, 0.0373 €/kWh $_{NG}$ in 2030 and 0.0640 €/kWh $_{NG}$ in 2050 (WETO H2 study). The cost of NG distribution via high-pressure pipeline has been assumed equal to 0.0004 EUR per kWh of natural gas.

Table 4. Input and output data for NG Extraction + Processing / GEMIS 4.1

	I / O	Value	Units
NG source	I	1.0242	[kWh/kWh]
NG	O	1.0	[kWh]
Process scale	-	10,000,000	[kW NG]
CH_4 emissions	O	0.3	[g/kWh]
CO_2 emissions	O	4.1	[g/kWh]
NO_x emissions	O	0.0162	[g/kWh]
Dust-particles emissions	O	0.0009	[g/kWh]
SO_2 emissions	O	0.0044	[g/kWh]
NMVOC emissions	O	0.0004	[g/kWh]
CO emissions	O	0.004	[g/kWh]
Useful lifetime	-	20	[yr]
Annual full load hours	-	8,760	[h/yr]
Cost in 2020	-	0.0284	[€/kWh]
Cost in 2030	-	0.0373	[€/kWh]
Cost in 2050	-	0.0640	[€/kWh]

- *Provision of Biomass*

Biomass may be issued from residual or farmed wood. The residual wood and wood plantation are chipped at the source and then transported to the gasification plant by trucks.

Residual Wood

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. The average transport distance for the transport of the wood chips is assumed to be 50 km.
The diesel consumption for wood chipping is indicated with 0.3 to 0.5% of the energy content (LHV) of the wood [Hartmann 1995].

The costs of biomass supply from residual wood without transport has been assumed to be 0.0189 €/kWh $_{Biomass}$ in 2020 and 0.022 €/kWh $_{Biomass}$ in 2030 (WETO H2 study).

- *Provision of Electricity*

The electricity may come from a European mix or from a national production mix. Besides, electricity may be considered to come directly from wind turbines or a dedicated nuclear reactor.

Table 5 gives the repartition of the different sources of the European electricity mix considered.

Table 5. Electricity mix in 2020 for Spain and Europe.
Values used are kWh (I) per kWh produced (O), i.e. kWh/kWh

Source	**I / O**	**Spain**	**MIX EU 15 [1)] (1999)**
Biomass	I	0.12	0.0074
Brown Coal	I	0.081	0.1956
Hard Coal	I	0.179	0.5512
Fuel Oil (1.8%S)	I	0.069	-
Geothermal	I	-	0.0016
Hydro	I	0.126	0.1239
Mineral Oil	I	-	0.2397
NG	I	0.8	0.3440
Nuclear	I	0.533	1.1354
Waste	I	-	0.1838
Wind Power	I	0.089	0.0044
Electricity	O	1.0000	1.0000
Equivalent CO_2 emissions	O	267 g/kWh	452 g/kWh

- Equivalent CO_2 emissions in [g / kWh]; ex power plants according to GEMIS without the energy requirements and associated emissions for the construction of the plants

As a result of the national mix, the total input of primary energy is about 2 kWh per kWh of delivered electricity leading to an electricity generation efficiency of about 50%. The GHG emissions for the Spanish electricity mix in 2020 are 267 [g / kWh] of electricity delivered.

In the next table, the feedstock rate into electricity production is detailed.

Table 6. Electricity mix in 2020 for Spain and Europe.
Source share in EU-mix according to the used feedstock's (%)

Source	**Spain**	**MIX EU 15 (1999)**
Biomass	6	0.30
Brown Coal	4.1	7.10
Hard Coal	9	19.90
Fuel Oil (1.8%S)	3.5	-
Geothermal	-	0.10
Hydro	6.3	4.40
Mineral Oil	-	8.70
NG	40.1	12.30
Nuclear	26.7	40.50
Waste	-	6.60
Wind Power	4.5	0.20
Electricity	100.00	100.00

Offshore wind power

An offshore wind energy plant typically consists of up to 1,000 single wind turbines. The water depth can be up to 40 m. According to the Department of Trade and Industry in UK the investment can be expected to be about 1,200 [€/kW] of installed capacity in 2010. The investment of the offshore wind power installation at Middelgrunden in Denmark, which has a total capacity of 40 MW and which is already in operation, has been indicated with 49,000,000 EUR leading to 1,250 [€/kW]. These wind turbines are rather close to the coast (2-3 km) and as a result the water depth in Middelgrunden is low (2-6 m). The investment of the offshore win power installation at Horns Rev (160 MW; water depth: 6.5-13.5 m; distance from coast: 17 km) is indicated with 268 million EUR or 1,675 [€/kW] including grid connection [Renewable Energy World 2002].
As a rough estimate it has been assumed that the investment for large offshore wind power installations at a water depth of 30 m is assumed to be 1,200 [€/kW] in 2020.

If offshore wind power is used to provide electricity, the next data apply.

Table 7. Technical and economic data of the wind turbine, offshore

Wind Energy (offshore)	**2020**	**2030**		**Units**
Capacity	4.5	4.5		[MW]
Water depth	30	30		[m]
Investment	5,400,000	3,622,500		[€]
Maintenance	4	4		[% of investment]
Overhead	-	-		[% of investment]
Useful lifetime	25	25		[yr]
Equivalent full load period	3,000	3,000		[h/yr]

Onshore wind power

The cost data of the wind turbine for 2004 has been derived from an Enercon model E-66 / 20.70. The investment in Table 8 includes the additional investment which has been assumed to be 28% of the investment for the wind turbine alone. The investment for the Enercon wind turbine with a tower hight of 84 m is indicated with 1,785,000 EUR [Windenergie 2004].
For 2020 and 2030 a learning curve has been assumed based on the EWEA target for the installed capacity in the EU (180 GW in 2020 and 300 GW in 2030). In 2004 about 30 GW already has been installed in the EU 25. The progress ratio for windpower installations is indicated with 0.80 to 0.85. For the calculation a progress ratio of 0.85 has been assumed.

Table 8: Technical and economic data of the wind turbine (onshore)

	2004	2020	2030
Capacity [MW]	2	2	2
Investment [EUR]	2,284,800 1)	1,501,062 1)	1,400,000 1)
Maintenance [% of investment]	1.5	1.5	1.5
Overhead [% of investment]	3.5	3.5	3.5
Useful lifetime [yr]	25	25	25
Equivalent full load period [h/yr]	2,100	2,100	2,100

1) incl. additional costs (foundation, grid connection etc.)

Dedicated nuclear reactor : EPR

The characteristics of the EPR reactor are listed in the table bellow.

Table 9. Technical and economic data of the EPR

EPR 2030	**Value**	**Units**
Life time	40	[yr]
Capacity	1 600	[$MW_{él}$]
Electricity cost	28.4	[€/$MWh_{él}$]
Efficiency	37	[%]
Overhead	-	[% of investment]
Uranium consumption	21	[mg/$kWh_{él}$]

- *Provision of Diesel*

Diesel is used as fuel for mechanical conversion of energy. Processes that uses diesel are: truck transport and wood chipping.

Table 10. Technical and economic data of diesel provision

	I / O	**Value**	**Units**
Mineral oil consumption	I	1.160	[kWh/kWh]
Diesel oil production	O	1.000	[kWh]
Production costs	-	0.02304	[€/kWh]
CO_2 emissions	O	51.500	[g/kWh]
NOx emissions	O	0.147	[g/kWh]
Dust-particles emissions	O	0.007	[g/kWh]
SO_2 emissions	O	0.13	[g/kWh]
NMVOC emissions	O	0.162	[g/kWh]
CO emissions	O	0.061	[g/kWh]

- *Provision of Coal*

The coal used in Spain is a typical mix of European coal. The values presented in Table 11 represent the amount of energy needed to obtain 1 [kWh] of hard coal ready for use in other processes.

Table 11. Composition of the energy used in EU-mix hard coal (values in kWh/kWh)

	I / O	**Value**
Brown Coal	I	0.002
Hard Coal	I	1.025
Hydro-power	I	0.003
Mineral oil	I	0.041
NG	I	0.010
Nuclear	I	0.011
Waste	I	0.002
Hard Coal	O	1.000

The GHG emissions for the mix EU hard coal are evaluated to be 55.2 [g CO_2/kWh]. The costs of coal supply has been assumed to be 0.0091 €/kWh $_{Coal}$ in 2020 , 0.0106 €/kWh $_{Coal}$ in 2030 and 0.0133 €/kWh $_{Coal}$ in 2050 (WETO H2 study).

A.2 Transport of Feedstock's

- *Natural Gas*

Pipeline transport

NG is transported in a large European pipeline. The gas is consequently distributed via a regional and a local NG pipeline grid under different pressures to hydrogen production plants. All transports require mechanical work made by gas turbines, which use a small amount of NG for their power. The data for the high-pressure (HP) natural gas distribution has been derived from [GEMIS 2002].

Table 12. Input and output data for NG distribution (high-pressure pipeline) over 1000 km

	I / O	Value	Units
Mechanical work	I	0.0058	[kWh/kWh]
NG	I	1.0016	[kWh/kWh]
NG	O	1.000	[kWh]
Process scale	-	10,000,000	[kW NG]
CH_4 emissions	O	0.115	[g/kWh]
Useful lifetime	-	30	[yr]
Annual full load hours	-	7,500	[h/yr]

The mechanical work needed for transport purposes is supplied by a gas turbine (efficiency: 30%).

Table 13. Input and output data for NG distribution (high-pressure pipeline) over 500 km

	I / O	Value	Units
Mechanical work	I	0.003	[kWh/kWh]
NG	I	1.00003	[kWh/kWh]
NG	O	1	[kWh/kWh]
Process scale	-	10,000,000	[kW NG]
CH_4 emissions	O	0.0022	[g/kWh]
Useful lifetime	-	30	[yr]
Annual full load hours	-	7,500	[h/yr]

For the local NG distribution no energy requirements and no GHG emissions occur. But the local NG distribution leads to additional costs. The costs for NG distribution via high-pressure pipeline of 500 km have been assumed to be 0.0004 EUR per kWh of natural gas.

Ship transport

The NG is liquefied nearby the NG field.

Table 14: NG liquefaction

Capacity [MW_{LNG}]	7,220
NG consumption [kWh/kWh_{LNG}]	1.069
Investment [EUR]	769,000,000
Maintenance [% of investment]	4
Equivalent full load period [h/yr]	7,920
Useful lifetime [yr]	20

The LNG is transported via a LNG carrier (one way distance: 2,000 km).

Table 15: LNG transport

Transport capacity [t LNG]	56,700
Transport distance (one way) [km]	2,000
Speed [km/h]	36
Equivalent full load period [h/yr]	8,760
Number of roundtrips [1/yr]	50
Fuel consumption (vaporized LNG) [kWh/kWh_{LNG}]	0.007
Fuel consumption (heavy fuel oil) [kWh/kWh_{LNG}]	0.0059
CO_2 emissions [g/kWh_{LNG}]	3.1
CH_4 emissions [g/kWh_{LNG}]	0.0001
N_2O emissions [g/kWh_{LNG}]	0.0001
Investment [EUR]	177,000,000
Maintenance [% of investment]	2.05
Labor [EUR/yr]	3,200,200
Useful lifetime [yr]	20

Table 16: LNG terminal

Throughput [t LNG/yr]	5,000,000
LNG input [kWh/kWh_{LNG}]	1.0101
Electricity consumption [kWh/kWh_{LNG}]	0.001
CO_2 emissions (from flaring) [g/kWh_{LNG}]	1.995
Investment [EUR]	386,000,000

At the terminal, the LNG is vaporized and fed into a regional steam methane reformer. The heat for the vaporization is derived from the combustion of natural gas. Therefore approximately 0.019 kWh natural gas per kWh of gaseous natural gas is required. Further about 0.004 kWh mechanical work per kWh of gaseous natural gas is required. The mechanical work is generated by a diesel engine (efficiency: 30%).

- *Biomass*

The wood chips are transported to the gasification plant via a 40 t truck. The maximum payload ranges between 80 and 100 m^3 and between 22 and 27 t [Kaltschmitt 2001]. A manufacturer of trailers for the transport of biomass indicates a maximum payload of 90 to 92 m^3 [Fahrzeugbau Langendorf 2001]. The water content of the wood chips is assumed to be 30%. The bulk density of wood ranges between 0.24 and 0.33 t/m3. For the calculation of this pathway a payload of 26 t wood chips has been assumed.

Table 17. Input and output data for biomass transport system truck wood chips over 50 km

	I / O	Value	Units
Wood Chips	I	1.0000	[kWh]
Travelling distance	I	0.0148	[t km / kWh]
Biomass	O	1.0000	[kWh]

Table 18. Input and output data for truck

	I / O	Value	Units
Diesel Oil	I	0.26	[kWh/tkm]
Travelling distance	O	1	[t km]
CH_4	O	0.005	[g / t km]
CO_2	O	68.6	[g / t km]
NO_X	O	0.341	[g / t km]
Dust-Particles	O	0.002	[g / t km]
SO_2	O	0.00043	[g / t km]
CO	O	0.146	[g / t km]
NMVOC	O	0.04	[g / t km]

- *Electricity*

Depending on the user, three types of electricity transport have been considered: transport at high-voltage (HV, 110-220 kV), transport at medium-voltage (MV, ~20 kV) and transport at low-voltage (LV, ~0.4 kV).

The costs for high voltage transport of electricity are indicated with about 0.004 €/kWh and the costs for the distribution (10-20 KV level and 0.4 kV level) are indicated with 0.027 €/kWh (RWE 1999). As a first approach it has been assumed that 0.020 € of the 0.027 €/kWh can be allocated to the 10-10 kV level and 0.007 € can be allocated to the 0.4 kV level.

Table 19. Input and output data for High-voltage transport of electricity (GEMIS 4.1), (RWE 1999)

	I / O	Value	Units
Electricity	I	1.0101	[kWh/kWh]
Electricity	O	1.0000	[kWh]
Process scale	-	80,000,000	[kWe]
Useful lifetime	-	50	[yr]
Annual full load hours	-	5,000	[h/yr]
Costs of electricity transport	-	0.004	[€/kWh]

Table 20. Input and output data for Medium-voltage transport of electricity (GEMIS 4.1), (RWE 1999)

	I / O	Value	Units
Electricity	I	1.0070	[kWh/kWh]
Electricity	O	1.0000	[kWh]
Process scale	-	1,300	[kWe]
Useful lifetime	-	50	[yr]
Annual full load hours	-	5,000	[h/yr]
Costs of electricity transport	-	0.020	[€/kWh]

Table 21. Input and output data for Low-voltage transport of electricity (GEMIS 4.1) (RWE 1999)

	I / O	Value	Units
Electricity	I	1.0120	[kWh/kWh]
Electricity	O	1.0000	[kWh]
Process scale	-	100	[kWe]
Useful lifetime	-	50	[yr]
Annual full load hours	-	5,000	[h/yr]
Costs of electricity transport	-	0.007	[€/kWh]

A.3 Hydrogen Production

In this section, production of hydrogen from the different feedstock's is presented. Also the process of hydrogen liquefaction is included, which delivers the hydrogen 'ready for use'.

- *Production of Hydrogen from Natural Gas*

Hydrogen production from natural gas is performed using steam methane reformers (SMR). The SMR may or may not include CO_2 capture and storage (CCS).
For central SMR plants without CCS, a SMR based on Linde have been considered. Onsite (de-central, DC) reformers without CCS uses SMR based on Haldor Topsoe. SMR data that includes the CCS process has been derived from a study carried out by Foster Wheeler [Foster Wheeler 1996].
For central SMR plants including CCS, the CO_2 capture is carried out via scrubbing process using AMDEA (activated methyl diethanol amine) units. There after, CO_2 becomes compressed to a pressure of approximately 11 MPa, leading to carbon dioxide liquefaction. Thereafter, CO_2 is transported in liquid state via pipelines and injected into depleted natural gas and oil fields. The plant consists of 3 single units (each 94,000 Nm^3 H_2/h). In contrast to the Linde SMR, the Foster Wheeler plant has no electricity export.

In **Erreur ! Source du renvoi introuvable.** technical and economic data used in modeling are given for different capacities of hydrogen plants.

Table 22. Technical and economic data for the different SMR plants

	Haldor Topsoe 2020, DC	**Linde [2] 1992, C1**	**Foster Wheeler [3] 1996, C2**
Inlet pressure [MPa]	1.6	**4.0**	**3.4**
Discharge pressure H_2 [MPa]	1.5	**3.0**	**6.1**
Capacity [Nm^3 H_2/h]	320	100,000	281,300
NG consumption [kWh/kWh_{H2}]	1.441	1.417	1.365
Electricity consumption [kWh/kWh_{H2}]	0.016	-	-
Output excess electricity [kWh/kWh_{H2}]	-	0.050	-
CO_2 emissions [g/kWh_{H2}]	292	288	42.7
CH_4 emissions [g/kWh_{H2}]	0.075	0.057	0.057
Investment [€]	830,000 [4]	78,000,000	453,090,000
Maintenance coefficient [% of Investment]	1	3	1.5
Labour [€/yr]	0	600,000	546,400
Overhead [% of investment]	0	0	0.1
Useful lifetime [yr]	15	20	25
Equivalent full load period [h/yr]	6,000	8,000	7,884

Cells with "-" : not applicable

[2] Without CO_2 capture and storage
[3] With CO_2 capture and storage
[4] Average investment per unit when 10,000 units are installed

In case of the Foster Wheeler plant the natural gas input pressure is lower than the pressure of the hydrogen at the outlet of the pressure produced hydrogen. The reason is that the Foster Wheeler plant has an additional hydrogen compressor downstream the pressure swing adsorption (PSA) plant.

- *Production of Hydrogen from Coal*

The hydrogen is produced via large-scale gasification of hard coal with or without CO_2 capture and sequestration (see Table 23).

Table 23. Technical and economic data of hydrogen generation via coal gasification with or without CO_2 capture and storage

	I / O	**With CCS**	**Without CCS**	**Units**
Capacity	-	844,866	844,245	[Nm^3 H_2/h]
Hard coal consumption	I	2.303	1.967	[kWh/kWhH2]
CO_2 emissions	O	20.3	659.9	[g/kWhH2]
Investment	-	1,168,100,000	859,360,000	[€]
Maintenance coefficient	-	3.57	3.6	[% of investment]
Labour	-	1,090,000	1,090,000	[€/yr]
Overhead	-	0.07	0.1	[% of investment]
Useful lifetime	-	25	20	[yr]
Equivalent full load period	-	7,884	7884	[h/yr]

- *Production of Hydrogen from Biomass*

The provided biomass is gasified. The gasification process includes biomass pre-treatment, syngas purification and syngas separation. The result is CGH_2.

The plant used for the wood gasification produces a synthesis gas (mixture of H_2, CO, CO_2 and CH_4), which is purified in two stages (CO shift and a Pressure Swing Adsorption) to get the pure H_2. For this plant the technical and economic data are given in Table 24.

Table 24. Technical and economic data for H_2 generation via biomass gasification

	I / O	**Value**	**Units**
Biomass	I	1.4624	[kWh/kWh]
Electricity	I	0.0820	[kWh/kWh]
CGH_2	O	1.0	[kWh]
Investment	-	152,960,000	[€]
Maintenance	-	3.9	[% investment per yr]
Labour	-	1,180,000	[€/yr]
Overhead coefficient	-	2.3	[% investment per yr]
Equivalent full load period	-	7 887	[h/yr]
Useful lifetime	-	25	[yr]
PM emissions [5]	O	0.0025	[g/kWh]

[5] CO_2 emissions are per definition of use of biomass equal to zero

- *Production of Hydrogen from Solar thermal ferrites cycles*

The Thermal power is converted into heat which is used to decompose $ZnFe_2O_4$ to produce GH_2 (mixed ferrites cycle). The total efficiency is 30%.

$ZnFe_2O_4 \rightarrow ZnO + 2/3\ Fe_3O_4 + 1/6\ O_2$
$H_2O + 3\ ZnO + 2\ Fe_3O_4 \rightarrow H_2 + 3\ ZnFe_2O_4$

For this plant the technical and economic data are given in Table 25.

Table 25. Technical and economic data for H_2 generation via solar thermal S/I cycles

	I / O	Value	Units
Thermal power	I	3.33	[kWh/kWh]
GH_2	O	1.0	[kWh]
Investment	-	418,700,000	[€]
Maintenance	-	5.875	[% investment per yr]
Equivalent full load period	-	2555	[h/yr]
Useful lifetime	-	25	[yr]
Process Scale	-	150,539	[kW]

- *Production of Hydrogen from Nuclear S/I cycles*

The nuclear heat is used to decompose H_2SO_4 to produce GH_2 (sulphur iodine cycle). The global efficiency is 47% (efficiency of conversion of thermal power into heat > 70% and efficiency of the S/I cycle is about 50%).

For this plant the technical and economic data are given in Table 25.

Table 26. Technical and economic data for H_2 generation via nuclear S/I cycles

	I / O	Value	Units
Nuclear	I	2.1277	[kWh/kWh]
GH_2	O	1.0	[kWh]
Investment	-	1,969,000,000	[€]
Maintenance	-	5	[% investment per yr]
Equivalent full load period	-	8000	[h/yr]
Useful lifetime	-	25	[yr]
Construction time	-	3	[yr]
Process Scale	-	1,128,000	[kW]

- *Production of Hydrogen from Mix Electricity*

Hydrogen is produced via water electrolysis. The central electrolysis plant consists of a large number of electrolyser units. If the total hydrogen generation capacity of the central electrolysis plant were 100,000 Nm^3/h the number of 800 Nm^3/h units would be 125. As a first approach for the central electrolysis, no learning curve has been applied for the investment.
Electrolysers presented in Table 27 have different capacities according to a central or de-central application and are characterised by different output pressures.

Table 27. Technical and economic data for electrolysis

		Central Electrolyser	On Site Electrolyser
Capacity	[Nm^3 H_2/h] / [kW]	2400	360
Electricity consumption	[kWh / kWhH_2]	1.433	1.6
Pressure	[MPa]	3.0	2.6
Investment	[€]	2,200,000	271,800 [6]
Maintenance	[% of investment]	0.9	0.9
Labour costs	[€/yr]	0	0
Overhead costs	[% investment/yr]	0	0
Useful lifetime	[yr]	8,000	6,000
Equivalent full load period	[h/yr]	20	20

- *Hydrogen production through HT electrolysis*

Hydrogen is produced via water HT electrolysis.
The maintenance is supposed to be equal to the one of an alkaline electrolysis plant with the same capacity. We also include in the maintenance the cost of cells change.

Table 28. Technical and economic data for HT electrolysis

		Units	HTE
Capacity		[Nm^3 H_2/h] / [kW]	2400
Electricity consumption		[kWh / kWhH_2]	1.076
Heat consumption		[kWh / kWhH_2]	0.15
Water consumption		[kg / kWhH_2]	0.27
Investment		[€]	2,191,634
Maintenance	2030 (cells lifetime = 5 yr)	[% of investment]	11.8
	2040 (cells lifetime = 7 yr)	[% of investment]	7.7
	2050 (cells lifetime = 10 yr)	[% of investment]	4.6
Useful lifetime		[yr]	20
Equivalent full load period		[h/yr]	8,000

[6] Average investment per unit when 10,000 units are installed

- *Liquefaction of Hydrogen*

To liquefy hydrogen, a liquefaction plant consuming only electricity as input has been used. The electricity consumption has been assumed to be 0.3 kWh per kWh of LH_2 produced (LHV). This assumption corresponds to large hydrogen liquefaction plants in the near future, as presented in the CONCAWE/JRC/EUCAR study. The investment, maintenance and labour costs have been derived from [NHEG 1992] via up scaling. These costs have been confirmed by [Linde 2004]. The technical and economic data of liquefier plant are given in Table 29.

Table 29. Technical and economic data of H_2 liquefaction plant

	I / O	Value	Units
Plant capacity	-	300,000	[kW]
GH_2 consumption	I	1.00	[kWh/kWh_{LH2}]
Inlet pressure	-	30	[bar]
LH_2 production	O	1.00	[kWh]
Electricity consumption	I	0.3	[kWh/kWh_{LH2}]
Investment	-	23,900,000	[€]
Maintenance	-	2.50	[% of investment]
Labour	-	1,230,000	[€/yr]
Equivalent full load period	-	8,000	[h/yr]
Useful lifetime	-	30	[yr]

- *Gasification of liquefied hydrogen*

To be used into family households CHP Fuel Cell, liquefied hydrogen needs to be gasified. The technical and economic data of gasification plant are given in Table 30.

Table 30. Technical and economic data of LH_2 gasification plant

	I / O	Value	Units
Plant capacity	-	437.5	[kW]
LH_2 consumption	I	1.00	[kWh/kWh]
GH_2 production	O	1.00	[kWh]
Electricity consumption	I	0.0212	[kWh/kWh]
Investment	-	150,000	[€]
Maintenance	-	2	[% of investment]
Equivalent full load period	-	8,760	[h/yr]
Useful lifetime	-	20	[yr]

A.4 Transport of Produced Hydrogen

- *Compressed Hydrogen Gas (CGH_2)*

The supply of CGH_2 is performed through a hydrogen pipeline grid. It has been assumed that the hydrogen grid consists of large pipelines (50/100 km) with a throughput of 240 GWh H_2 per year and pipeline and some smaller pipelines (5 km) with a throughput of 8 GWh H_2 per year and pipeline. The pressure drop during the pipeline transport has been neglected.

Technical and economic data for CGH_2 pipelines is given in
Table 31.

Table 31. Technical and economic data for H2 pipelines

	Units	5 km	50 km	100 km
Annual hydrogen throughput	[GWh H_2/yr]	8	240	240
Diameter	[mm]	100	150	150
Wall thickness	[mm]		7.1	
Investment	[M€]	0.895	8.95	17.9
Labour, maintenance etc.	[€/yr]	21,000	261,000	522,000
Annual full load	[hr]	8000	8000	8000
Useful lifetime	[yr]	30	30	20

The supply of CGH_2 can also be performed by truck. Firstly, the hydrogen has to be compressed. Technical and economic data for the compressor is given in Table 32.

Table 32. Technical and economic data for the compressor

	I / O	Value	Units
Electricity	I	0.0356	[kWh /kWh]
GH_2	I	1	[kWh /kWh]
CGH_2	O	1	[kWh]
Process Scale	-	1920	[kW]
Investment	-	186,622	[€]
Maintenance	-	10%	[% of investment]
Lifetime	-	20	[yr]
Annual full load hours	-	8000	[hr/yr]

Then, the CGH2 is transported by truck on 50 km. The truck is supplied by diesel. Technical and economic data for the truck is given in Table 33.

Table 33. Technical and economic data for the truck

	I / O	Value	Units
Distance	I	0.0866	[tkm /kWh]
CGH_2	I	1	[kWh /kWh]
CGH_2	O	1	[kWh]
Process Scale	-	1658	[kW]
Investment	-	332,340	[€]
Maintenance	-	1.7%	[% of investment]
Labour	-	72,000	[€/yr]
Lifetime	-	20	[yr]
Annual full load hours	-	8760	[hr/yr]

- *Liquefied Hydrogen (LH_2)*

LH_2 is transported by truck on 150 km (roundtrip = 300 km). The truck gross weight is 40 t while the payload is about 27 t. Because the tank mass is estimated to be approximately 24 t, the transport capacity of the LH_2 trailer is approximately 3.5 t LH_2. The fuel consumption of the 40 t truck is about 3.5 kWh/km or 35 l diesel per 100 km.

Table 34. Technical and economic data for LH_2 truck transport

	I / O	**Value**	**Units**
Fuel use	I	0.2600	[kWh/t km]
Energy use	O	0.0354	[t km/kWh]
Investment	-	500,000	[€]
Maintenance	-	2%	[% of investment]
Lifetime	-	15	[yr]
Annual full load hours	-	8760	[hr/yr]

A.5 Hydrogen Usage

- *Vehicle Filling Stations*

Two different filling stations for gaseous hydrogen distribution and one filling station for gaseous hydrogen distribution from liquefied hydrogen inlet have been used. The difference between these filling stations is the suction pressure considered.

Characteristics of filling stations delivering CGH_2 for the year 2004 are presented in Table 35. Table 36 presents the derived data for the year 2020. The electricity voltage level is 0.4 kV except for filling stations which are connected with an onsite electrolyzer. In case of onsite electrolysis the electricity voltage level is 10 kV. The 10-20 kV level is reasonable if the maximum power demand exceeds 1 MW.

Erreur ! Source du renvoi introuvable. presents the data of the CGH_2/LH_2 filling station for the years 2010 and 2020.

Table 35. Technical and economic data for the CGH_2 filling station, year 2004

	Suction pressure	**2.0 MPa**	**2.6 MPa**
Annual fuel output	[t H_2/yr]	120	120
Electricity consumption	[kWh/kWh$_{H2}$]	0.070	0.0647
Investment [7]	[€]	496,000	496,000
Maintenance	[% of investment]	2.7	2.7
Useful lifetime	[yr]	20	20
Efficiency	[-]	98%	

Table 36. Derived technical and economic data for the CGH_2 filling station, year 2020

	Suction pressure	**2.0 MPa**	**2.6 MPa**
Annual fuel output	[t H_2/yr]	120	120
Electricity consumption	[kWh/kWh$_{H2}$]	0.070	0.0647
Investment [7]	[€]	231,000	231,000
Maintenance	[% of investment]	3.7	3.7
Useful lifetime	[yr]	20	20

[7] Average investment per unit when 10,000 units are installed.

- *Vehicle data*

The passenger vehicle data has been derived from the CONCAWE/EUCAR/JRC study [CONCAWE 2/2003]. The passenger vehicles are based on a VW Golf.
Table 37 and Table 38 present the vehicle technical data used in the study.

Table 37. Passenger cars data

	Fuel consumption [kWh/km]	**GHG emissions [g CO_2 equiv./km]**
CGH_2 FC car	0.261	0
CGH_2 FC car hybrid	0.233	0
CGH_2 ICE car	0.465	0.5
CGH_2 ICE car hybrid	0.413	0.5
LH_2 FC car	0.261	0
LH_2 FC car hybrid	0.233	0
LH_2 ICE car	0.465	0.5
LH_2 ICE car hybrid	0.393	0.5
NG+5%H_2 car	0.465	0

Table 38. Buses data

	Fuel consumption [kWh/km]	**GHG emissions [g CO_2 equiv./km]**
CGH_2 FC bus	2.86	0
CGH_2 ICE bus	4.90	4
LH_2 FC bus	2.74	0
LH_2 ICE bus	4.90	4
HCNG ICE bus	5.38	1092

For CGH_2 fuelled FC vehicles and hydrogen generated via electrolysis a de-Oxo dryer has been installed at the filling station to elevate the hydrogen purity from 99.95% to 99.995%. For CGH_2 fuelled ICE vehicles no de-Oxo dryer is required.

Table 39. Technical and economic data for a de-Oxo dryer [Stuart Energy 2004]

	I / O	**Value**	**Units**
Capacity	-	120	[Nm3 H2/h]
Electricity consumption	O	0.0139	[kWh/kWhH2]
Investment	-	94,500	[€]
Maintenance	-	0.24	[% of investment]
Useful lifetime	-	20	[yr]
Equivalent full load period	-	6,000	[h/yr]

The purity of LH_2 is above 99.995% in any case.

- *Stationary use of Hydrogen*

CHP plants generate electricity and heat. One approach is to look at the consumer e.g. a single-family user. The single-family user requires electricity and heat, the last one being supplied by a FC CHP plant including a peak boiler.

Heat as main product

The single-family user needs electricity and heat, the last one being supplied by a FC CHP plant including a peak boiler. The electricity may be supplied to the electricity grid.

The main output is „heat + electricity“ . If the electricity generation of the FC CHP plant is higher than the demand then a net export of electricity occurs.

Table 40. FC CHP plant with H2 fuelled peak boiler for a single-family user

	Input/ Output	Value	Units
GH_2	I	1.203	[kWh/kWh]
Electricity to grid	O	0.2736	[kWh/kWh]
Heat + Electricity	O	1.000	[kWh]
Process scale	-	2.8	[kWh/h]
Investment	-	4,054	[€]
Maintenance	-	12	[% of I /yr]
Equivalent full load period	-	4585	[h/yr]
Useful lifetime	-	20	[yr]

The investment includes the investment for a peak boiler. The maintenance costs include stack replacement after every 5 years. The lifetime of the FC is indicated with 5 years.

A.6 Auxiliary Processes

Auxiliary processes are those that do not take part in hydrogen generation (from well to H_2 production), but help to realize the production or distribution. These processes are:

- Gas Turbines (mechanical work for pumping gas through pipelines)
- Wood chipping

- *Gas Turbines*

Table 41. Input and output data for used gas turbines (GEMIS 4.1.3.2)

	I / O	Value	Units
Natural gas	I	3.3333	[kWh/kWh]
Heat	O	1.0000	[kWh]
Process scale	-	10,000	[kWh/h]
Useful lifetime	-	15	[yr]
Annual full load hours	-	5,000	[h/yr]
CO_2 emissions	O	677	[g/kWh]
NO_X emissions	O	3.527	[g/kWh]
Dust-particles emissions	O	0.050	[g/kWh]
SO_2 emissions	O	0.005	[g/kWh]
NMVOC emissions	O	0.101	[g/kWh]
CO emissions	O	1.008	[g/kWh]
CH_4 emissions	O	0.050	[g/kWh]
N_2O emissions	O	0.030	[g/kWh]

- *Wood chipping*

In case of residual woody biomass from forestry the wood is chipped nearby the forest via mobile wood chipper.

Table 42. Input and output data for Wood Chipping / Hartmann 1995

	I / O	Value	Units
Woody Biomass	I	1.025	[kWh/kWh]
Woody Biomass	O	1.0	[kWh]
Diesel [kWh/kWh_{wood}]	I	0.004	[kWh/kWh]
Process Scale	-	50,000	[kW]
CO_2 emissions	O	1.32	[g/kWh]
NO_x emissions	O	0.0581	[g/kWh]
Dust-particles emissions	O	0.0048	[g/kWh]
CH_4 emissions	O	0.0002	[g/kWh]
N_2O emissions	O	0.0002	[g/kWh]
NMVOC emissions	O	0.0002	[g/kWh]
CO emissions	O	0.0126	[g/kWh]
Useful lifetime	-	10	[yr]
Annual full load hours	-	1,000	[h/yr]
Cost	-	0.0135	[€/kWh]

9. Literature

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