HyWays

"Hydrogen supply chains for Italy"

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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 Italy 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 Italy, 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 Italy. 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 Italy, 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 Italy, the following new processes were introduced:

- GH2/ Solar/ Thermo chemical cycles (Sulphur-Iodine),
- Power Station / Mix Italy 2020 (Electric mix in Italy).

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 Italy

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, waste, coal, solar, by-product and electricity (Italy mix, 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 Italy.

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 Italy, eight hydrogen chains were selected. It leads to 15 sub-chains, 10 for mobile applications and 5 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 Italian Chains for the Hydrogen pathway

N°		Feedstock	Production Process	Transport	CO_2 seq.	Gas / Liquid	Application
1	1-A-0	NG (pipeline)	On Site SMR	GH_2 pipeline	No	Gas	Car FS
	2-A-0	NG (pipeline)	Central SMR	GH_2 pipeline	Yes	Gas	Car FS
	2-A-B	NG (pipeline)	Central SMR	-	Yes	Gas	Power Station
	2-B-0	NG (pipeline)	Central SMR	LH_2 truck	Yes	Liquid	Car FS
2	3-A-0	Biomass	On Site Gasification	GH_2 pipeline	No	Gas	Car FS
	3-A-B	Biomass	On Site Gasification	GH_2 pipeline	No	Gas	FC CHP
3	3-B-0	Waste	On Site Gasification	GH_2 pipeline	No	Gas	Car FS
	3-B-B	Waste	On Site Gasification	GH_2 pipeline	No	Gas	FC CHP
4	4-A-0	Coal	Gasification	GH_2 pipeline	Yes	Gas	Car FS
	4-B	Coal	Gasification	GH_2 pipeline	Yes	Gas	Power Station
5	5-A-0	Mix Electricity	On Site Electrolysis	GH_2 pipeline	No	Gas	Car FS
6	6-A-0	Wind Power	On Site Electrolysis	GH_2 pipeline	No	Gas	Car FS
	6-A-B	Wind Power	On Site Electrolysis	GH_2 pipeline	No	Gas	FC CHP
7	7-A-0	Solar	Thermal conversion	GH_2 pipeline	No	Gas	Car FS
	7-A-B	Solar	Thermal conversion	GH_2 pipeline	No	Gas	FC CHP
8	8-A-0	By-product	-		No		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 seven selected hydrogen chains for Italy 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-0 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 Italian gas network (1000 km distance) and becomes distributed to an on-site SMR (250 km distance at high pressure + 10 km distance at medium pressure, on average). The produced hydrogen becomes subsequently distributed to the filling station.

Electricity required at the SMR plant and the filling station is obtained from Italian mix at low-voltage level.

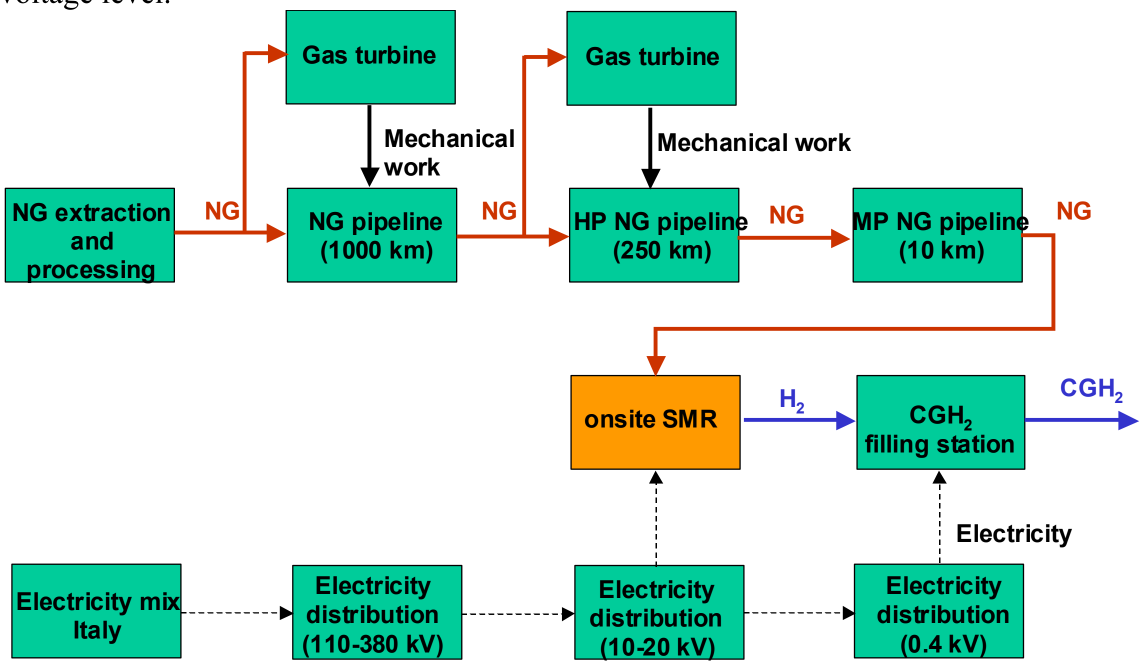

Figure 1. Modelled hydrogen chain for NG (pipeline) with on-site SMR and no CCS, for use in FS

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
- Filling station A.5

4.2. Chain 2-A-0 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 Italian 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 (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 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 Italian mix.

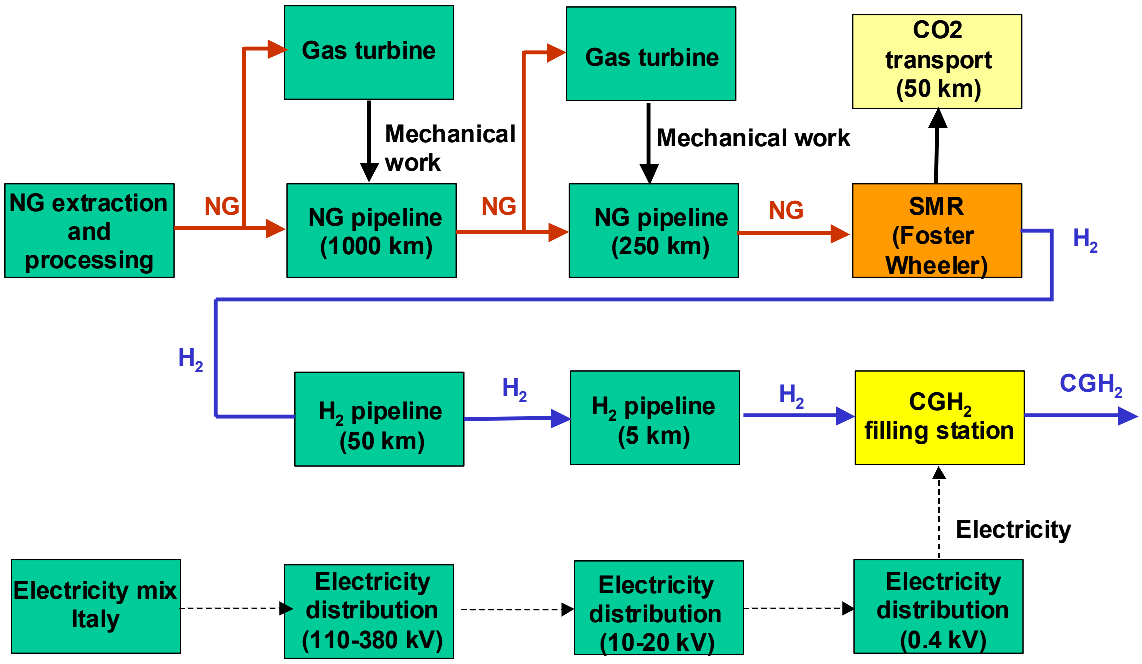

Figure 2. Modelled hydrogen chain for NG (pipeline) with central SMR with CCS, for use in FS

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 A.3
- Filling station A.5

4.3. Chain 2-A-B Natural Gas pipeline, Central SMR with CCS; use: CCGT

Description

Natural gas extracted and processed in NG producer countries is transported into the Italian 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 Power Station CCGT (Combined Cycle Gas Turbine) which delivers electricity.

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

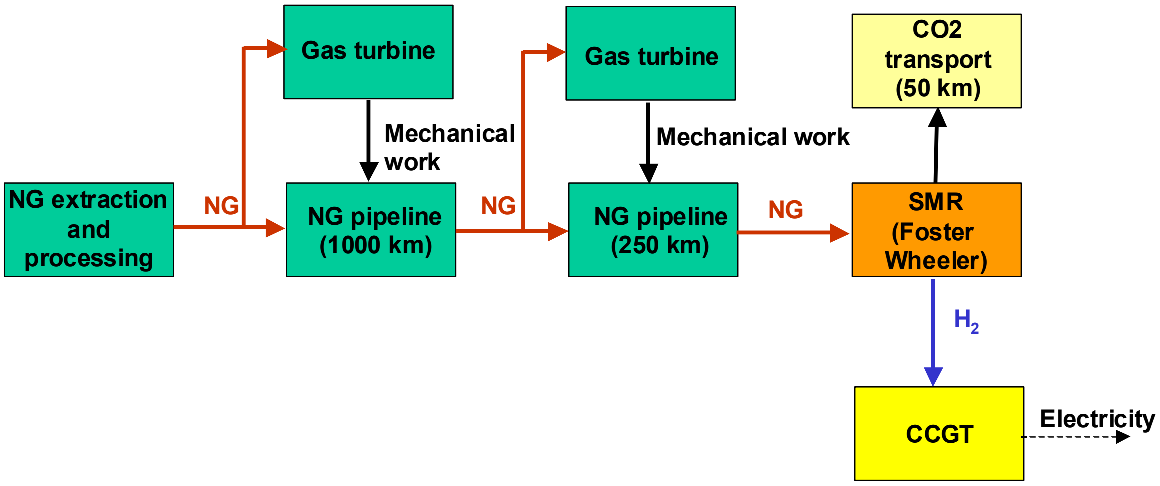

Figure 3. Modelled hydrogen chain for NG (pipeline) with central SMR with CCS, for use in CCGT

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
- Hydrogen production from natural gas A.3
- Power Station CCGT A.5

4.4. Chain 2-B-0 Natural Gas pipeline, Central SMR with CCS, LH_2 trucks; use: car filling station

<u>Description</u>

Natural gas extracted and processed in NG producer countries is transported into the Italian 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 central SMR separates the produced CO_2, which becomes subsequently stored in old gas/oil fields after transport (50 km distance, on average).
Electricity required at the liquefaction plant is obtained from Italian mix at a high-voltage level, whereas electricity required at the filling station is required at low-voltage level.

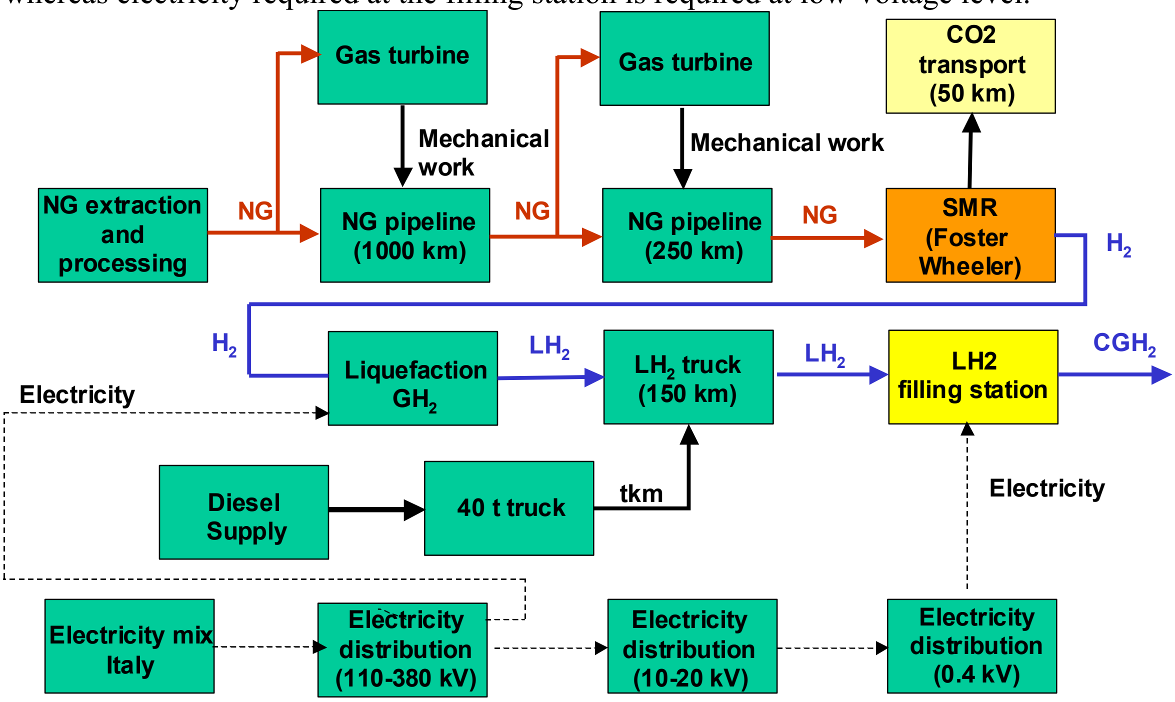

Figure 4. Modelled hydrogen chain for NG (pipeline) with central SMR with CCS, for use in FS

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 A.3
- Filling station A.5
- Liquefaction of hydrogen A.3
- Transport of liquefied hydrogen A.4

4.5. Chain 3-A-0 Biomass, On-site Gasification, no CCS; use: car filling station

Description

Italian 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 of some small 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.

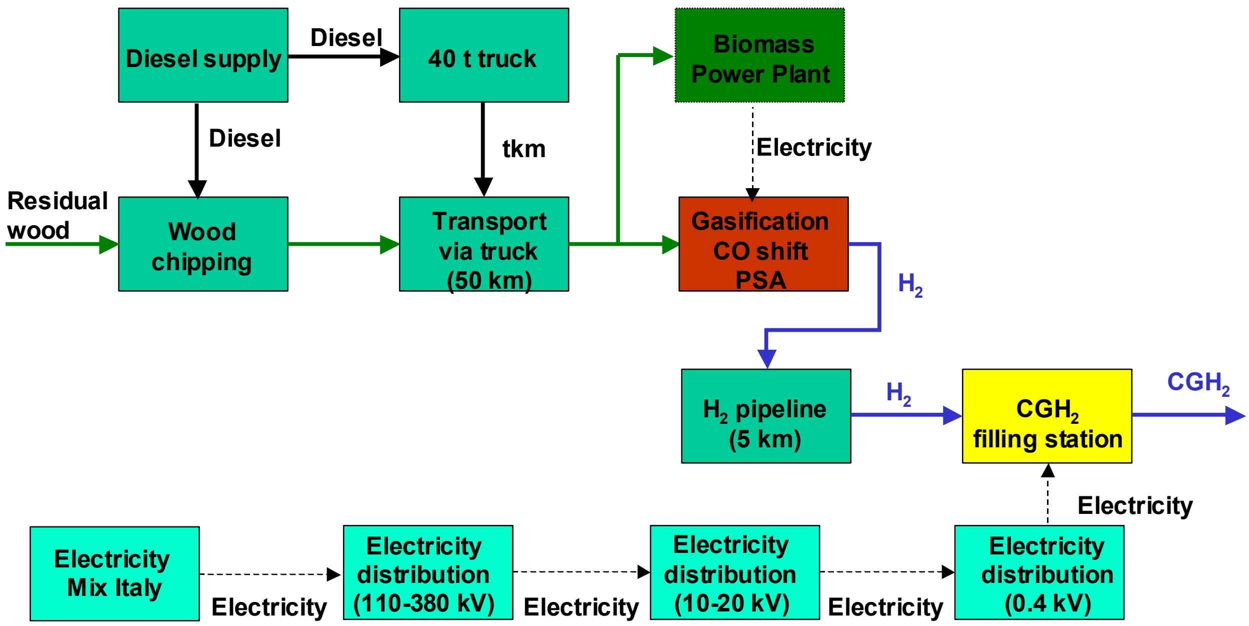

Figure 5. Modelled hydrogen chain for Biomass gasification, for use in filling stations

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

4.6. Chain 3-A-B Biomass, On-site Gasification, no CCS; use: FC CHP

Description

Italian 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 combined heat and power fuel cell (FC CHP) through a pipeline grid consisting of some small pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year. The FC CHP 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".

The wood chipping process uses also diesel fuel for the conversion of energy into mechanical work.

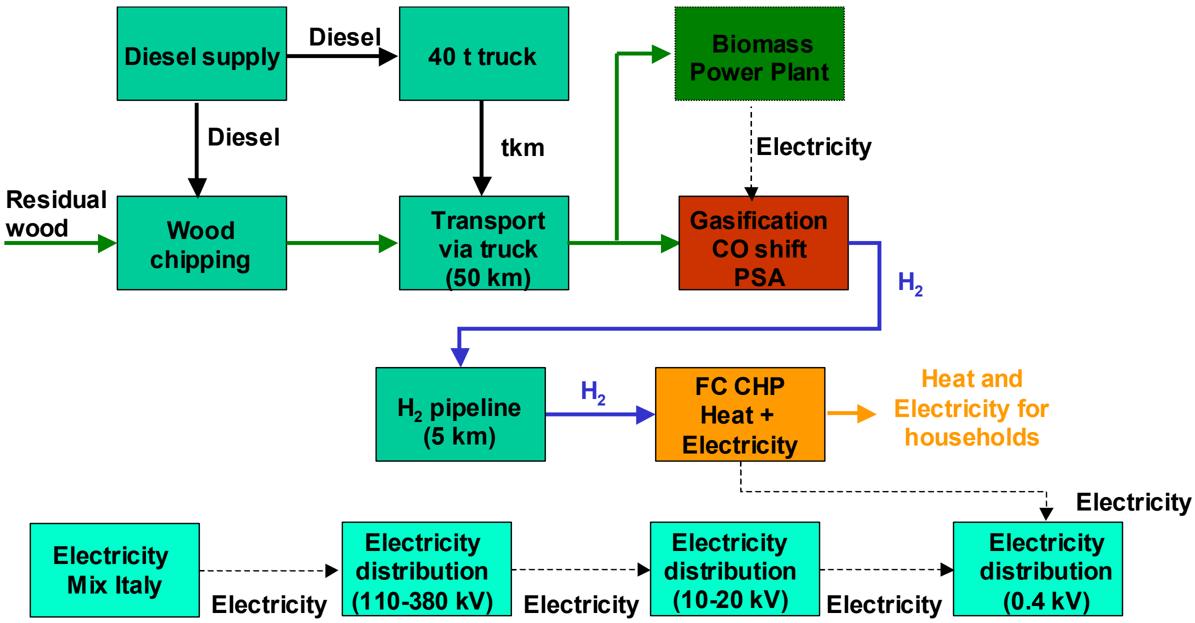

Figure 6. Modelled hydrogen chain for Biomass gasification, for use in FC CHP

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
- FC CHP	A.5
- Biomass power plant	A.6

4.7. Chain 3-B-0 Municipal Waste, On-site Gasification, no CCS; use: car filling station

Description

Italian municipal waste is transformed into GH_2 at a gasification plant using electricity produced by waste burning. The GH_2 is transported to the filling stations through a pipeline grid consisting of some small pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year.

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

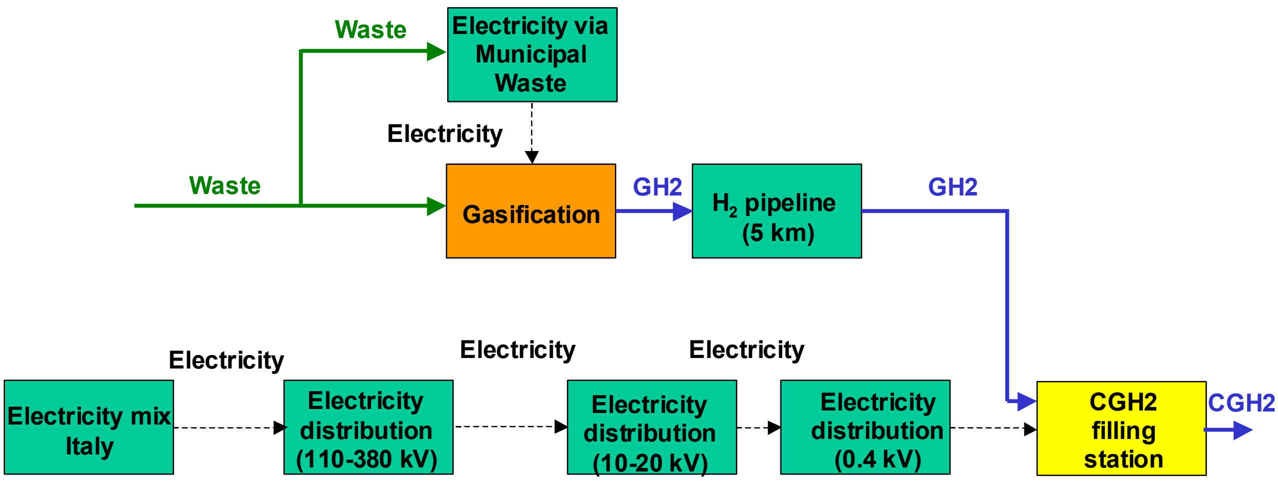

Figure 7. Modelled hydrogen chain for Municipal Waste gasification, for use in filling stations

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 from waste A.3
- Hydrogen transport by pipeline A.4
- Filling station A.5

4.8. Chain 3-B-B Municipal Waste, On-site Gasification, no CCS; use: FC CHP

Description

Italian municipal waste is transformed into GH_2 at a gasification plant using electricity produced by waste burning. The GH_2 is transported to the combined heat and power fuel cell (FC CHP) through a pipeline grid consisting of some small pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year. The FC CHP 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".

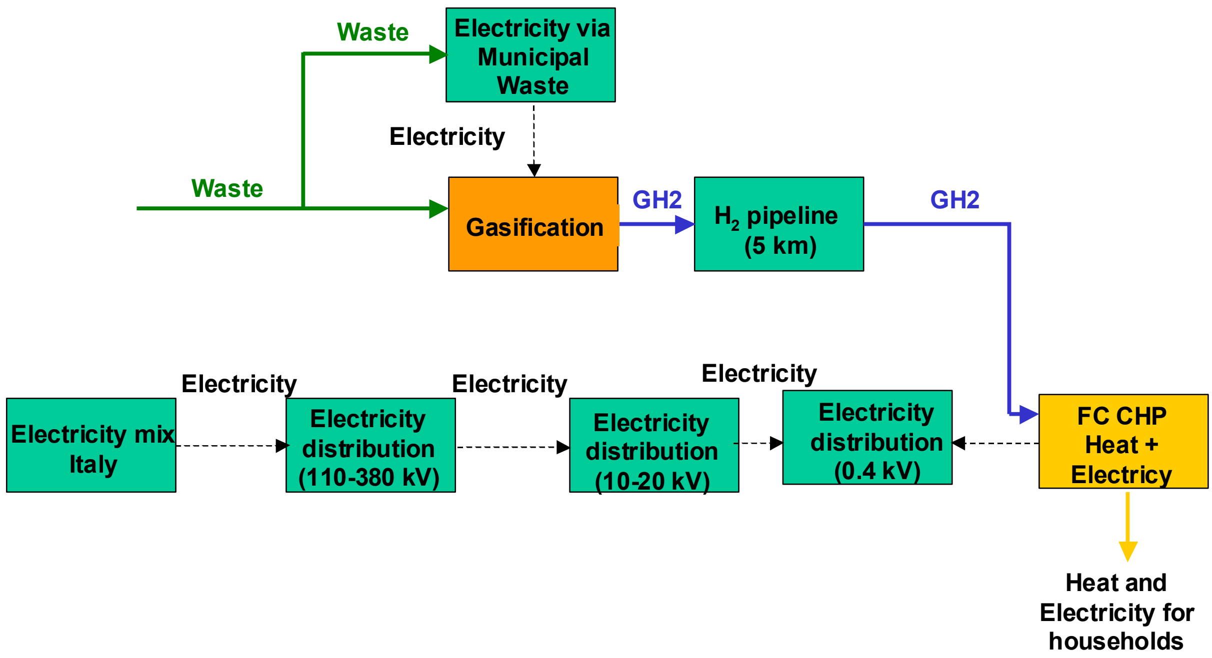

Figure 8. Modelled hydrogen chain for Municipal Waste gasification, for use in FC CHP

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 from waste A.3
- Hydrogen transport by pipeline A.4
- FC CHP A.5

4.9. Chain 4-A-0 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 (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 filling station is obtained from Italian mix at low-voltage level.

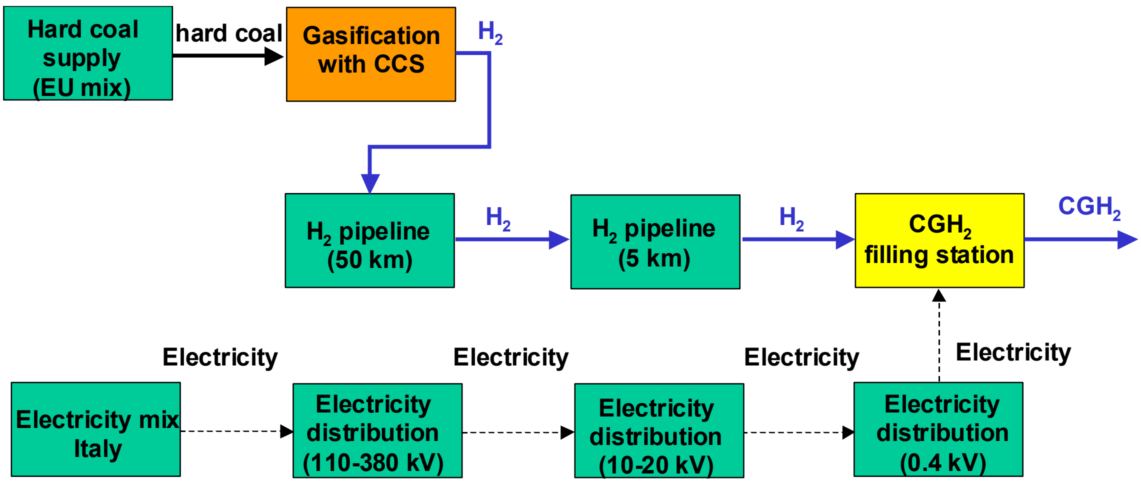

Figure 9. Modelled hydrogen chain for coal gasification with CCS, for use in filling stations

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

4.10. Chain 4-B Hard Coal, Gasification with CCS, GH_2 pipeline; use: CCGT

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 CGH_2 becomes subsequently distributed to the Power Station CCGT (Combined Cycle Gas Turbine) which delivers electricity.

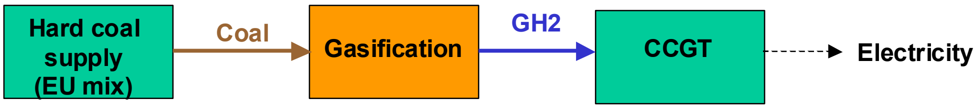

Figure 10. Modelled hydrogen chain for coal gasification with CCS, for use in Power Station CCGT

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

- Coal provision A.1
- Hydrogen production from coal A.3
- Power Station CCGT A.5

4.11. Chain 5-A-0 Italian Mix Electricity, On Site Electrolysis, GH_2 pipeline; use: car filling station

Description

Electricity coming from the Italian 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 Italian mix at a medium-voltage level whereas electricity required at the filling stations is obtained from Italian mix at a low-voltage level.

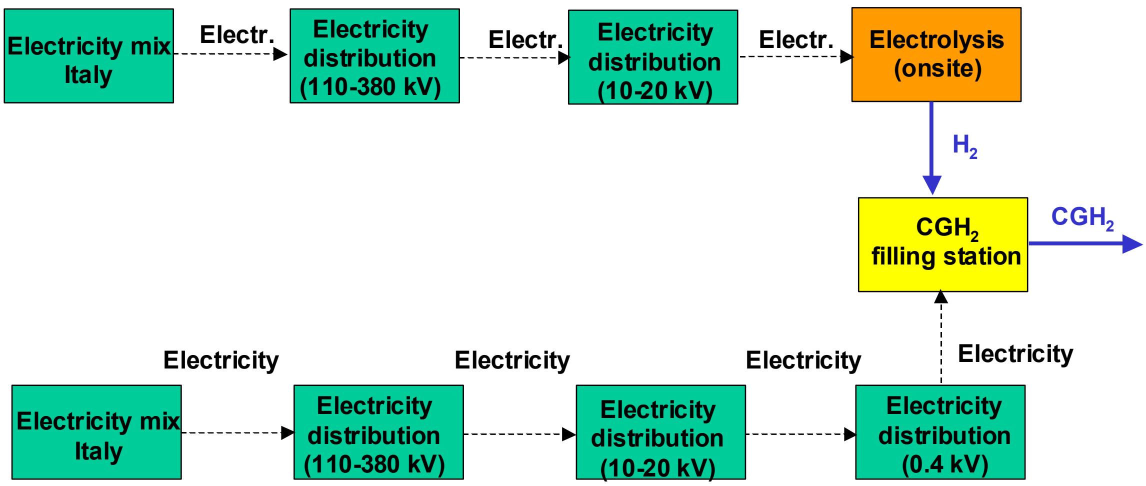

Figure 11. Modelled hydrogen chain for Italian Mix Electricity, On site electrolysis, GH_2 pipeline, for use in filling stations

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
- Filling station A.5

4.12. Chain 6-A-0 On shore wind power, on site electrolysis, GH_2 pipeline; use: car filling station

Description

Electricity generated by on-shore wind turbines 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 Italian mix at a medium-voltage level whereas electricity required at the filling stations is obtained from Italian mix at a low-voltage level.

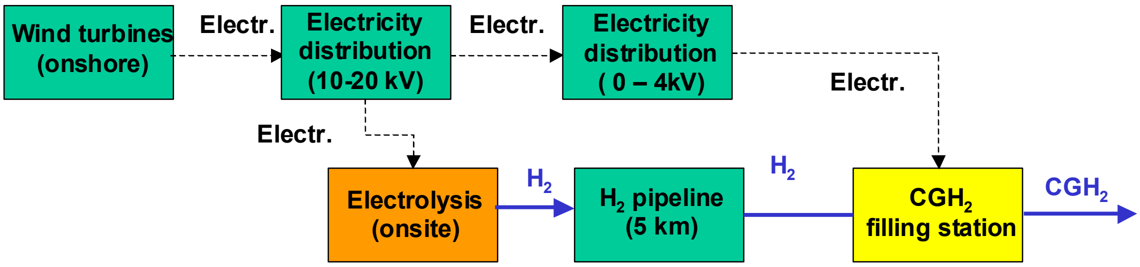

Figure 12. Modelled hydrogen chain for on-site electrolysis with on-shore wind turbines, for use in filling stations

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

4.13. Chain 6-A-B On shore wind power, on site electrolysis, GH_2 pipeline; use: FC CHP

Description

Electricity generated by on-shore wind turbines is distributed to an on site electrolysis plant. The GH_2 is transported to the combined heat and power fuel cell (FC CHP) through a pipeline grid consisting of some small pipelines (5 km) with a throughput of 8 GWh H_2 per pipeline and year. The FC CHP 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".

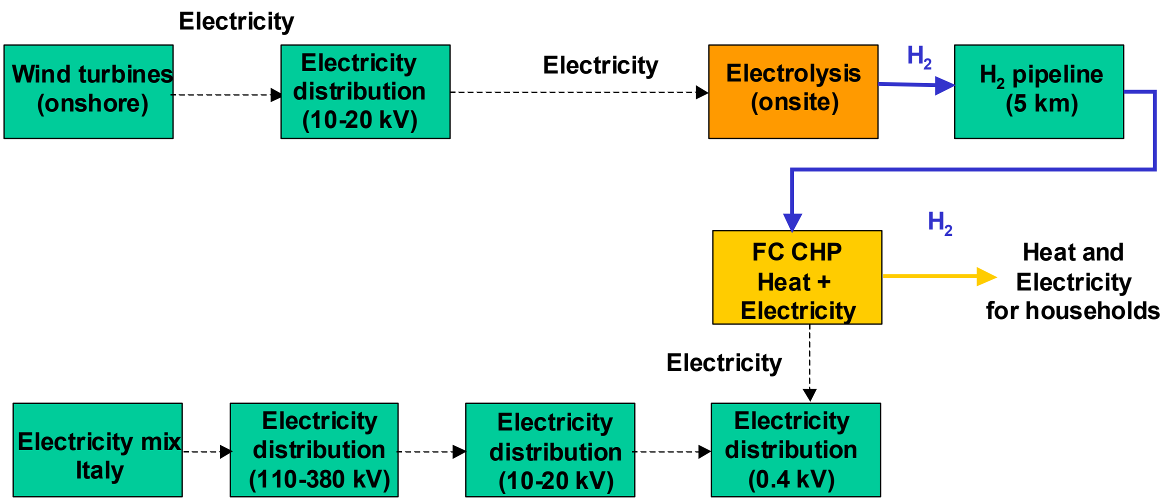

Figure 13. Modelled hydrogen chain for on-site electrolysis with on-shore wind turbines, for use in FC CHP

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

4.14. Chain 7-A-0 Solar thermal, thermo chemical cycles (sulphur iodine), GH_2 pipeline; use: car filling station

Description

The Thermal power is converted into heat which is used to decompose H_2SO_4 to produce GH_2 (sulphur iodine 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 (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 filling station is obtained from Italian mix at low-voltage level.

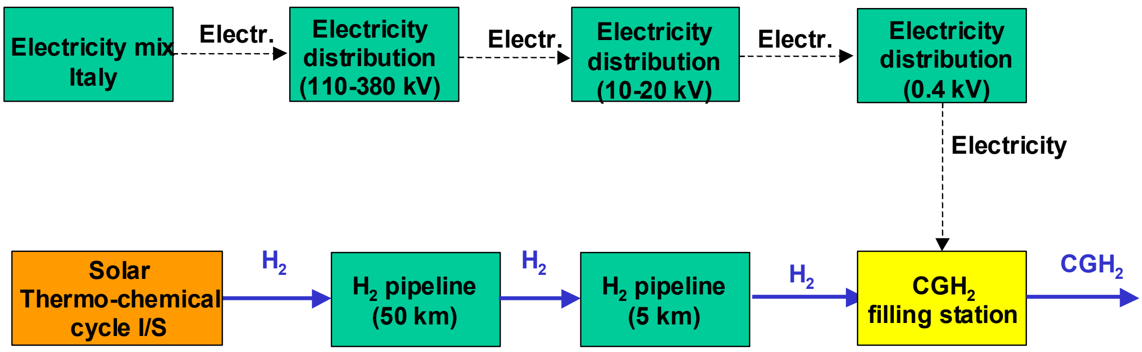

Figure 14. Modelled hydrogen chain for solar thermal, thermo chemical cycles S/I, GH_2 pipeline, for use in filling stations

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

4.15. Chain 7-A-B Solar thermal, thermo chemical cycles (sulphur iodine), GH_2 pipeline; use: FC CHP

Description

The Thermal power is converted into heat which is used to decompose H_2SO_4 to produce GH_2 (sulphur iodine cycle).

The GH_2 is transported to the combined heat and power fuel cell (FC CHP) through a pipeline grid consisting 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. The FC CHP 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".

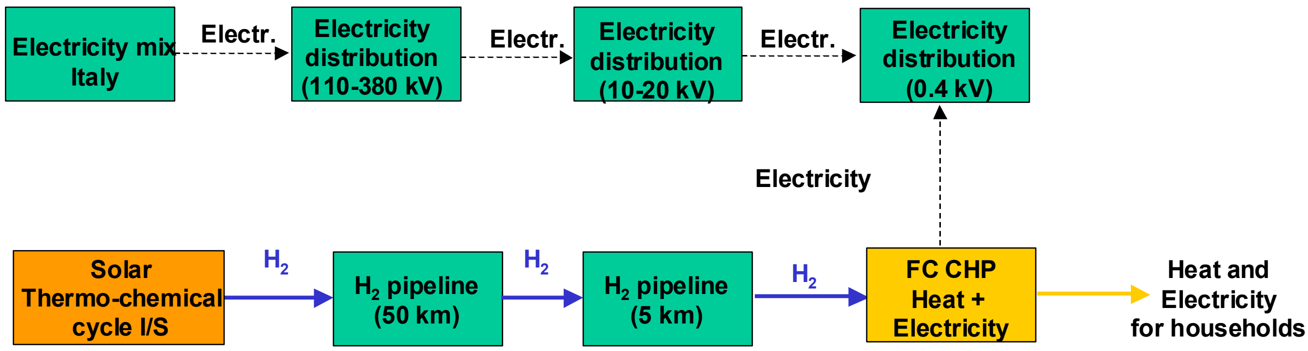

Figure 15. Modelled hydrogen chain for solar thermal, thermo chemical cycles S/I, GH_2 pipeline, for use in FC CHP

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

4.16. Chain 8-A-0 By-product, LH_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 liquefied and then transported by a LH_2 truck on 150 km to the filling stations.

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

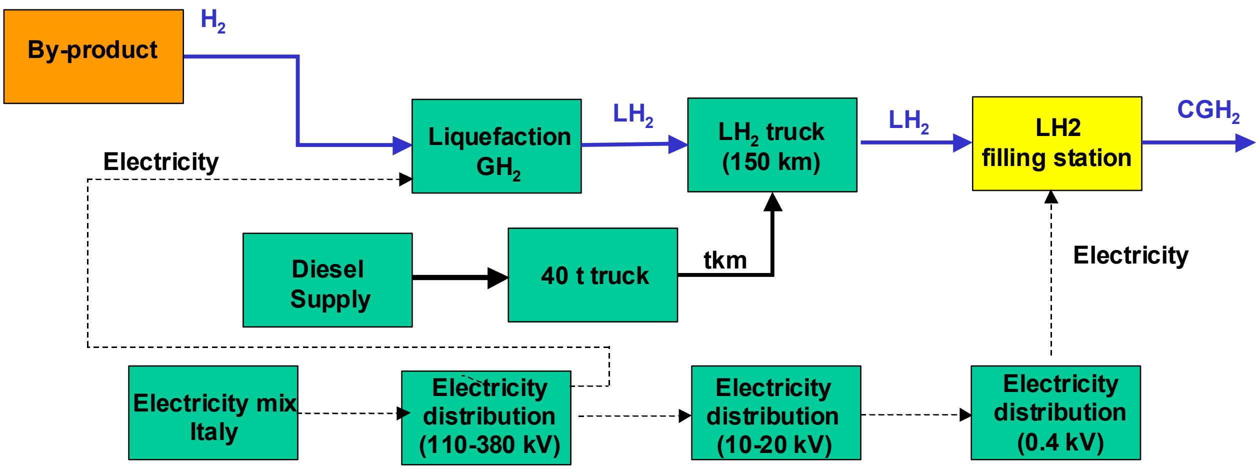

Figure 16. Modelled hydrogen chain for by-product, for use in filling stations

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

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 Italy, 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-0 Natural Gas (pipeline), On-site SMR, no CCS, GH_2 pipelines; (2020)
Chain 2-A-0 Natural Gas pipeline, Central SMR with CCS, GH_2 pipelines; (2020, 2030, 2050)
Chain 2-B-0 Natural Gas pipeline, Central SMR with CCS, LH_2 trucks; (2020, 2030)
Chain 3-A-0 Biomass, On-site Gasification, no CCS; (2020, 2030, 2050)
Chain 3-B-0 Municipal Waste, On-site Gasification, no CCS; (2020, 2030, 2050)
Chain 4-A-0 Hard Coal, Gasification with CCS, GH_2 pipeline; (2030, 2050)
Chain 5-A-0 Italian Mix Electricity, On Site Electrolysis, GH_2 pipeline; (2020)
Chain 6-A-0 On shore wind power, on site electrolysis, GH_2 pipeline; (2020, 2030, 2050)
Chain 7-A-0 Solar thermal, thermo chemical cycles (sulphur iodine), GH_2 pipeline; (2030, 2050)
Chain 8-A-0 By-product, LH_2 truck; (2020)

Description of stationary use of hydrogen supply chains

Chain 2-A-B Natural Gas pipeline, Central SMR with CCS; use: CCGT ; (2020, 2030, 2050)
Chain 3-A-B Biomass, On-site Gasification, no CCS; use: FC CHP ; (2020, 2030, 2050)
Chain 3-B-B Municipal Waste, On-site Gasification, no CCS; use: FC CHP ; (2020, 2030, 2050)
Chain 4-B Hard Coal, Gasification with CCS, GH_2 pipeline; use: CCGT; (2030, 2050)
Chain 6-A-B On shore wind power, on site electrolysis, GH_2 pipeline; use: FC CHP ; (2020, 2030, 2050)
Chain 7-A-B Solar thermal, thermo chemical cycles (sulphur iodine), GH_2 pipeline; use: FC CHP ; (2030, 2050)

Figure 17 shows the efficiencies of the selected chains for the provision of hydrogen for mobile end users.

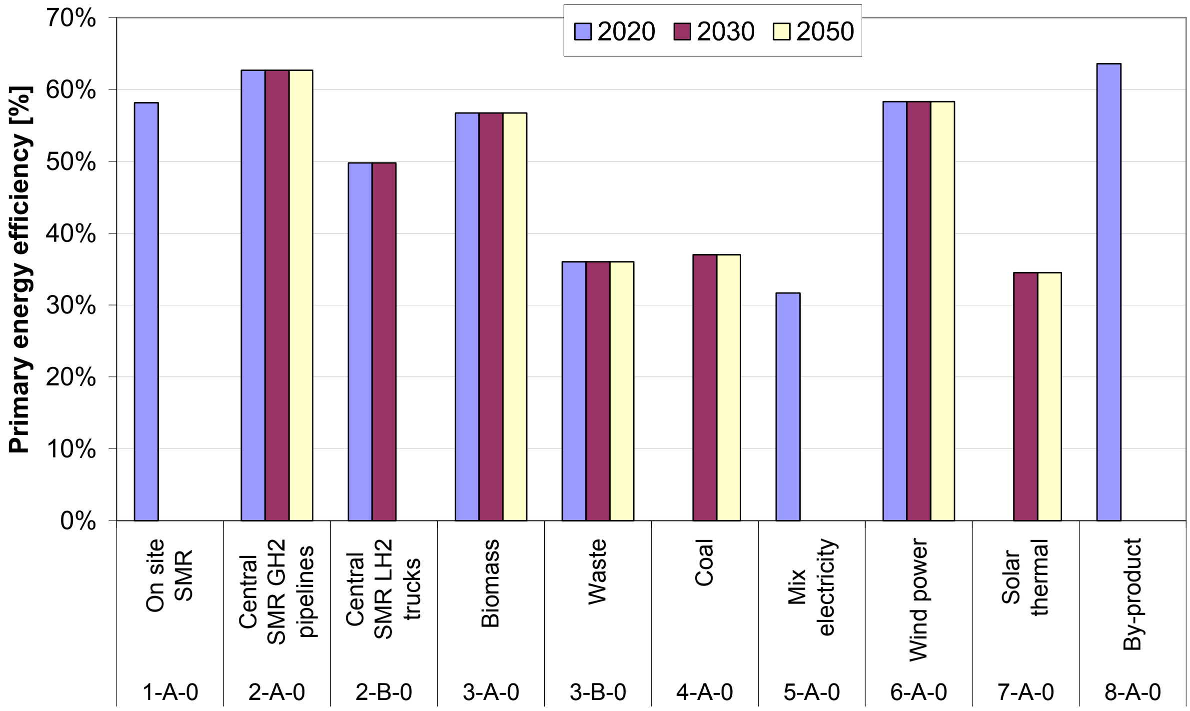

Figure 17. Efficiencies of selected mobile H2 supply chains

Figure 18 shows the efficiencies of the selected chains for the provision of hydrogen for stationary end users.

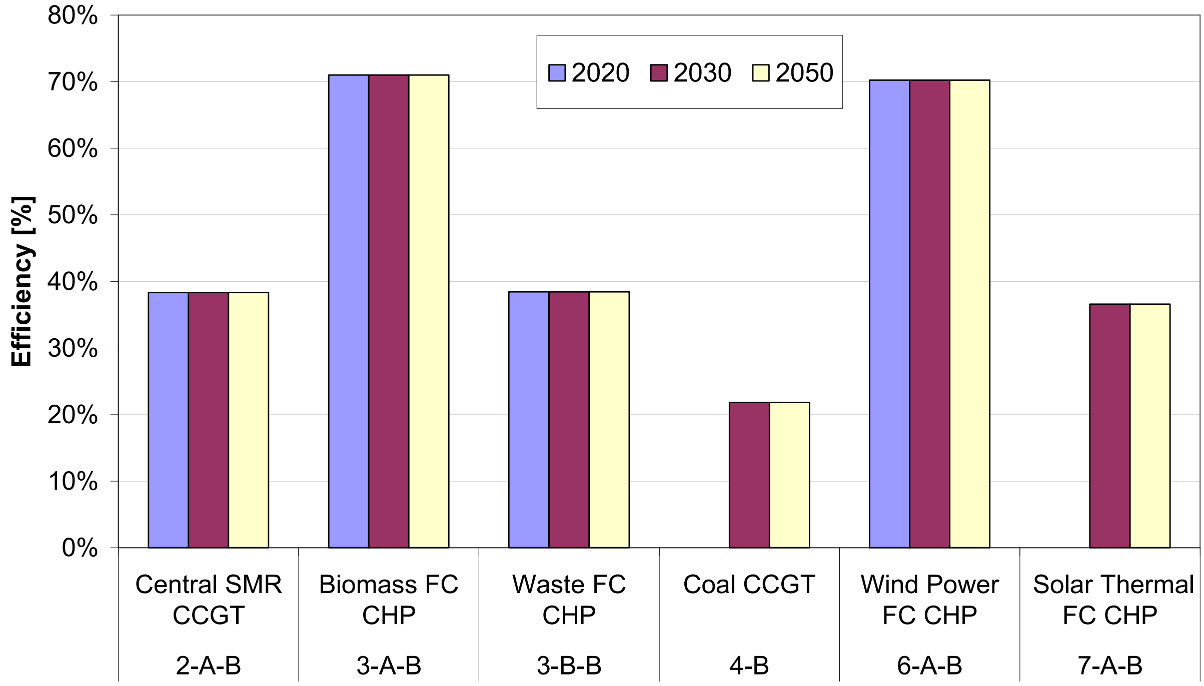

Figure 18. Efficiencies of selected H_2 supply chains for stationary use

5.3. Greenhouse Gas Emissions: WTT and WTStU

In 2020 there are six ways to produce hydrogen for the mobile applications : Steam Methane Reforming (without CCS for on-site plant and with CCS for central plant), Biomass gasification, Waste, Electrolysis with mix electricity, Wind Power electrolysis (on-shore) and By-product. Figure 19 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

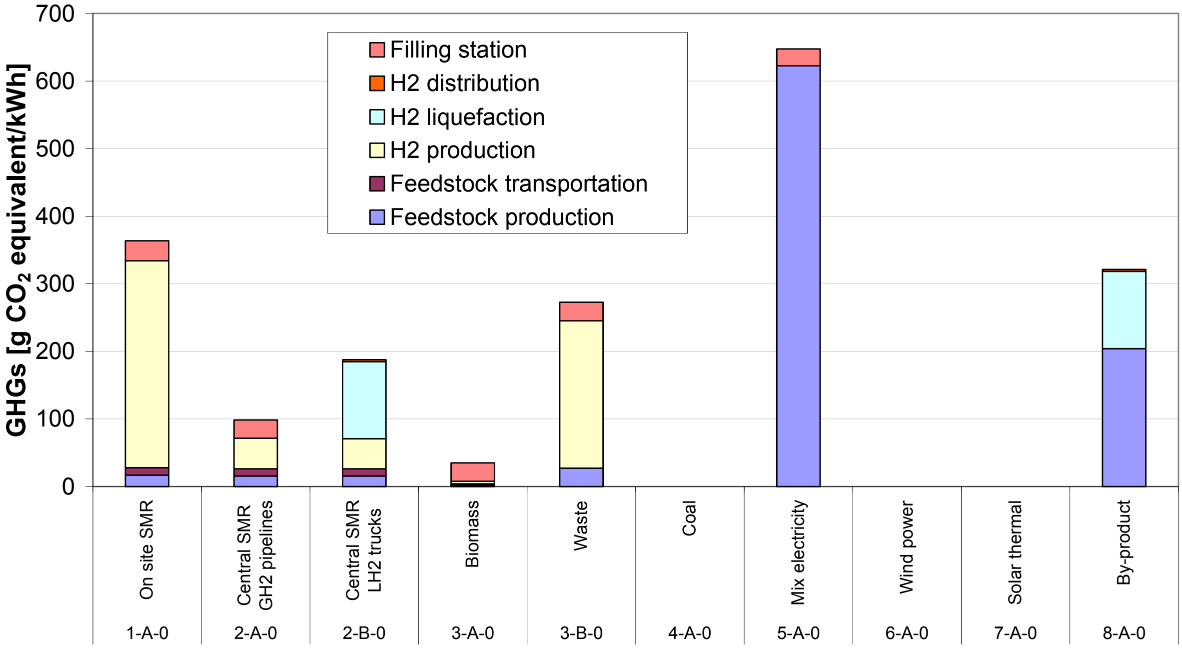

Figure 19. CO_2-equivalent emissions of mobile H_2 supply chains in 2020

In 2020, since the Italian mix produces many GHG, the use of electrolysis is worth only with wind power (no emissions). On-site SMR has also many GHG since the CCS is possible only for central plants.

In 2030 there are six ways to produce hydrogen for the mobile applications : Steam Methane Reforming (with CCS, central plant), Biomass gasification, Waste, Coal gasification, Wind Power electrolysis (on-shore) and Solar thermal. Figure 20 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

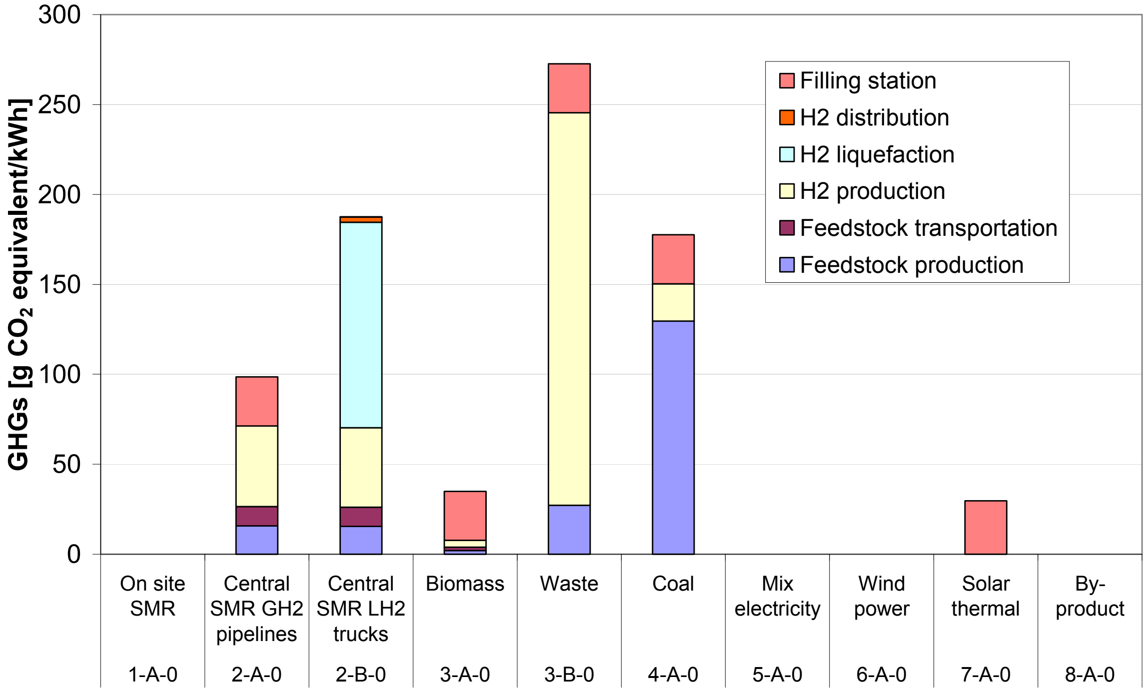

Figure 20. CO_2-equivalent emissions of mobile H_2 supply chains in 2030

In 2030, we have the fewest emissions for on-shore wind power electrolysis, then solar thermal (emissions only due to the use of mix electricity in the filling station) and finally biomass gasification.

We underline the fact that using hydrogen liquefaction almost double the emission for the central SMR with CCS.

In 2050 there are six ways to produce hydrogen for the mobile applications : Steam Methane Reforming (with CCS, central plant), Biomass gasification, Waste, Coal gasification, Wind Power electrolysis (on-shore) and Solar thermal. Figure 21 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

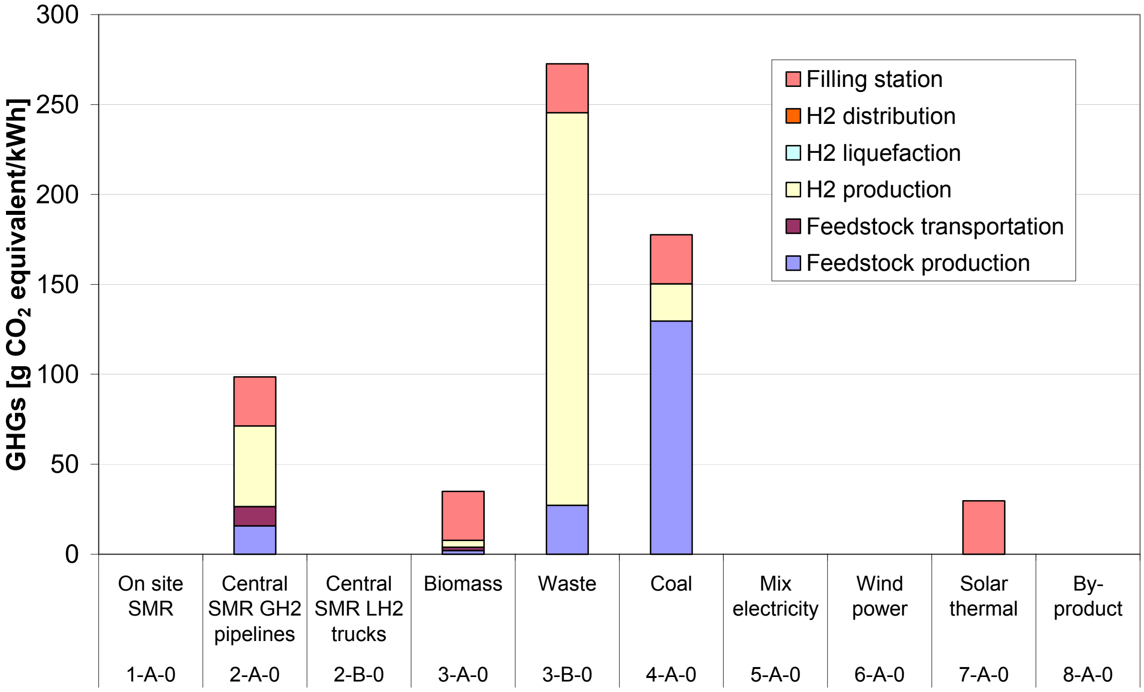

Figure 21. CO_2-equivalent emissions of mobile H_2 supply chains in 2050

In 2050, the emissions are similar to the ones in 2030.

There are five ways to produce hydrogen for the stationary applications : Central SMR with CCS and GH_2 pipelines and CCGT (2020, 2030, 2050), Biomass gasification and FC CHP (2020, 2030, 2050), Waste and FC CHP (2020, 2030, 2050), Coal gasification and CCGT (2030, 2050), Wind power and FC CHP (2020, 2030, 2050) and Solar thermal and FC CHP (2030, 2050). Figure 22 shows the Greenhouse Gas Emissions of the selected chains for the provision of hydrogen for mobile end users.

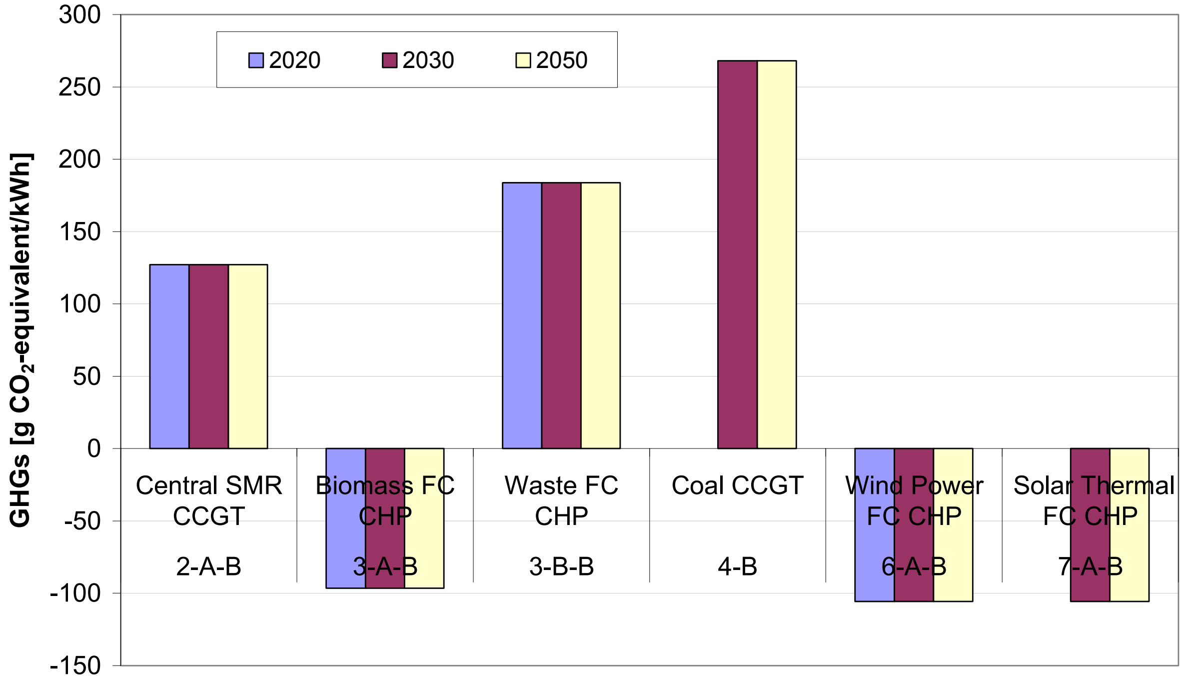

Figure 22. CO_2-equivalent emissions of stationary use of H_2 supply chains

The coal gasification is the main GHG producer.
The negative GHG in the case of biomass gasification (respectively on-shore wind power and solar thermal) can be explain by the fact that biomass gasification produces few GHG (respectively 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 23 and Figure 24, 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.

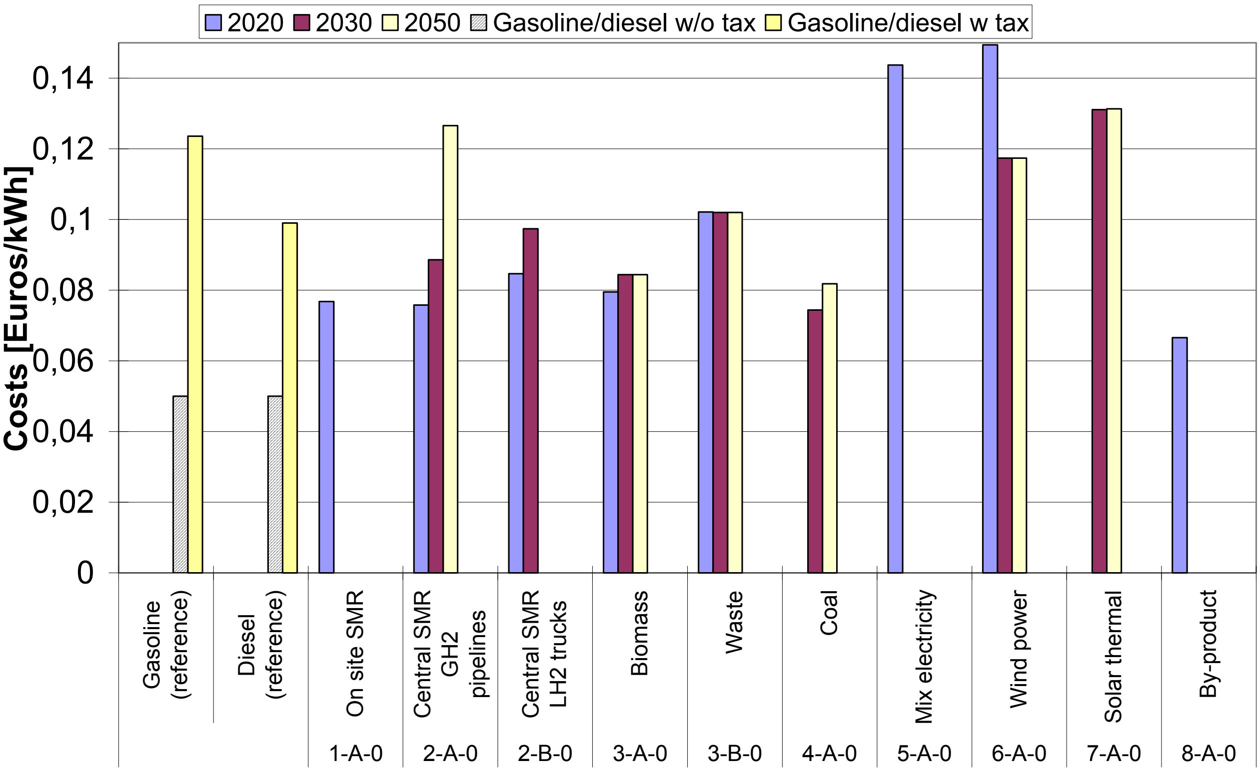

Figure 23. Costs of selected mobile hydrogen supply chains.

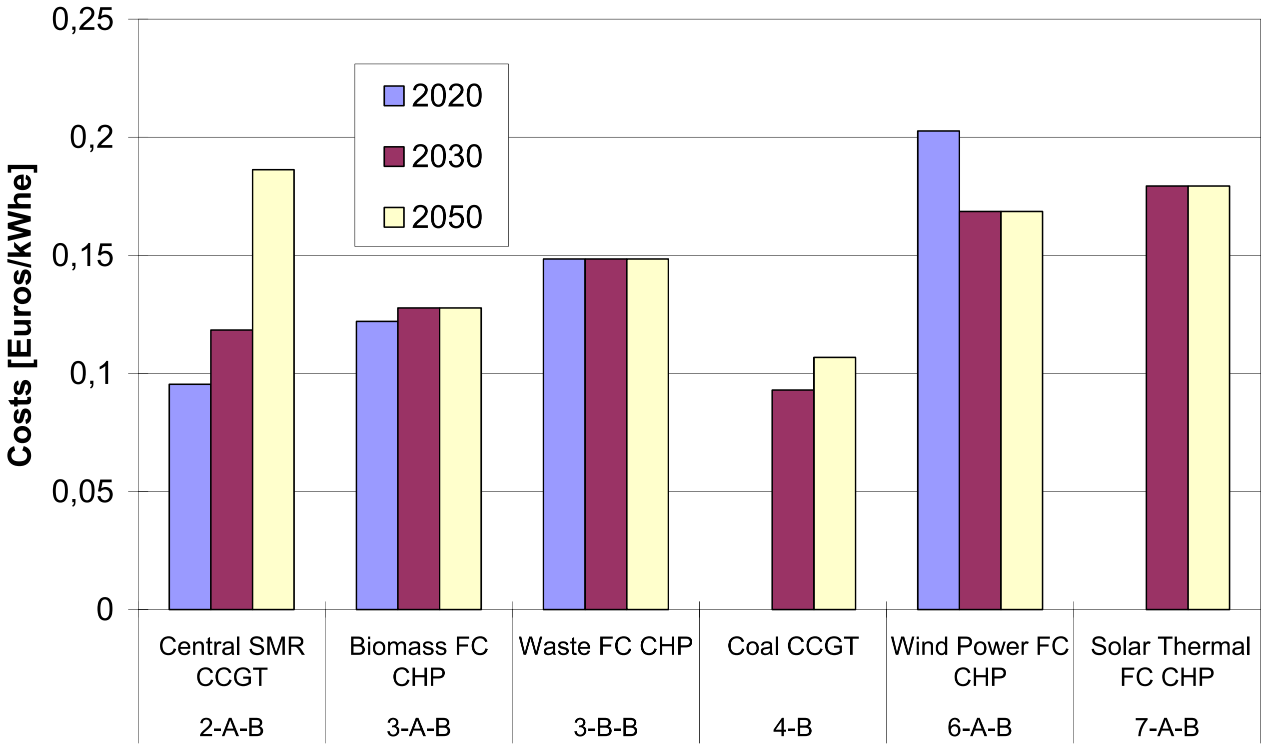

Figure 24. Costs of selected stationary use hydrogen supply chains.

The use of by-product is the cheapest way.
We can clearly see the increase of NG, biomass and Coal prices from 2020 to 2050. In 2050, SMR is no more competitive with Biomass and coal gasification.

6. Remarks

In this report a synthesis of the selected chains and data for Italy 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

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

$$C_{T2} = C_{T2(t)} \cdot T2$$ [€]

- *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

$$LEC = \frac{C_{T1} + C_{T2} + C_{T3}}{T2 \cdot AFLH_t \cdot P}$$ [€/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 Italian 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.

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

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

Source	I / O	Italy	MIX EU 15 [1) (1999)]
Biomass and wastes	I	0.081	0.1912
Brown Coal	I	0.13	0.1956
Hard Coal	I	0.13	0.5512
Fuel Oil (1.8%S)	I	0.146	-
Geothermal	I	-	0.0016
Hydro	I	0.142	0.1239
Mineral Oil	I	-	0.2397
NG	I	1.164	0.3440
Nuclear	I	-	1.1354
Wind Power	I	0.035	0.0044
Electricity	O	1.0000	1.0000
Equivalent CO_2 emissions	O	375 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 1.83 kWh per kWh of delivered electricity leading to an electricity generation efficiency of about 54%. The GHG emissions for the Italian electricity mix in 2020 are 375 [g / kWh] of electricity delivered.

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

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

Source	Italy	MIX EU 15 (1999)
Biomass and wastes	4.4	6.90
Brown Coal	7.1	7.10
Hard Coal	7.1	19.90
Fuel Oil (1.8%S)	8	-
Geothermal	-	0.10
Hydro	7.8	4.40
Mineral Oil	-	8.70
NG	63.7	12.30
Nuclear	-	40.50
Wind Power	1.9	0.20
Electricity	100.00	100.00

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 7 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 7. 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.)

Waste incineration

The characteristics of the waste incinerator are listed in the table bellow.

Table 8. Technical and economic data of the waste incinerator

Waste incinerator	**I / O**	**Value**	**Units**
Waste	I	9.3852	[kWh/kWh]
Electricity	O	1.0	[kWh]
Process scale	-	10,000	[kW]
CH_4 emissions	O	0.0995	[g/kWh]
CO_2 emissions	O	870.16	[g/kWh]
NO_x emissions	O	4.9757	[g/kWh]
Dust-particles emissions	O	1.132	[g/kWh]
SO_2 emissions	O	3.3007	[g/kWh]
NMVOC emissions	O	1.9903	[g/kWh]
CO emissions	O	1.9903	[g/kWh]
N_2O emissions	O	0.0498	[g/kWh]
CO_2 equivalent emissions	O	887.1893	[g/kWh]
Useful lifetime	-	15	[yr]
Annual full load hours	-	6,600	[h/yr]
Investment	-	89,483,300	[€]
Maintenance	-	6	[% of investment]

- *Provision of Diesel*

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

Table 9. 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 Italy is a typical mix of European coal. The values presented in Table 10 represent the amount of energy needed to obtain 1 [kWh] of hard coal ready for use in other processes.

Table 10. 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 11. 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 12. Input and output data for NG distribution (high-pressure pipeline) over 250 km

	I / O	Value	Units
Mechanical work	I	0.0015	[kWh/kWh]
NG	I	1.000015	[kWh/kWh]
NG	O	1	[kWh/kWh]
Process scale	-	10,000,000	[kW NG]
CH_4 emissions	O	0.0011	[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 250 km have been assumed to be 0.0004 EUR per kWh of natural gas.

- *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 13. 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 14. 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 15. 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 16. 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 17. 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).
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). The Foster Wheeler plant has no electricity export.

In Table 18 technical and economic data used in modeling are given for different capacities of hydrogen plants.

Table 18. Technical and economic data for the different SMR plants

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

Cells with "-" : not applicable

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.

[2] With CO_2 capture and storage
[3] Average investment per unit when 10,000 units are installed

- *Production of Hydrogen from Coal*

The hydrogen is produced via large-scale gasification of hard coal with CO_2 capture and sequestration (see Table 19).

Table 19. Technical and economic data of hydrogen generation via coal gasification with CO_2 capture and storage

	I / O	With CCS	Units
Capacity	-	844,866	[Nm^3 H_2/h]
Hard coal consumption	I	2.303	[kWh/kWhH2]
CO_2 emissions	O	20.3	[g/kWhH2]
Investment	-	1,168,100,000	[€]
Maintenance coefficient	-	3.57	[% of investment]
Labour	-	1,090,000	[€/yr]
Overhead	-	0.07	[% of investment]
Useful lifetime	-	25	[yr]
Equivalent full load period	-	7,884	[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 20.

Table 20. 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 [4]	O	0.0025	[g/kWh]

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

- *Production of Hydrogen from Waste*

Metals and other inert materials has to be removed before the waste is inserted into the gasifier. In Mexico all materials are removed. Here a "MBA" is employed which converts the waste into the so-called "Trockenstabilat".
The provided waste is gasified. The gasification process includes waste pre-treatment (31,000,000 €), syngas generation (39,200,000 €), CO shift (3,600,000 €) and PSA (1,100,000 €). The result is GH_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.

Table 21. Technical and economic data for H_2 generation via waste gasification

	I / O	Value	Units
Waste	I	2.31	[kWh/kWh]
Electricity	I	0.03	[kWh/kWh]
GH_2	O	1.0	[kWh]
Aluminum-Scrap	O	0.008	[kg/kWh]
Steel-Scrap	O	0.033	[kg/kWh]
Investment	-	74,900,000	[€]
Maintenance	-	5	[% investment per yr]
Process Scale	-	19,600	[kW]
Equivalent full load period	-	7 500	[h/yr]
Useful lifetime	-	20	[yr]
CO_2 emissions	O	214	[g/kWh]

- *Production of Hydrogen from Solar thermal S/I cycles*

The Thermal power is converted into heat which is used to decompose H_2SO_4 to produce GH_2 (sulphur iodine cycle). The thermo chemical efficiency is 37% (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 22.

Table 22. Technical and economic data for H_2 generation via solar thermal S/I cycles

	I / O	Value	Units
Thermal power	I	2.7	[kWh/kWh]
GH_2	O	1.0	[kWh]
Investment	-	855,110,000	[€]
Maintenance	-	2	[% investment per yr]
Labour	-	17,102,200	[€/yr]
Equivalent full load period	-	7200	[h/yr]
Useful lifetime	-	25	[yr]
Process Scale	-	142,950	[kW]

Production of Hydrogen from Mix Electricity

Hydrogen is produced via on-site water electrolysis.

Table 23. Technical and economic data for electrolysis

		On Site Electrolyser
Capacity	[Nm^3 H_2/h] / [kW]	360
Electricity consumption	[kWh / kWhH_2]	1.6
Pressure	[MPa]	2.6
Investment	[€]	271,800 [5]
Maintenance	[% of investment]	0.9
Labour costs	[€/yr]	0
Overhead costs	[% investment/yr]	0
Useful lifetime	[yr]	6,000
Equivalent full load period	[h/yr]	20

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 24.

Table 24. 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]

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

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 25.

Table 25. 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

- *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 26. 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 27. Table 28 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.

Table 27. 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 [6]	[€]	496,000	496,000
Maintenance	[% of investment]	2.7	2.7
Useful lifetime	[yr]	20	20
Efficiency	[-]	98%	

Table 28. 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 [6]	[€]	231,000	231,000
Maintenance	[% of investment]	3.7	3.7
Useful lifetime	[yr]	20	20

[6] 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 29 and Table 30 present the vehicle technical data used in the study.

Table 29. 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 30. 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 31. 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 32. 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 33. 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 34. 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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