Chapter 3

# Assessment of Selected Hydrogen Supply Chains—Factors Determining the Overall GHG Emissions

**Anne Rödl*, Christina Wulf† and Martin Kaltschmitt***

**Hamburg University of Technology (TUHH), Institute of Environmental Technology and Energy Economics (IUE), Hamburg, Germany, †Institute of Energy and Climate Research—Systems Analysis and Technology Evaluation (IEK-STE), Forschungszentrum Julich, Julich, Germany*

## 3.1 INTRODUCTION AND SCOPE

Passenger transport volumes in cars, buses, and powered two-wheelers, as well as volumes of inland freight transports, have increased in Europe since the late 1990s (EEA, 2016c,d). Today the mobility sector is the largest emitter of greenhouse gas emissions (GHG) within the European Union (EU), even without taking shipping and aviation into account (EEA, 2016b). As shown in Fig. 3.1 road transport has the highest share of GHG emissions in the transport sector (EPSC, 2016). The mobility sector is also a major contributor to overall $NO_x$ emissions and contributes at a lower share to total CO, particle, and NMVOC emissions within the EU (EEA, 2016a).

In 2016 the European Commission published a strategy for low-emission mobility (European Commission, 2016) that, among other things, focusses on the transition toward zero-emission vehicles, such as hydrogen-powered fuel cell vehicles. By the middle of the 21st century 60% of the 1990 GHG emissions from the transport sector should be reduced (European Commission, 2011). Also other air pollution emitted from the transport sector should be reduced significantly (European Commission, 2016).

Thus, growing mobility demands on the one hand and increasingly stringent targets for GHG emissions and other airborne pollutants on the other hand require a shift toward low-carbon and low-emission mobility. Existing mobility options have to be improved considerably and new concepts for road transport systems have to be developed and deployed.

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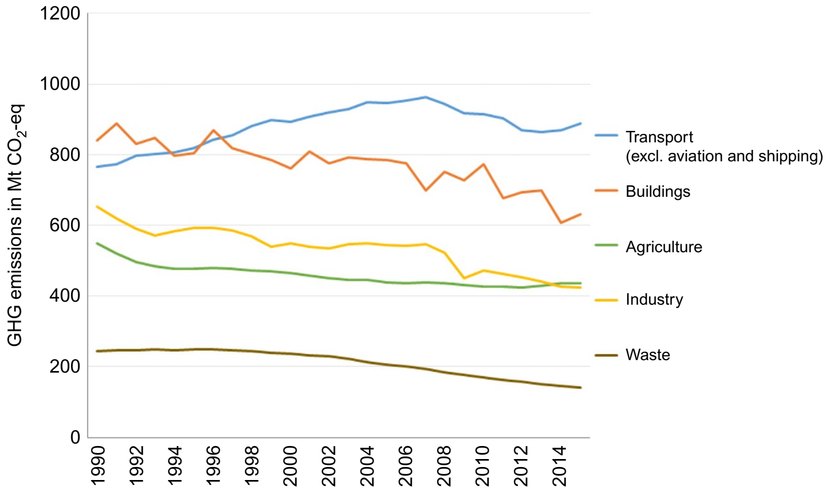


**FIG. 3.1** Historic trends of GHG emissions between 1990 and 2015. *(Data from EEA, 2016b. GHG Emission Trends and Projections. Data Visualization. European Environment Agency. Available at: https://www.eea.europa.eu/data-and-maps/daviz/ghg-emission-trends-and-projections#tab-chart_3 (Accessed 12 May 2017).)*

Fuel cell vehicles powered by hydrogen from renewable sources could be such an innovative solution (IEA, 2015). This approach might help to solve problems with GHG emissions and other locally effective emissions, such as NOx, CO, and particles. The latter group is mostly responsible for toxic effects on humans and the natural environment. By introducing fuel cell vehicles, particle emissions are shifted from the vehicle operation stage to the fuel production stage, or will be completely avoided if renewable energy sources are used (Ahmadi and Kjeang, 2015).

At present hydrogen is mainly produced from fossil energy sources (da Silva Veras et al., 2017). However, due to the legal requirements outlined above, alternatives for the provision of "green" hydrogen from renewable energy sources are being explored. There is a variety of possible renewable supply chains that could be used to implement hydrogen as an alternative transport fuel in the market. These options need to be assessed from an environmental point of view to allow the identification of the most promising supply chains with minimal environmental impacts.

Against this background the overall goal of this chapter is to analyze the environmental impacts of different hydrogen production options and their respective transport needs. An assessment of the most important elements of the hydrogen provision chains should be considered when designing a future hydrogen infrastructure for sustainable supply of the transport sector. To this end, this chapter provides information on non-renewable energy consumption and GHG emissions of different hydrogen provision chains and their various

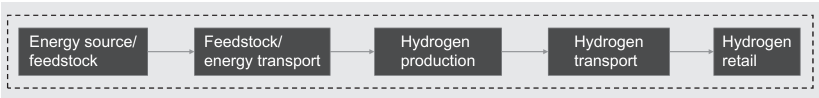


**FIG. 3.2** Overview of the analyzed hydrogen supply chains.

system elements. These elements, such as feedstock provision, hydrogen generation, and transportation, as illustrated exemplarily in Fig. 3.2, are analyzed in relation to their contribution to overall non-renewable energy consumption and GHG emissions.

The hydrogen supply chains are investigated based on a well-to-tank approach, including energy for feedstock provision, hydrogen production technologies, transport, and the sale of the final product. The influence of hydrogen production infrastructure design on the overall emissions and energy consumption of hydrogen provision is assessed in detail. The greenhouse gas emission saving potential of the different renewable pathways of hydrogen provision is compared to that of hydrogen provision based on fossil fuels.

## 3.2 BACKGROUND

In the following the status and future plans for hydrogen infrastructure development in Europe and Germany are discussed in detail.

Although fuel cell vehicles were developed in the 1960s, most of the vehicles operated today are fueled by fossil fuels, such as gasoline and diesel. Nevertheless, hydrogen is produced in considerable quantities and used mainly within the chemical and the crude oil refinery industry (IEA, 2015).

In Europe only 4% of the overall new vehicle registrations have been cars with engines based on alternative fuels (Eurostat, 2015) in 2013. The majority of these vehicles are hybrid electric vehicles; they sum up to 2.1% of the overall newly registered cars (ACEA, 2017). However, there are no official statistics on the number of fuel cell vehicles in use; statistics available in Europe (Eurostat, 2015; ACEA, 2017; KBA, 2017b) just distinguish between conventional fossil and alternative fuel engines. The latter can be fueled by electricity, LPG (liquefied petroleum gas), CNG (compressed natural gas), alcohols (B85, B100), hydrogen, or biodiesel (B100).

Globally, roughly 550 fuel cell electric vehicles (including cars and buses) were in use in 2014 (IEA, 2015). Thus, it is likely that in Europe only a few hundred of such vehicles are in operation. This is an extremely small number compared to the total number of 1.2 billion vehicles in use worldwide and roughly 250 million passenger cars operated within the EU-28 in 2014 (ACEA, 2017; Eurostat, 2015).

So far, Europe, the United States, and Japan have been the most active in promoting hydrogen use within the transportation sector and in developing the necessary refueling infrastructure (Hydrogen Council, 2017). In Europe the hydrogen refueling infrastructure is already quite advanced with 22 active refueling stations in Germany, 15 in the United Kingdom, 11 in Denmark, 9 in France, and 6 in Switzerland. In Scandinavia (Finland, Sweden, Norway) 6 hydrogen refueling stations can be found, 4 each in Austria and Spain, 3 in Belgium, 3 in the Netherlands, 2 in Italy, 1 in the Czech Republic, and also 1 in Slovenia (status early 2017). In the United States, hydrogen refueling stations have been mainly installed on the East Coast, the Great Lakes Area, and in California (TÜV SÜD, 2017).

This infrastructure development goes hand in hand with the planned expansion of the fuel cell vehicles market. It is planned to have 520,000 fuel cell vehicles on the streets globally in 2020 (IEA, 2015). Depending on the development scenario, the share of fuel cell vehicle sales will range between 4% and 11% in 2050 (Pasaoglu et al., 2016). This requires an efficient hydrogen refueling infrastructure.

In Germany, about 215 fuel cell vehicles have been registered at the beginning of 2016. Most of them are used within demonstration projects initiated and sponsored by the National Innovation Program (NIP) for Hydrogen and Fuel Cell Technology (BMVI, 2016). However, due to the high cost of these vehicles and the still only scarcely developed fuel provision infrastructure, market development is only very limited so far. Only 49 new fuel cell passenger cars have been registered throughout the year 2016 (Gerster and Wimmelbücker, 2017).

Therefore, it is planned to significantly expand the network of refueling stations in the coming years to achieve much better coverage, and thus clearly improved fuel availability. Based on the 22 hydrogen refueling stations currently in use in Germany, it is planned to have around 400 active refueling stations in 2025 (H2 Mobility, 2017). Until 2020 the installation of 100 refueling stations will be supported by governmental institutions regardless of the number of registered vehicles (BMVI, 2016).

Investigations have shown that hydrogen could provide 40% of the German end energy demand within the transportation sector (H2 Mobility, 2017; Robinius, 2015). For 2050 an final energy demand of the overall German mobility sector of 2412 PJ/a has been projected (Blanck et al., 2013). About 965 PJ/a (roughly 40%) could be provided by hydrogen (Joest et al., 2009).

Assuming such a prosperous development and an unchanged number (about 14,500) of refueling stations (Statista, 2017), each station would have to provide >2 t/d of hydrogen. Currently, the largest hydrogen refueling station in operation can deliver 1 t/d of hydrogen. To reach sufficient coverage, at least 10 hydrogen refueling stations within each major urban center and in a 90 km distance along major motorways between the urban centers should be erected (Altmann et al., 2014). Most likely, the capacity of these refueling stations will be adapted according to the expected demand; at the earliest in the 2020-years it is likely that there will be a mixture of small refueling stations (212 kg/d), medium-sized stations (420 kg/d), and large ones (1000 kg/d). An overall hydrogen demand of about 45,300 t/a in 2023 can be expected if the market develops as discussed (calculated on the basis of: Altmann et al., 2014).

## 3.3 HYDROGEN PRODUCTION AND TRANSPORTATION

There are a variety of possible strategies for hydrogen production, distribution, storage, and refueling. From these various options only the environmental performance of proven hydrogen production technologies will be analyzed here.

Established technologies for hydrogen production are steam reforming of natural gas, coal gasification, and water electrolysis (Sgobbi et al., 2016). In the future, further opportunities might become available through biomass-based $H_2$ production technologies, solar steam reforming of methane by CSP (concentrated solar power) in countries with high solar radiation, and also by coal gasification with a subsequent water-gas-shift-reaction with carbon capture and storage (Sgobbi et al., 2016). Further options based on bacterial hydrogen production, such as dark fermentation and photofermentation, as well as thermochemical cyclic processes, are still in an early demonstration stage or even just available on a lab scale (Nikolaidis and Poullikkas, 2017).

Based on these conversion technologies, hydrogen can be produced in small-scale facilities onsite close to the refueling station or offsite in large-scale, optimized facilities with huge hydrogen production capacities. If hydrogen is produced offsite in large-scale plants it has to be delivered by truck or pipeline to the refueling station (Altmann et al., 2014). This can be realized in a gaseous form at high pressure or in a liquid state at very low temperatures. At the refueling station, hydrogen can be stored also pressurized or in a liquid form. Consequently, different hydrogen provision concepts require different means of transportation.

Initially the feedstock (e.g., biomass, coal) and the energy (e.g., electricity) have to be transported to the small-scale or large-scale production plant. Feedstock is transported by truck or pipeline and electricity is conducted via electrical lines. Finally, the hydrogen needs to be transported to the refueling station via pipeline or truck.

Table 3.1 gives an overview of the various hydrogen production technologies that are assessed in this chapter. In the following these technologies will be explained in detail.

### 3.3.1 Steam Methane Reforming (SMR)

Currently around 95% of worldwide commercial hydrogen production is based on fossil fuels. The largest part of it is produced via SMR from natural gas (Hydrogen Council, 2017; Santos, 2015; Abe, 2008). Essentially all hydrogen-rich gases, biomethane for example, can be used for hydrogen production via such a process. However, natural gas is the currently the method of choice because of its easy availability and low costs, mainly in large-scale production facilities (HPTT, 2009). Thus, at present SMR is, besides coal gasification, the cheapest hydrogen production option and has the lowest $CO_2$ emissions compared with other fossil fuel-based hydrogen production options

**TABLE 3.1 Conversion Efficiencies of Different Hydrogen Production Technologies**

| Hydrogen Production Technologies | Plant Capacity (MW) | Conversion Efficiency | | References |
|---|---|---|---|---|
| | | Min (%) | Max (%) | |
| Large-scale steam methane reforming (SMR) | 150–300 | 70 | 85 | 3; 4; 2; 5 |
| Small-scale steam methane reforming (SMR) | 0.15–15 | 51 | 80 | 3; 2 |
| Biogas reforming | ~100 | 22 | 32 | 6 |
| Alkaline electrolysis (large scale) | Up to 150 | 65 | 82 | 4; 2 |
| PEM electrolysis | Up to 1 | 65 | 78 | 3; 2; 5 |
| Biomass gasification | 4–160 | 35 | 53 | 1; 2; 5, 6; 7 |

*1, Hosseini and Wahid, 2016; 2, IEA, 2015; 3, Nilsen et al., 2007; 4, Altmann et al., 2014; 5, US Department of Energy, 2015b; 6, Gellert, 2013; 7, Vakkilainen et al., 2013.*

(Sharma and Ghoshal, 2015). Additionally, some small-scale reforming units exist on a demonstration level (IEA 2015). Such small-scale reformers would allow a distributed (decentralized) natural gas reforming directly at fueling stations and is therefore considered as a near-term option for relatively cheap hydrogen provision (HPTT, 2009; Schjolberg et al., 2015).

Natural gas reforming consists of two coupled process steps. First the hydrocarbon is converted together with steam to a synthesis gas containing hydrogen ($H_2$) and carbon monoxide (CO). In the respective exothermic chemical reaction methane is partly oxidized to CO by reducing water to $H_2$. The product gas is then treated within a second process step in which additional water is reduced to hydrogen within a catalytically controlled conversion process by oxidizing the carbon monoxide to carbon dioxide (Sharma and Ghoshal, 2015). Afterwards the produced gas is purified in a final cleaning step by pressure swing adsorption to provide hydrogen with a purity of nearly 100%. On average SMR plants show conversion efficiencies between 74% and 85% (Nikolaidis and Poullikkas, 2017).

## 3.3.2 Electrolysis

Another common way of producing hydrogen is electrolysis. This process splits water into hydrogen and oxygen by applying electricity; electrical energy is the driving force of the chemical reaction and provides the energy to split water into its components. Thus, it is an endothermic reaction characterized by a high energy (here: electricity) demand and the provided products (hydrogen and oxygen) are more energy rich than the reactant (water). The energy input-output ratio amounts to approximately 1.5 (Nikolaidis and Poullikkas, 2017). Only 4% of the world's commercial hydrogen production is based on electrolysis (IEA, 2015). However, a great future is predicted for this option because electricity from volatile renewable sources of energy (e.g., wind, solar) can be converted into a storable gas to be used as an energy carrier or as a raw material for the chemical industry.

Alkaline water electrolyzers using alkaline electrolytes, such as potassium hydroxide, are currently the most mature technology used for hydrogen provision via this technical approach (Ursua et al., 2012; IEA, 2015). Commercial-scale alkaline electrolyzers operate with an overall efficiency of 65%–80% (see Table 3.1). Electrolysis via PEM (Polymer Electrolyte Membrane) is a variation where the electrolyte membrane is a plastic material (US Department of Energy, 2017). Large-scale water electrolysis plants can produce 50,000 to 750,000 kg of hydrogen per day. In comparison, distributed small-scale systems located, e.g., at refueling stations, have much lower capacities and can provide up to 1500 kg of hydrogen per day.

In most cases electricity from the public grid is used for hydrogen production within an electrolyzer operated at commercial scale. Water electrolysis using only electricity provided by wind energy (from onshore, and especially offshore wind parks) or solar radiation (e.g., large-scale photovoltaic power plants) is seen as an important future technology that might reach full market maturity within the next 5–10 years. This time schedule is realistic because PEM electrolysis demonstration systems already exist at selected locations (Miller, 2011).

Hydrogen production from electrolysis is considered as a possibility to store surplus electricity from wind or solar in order to facilitate the integration of their fluctuating supply characteristics into the energy system and to provide a "clean" and flexible fuel for several applications. Thus, hydrogen is often regarded as the most important solution to realize an energy system based fully on renewable energies with fluctuating characteristics; in a figurative sense this is also true for the mobility sector.

### 3.3.3 Solid Biomass Gasification

Gasification is defined as the thermochemical conversion of solid biomass within different mediums, such as air, oxygen, or steam, into a synthesis gas (Nikolaidis and Poullikkas, 2017; Kaltschmitt et al., 2016). Within such a gasifier the solid organic matter (e.g., wood chips) reacts chemically at high temperatures (700–1400 °C), among others, with an oxidation agent to hydrogen. If water steam is used as an oxidation agent, the relative amount of hydrogen per unit biomass is higher compared with the use of oxygen, because with water additional hydrogen is introduced into the system. Such a steam gasification can reach an efficiency of 44%, on average. It requires a primary energy input of 2.3 MJ per MJ of hydrogen. Typically, such systems are realized within an intermediate size. Economies of scale prevent very small systems from being profitable because the costs of producing one unit is higher the smaller facility. The size limit is defined by the biomass logistic costs, which are increasing with the transportation distance.

## 3.3.4 Hydrogen Transportation

### *3.3.4.1 Pipelines*

Hydrogen pipelines are constructed in a similar manner to pipelines for natural gas. There are already some examples of such hydrogen networks in Germany, the United States, France, and Belgium (Krieg, 2012). They are made of steel or tough cast iron and do have significant requirements on the weld seams.

### *3.3.4.2 Trucks*

Hydrogen can be transported by truck in compressed or liquid form. Hereafter the advantages and disadvantages are highlighted briefly.

#### Compressed transportation

Compressed hydrogen can be transported by trucks in gas cylinders or gas tubes with pressures between 200 and 500 bar. Usually several cylinders or tubes are bundled to modules in a 20′ or 40′ container that is mounted on a trailer (tube trailer).

The transport capacities and tank weights are important variables in assessing the GHG emissions and non-renewable energy consumption in hydrogen transportation via truck. Typically, the high weight of the cylinders or tubes limit the maximum hydrogen load that can be transported. A tube trailer with steel cylinders can store up to 25,000 liters of hydrogen compressed to 200 bar (Wystrach GmbH, 2017a), which amounts to around 420 kg of hydrogen.

Currently lighter tank materials (composite materials for gas cylinders or gas tubes) that can be operated at higher pressure are under development in order to increase the hydrogen transport quantities per trailer. For example, superlight cylinder materials consisting of carbon fiber over high-density polyethylene liners (Wystrach et al., 2012) have been investigated. Trailers with such composite cylinders can carry up to 39,600 liters of hydrogen with a pressure level of 200 bar equivalent to about 666 kg of hydrogen (Wystrach GmbH, 2017b).

Recently a jumbo trailer was released that can carry 13,000 $m^3$ of hydrogen compressed with 500 bar (Linde Group, 2013), which amounts to a transported hydrogen weight of about 1100 kg.

#### Liquid transportation

If hydrogen is transported in liquid form, it has to be cooled down to a temperature of at least −253 °C using a very energy consuming process. Typically, 10 kWh of electricity are needed per kg of liquid hydrogen; this represents around 30% of the energy content of the hydrogen (Krieg, 2012). The latest research has shown that energy consumption for liquefaction can be reduced to 6.7–7.5 kWh/kg $H_2$ (Cardella et al., 2017; Stolzenburg et al., 2013). Because of the higher energy density resulting from liquefaction, the transport capacities for liquid hydrogen per supply task are higher than for compressed hydrogen. Furthermore, about 1.65% of the hydrogen is lost during the liquefaction process and around 0.3% of the liquefied hydrogen is "boiled-off" per day during transportation and storage (Stolzenburg and Mubbala, 2013).

## 3.4 ASSESSMENT OF HYDROGEN SUPPLY CHAINS

### 3.4.1 Method

In this part of the chapter life cycle assessment (LCA) results on different hydrogen supply chains based on a literature review are presented. Further, literature data is used for calculating GHG emissions and energy consumption of hydrogen transport processes.

In general, a LCA looks at potential environmental impacts during the lifetime of a product (DIN EN ISO, 2006). In this approach, all inputs and outputs of manufacturing, and the use and disposal of products and services, including all related upstream processes, are summarized. Thus, all data assessed below use the LCA method to determine the environmental impacts of the different hydrogen provision pathways.

The functional unit chosen here is 1 MJ contained in the final product hydrogen at an ambient temperature of 15 °C, 1.5 MPa, and a purity of 99.999%, required to operate fuel cell vehicles successfully. It is assumed that 1 kg of hydrogen contains 120.1 MJ. The assessment concentrates on the situation in Central Europe. Assumptions for the parameters that have been taken into account for own calculations are presented in the subsequent sections.

### 3.4.2 Supply Chains

The following hydrogen supply chains have been assessed here:

**(1)** *SMR from natural gas*

- Natural gas (German mix available from the gas grid) ➔ large-scale SMR unit ➔ pipeline or truck transportation (liquid or compressed) ➔ compression retail
- Natural gas (German mix available from the gas grid) ➔ small-scale[1] SMR unit ➔ compression retail

1. Regional distribution at the refueling station.

**(2)** *SMR from biogas*

- Biogas from maize (energy crops) and from animal manure ➔ large-scale SMR unit ➔ transportation via pipeline or truck (compressed or liquid) ➔ compression retail

**(3)** *Electrolysis based on electrical energy from wind power*

- Offshore wind park ➔ electricity distribution ➔ large-scale electrolysis unit ➔ pipeline or truck transportation (liquid or compressed) ➔ compression retail
- Onshore wind park ➔ electricity distribution ➔ large-scale electrolysis unit ➔ pipeline or truck transportation (liquid or compressed) ➔ compression retail
- Locally distributed wind power generation ➔ small-scale electrolysis unit[1] ➔ compression retail

**(4)** *Electrolysis based on electricity from solar radiation (PV)*

- Solar park ➔ electricity distribution ➔ large-scale electrolysis unit ➔ pipeline or truck transportation (liquid or compressed) ➔ compression retail

**(5)** *Electrolysis based on grid power*

- Electricity provision and distribution ➔ large-scale electrolysis unit ➔ pipeline or truck transportation (liquid or compressed) ➔ compression retail
- Electricity provision and distribution ➔ small-scale electrolysis unit[1] ➔ compression retail

**(6)** *Biomass gasification*

- Farmed wood (short rotation plantation) ➔ large-scale gasification unit ➔ pipeline or truck transportation (compressed or liquid) ➔ compression retail

Fig. 3.3 gives an overview of the different hydrogen supply chains considered here. Depending on the assessed hydrogen production option, the analyzed chains start with feedstock provision or electricity generation.

### 3.4.3 Assumptions and Data

The assessment of the above defined hydrogen supply chains is based on various data and assumptions that will be explained in detail below.

#### *3.4.3.1 Feedstock and Energy Resources*

The most important data related to the implemented feedstock and the necessary energy resources are presented in the following.

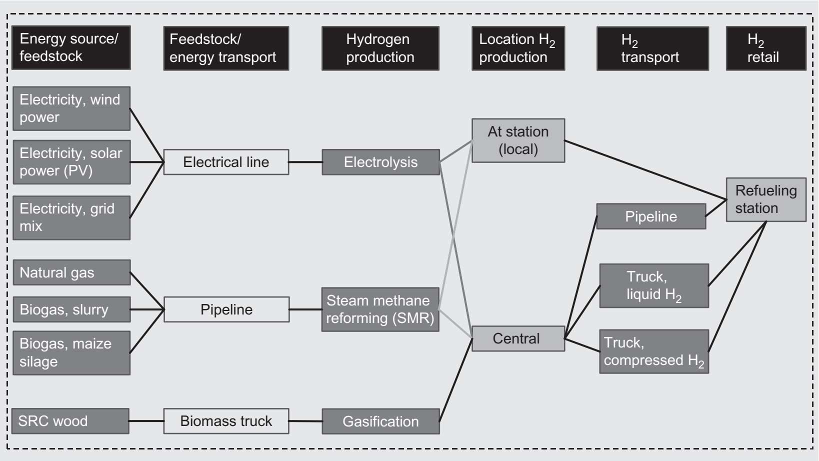


**FIG. 3.3** Overview of the hydrogen supply chains considered.

*Electricity*. Three options for electricity provision are considered for electrolytic hydrogen production, namely, from wind and solar power, and from the German electricity mix as a reference. The LCA data for the German electricity mix have been taken from a commercially available database (Ecoinvent, 2016). The used dataset represents the consumption mix for the year 2015, and includes, among others, electricity inputs produced in Germany and from imports, the losses within the transmission network, as well as direct emissions to the ambient air. Table 3.2 contains the considered data sources for modelling electricity provision for the electrolytic hydrogen production.

*Methane*. Natural gas supply for the large-scale and small-scale steam methane reformers (SMR) is realized via the German natural gas pipeline network. According to Table 3.3, the average LCA data representing the mix of gas imports from domestic production in Germany is found in Ecoinvent (2016).

For the cases in which biomethane is used for SMR, biogas produced from two different types of feedstock have been taken into consideration:

- biomethane from cultivated biomass—maize, whole crops, grass.
- biomethane from residues and byproducts—agricultural and industrial organic waste streams.

The system boundaries for biomethane production from cultivated biomass include the cultivation, transportation, and storage of the energy crops, whereas the assessment of biomethane production from biowaste starts with the collection and transportation of the organic waste materials. For both chains, biomass fermentation, fermentation residue storage, and their transportation and application are considered, as well as the upgrading of the biogas to biomethane and its feed-in into the local gas network (Westerkamp et al., 2014).

**TABLE 3.2 LCA Data Used for Modelling the Impacts of Energy Provision for the Respective Hydrogen Supply Chains**

| Energy Source | Dataset Name/Parameters | Reference |
|---|---|---|
| Electricity grid mix (large-scale application) | Market for electricity, high voltage—DE[a] | Ecoinvent (2016), v.3.3 |
| Electricity grid mix (small-scale application) | Market for electricity, medium voltage—DE[a] | Ecoinvent (2016), v.3.3 |
| Wind energy, onshore | Energy generation onshore (3,5 MW, 5,5 m/s) | Kaltschmitt et al. (2013b) |
| Wind energy, offshore | Energy generation offshore (6 MW, 9,5 m/s) | Kaltschmitt et al. (2013b) |
| Solar radiation, PV | Energy generation, polysilicon cells, solar park | Kaltschmitt et al. (2013a) |

[a] *DE—data representing German Electricity Mix.*

**TABLE 3.3 LCA Data Used for Modeling Methane Sources for Hydrogen Supply Chains From SRM (Steam Methane Reforming)**

| Feedstock | Dataset Name/Parameters | Reference |
|---|---|---|
| German natural gas mix | Market for natural gas, high pressure—DE[a] | Ecoinvent (2016), v.3.3 |
| Natural gas from low-pressure network | Market for natural gas, low pressure—ROW[b] | Ecoinvent (2016), v.3.3 |
| Biomethane from cultivated biomass | Cultivation maize (82%), whole crops (8%), grass (10%)—fermentation, covered—upgrading—feed-in | Westerkamp et al. (2014) |
| Biomethane from organic wastes | Collection of biogenic wastes from agricultural (17%) and industry (83%), fermentation, covered—upgrading—feed-in | Westerkamp et al. (2014) |

[a] *DE—data representing German Electricity Mix.*
[b] *ROW—data representing a worldwide average.*

*Solid biofuels*. The biomass gasification process is fueled by poplar wood chips from a short rotation plantation in Germany (Table 3.4). The data considered include cultivation with fertilizer application and the harvesting of trees with special choppers that chip the trees and blow them into a tractor transport container. Transportation to the gasification plant is realized by truck (Roedl, 2010).

**TABLE 3.4** LCA Data Used for Modeling of the Solid Biofuels

| Feedstock | Dataset Name/Parameters | Reference |
|---|---|---|
| Wood chips from short rotation coppice (SRC) | SRC poplar, fertilized, chipped, transported | Roedl (2010) |

### *3.4.3.2 Hydrogen Production*

Three different options for hydrogen production are considered here. These are SMR, electrolysis, and biomass gasification. They mark the currently most likely technology for small-scale (locally distributed at a refueling station) and large-scale hydrogen production. The following framework has been defined.

*SMR*. Hydrogen production is assumed to be realized from natural gas via SMR in two different plant sizes: a large-scale plant and a small-scale system at a retail site. Biomethane reforming is also taken into consideration, in addition to natural gas. This can be realized from two different types of feedstock, cultivated biomass and biowaste. The following assumptions are made on the efficiency of the reformers, regardless of the origin of their feed-in gases:

- Small-scale steam reformer typically used at refueling station: efficiency 69% (Edwards et al., 2014).
- Large-scale reformer typically used at large-scale production sites: efficiency 76% (Edwards et al., 2014).

The natural gas input for the small-scale reformer is assumed to be 1.4 MJ/MJ hydrogen and 1.3 MJ/MJ for the large-scale reformer (Edwards et al., 2014). These gas demands are also considered if biomethane is used as a feedstock. The average heating value of natural gas is assumed to be 35.7 MJ/m$^3$ and 35.9 MJ/m$^3$ for biomethane upgraded from biomass. The small difference results from the purity of the gas, which is slightly higher for biomethane than for natural gas (which is a bit more polluted with nitrogen and carbon dioxide).

*Electrolysis*. For hydrogen production via electrolysis a PEM electrolyzer is considered. This technological solution is characterized by an efficiency of 65% (Edwards et al., 2014), i.e., an electricity input of around 1.5 MJ/MJ hydrogen is needed regardless of the origin of the electricity (Edwards et al., 2014).

*Gasification*. For the hydrogen provision route via gasification of woody biomass, a large-scale gasifier with an efficiency of 44% is considered (Edwards et al., 2014). The required wood input amounts to 2.3 MJ/MJ hydrogen.

### *3.4.3.3 Hydrogen Transportation*

The options for hydrogen transportation assessed here are discussed and defined in detail below. If the hydrogen is not produced in a facility close to the point of retail a transport distance of 250 km is taken into consideration.

*Pipeline*. Data on the emissions and energy requirements for the construction of a hydrogen pipeline have been transferred from the construction of high-pressure natural gas pipelines (Ecoinvent, 2016). This is justified by the fact that both pipeline systems are quite similar. On its way through the pipeline the hydrogen gas loses pressure and has to be recompressed regularly (Faist-Emmenegger et al., 2007). It is assumed that a gas recompression is necessary every 100 km. Energy consumption for recompression and further assumptions concerning the pipeline properties are shown in Table 3.5. Recompression units and pipeline networks have to be maintained on a permanent basis. As an adjustment, 2% of the initial GHG emissions resulting from pipeline construction have been assumed for maintenance work per year.

*Truck (compressed)*. The assumptions outlined in Table 3.6 related to tank types, volumes, and weights, as well as storage capacities have been made.

**TABLE 3.5 Data for the Pipeline Considered**

| Service Life Time | 40 | a |
|---|---|---|
| Maintenance | 2 | %/a |
| Mass flow | 35 | t/d |
| Length | 250 | km |
| Recompression every 100 km | 0.02 | kWh/kg hydrogen |

**TABLE 3.6 Capacity and Weights of Selected Tank Types for Compressed Hydrogen Transportation Used in the Assessment**

| Tank Type | Volume (L) | Pressure (bar) | $H_2$-Capacity (kg) | Tank Tare Weight (kg) |
|---|---|---|---|---|
| Steel cylinder container (SC)[a] | 23,800 | 200 | 400 | 26,298 |
| Steel tubes (ST)[b] | 19,292 | 200 | 324 | 27,254 |
| Composite super light container (CC)[c] | 45,500 | 250 | 957 | 18,854 |
| Composite (TITAN V) trailer (CT)[d] | 44,200 | 250 | 979 | 21,810 |

[a] *Wystrach GmbH (2017a).*
[b] *CMW (2017).*
[c] *Wystrach GmbH (2017b).*
[d] *Hexagon Composites (2012).*

Before a truck can be loaded the hydrogen has to be compressed. Therefore, it is assumed that the hydrogen is generated at a 20-bar level. Values on the necessary energy consumption for compression vary in literature. However, the energy demand for compression primarily depends on the pressure level of the hydrogen to be compressed. For example, an energy demand of 0.5 kWh/kg hydrogen has been presented for compression to 160 bar (Krieg, 2012). Here it is assumed that hydrogen is compressed from 20 to 200 bar or 250 bar. For 1 kg of hydrogen, it is assumed that 0.7 kWh electricity is needed for a compression to 200 bar and 0.9 kWh/kg for a compression to 250 bar. Conventional high-voltage power from the public grid is used for this purpose (Ecoinvent, 2016).

Throughout the overall production, distribution, and retail chain of compressed hydrogen about 4% losses occur (Bond et al., 2011). Additionally, during discharge of the compressed hydrogen gas from the cylinders, a small amount of hydrogen remains within the transportation unit and cannot be used. This reduces the net amount of the compressed hydrogen to be transported.

In summary, during each trip almost 980 kg of compressed hydrogen can be delivered to a refueling station. To ensure a continuous supply at least two deliveries per day are needed if an average hydrogen demand of 1500 kg/d is assumed (Krieg, 2012).

*Truck (liquefied)*. The assessment of the respective transport emissions and energy use is based on a transported amount of 4000 kg liquid hydrogen per supply task. This is a rather conservative assumption because the latest published results indicate a transport capacity of approximately 4500 kg of liquid hydrogen per truck (US Department of Energy, 2015a). The empty tank has a weight of 24,400 kg (Krieg, 2012). A standard refueling station with a demand of 1500 kg/d hydrogen would have to be supplied roughly every three days.

For the total liquefaction process a conservative assumption on electricity demand of 10 kWh/kg hydrogen is made. Modern high-end liquefaction facilities have been demonstrated to require less energy already. However, this value is chosen also to consider the energy demand for auxiliaries, flash gas management, losses, and boil-off during the liquefaction process (Stolzenburg and Mubbala, 2013).

Modern tanks for liquid hydrogen production reduce boil-off losses to a minimum (Linde AG, 2014). Nevertheless, it is assumed that roughly 1% of the liquefied hydrogen will be lost due to boil-off per day during hydrogen storage at the refueling station (Krieg, 2012). An average storage period of approximately three days is assumed.

For all truck transports the distance from the hydrogen production plant to the refueling station (250 km) and back to the production facility is considered. On the outward journey the truck is fully loaded, while it goes back with an empty tank. The vehicle considered is in each case a 40 t freight lorry fulfilling EURO 5 emission standards (KBA, 2017a).

*Electricity transport*. For transportation of electricity to the electrolysis unit, losses of 2% have been assumed (Edwards et al., 2014).

**TABLE 3.7 Energy Demand for Compression or Vaporization at Refueling Station**

| | |
|---|---|
| Onsite hydrogen production (from 15 to 880 bar) | 3.1 kWh/kg hydrogen |
| Pipeline delivery (from 20 to 880 bar) | 3.1 kWh/kg hydrogen |
| Compressed truck delivery (200–880 bar) | 2.4 kWh/kg hydrogen |
| Compressed truck delivery (250–880 bar) | 2.3 kWh/kg hydrogen |
| Liquid truck delivery (compression and dispensing) | 1.7 kWh/kg hydrogen |

#### *3.4.3.4 Conditioning at the Point of Retail*

Depending on the mode of transport, hydrogen has to be compressed or vaporized at the refueling station to be ready for sale. The worldwide automotive industry, as well as gas and plant suppliers, have agreed on a standard for hydrogen fueling of light duty vehicles (SAE, 2016). It regulates the fuel delivery temperature, maximum fuel flow rate, and refueling pressure. Thus, hydrogen refueling stations for passenger cars operate with 700 bar compressed hydrogen, buses are refueled with 350 bar compressed hydrogen (BMVI, 2016). To fill vehicles in practice actually requires a higher pressure of 880 bar (Gardiner and Satyapal, 2009). The refueling of passenger cars takes 3 min with hydrogen cooled to −33 to −40 °C (H2ME, 2016). Energy requirements for compression of the delivered hydrogen at the refueling station are calculated according to the assumptions displayed in Table 3.7 (Edwards et al., 2014; Gardiner and Satyapal, 2009; Krieg, 2012).

## 3.5 RESULTS

The results presented below are based on the assumptions discussed above.

### 3.5.1 Energy Demand

The analysis of the cumulative energy input of non-renewable energy (fossil biogenic resources, such as crude oil, natural gas, and coal, as well as fossil mineral resources, such as uranium) per energy unit hydrogen is shown in Fig. 3.4. The presented results can be summarized as follows.

- The lowest non-renewable energy input is required for hydrogen provision chains based on wind energy followed by solar energy-based chains.
- The highest non-renewable energy input is required when hydrogen is produced from grid electricity.
- The lowest overall energy inputs can be realized if the produced hydrogen is transported via pipeline.

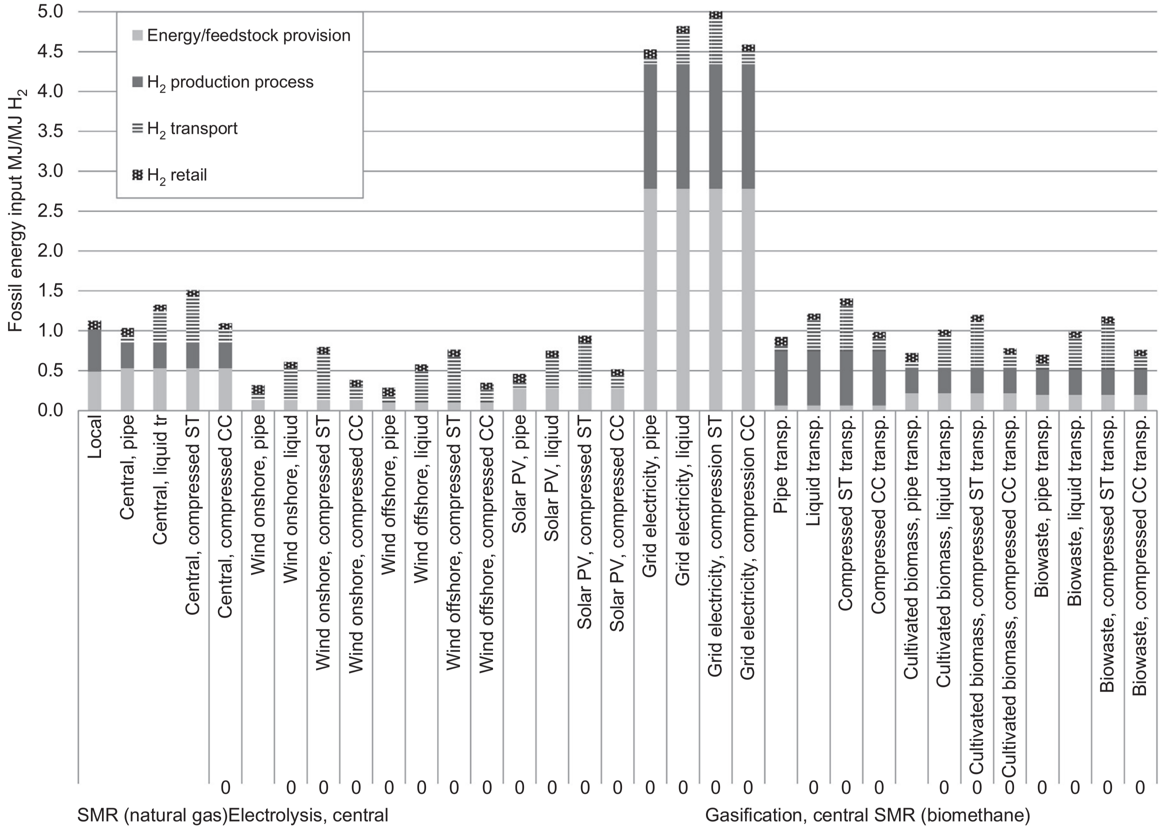


**FIG. 3.4** Cumulative energy consumption of the assessed hydrogen supply pathways.

- Non-renewable energy demand for transportation has a high share on the overall energy demand of the whole chain if liquid hydrogen is transported or heavy steel tubes are used for compressed hydrogen transportation.
- The overall energy demand of hydrogen provision is rather low if biomethane from biowaste is used via SMR or farmed wood (SRC) is converted into hydrogen via gasification.

### 3.5.2 Greenhouse Gas Emissions

Below the greenhouse gas (GHG) emissions, expressed in $CO_2$-equivalents ($CO_2$e) of the overall hydrogen supply chain and its respective production steps, are discussed related to 1 MJ hydrogen. Fig. 3.5 shows a close relationship to the results presented in Fig. 3.4 for the demand for non-renewable energy. This is caused by the fact that the use of non-renewable energy, such as oil, natural gas, and coal, leads directly to GHG emissions. Typically, the use of natural gas shows relatively low GHG emissions, the use of crude oil intermediate GHG emissions, and the use of hard coal relatively high GHG emissions related to one unit of energy. Thus, the energy balances of the various hydrogen provision routes show that a substantial part of the non-renewable energy is needed to provide hydrogen at the refueling station. Only a small share of the overall GHG emissions occur, for example, from fermentation processes or from gas releases from soil or pipeline leaks.

Looking at the complete hydrogen supply chain, the lowest GHG emissions per MJ of hydrogen are produced if wind energy or solar radiation, that is, renewable sources of energy, are converted to hydrogen via electrolysis (25–89 g $CO_2$-eq/MJ). There are only emissions resulting from the upstream processes of the electricity provision due to the construction of the wind mills or the PV systems, as well as from the electricity distribution system. Due to the large-scale electrolysis assumed here, additional emissions are caused by hydrogen transportation. There are no emissions from the hydrogen production process itself due to the use of renewable energy as outlined above.

The situation is completely different if electricity provision from conventional sources, as in the current German electricity mix, is assumed as a feedstock for hydrogen production. According to Fig. 3.5, the hydrogen supply chains based on electrolysis from grid electricity (German electricity mix with roughly 40% of electricity coming from hard coal and lignite) have the highest overall GHG emissions (317–370 g $CO_2$-eq/MJ).

The calculated GHG emissions from gasification and subsequent hydrogen production from woody biomass are also rather low (27–80 g $CO_2$-eq/MJ). Like the production chains based on biomethane (0.5 g $CO_2$-eq/MJ), the hydrogen production process based on thermochemical gasification causes only low emissions of GHG (0.4 g $CO_2$-eq/MJ) and is almost not visible in Fig. 3.5. Biomethane provision causes higher GHG emissions than supply with woody biomass, especially if biomethane is produced from cultivated biomass.

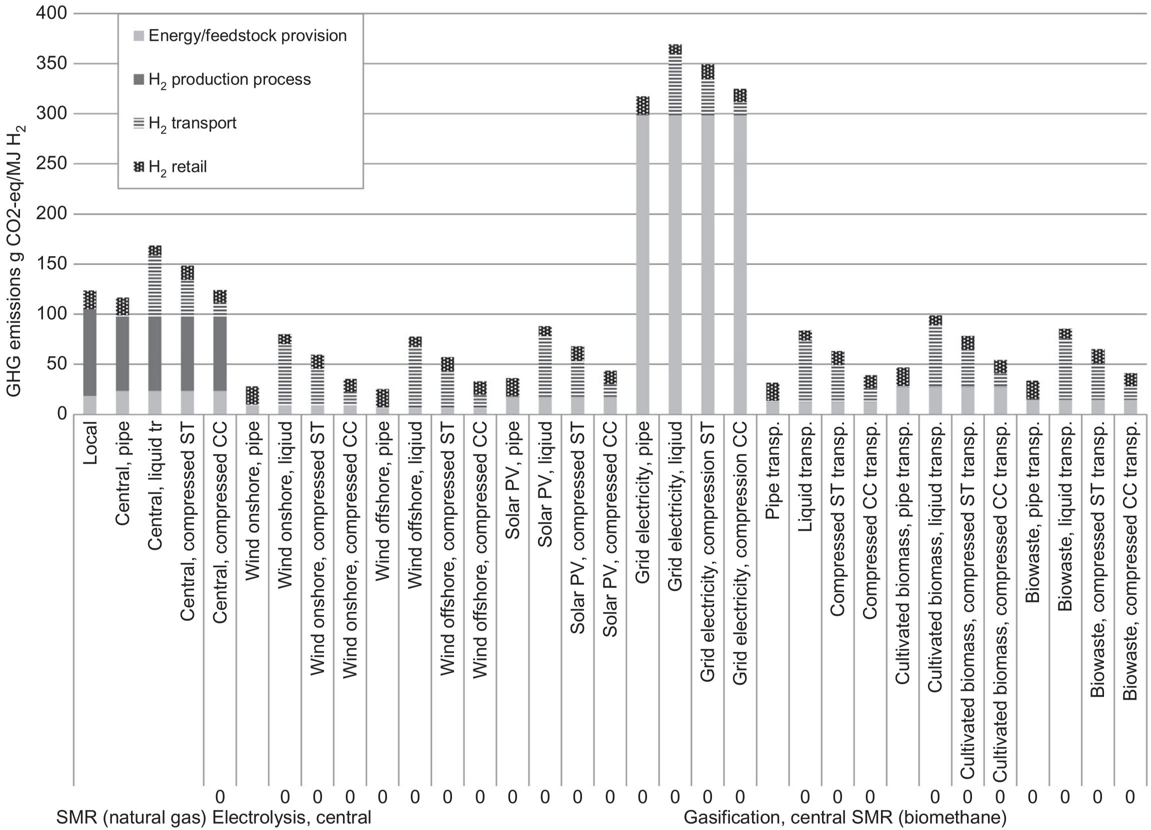


**FIG. 3.5** Greenhouse gas (GHG) emissions of the assessed hydrogen supply pathways.

This is due to higher fertilizer inputs for agricultural crops compared with tree plantations and GHG emissions released during fermentation of the organic matter. The use of biowaste instead of cultivated biomass for biomethane production reduces GHG emissions of the overall hydrogen supply chains.

In comparison, hydrogen production based on natural gas releases significant amounts of GHG emissions during the feedstock provision phase as well as the hydrogen production phase. Therefore, the overall hydrogen provision chains from natural gas have the second highest GHG emissions per MJ of hydrogen (116–169 g $CO_2$-eq/MJ). Locally realized small-scale SMR causes slightly higher emissions (87 g $CO_2$-eq/MJ) compared to large-scale reforming (74 g $CO_2$-eq/MJ); this is mainly due to the lower conversion efficiencies of small-scale systems compared to large-scale units. However, if the hydrogen is produced at the place of retail, GHG emissions from hydrogen transportation do not occur so that the overall GHG emissions of the complete supply chain are lower for the distributed hydrogen production chains. Only if hydrogen from a large-scale SMR plant is transported by pipeline the total GHG emissions of the supply chain are lower than the overall emissions of locally realized hydrogen production. Higher production-related GHG emissions are not compensated by pipeline transport emissions (1.2 g $CO_2$-eq/MJ).

The contribution of the different production steps to the overall GHG emissions throughout the total hydrogen supply chains are displayed in Fig. 3.6. Thus, overall GHG emissions of hydrogen production chains from large-scale and small-scale SMR are dominated by GHG emissions from the hydrogen production process itself. GHG emissions of an electrolysis-based hydrogen production can mainly be traced back to energy requirements for compression at the retail site. As explained above, overall emissions are low because the production process itself causes almost no additional emissions and it is assumed that only electricity from renewable sources of energy, characterized by very low GHG emissions, is used. Therefore, the shares of conditioning and transportation are higher. Biomass-based hydrogen production pathways are mainly determined by the feedstock provision and the conditioning of the gas at the retail site. Thus, transport is a critical issue in the overall emissions balance.

The transport emissions in the studied supply chains (Fig. 3.5) are based on assumptions of a fixed transport distance. However, the results of the overall chains differ with the transported amounts of hydrogen and the transport distances. According to Fig. 3.7, GHG emissions due to truck transport of the hydrogen consist of two components. GHG emissions represented by the intercept with the y-axis are caused by the compression or liquefaction. With increasing distance of the transported hydrogen, the total GHG emissions rise because the truck releases GHG emissions from the combustion of diesel fuel during operation; this is especially true for transport modes with heavy hydrogen tanks. As apparent from Fig. 3.7 transport of liquefied hydrogen causes the highest GHG emissions per transported MJ of hydrogen.

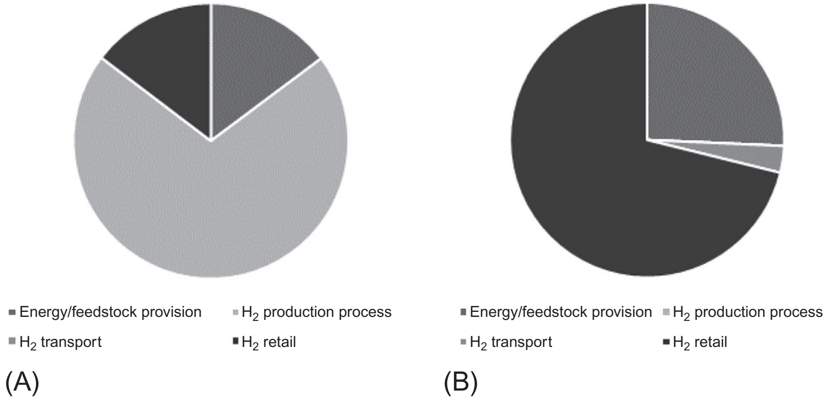


**FIG. 3.6** (A–D) Contribution of the individual process steps to the overall GHG emissions of the different hydrogen production chains (exemplary for each hydrogen production option). (A) Steam methane reforming, natural gas, small scale. (B) Electrolysis wind offshore, pipeline transport. (C) Gasification, short rotation coppice wood, pipeline transport. (D) Steam methane reforming, biomethane from biowaste, pipeline transport.

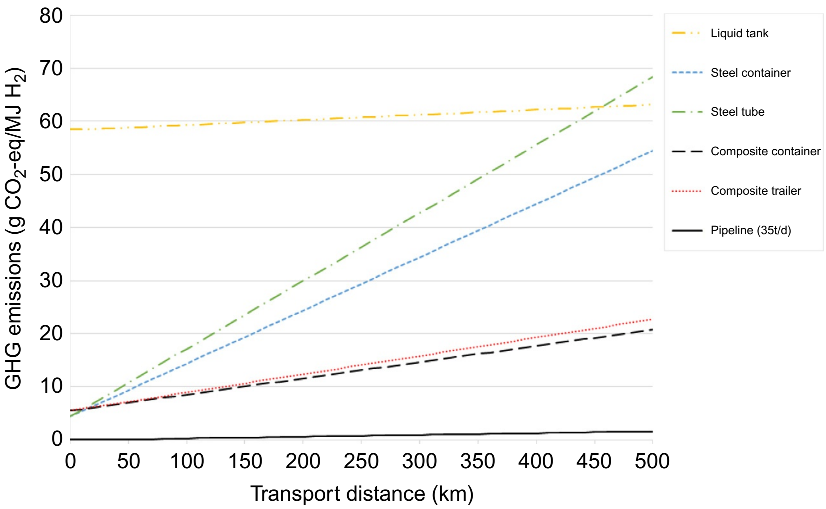


**FIG. 3.7** Comparison of GHG emissions from the different hydrogen transportation options.

However, for large transport distances above 450 km, the calculation results show that liquid hydrogen transportation can be more advantageous than compressed transportation in steel tubes. Although the liquid transportation causes higher initial GHG emissions due to the higher energy demand for liquefaction, GHG emissions do not increase as fast per transported kilometer because of the higher energy content of the transported liquid hydrogen. Therefore, the GHG emissions of compressed hydrogen transportation with heavy steel tubes exceed those of liquid transportation on long distances because of the higher fuel demand of the truck.

If hydrogen is transported as a compressed gas, the use of composite tank materials is advisable to reduce GHG emissions over long distances. The lighter the transport vessels, the lower the GHG emissions per transported energy unit. Especially over long distances, this effect increases. On short distances up to 20 km, initial emissions from the compression outweigh the total GHG emissions per transported MJ of hydrogen. This is because larger amounts of hydrogen can be transported in composite vessels than in steel vessels. Initially the compression of these larger amounts requires more energy but with every traveled kilometer they are offset by lower fuel requirements because of the lighter specific weight of the composite vessels. Therefore, GHG emissions per inherent MJ are lowest if hydrogen is transported in composite vessels over distances above 20 km.

Compared to truck transport, the specific GHG emissions of hydrogen transportation via pipeline are rather low. They increase only slightly with an increasing transport distance. If the GHG emissions of hydrogen transportation are displayed per t km (Fig. 3.8), the GHG emissions from truck transportation decrease strongly with every driven kilometer; again, the reason is that the GHG emissions of compression or liquefaction are allocated to a longer transport distance. In comparison, GHG emissions from pipeline transport increase slightly per t km because of the need for recompression every 100 km.

GHG emissions from pipeline transport are not only dependent on the transportation distance but also on the total pipeline capacity because the overall GHG emissions of the pipeline construction have to be allocated to the overall amount of hydrogen passing through the pipeline during its entire service lifetime. The more hydrogen is transported within an existing pipeline, the lower the GHG emissions per unit of hydrogen. Fig. 3.9 shows that if a long-distance pipeline is only used for the transportation of a low amount of hydrogen, GHG emissions increase sharply if the pipeline diameter is assumed to be constant (the pressure level is increased). If the throughput of the pipeline has to be increased significantly, the pipeline itself needs to be enlarged with the result that the GHG emissions resulting from the pipeline construction also rise.

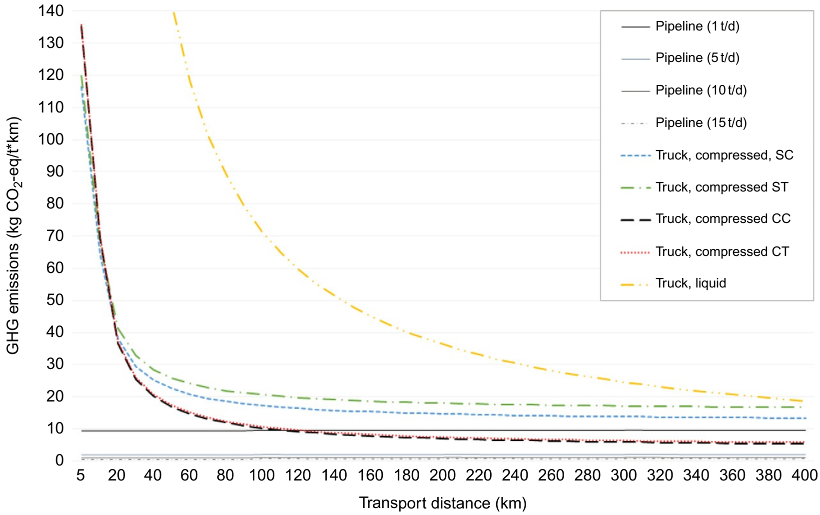


**FIG. 3.8** Comparison of GHG emissions from different hydrogen transportation options via truck (SC, steel container; ST, steel tube; CC, composite container; CT, composite trailer) and pipeline.

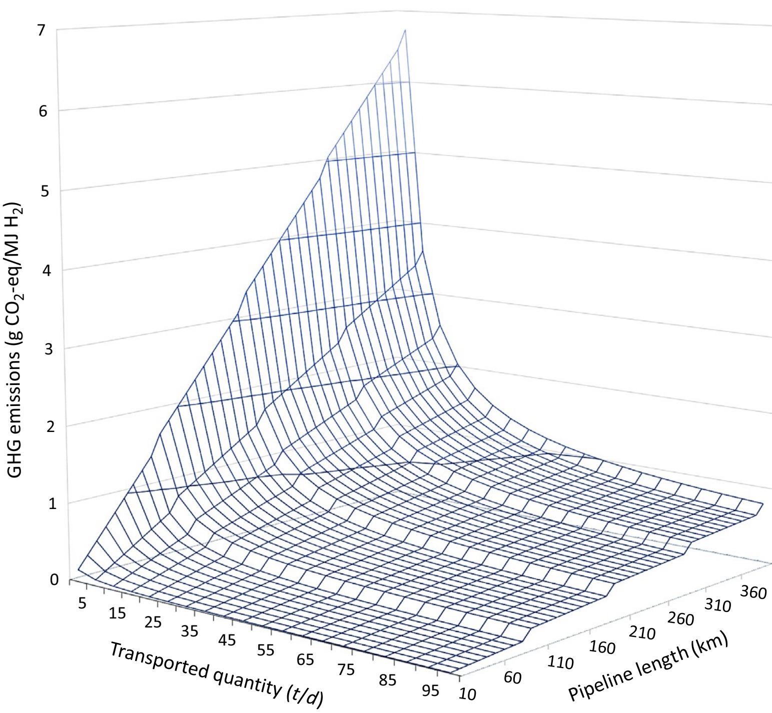


**FIG. 3.9** GHG emissions due to pipeline transport in relation from pipeline length and total capacity.

## 3.6 FINAL CONSIDERATIONS

Hydrogen as a transportation fuel is seen as the great hope for climactically sound ground transportation. Within this context, the overall goal of this chapter has been to assess different possible hydrogen supply chains from a life cycle perspective related to the overall GHG emissions. Additionally, the sensitivity of these environmental effects to the design of the provision chain (e.g., transportation distances, location of the production facility) has been assessed. Based on these variations, promising hydrogen provision chains with minimized environmental impact have been identified for the mobility sector.

The most important results can be summarized as follows:

- Hydrogen provision chains based on wind or solar energy produce the least GHG emissions of all investigated pathways.
- Hydrogen production from natural gas via SMR is in each case more energy consuming and causes more GHG emissions than all other provision chains based on renewable feedstocks.
- The worst option of all investigated cases, in terms of non-renewable energy consumption and GHG emissions, is the use of electricity from the current grid, which is mostly based on non-renewable resources, such as coal and natural gas.
- With an increasing proportion of renewable electricity from the grid, it will become a more climate friendly feedstock for hydrogen production.
- If hydrogen is transported via pipelines from the production facility to the retail station, GHG emissions of the overall provision chain can be minimized.
- If pipeline transportation is not possible, hydrogen should be transported in vessels made of composite materials.
- For very long distances (> 450 km), hydrogen transport in liquid form can be advantageous instead of in trucks with steel vessels.

The results summarized above can be compared to literature results. Fig. 3.10 displays the average GHG emissions from different studies published in the past. These results show great variations because of differences in the assumed system boundaries, the assumptions related to the hydrogen provision chain, as well as the database used. In general, it has also been found in the literature that emissions of hydrogen production from electrolysis with renewable electricity are the lowest, followed by gasification, and SMR from biomethane. The highest GHG emissions occur from SMR of natural gas. These findings support the results presented here.

In conclusion, it can be stated that large-scale hydrogen production combined with pipeline transport can contribute to reduced GHG emissions and non-renewable energy use of hydrogen provision chains. GHG emissions can be minimized if electricity from renewable sources is used for electrolytic hydrogen production. However, if pipelines are used, they should be utilized up to the installed transportation capacity. In this respect, it has to be kept in

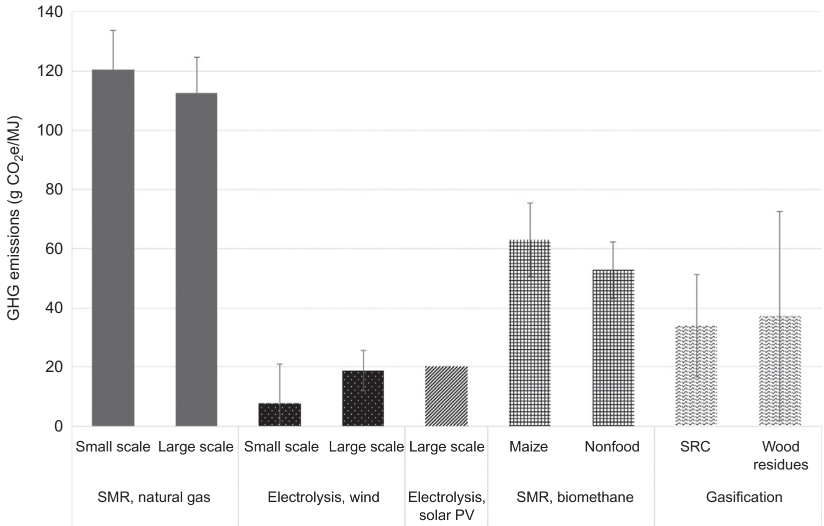


**FIG. 3.10** Average GHG emissions of different hydrogen supply chains compiled from literature (Ruth et al., 2009; Altmann et al., 2004; Albrecht et al., 2015; Edwards et al., 2014; Wulf and Kaltschmitt, 2012, 2013; Suleman et al., 2016; Hajjaji et al., 2016; Cetinkaya et al. 2012).

mind that pipelines would mean erecting a new infrastructure beside the existing natural gas grid. For shorter transport distances, compressed delivery is suitable, especially if modern hydrogen transport tanks from composite materials are used. With longer distances, the transport of liquid hydrogen becomes increasingly more feasible in terms of GHG emissions and energy consumption.

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