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Environmental Assessment of Climate-friendly Hydrogen Supply Chains – A Trade-off between Capacity Utilization and Transport Distance?[#]

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ABSTRACT
Renewable energy sources have gained increasing importance for mitigating the negative effects of climate change while meeting the globally rising demands for energy. In reality, however, regions where renewable energy sources can be readily tapped are often far away from industrial or urban centers of energy demand, necessitating long distance energy imports. Transmitting electricity over long distances is impractical and costly. Secondary energy carriers such as hydrogen produced through water electrolysis could be a sustainable means to convert renewably generated electricity, e.g., from wind or photovoltaic power plants, to chemical products that can be readily transported and stored. This work compares the environmental impacts of local hydrogen production to its remote production with the associated transport over various distances. We aim to evaluate, if and under which conditions the import of hydrogen is environmentally more favorable than local hydrogen production. It was found that hydrogen produced by water electrolysis powered by renewable energy sources is more climate-friendly than that generated locally by conventional steam methane reforming. Even so, to minimize the global warming impact related to hydrogen production, there is indeed an environmentally relevant trade-off: Balancing the best available local conditions for hydrogen production via renewable sources with the minimum transport distance to the consumers.

Keywords: Water electrolysis, Hydrogen import, Energy transport, Life Cycle Assessment, Renewable energy sources, Climate change mitigation

NOMENCLATURE

Abbreviations	
API	American Petroleum Institute
CO_2-eq.	CO_2-equivalent
FLH	Full load hours
GWI	Global Warming Impact
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
PEM	Polymer electrolyte membrane
PV	Photovoltaic
RES	Renewable energy sources
Symbols	
E	Generated amount of electricity
P	Power
g	Elementary flows
m	Mass
n	Lifetime of a plant
$\dot{m}$	Mass flow rate
Chemical Formulas	
CO_2	Carbon dioxide
H_2	Hydrogen

1. INTRODUCTION

A key step towards achieving global climate targets is the development of a so-called hydrogen economy [1], i.e. the reduction of greenhouse gas emissions by producing climate-friendly hydrogen and implementing it as an energy carrier, commodity, and feedstock in the most energy-intensive sectors. For producing climate-friendly hydrogen, water electrolysis technologies appear to be particularly promising, but only if their electricity supply is primarily based on renewable energy sources (RES) [2].

Exploitable RES comprise wind and solar energy, biomass, hydropower, as well as tidal, geothermal, and wave energy [3]. Whereas hydropower, biomass, and geothermal energy are suited for baseload services providing constant power outputs [4], wind and solar energy inherently show high volatility [5]. The intermittency in renewable power supply leads to

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temporary mismatches between supply and demand of electricity resulting in both shortfalls and excesses [6].

Suitable storage technologies need to be established to balance electricity supply and demand. Whereas it is difficult to store electricity in sufficient quantities and over long periods of time [7], using renewably generated electricity to produce hydrogen *via* water electrolysis is considered a sustainable and feasible way to convert electric power to chemical products, thereby increasing its storability and transportability. This concept is often called “Power-to-X” [8].

Wind and photovoltaic (PV) power plants are the preferred suppliers of electricity for generating climate-friendly hydrogen *via* water electrolysis as they allow for harnessing the most widespread RES [4]. Even so, from an economical and environmental point of view, both the renewable power plants and the water electrolyzers require extensive operating hours to compete with conventional hydrogen production [9]. Consequently, climate-friendly hydrogen should be generated preferentially in regions where favorable conditions for harnessing RES prevail. In case of wind and PV power plants, for example, such regions should have sufficiently high and persistent wind speeds and solar irradiance, respectively, to allow for high power rates and operating hours. Regions with high renewable energy potential are unevenly distributed throughout the world [10]. Often, these regions are far away from the centers of energy demand, thereby requiring hydrogen transport within and across national borders. Transporting hydrogen or chemical products derived from hydrogen is, however, energy-intensive and may severely harm the environment due to the development and operation of a suitable transport infrastructure [8].

At present, hydrogen is transported in gaseous or liquid state, by trailer, ship, or *via* pipeline. For medium distances and large quantities, gaseous hydrogen transport *via* pipeline is preferred [11]. Thereby, both the energy demand and the environmental impact of hydrogen supply increase with the transport distance [12]. Consequently, upon striving for the best-suited location for climate-friendly hydrogen production and supply, there may be a trade-off between maximum operating hours of hydrogen production plants and minimum hydrogen transport distance.

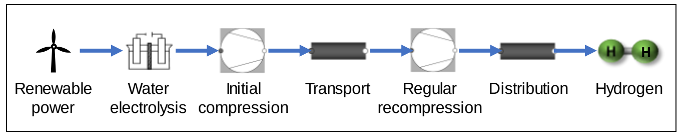
This current work compares the energy demands and environmental impacts of hydrogen production and supply relative to the locally achieved operating hours and necessary hydrogen transport distance *via* pipeline. It is evaluated under which circumstances importing hydrogen is more favorable than its local production.

2. MATERIAL AND METHODS

The environmental impacts of hydrogen supply were assessed following the methodology of Life Cycle Assessment (LCA). ISO 14040 [13] and ISO 14044 [14] provide the principles and framework as well as requirements and guidelines of the LCA methodology.

2.1 Goal and scope definition

The primary goal of this study is to quantify and compare the environmental impacts associated with the supply of hydrogen from domestic and remote production sites. The scope of this study is from “*cradle-to-gate*”, which means from resource extraction to the consumer. Only those activities which are environmentally relevant for the supply of hydrogen fall within the boundaries of the system investigated (Scheme 1).



Scheme 1. Investigated activities for assessing the environmental impact that is related to the supply of 1 kg hydrogen at 10°C and 80 bar to the consumer.

In LCA, the purpose of the investigated system is defined in terms of a *functional unit*, a quantitative measure that permits an objective comparison [13,14]. In this study, the *functional unit* is defined as 1 kg of hydrogen at a pressure of 80 bar and at a temperature of 10°C which has been produced and supplied to the consumption site. All input and output data of the system are mathematically normalized to this reference.

2.2 Inventory analysis

In the inventory analysis, the activities throughout the hydrogen supply chain were analyzed in the form of material- and energy flows that interact with other activities or the environment. By combining and linking these activities, a product system was formed, which can serve the purpose defined in the functional unit.

2.2.1 Renewable power generation

Electricity for producing hydrogen by water electrolysis was assumed to be generated solely from renewable energy sources (RES). Herein, wind and photovoltaic (PV) power plants were considered. To analyze the environmental impacts of renewable power generation and hydrogen production, the actually achieved full load hours (FLH) of wind and PV power plants were adjusted to the locally prevailing RES potential. The FLH of a power plant hereby represent the number of hours that the plant would theoretically need to run at full capacity to achieve its actually generated amount of electricity. The term FLH is defined as the ratio of the annually generated amount of electricity of a power plant (E_{total}) to its rated power output (P_{rated}).

$$FLH = \frac{E_{total}\ [MWh]}{P_{rated}\ [MW]} \quad (1)$$

Data for renewable power generation were based on the ecoinvent v3.6 cut-off database [15] and comprised material- and energy flows for the construction, operation, maintenance, and dismantling of wind and PV power plants. For wind power generation, 4.5 MW onshore turbines with a lifetime of 20 years were examined. PV power was considered to be generated by 570 kWp multi-crystalline silicon panels having a lifetime of 30 years [15]. For this study, the FLH of wind and PV power plants were adjusted to the locally prevailing conditions at their installation site.

2.2.2 Hydrogen production

For producing hydrogen, a polymer electrolyte membrane (PEM) water electrolysis system was considered. Data comprising material- and energy flows for manufacturing and operating a 1 MW PEM electrolyzer system were taken from Hermesmann *et al.* [2] and were initially based on Bareiß *et al.* [16]. Multiple electrolyzer stacks were combined to form one electrolysis plant capable of industrial-scale hydrogen production. It was assumed that the electrolyzer plant including utilities consumes 55 kWh for producing 1 kg hydrogen at a pressure of 30 bar and a temperature of 60°C. Based on the lower heating value of hydrogen (33.3 kWh/kg), this corresponds to an overall system efficiency of 60.55%. The lifetime of the stack and the balance of plant was estimated at 10 and 20 years, respectively. As for renewable power generation, the FLH of the electrolyzer system were adapted to the locally prevailing RES potential. Thereby, it was assumed that the installed capacities of the renewable power plants and the electrolyzer system at the production site are well harmonized.

2.2.3 Hydrogen transport

Data for hydrogen pipelines were taken from Tsiklios *et al.* [12] and were based initially on ecoinvent datasets for natural gas pipelines [15], as further described by Emmenegger *et al.* [17,18]. The dataset comprised the manufacture, installation, and dismantlement of seamless steel line pipes. As far as necessary, the data were tailored to the specific characteristics of hydrogen pipeline networks [12].

Table 1 gives the characteristic parameters of the pipeline network investigated in this study. The pipelines were assumed to have an outer diameter of 48” (1.22 m) and to be designed for a maximum pressure of 100 bar. The line pipes were assumed to be made of high-strength API 5L grade X52 steel, which is considered suitable for hydrogen pipelines. Pipe dimensioning and resulting material demands were based on Barlow´s formula for thin-walled pipes by applying a safety factor of 1.6. The lifetime of hydrogen pipelines was estimated at 40 years.

Table 1. Characteristic parameters of the hydrogen pipeline network investigated in this study.

Component	Parameter	Value
Pipeline	Transport capacity	13 GW
	Nominal diameter	48”
	Operating hours	8,000 h/a
	Maximum operating pressure	100 bar
	Operating pressure	80 bar
	Absolute roughness	0.1 mm
	Lifetime	40 a
Compressor	Compressor type	centrifugal
	Isentropic efficiency	0.8
	Mechanical-electrical efficiency	0.96
	Maximum pressure ratio	1.2
	Operating hours	8,000 h/a
	Lifetime	20 a

A Galvalume® coating layer was supposed to protect the inner surface of the steel line pipes from hydrogen embrittlement, thereby increasing their durability. On the outer surface, an external 3-layer polyethylene coating consisting of an epoxy resin primer (thickness 0.15 mm), a copolymer adhesive, and a low-density polyethylene top-layer (thickness 3.0 mm) was supposed to electrically insulate the underground line pipes. In addition, galvanic corrosion was assumed to be impeded further by an impressed current system.

The temperature of the gas was set equal to the temperature of the surrounding soil remaining constant at 10°C. This implies that the underground line pipes are thermally uninsulated. To ensure a constant gas temperature, the hydrogen flow was cooled after each compression step. The operating pressure of the pipeline network was set at 80 bar, which corresponds to a transport capacity of 390 t of hydrogen per hour and an energy flow of 13 GW based on the lower heating value. Assuming a 40-year lifetime and 8,000 annual operating hours, this yields 124.81 Mt of hydrogen that are transported over the lifetime of the pipeline network.

For operating the pipeline network, equally distributed compressor stations were selected to recompress the hydrogen gas flow at regular intervals along the transport route. The required compression effort was calculated with hydraulic simulations in the modelling and simulation environment Dymola [19]. Thereby, the minimally required number of compressor stations and their optimal distribution along the transport route were determined. One example of each of the two most common compressor classes for hydrogen compression was considered in this study. Whereas a centrifugal compressor was chosen to represent the class of dynamic compressors, a reciprocating compressor was selected to model positive displacement compressors. For both compressor types, a maximum compression power of 32 MW and a mechanical-electrical efficiency of 0.96 was assumed. The centrifugal compressors had a maximum pressure ratio of 1.2 and an isentropic efficiency of 0.80. For reciprocating compressors, a maximum pressure ratio of 2.0 and an isentropic efficiency of 0.65 were assumed.

The absolute roughness of the modeled pipe´s inner layer was set at 0.1 mm. Thermophysical property data for hydrogen were calculated by fundamental Equations of State [20] and a wide-ranging correlation for the viscosity of normal hydrogen [21]. The hydrogen flow is mathematically described by a frictional isothermal compressible pipe flow. A detailed description of the thermodynamic model implemented in Dymola can be found in Tsiklios *et al.* [12].

Data for the manufacture, installation, operation, and end-of-life of large-scale centrifugal compressors were taken from Tsiklios *et al.* [12] and initially based on Peng *et al.* [22]. The compressors were assumed to have a lifetime of 20 years and the same operating hours as the pipeline system. The compressors were driven by electric motors due to their greater efficiency [23,24] compared to gas turbines. Due to their wide distribution, the electric motors were supposed to be powered from the grid. Average environmental impacts for electricity originating from the European power grid in the year 2019 (0.421 kg CO_2-eq./kWh) were taken from the ecoinvent v3.6 cut-off database [25,26].

2.3 Impact assessment

The environmental impacts of hydrogen supply were determined by assigning the material- and energy flows of the system that are exchanged with the environment to appropriate impact categories. In this study, the environmental impacts were assessed with respect to the category *climate change*, since the installation of innovative hydrogen supply chains often primarily aims to reduce so-called "greenhouse gas" emissions that contribute to this category. The category *climate change*, also known as *global warming*, weights all greenhouse gas emissions according to their global warming potential (GWP) in kg CO_2-equivalents (kg CO_2-eq.), which allows their aggregation into one single global warming impact (GWI). Table 2 gives the applied method for assessing environmental impacts in the category *climate change* as recommended by the European Commission´s Joint Research Centre [27].

Table 2. Applied method for assessing environmental impacts in the category climate change as recommended by the European Commission´s Joint Research Centre [27].

Impact category	Reference indicator	Unit	Model
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2-eq.	Baseline model of 100 years of the IPCC (based on IPCC 2013)

3. RESULTS AND DISCUSSION

The results of the environmental assessment on hydrogen supply chains are presented and discussed in the following sections. By first varying both the locally achievable full load hours and the necessary hydrogen transport distance separately, it was assessed how and to what extent these two parameters affect the Global Warming Impact (GWI) of hydrogen supply.

A subsequent comprehensive parameter study showed that there may be a relevant trade-off between maximum full load hours and minimum transport distance upon searching for climate-friendly hydrogen supply solutions. Therefore, it was estimated to which extent the achievable full load hours at remote production sites would need to be in order to environmentally justify the import of hydrogen over certain distances. Knowing this allows identifying and evaluating promising locations for climate-friendly hydrogen supply.

3.1 Full load hour variation

Fig. 1 illustrates the GWI of local hydrogen production by water electrolysis with electricity from either wind or PV power plants by varying full load hours. In this scenario, hydrogen is produced directly at the site of the consumer, which means that no transport is required.

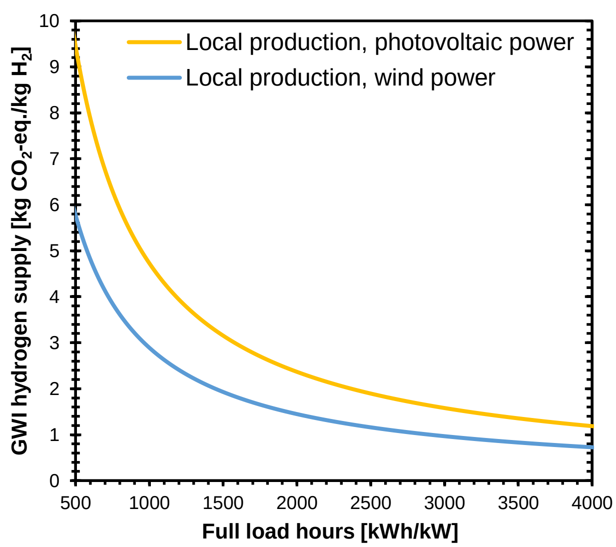


Fig. 1. Global Warming Impact (GWI) for local hydrogen production.

The local production of hydrogen by water electrolysis utilizing electricity from wind power plants results in a GWI ranging from 0.727 to 5.775 kg CO_2-eq. per kg H_2 for 4000 and 500 full load hours, respectively. For equal full load hours but with electricity from PV power plants, the GWI that is associated with the local production of hydrogen ranges from 1.186 to 9.450 kg CO_2-eq. per kg H_2. Here, the differences in the forecasted GWI can be fully attributed to the upstream chains of the applied power generation technology. Assuming that comparable full load hours for wind and PV power plants may be achieved at a certain location, current wind power plants enable a more climate-friendly power generation as well as hydrogen production by water electrolysis than state-of-the-art PV power plants.

For both wind- and PV-powered water electrolysis, an exponential decay in the GWI-curve can be observed if the full load hours increase. As described previously, in LCA, all material- and energy flows (g_i) and their associated global warming potential (GWP_i) are mathematically normalized to the functional unit of 1 kg hydrogen by dividing them by the total amount of hydrogen produced over the entire lifetime of the production plant $(m_{H_2,total})$. The total amount of hydrogen is, in turn, the product of the hydrogen flow at full capacity $(\dot{m}_{H_2,max})$, the lifetime in years (n), and the full load hours (FLH) of the production plant and is, thus, directly proportional to the achieved full load hours. Consequently, the total GWI related to hydrogen supply with wind- or PV-powered water electrolysis is inversely proportional to the achieved full load hours.

$$\mathrm{GWI} = \frac{\mathrm{GWI}_{total}}{m_{H_2,total}} = \frac{\int_{t=1}^{n} \sum_i g_i * \mathrm{GWP}_i \, dt}{\dot{m}_{H_2,max} * \mathrm{FLH} * \mathrm{n}} \tag{2}$$

In a mathematical sense, the GWI related to hydrogen supply exhibits hyperbolic growth if the full load hours decrease. For zero full load hours, there would not be any hydrogen production at all, which yields a value of zero as denominator. As a result, the GWI has a singularity at zero full load hours, meaning that the limit as $\mathrm{FLH} \to 0$ is infinite.

$$\lim_{\mathrm{FLH} \to 0} \mathrm{GWI(FLH)} = \infty \tag{3}$$

The herein described hyperbolic growth of the GWI related to electricity generation by renewable power plants as a function of their full load hours or similar parameters such as their annual amount of energy produced is in accordance with previous studies [28,29].

3.2 Transport distance variation

The following analyzes the effect of the hydrogen transport distance on the total GWI of hydrogen supply. First, the compression of the produced hydrogen gas prior to its injection into the gas grid is assessed. Next, the GWI related to hydrogen transmission is quantified, including the impacts that are associated with the construction and operation of the pipeline network.

3.2.1 Hydrogen injection

The operating pressure of hydrogen pipeline networks ranges from 16 to 100 bar [30]. After its production, an initial compressor station needs to pressurize the hydrogen gas prior to its injection into the gas grid. The required number of compression stages depends on both the operating pressure of the pipeline network and the given hydrogen production technology. In this study, hydrogen is assumed to be produced at 30 bar *via* pressurized PEM water electrolysis and subsequently to be compressed to the operating pressure of the pipeline network that is estimated at 80 bar. Table 3 summarizes the results of the thermodynamic analysis that are associated with this initial compression step.

Table 3. Results of the thermodynamic analysis for the initial compression of hydrogen from 30 bar to 80 bar before its injection into the pipeline network.

Compressor type	**Centrifugal compressor**	**Reciprocating compressor**
Required compression stages [-]	6	2
Required compression ratio [-]	1.178	1.633
Total power consumption [MW]	170.58	224.21

For the centrifugal compressors, pressurizing the predefined hydrogen gas flow of 108.34 kg/s from 30 to 80 bar requires six consecutive compression stages with a pressure ratio of 1.178. This yields a total power consumption of 170.58 MW. For the reciprocal compressors, two compression stages with a pressure ratio of 1.633 are required. The cumulative power consumption of these compressor stages amounts to 224.21 MW, which corresponds to a 31.44% higher power consumption compared to the compression with centrifugal compressors. Note that the aforementioned results do not consider possible volume flow restrictions of the respective compressor designs. Consequently, even though reciprocal compressors enable pressurizing the considered hydrogen gas flow in fewer compression stages because of their higher maximum pressure ratio, this occurs at the expense of energy efficiency. Therefore, in the following, this study assumes the use of centrifugal compressors for initial hydrogen compression due to its higher energetic efficiency.

Overall, the initial compression of the hydrogen gas prior to its injection into the pipeline network results in a total GWI of 0.184 kg CO_2-eq. per kg H_2. Most of this impact (> 99%) stems from the supply of electricity from the power grid for driving the compression system, whereas only a minor share (<1%) relates to the compressor station itself. The required electricity for initial compression amounts to 1.31% of the energy contained in the hydrogen gas flow based on the lower heating value (13 GW).

3.2.2 Hydrogen transmission

From the point of its injection, the hydrogen gas flows through high-capacity transmission pipelines to numerous substations. There, a part of the gas is withdrawn, decompressed and further fed into the distribution network, in which it is delivered to its point of consumption. Along the transport route, intermediate compressor stations need to compensate for pressure losses in the pipeline system. Depending on the operating conditions and the specific design of the pipeline system, the hydrogen flow needs to be recompressed every 100 to 600 km.

To determine the minimum number of compressor stations and their optimal distribution for certain transport distances, hydraulic simulations were performed with Dymola. Fig. 2 illustrates the cumulative power consumption for recompressing the assumed hydrogen gas flow of 108.34 kg/s over up to 4000 km using either centrifugal or reciprocating compressors.

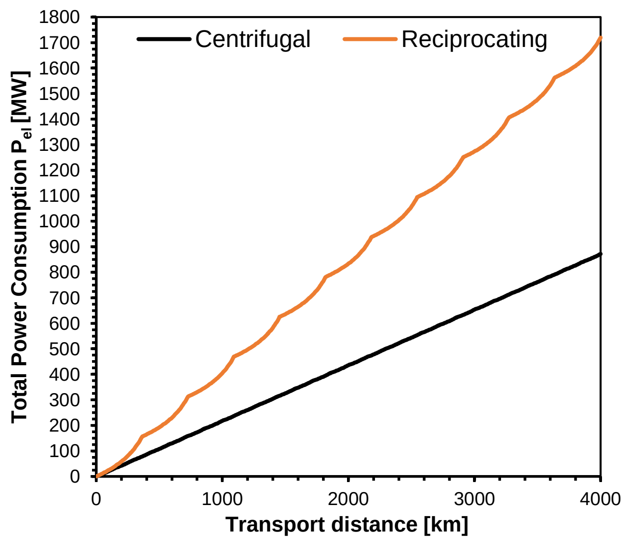


Fig. 2. Total power consumption of the pipeline network for transporting hydrogen over distances of up to 4000 km while complying with the maximum pressure ratio of centrifugal and reciprocating compressors.

Within the given framework conditions, a minimum of 11 reciprocating compressor stations are required to cover a hydrogen transport distance of 4000 km. This means 11 pipeline sections, each of which is 363.64 km long and situated between two consecutive compressor stations. Within each of these pipeline sections, the pressure loss and, thus, the power consumption exponentially increases with the transport distance.

By contrast, the power consumption of centrifugal compressors increases at a less pronounced rate over the transport distance. Due to their lower maximum pressure ratio than that of reciprocating compressors, at least 28 centrifugal compressor stations are needed to compensate for the pressure loss that arises over a distance of 4000 km. Here, the higher number of intermediate compressor stations leads to shorter transport intervals which, in turn, counteracts the exponential increase in pressure loss at an early stage.

The following assumes centrifugal compressors to recompress the hydrogen gas flow at regular intervals. Table 4 shows the results for the regular recompression of hydrogen by centrifugal compressors along a distance of 1000 km. For transporting the considered hydrogen gas over a distance of 1000 km while complying with the maximum pressure ratio of 1.2, seven centrifugal compressor stations need to be installed at regular intervals of 142.86 km. Each compressor has an actual required pressure ratio of 1.193 and a minimum required compression power of 31.14 MW, which results in a total power consumption of 217.96 MW.

Table 4. Results of the thermodynamic analysis for transporting hydrogen over a distance of 1000 km.

Component	Parameter	Value	Unit
Pipeline	Total length	1000	km
	Length per section	142.86	km
	Hydrogen mass flow	108.34	kg/s
	Total pressure drop	90.54	bar
	Pressure drop per section	12.93	bar
Centrifugal compressor	Required compression units	7.00	-
	Compression ratio per unit	1.193	-
	Total power consumption	217.96	MW
	Compression capacity per unit	32.00	MW
	Power consumption per unit	31.14	MW

The total estimated GWI for transmitting hydrogen over a distance of 1000 km is 0.2491 kg CO_2-eq. per kg H_2. The major fraction (94.42%) of the total impact is related to operating the pipeline network and, thus, analogous to the injection of hydrogen into the gas grid, is primarily associated with the electricity demand for hydrogen compression. The required electricity for recompression amounts to 1.68% of the energy contained in the hydrogen gas flow based on the lower heating value (13 GW). The remaining impacts on global warming can be traced back to the transport infrastructure, comprising the transmission pipelines (5.55%) and centrifugal compressor stations (0.03%).

3.3 Trade-off

Fig. 3 illustrates the contributions to the total GWI that are related to the supply of 1 kg hydrogen from wind-powered water electrolysis by assuming different full load hours and transport distances. Herein, the contributions to the GWI of hydrogen supply are subdivided into the life cycle steps of hydrogen production by wind-powered water electrolysis and hydrogen transport *via* pipeline.

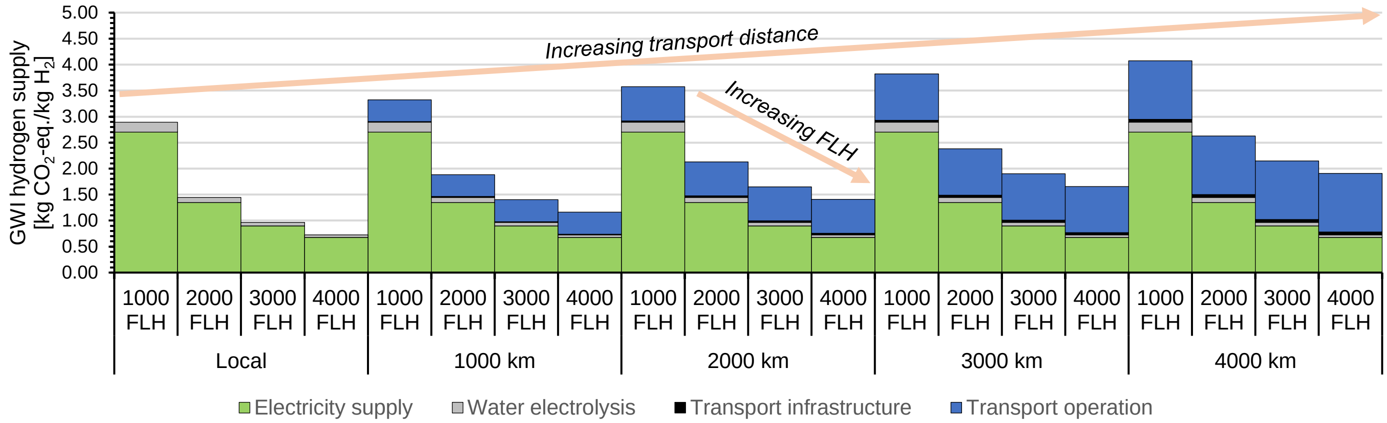


Fig. 3. Contributions to the total Global Warming Impact (GWI) related to the supply of 1 kg hydrogen from wind-powered water electrolysis by assuming different full load hours (FLH) and transport distances. The overall GWI of hydrogen supply decreases for decreasing transport distances and increasing FLH, with a minimum GWI in case of the local production of hydrogen at maximum FLH. This reveals that upon evaluating promising locations for climate-friendly hydrogen production and supply, there is indeed an environmentally relevant trade-off which requires careful evaluation of both the locally prevailing conditions for renewable power generation and the resulting necessary hydrogen transport distance.

In accordance with previous studies [2], the major fraction of the GWI (≈93%) that is related to the production of hydrogen by water electrolysis can be traced back to the underlying electricity supply chain, i.e. the upstream chains of the wind power plants. Likewise, for hydrogen transport *via* pipeline, most of the GWI (>95%) can be attributed to the operation of the pipeline network or, more precisely, to the supply of electricity required for driving the compressor stations at the point of injection and along the transport route. Consequently, both climate-friendly electricity supply chains based on renewable energy sources as well as an energy-efficient operation of the pipeline network are crucial for ensuring a climate-friendly hydrogen supply.

As depicted in Fig. 3, the total GWI of hydrogen supply ranges from 0.727 to 4.071 kg CO_2-eq. per kg H_2 and, thus, varies considerably upon varying the assumed number of full load hours and the hydrogen transport distance. Here, the highest GWI is associated with the lowest full load hours (1000 h) and the highest transport distance (4000 km) considered, whereas the lowest impact is reached for the scenario of highest full load hours (4000 h) and local hydrogen production without any hydrogen transport (0 km). From these variations, it can be concluded that both the achieved full load hours and the hydrogen transport distance substantially affect the GWI related to hydrogen supply. However, whereas the GWI increases for higher transport distances, an increase in the full load hours of renewable power plants leads to a significant decrease in the total GWI.

Hence, upon searching for a site that allows for climate-friendly hydrogen production and supply, there is a relevant trade-off which requires careful evaluation of both the locally prevailing conditions for renewable power generation and the resulting necessary hydrogen transport distance.

Fig. 4 and Fig. 5 illustrate this trade-off by showing the total GWI of hydrogen supply from wind- and PV-powered water electrolysis as a function of the locally prevailing full load hours at various distances of hydrogen transport *via* pipeline. Under the condition of equal full load hours, the GWI for local production of hydrogen is lower than the GWI of hydrogen supply from remote production sites due to the required transport to the consumer, which raises the environmental impact. With increasing full load hours, the earlier discussed exponential decrease in the GWI can be observed for both wind- and PV-power-based water electrolysis. By contrast, the total GWI of hydrogen supply increases approximately linearly with the transport distance.

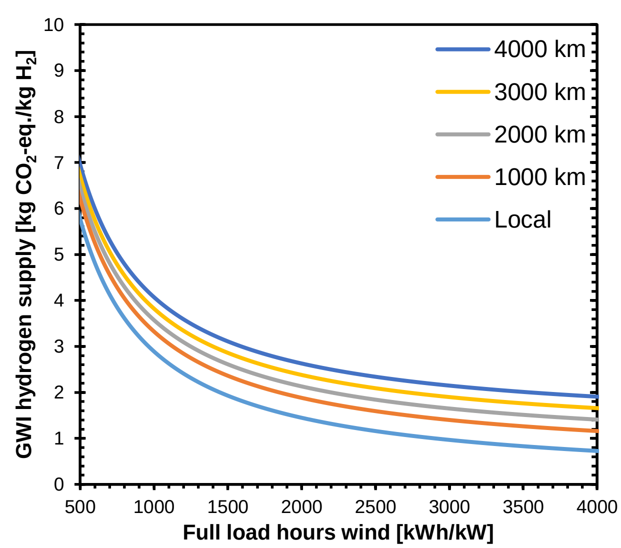


Fig. 4. Global Warming Impact (GWI) of hydrogen produced by water electrolysis supplied by wind power plants with varying full load hours (500-5000 h) and transported over different distances via pipeline (1000, 2000, 3000, 4000 km).

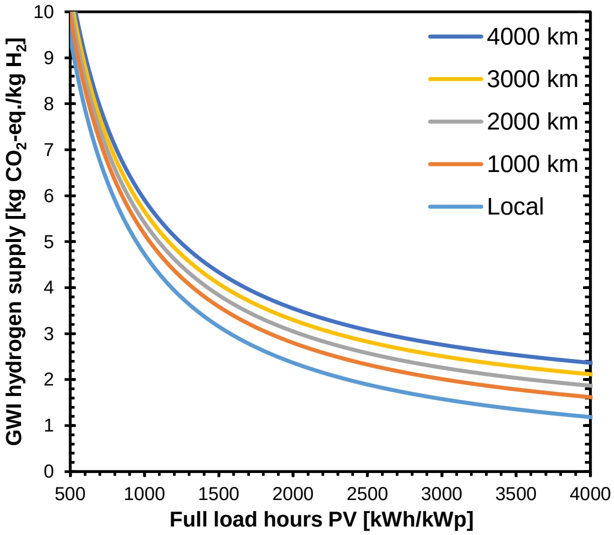


Fig. 5. Global Warming Impact (GWI) of hydrogen produced by water electrolysis supplied by photovoltaic (PV) power plants with varying full load hours (500-5000 h) and transported over different distances via pipeline (1000, 2000, 3000, 4000 km).

This direct proportionality is indicated by the equal vertical distance between the curves that represent the supply of hydrogen including a transport distance of 1000, 2000, 3000, and 4000 km. The curves that depict the local production and the supply over 1000 km are wider apart, because the initial compression for injecting hydrogen into the gas grid is not needed for the case of local production.

The highest total GWI related to hydrogen supply is attributed to PV-powered water electrolysis by assuming 500 full load hours and a hydrogen transport of 4000 km. Nevertheless, the resulting GWI of 10.630 kg CO_2-eq. per kg H_2 is still comparable to values of approximately 9.07–12.71 kg CO_2-eq. per kg H_2 for conventionally producing hydrogen by steam methane reforming in Europe [2]. Hence, it appears that producing hydrogen by water electrolysis based on renewably generated electricity is more climate-friendly than its conventional production, even for considerably low full load hours and high transport distances of several thousands of kilometers. Higher reduction potentials compared to conventional steam methane reforming can be achieved with higher full load hours and shorter transport distances.

For producing hydrogen from water electrolysis based on renewable electricity, deciding whether an import is environmentally favorable compared to a local production requires balancing between the achievable full load hours at the respective sites and the resulting hydrogen import distance. As depicted in Fig. 6, from this balance it is possible to determine which increase in full load hours is required for environmentally justifying the transport of hydrogen over certain distances.

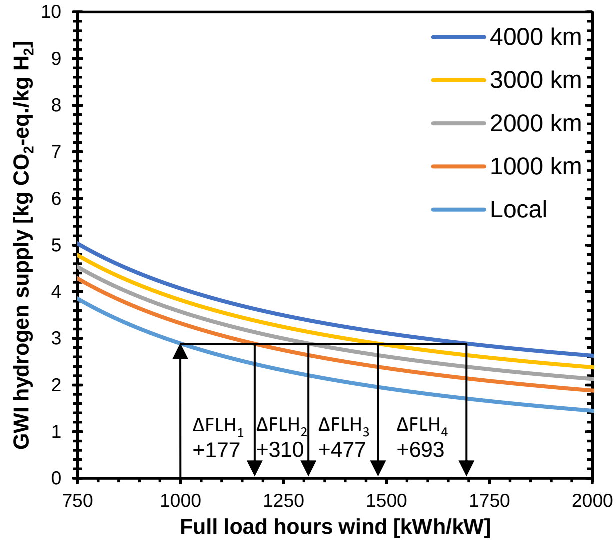


Fig. 6. Required increase in full load hours compared to the local production of hydrogen by wind-powered water electrolysis with 1000 full load hours to justify hydrogen import from remote production sites located thousands of kilometers away.

Table 5 summarizes the required increases in full load hours for various local full load hours and transport distances.

Table 5. Required increases in full load hours compared to the local production of hydrogen by wind-powered water electrolysis to justify hydrogen import from remote production sites located thousands of kilometers away.

Transport distance [km]	Local full load hours				
	500 h	1000 h	2000 h	3000 h	4000 h
1000 km	+40	+177	+859	+2461	-
2000 km	+67	+310	+1796	-	-
3000 km	+96	+477	+3647	-	-
4000 km	+128	+693	-	-	-

For instance, the GWI of local hydrogen production by wind-powered water electrolysis with 1000 full load hours amounts to 2.890 kg CO_2-eq. per kg H_2. To achieve an equivalent GWI for supplying hydrogen from an alternative production site that is situated 1000 km apart, there are at least 1177 full load hours required for compensating for the additional GWI that results from hydrogen transport. For transport distances of 2000 km, 3000 km, and 4000 km, the minimally required number of full load hours at the remote production sites increases to 1310, 1477, and 1693, respectively.

If, instead, 2000 full load hours are achieved at the local production site, this yields a GWI of 1.448 kg CO_2-eq. per kg H_2 and minima of 2859 FLH, 3796 FLH, and 5647 FLH for environmentally justifying a transport over 1000 km, 2000 km, and 3000 km, respectively. For production sites that are situated 4000 km apart, the minimally required number of full load hours would exceed the total number of hours per year (8760), which is physically impossible. This implies that, in this case, the local production of hydrogen is more climate-friendly than its import, regardless of the full load hours that are achieved at the remote production site.

As Table 5 exemplifies, the hydrogen import distance that is environmentally justifiable decreases if the locally achievable full load hours increase. For 3000 local full load hours, only the import from nearby production sites that allow significantly higher full load hours would be reasonable. In this case, justifying an import distance of 1000 km requires at least 5461 full load hours. For 4000 full load hours, hydrogen almost always ought to be produced locally as not even a transport over a relatively short distance of 1000 km is environmentally reasonable.

It can be concluded that the additional full load hours that would be required for compensating for a certain import distance from a remote production site increase with the full load hours that are locally achievable. Consequently, importing hydrogen, especially over very long distances, is only suitable for areas with a considerably low renewable energy potential.

Noteworthy is that the herein presented results assume that the electricity for driving the compressor stations of the pipeline network originates from the current European power grid. In some countries, however, currently a substantial share of electricity in the grid mix is primarily generated from fossil resources, such as natural gas and coal [2]. Shifting electricity generation towards more climate-friendly technologies could be an important way to reduce the GWI of hydrogen transmission via pipeline networks in the future, which, in turn, could environmentally justify the import of hydrogen over greater distances.

4. CONCLUSIONS

This study reveals that evaluating promising locations for climate-friendly hydrogen production often requires balancing the best available conditions for renewable power generation and the minimally possible hydrogen import distance. Even so, there is indeed an environmentally relevant trade-off between these two parameters. Using parameter studies, it was estimated, how much greater the achievable full load hours at remote hydrogen production sites would need to be in order to environmentally justify the import of hydrogen over certain distances. This allows identifying and evaluating promising locations for climate-friendly hydrogen supply.

Our results show that the import of hydrogen produced through water electrolysis powered by renewably generated electricity is more climate-friendly than local hydrogen production by conventional steam methane reforming, even for relatively low full load hours of the renewable power plants and import distances of several thousand kilometers. Compared to the local production of hydrogen through water electrolysis, importing climate-friendly hydrogen over great distances turned out to be environmentally reasonable only for areas with low renewable energy potentials. In the future, though, hydrogen import and associated transport over greater distances may be environmentally justifiable given the ongoing energy transition to more climate-friendly power generation technologies.

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