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Life-cycle global warming impact of hydrogen transport through pipelines from Africa to Germany

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Various hydrogen pipeline structures for the export of hydrogen from Africa to Germany are analyzed by life cycle analysis (LCA) in order to determine the global warming potential (GWP) of the production and transportation of 1 kg of hydrogen. This analysis was motivated by the fact that a hydrogen pipeline infrastructure can be built cost-effectively by partially using existing natural gas pipelines. However, little is known about its possible environmental impact. In this paper, the LCA method is used to compare different import options, including possible changes to future supply chains. Three supply locations – Morocco, Senegal, and Nigeria – are compared with each other and evaluated using Germany's domestic hydrogen supply as a reference. Hydrogen transport *via* a pipeline from Morocco shows emissions of 0.07–0.11 kg CO_2-eq per kg H_2, and hydrogen transport from Nigeria causes emissions of 0.27–0.38 kg CO_2-eq per kg H_2. These figures are highly dependent on the flow rate of hydrogen, the GWP of PV electricity used to power the hydrogen compressors along the way, and compression efficiency. However, the GWP due to pipeline transport is negligible compared to the emissions caused by PV electrolysis. The total emissions of the African supply chain amount to 1.9–2.5 kg CO_2-eq per kg H_2. From a sensitivity analysis, it can be concluded that, by using identical PV panels, the GWP of German domestic hydrogen production (3.0–3.1 kg CO_2-eq per kg H_2) still has a higher GWP than hydrogen produced in Africa and imported through pipeline supply chains.

1. Introduction

The importance of hydrogen in the European transition to a net-zero emissions economy in the future is widely acknowledged. Currently (2022), hydrogen is mainly produced from fossil fuels consisting of 76% natural gas and 22% coal gasification, while only 2% of hydrogen is produced *via* electrolysis.[1] Fossil fuel pathways have a high global warming potential (GWP) of at least 10 kg CO_2-eq per 1 kg H_2.[2] According to prior studies, hydrogen production *via* electrolysis will guarantee emissions reductions of up to 80% compared to hydrogen production dependent on fossil fuels.[3]

Accelerating the integration of renewable energy resources, especially photovoltaics (PV), in the production of hydrogen is therefore of great importance when it comes to mitigating the effects of global warming.[4] This will be even more significant in the future, given the anticipated development of the hydrogen market in the context of Germany's national climate plan. In addition to existing hydrogen consumption in oil refining and ammonia production, the demand for hydrogen as a transportation fuel for road transport, maritime applications, aviation, electricity generation, storage, and heating will significantly increase in the upcoming decades.[5] Germany's predicted hydrogen demand in 2045 is 226 to 600 TW h.[6] Of this long-term German demand, 50–90% will have to be imported from regions with favorable production conditions and enough space for hydrogen production for self-consumption and export.[7] In new initiatives, Germany is collaborating with African countries to explore Africa's hydrogen production potential.

Information about the environmental impact of this route is limited because even "green" hydrogen production *via* electrolysis is associated with different GWP levels depending on the origin of the electricity used to power the operation of electrolyzers. However, hydrogen production in Africa could yet be financially viable. It has been shown, for instance, that PV electricity for the electrolyzer can be generated below 2 cents per kW h in many African locations, making it possible to save 30% on hydrogen production costs compared to Germany's self-supply.[8]

Transporting vast amounts of hydrogen produced overseas is challenging. Previous studies show that pipelines are the most cost-efficient solution to transport large hydrogen volumes.[9] A key benefit is the opportunity to convert existing European natural gas pipelines to transport pure hydrogen, an economical and time-saving alternative to building entirely new

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infrastructure.[10] The European Hydrogen Backbone (EHB), a group of 31 energy infrastructure operators, works on repurposing the pipeline infrastructure in Europe and enabling the renewable hydrogen market. EHB has already identified large-scale pipeline corridors to import significant quantities of green hydrogen from Africa to Germany (see Fig. 1).[3]

Despite these ambitious initiatives, only a few studies have been conducted which quantitatively capture the GWP of large-scale hydrogen infrastructure. Extensive analysis of environmental burdens of hydrogen production (excl. transport) was completed by Terlouw *et al.*[11] Also Tayarani & Ramji[12] have already analyzed the GWP of the pipeline transportation of hydrogen in gaseous form, although only for the case of the USA. These results show that one ecologically beneficial pathway is PV-powered electrolysis transported through pipelines. Kolb *et al.*,[13] studied liquid hydrogen imports to Germany. Ozawa *et al.*,[14] Al-Breiki & Bicer[15] analyzed the GWP of hydrogen for overseas shipping, albeit only in liquid form. An overview of general hydrogen LCA studies can be found in Osman *et al.*[16] and Kanz *et al.*[17] As for international gaseous hydrogen transport *via* pipeline from Africa to Europe, the environmental impact on global warming is still unknown.

In response to an accelerating development of the hydrogen market in combination with a gap in the literature, this work evaluates the GWP of hydrogen production and import through the pipeline from Africa to Germany. The hydrogen supply chain has been evaluated in terms of GWP using LCA. This paper is structured into four sections. After the Introduction, Section 2 explains the LCA method as well as the framework of the systems to be investigated. Section 3 focuses on the life cycle inventory (LCI) and operation parameters. The results of the study and scenario analysis are presented in Section 4. The paper is rounded off with discussions and a conclusion in Sections 5 and 6.

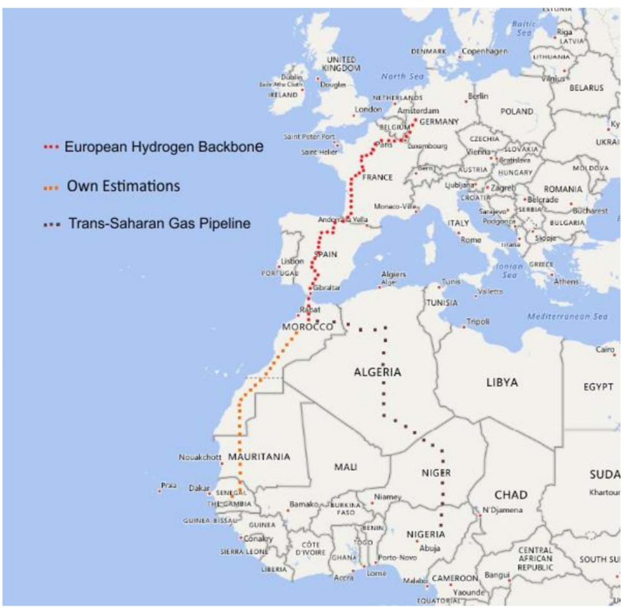

Fig. 1 Hydrogen supply chain. Red-colored route is possible corridor for German imports based on existing natural gas infrastructure (European Hydrogen Backbone).[28] The routes in Africa are estimated on the basis of our own calculations and the planned Trans-Saharan Gas Pipeline project.

2. Research method, system framework, and data input

2.1 Life cycle assessment method

LCA is a valuable instrument for analyzing the environmental performance of any product or system. LCA is described as a compilation and evaluation of the inputs (materials and energy), outputs (emissions), and potential environmental impacts of a product system during its life cycle. LCA studies consist of four phases, which are covered by ISO standards (see Fig. 2).[18,19]

The first phase of the LCA is used to outline the goal and scope of the study. In the second step, data are collected in the LCI. The LCI analysis measures elementary flows related to individual processes, such as mass (materials and resources) and energy flows, land use, emissions to air, and water, *etc.* The third step of the LCA is the life cycle impact assessment (LCIA). In the LCIA, all the inputs and outputs are placed in the environmental framework. The last step is the interpretation, where the information resulting from the LCIA is systematically evaluated. For the calculations, a well-known LCA tool named GaBi was used.[20]

One of the 17 impact categories of an LCA – the global warming potential (GWP in grams of CO_2 equivalent emissions) – is a significant factor in today's energy policy and, therefore, essential for any comparative energy technology assessment. The LCIA is completed for this category and the results are used as an indicator of the contribution to climate change following the International Reference Life Cycle Data System (ILCD) Handbook.[21] Based on the latest IPCC, GWP100 is used for this study. Limiting global warming to 2 °C by 2100 requires a GWP100 (100 years of evaluation time). The GWP100 measures the impact of radiative forcing (caused by greenhouse gases in the atmosphere) over 100 years and provides a standard unit of measure. The GWP is normalized to CO_2 equivalent emissions, including the contribution of all significant carbon dioxide, methane, nitrous oxide, and chlorofluorocarbon emissions.[18,19] Further descriptions of the LCA method are provided by Kanz *et al.*[17]

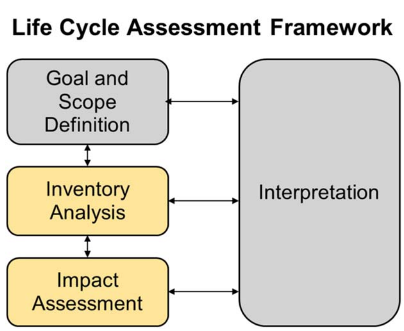

Fig. 2 Schematic illustration of the life cycle assessment framework.

2.2 System framework

While defining the scope for developing inventory, it must be determined which emission sources should be included within the selected organizational boundary for the inventory. The system boundary for hydrogen imports in this paper includes production, compression, and long-distance hydrogen transport, following the cradle-to-gate principle (see Fig. 3). Dedicated green hydrogen refers to hydrogen production *via* electrolysis using electricity generated from PV in the numerous importing regions selected on the basis of the geopolitical and climatic criteria of H_2Atlas-Africa project.[8] The production regions were evaluated based on location information related to PV electricity costs, local energy demands, and land and water eligibility. Three production "hot spots" in Morocco, Senegal, and Nigeria were selected, and production is based partly on the simulation and LCA model used in our previous work.[17] Processes within the system boundary are the foreground and background processes of hydrogen supply chains, including the essential upstream processes such as raw material extraction, for example the electrolyzer and pipeline, and PV panels for electricity generation. Fig. 3 shows the system boundaries of this LCA, and Section 3.1 gives a detailed overview of the electrolyzer and PV parameters.

The functional unit (FU) definition is a significant element for modeling a product system in an LCA. An FU refers to the product, service, or system whose impacts are calculated using an LCA. The final conditions of the FU are defined as the "1 kg of hydrogen" (purity > 99% vol. pressure 100 MPa (p_2), temperature 25 °C) supplied to the distribution pipeline in Germany, as proposed by the FC-HyGuide guidance document.[22] A detailed description of the FU decision process can be found in our previous work.[17] To allow for comparisons with competing energy carriers on an energetic basis, we indicate emissions related to 1 kW h of hydrogen in our results using a lower heating value of 33.32 kW h per kg H_2. The results are also converted to kW h (LHV) to give the reader a more straightforward evaluation.

2.3 Data input

Most data were collected from the ecoinvent database (version 3.6), secondary literature, other LCA studies, and manufacturer datasheets. Electricity was either assumed to be supplied by country-specific electricity grid mixes based on ecoinvent databases or exclusively from PV from a particular country based on data taken from public weather databases and the PVGiS online tool.[23] The main PV characteristics are in agreement with IEA-PVPS Task 12 reports.[24] As a reference framework, a guidance document published by the European Union and Fraunhofer ISE was applied.[22]

3. Life cycle inventory

This section provides an overview of the following components: electrolyzers (Section 3.1), pipeline infrastructure (Section 3.2), and compressor stations (Section 3.3). Furthermore, pipe capacity and leakage assumptions are clarified in Section 3.4.

3.1 Electrolyzer inventory and operation

The electrolysis systems used for this study are proton exchange membrane (PEM) electrolyzers. PEM electrolyzers can produce hydrogen at low temperatures without any external heating. PEM electrolyzers have a higher efficiency at a lower current density compared to alkaline electrolyzers. They, therefore, operate efficiently with intermittent PV electricity. The electricity needed to produce 1 kg of hydrogen at the theoretical efficiency limit is 39.4 kW h. For present-day production, electricity consumption is realistically about 55–57.5 kW h per kg H_2.[22] The LCIA of a 1 MW PEM stack and balance of plant was exhibited based on the data from Bareiß *et al.*[25] The data for the Nafion membrane are unavailable, which is why the perfluoro sulfonyl fluoride data were used instead. Since oxygen produced during electrolysis is not technically used, no multi-functionality occurred. The production of deionized water for the electrolyzers follows the ecoinvent processes.[20]

To produce hydrogen, an oversized grid-connected Si-wafer 3 MWp PV plant and a 1 MW PEM electrolyzer were investigated. The electrolyzer operates 3500 full-load hours and a constant hydrogen production profile assumed in the study. The lifetime of the PV electrolyzer configuration is 25 years. Replacement of electrodes in the electrolyzer is mandatory once in a lifetime.[17] The manufacture and operation of the whole system are considered in the model based on GaBi database.[24] The model considers the background country-specific annual irradiance values of PVGIS.[20] PVGIS-SARAH2 was applied as database, system loss is assumed to be 14% and total loss 23.91%, with a slope angle of 35° and azimuth angle of 0°. A degradation rate

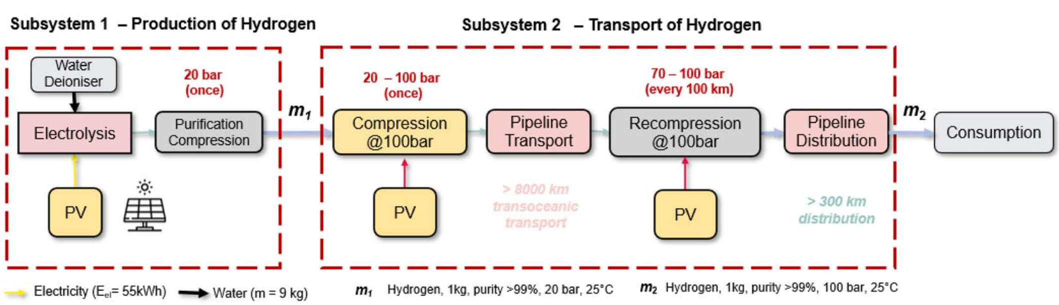

Fig. 3 System boundaries of hydrogen transport. Left – subsystem 1: production of hydrogen; right – subsystem 2: transport of hydrogen.

of 0.7% per year and a life expectancy of 25 years were selected in line with the IEA-PVPS Task 12 reports.[24] Furthermore, since the operation in Africa led to a decline in the amount of power produced due to dust, a loss of 4.4% was added.[27]

The following countries were evaluated as operating regions for electrolysis: Germany (DE), Morocco (M), Senegal (S), and Nigeria (N). The electricity demand for hydrogen production was assumed to be covered by the same PV set in order to have an adequate and comparable outcome. Cologne (Germany) was chosen as a location for a domestic production case as a reference. A representative average domestic site was taken for hydrogen production in the center of Germany.

3.2 Hydrogen transport *via* pipeline

The pipeline routes from Africa to Germany were selected according to the large-scale pipeline corridors of the European Hydrogen Backbone (EHB) (see Fig. 1).[28] For this study, 60% of the European infrastructure is assumed to be built on repurposed pipelines. The pipes in Africa and offshore pipes are expected to be newly built. The routes between Morocco and Nigeria have been selected in accordance with the Trans-Saharan Gas Pipeline (TSGP) project.[29] Due to a lack of data, the remaining infrastructure in Africa had to be estimated based on distances calculated using Google Maps.[30] The pipes have outer diameters of 500 mm, 900 mm, and 1200 mm. The percentage distribution of pipeline diameters was assumed based on the European design of EHB. Fig. 1 and Table 7 give an overview of the distances and pipeline types used in the study. Pipeline materials were based on the information of manufacturers, such as Mannesmann Line Pipe. The pipe material used in this study is L360/X52. The primary materials are chromium, carbon, copper, manganese, molybdenum, nickel, phosphorus, and sulfur. In order to repurpose the natural gas pipes to transport gaseous hydrogen, extra protection for the pipeline material in the form of corrosion and mechanical protection coating is to be added. A three-layer system consisting of an epoxy primer, an adhesive, and a polyethylene layer coats the exterior of the pipeline. A thickness of 300 mm is assumed for each epoxy layer and the adhesive, and a thickness of 5 mm for the PE topcoat.[31] The LCI of Nord Stream II was used to model the Strait of Gibraltar crossing. Additionally, a protective layer coating and a concrete jacket to weigh down the pipeline were considered in the model.[32] Tables 4 and 5 show the offshore and onshore pipeline life cycle inventory. Current natural gas infrastructure has a lifetime prediction of 50 years.[33] The same lifetime can be expected for newly built hydrogen pipelines. The repurposed pipelines are assumed to have a service life of 30 years, during which they can be used for hydrogen transport. Similarly, emissions from the repurposed natural gas pipelines are now assumed to only amount to 30% of total emissions, since the pipelines have already been used for natural gas transportation (Öko-Institut e.V., 2021).

3.3 Compressor stations

The operation pressure in the pipe is assumed to be between 70 and 100 bar. PV-powered compressor stations are installed every 100 km to maintain the operating pressure.[10] For assumed hydrogen flow rates and pressure levels, piston compressors such as the LCA NEA API 618 are the most economical solution. Fig. 4 demonstrates a hydrogen piston compressor of the Neuman & Esser Group.[34]

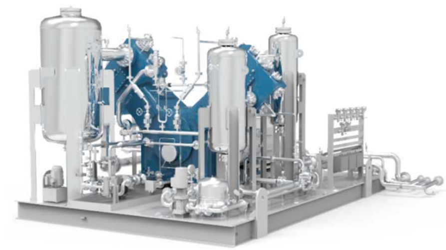

Fig. 4 NEA hydrogen piston compressor, NEUMAN & ESSER GROUP. Copyright© NEUMAN & ESSER Verwaltungs- und Beteiligungsgesellschaft.

Table 1 Input parameters of the compression station model

Parameter	Value	
Service life (new construction)	50	years
Net power demand every 100 km	0.1 (35)	kW h per kg H_2
Compressor power	12 (10)	MW
Overall efficiency	50	%
Inlet pressure	70	bar
Outlet pressure	100	bar

Table 1 shows the most critical parameters of the compression station for the LCA. Detailed inventories of the compressor stations can be found in Table 6. The emissions of PV electricity used to power the compression are calculated nationwide based on the current production routes and a market mix of installed PV technologies.[20]

3.4 Hydrogen capacity and leakage

Based on the mechanical work of the compressor stations, the maximum speed of hydrogen was calculated for different pipe diameters. The Darcy–Weisbach equation was applied for the turbulent flow to calculate the maximum speed.[36] Based on this equation, operation at maximum speed for 208 days a year leads to an annual flow of 69 TW h a^{-1} for a 900 mm pipe. However, looking at existing natural gas pipelines like Nord Stream 1, it should be possible to operate the pipeline 350 days a year.[37] This would almost double capacity. For the 900 mm pipe, a mass flow of 115 TW h a^{-1} at the maximum speed is possible. Since it is difficult to predict the operation mode, both flow rates are evaluated in the results section and referred to as "flow rate min" and "flow rate max".

The possibility of hydrogen leakage cannot be ruled out, even in newly constructed pipes. A Frazer-Nash study reports that the long-distance transport of hydrogen may cause 0.5% losses per 1000 km.[39] This study assumes 1.49–3.74% leakage for analyzed import distances based on these numbers. The FU was recalculated based on these losses. Additionally, since hydrogen is an indirect greenhouse gas, its GWP of 5.8 over a 100 year time

Table 2 Parameters of the baseline scenario

Parameter	Value	Unit
Expected lifetime (new)	50	years
Expected lifetime (reused)	30	years
Maintenance	2	% y^{-1a}
Compression (every 100 km)	0.1	kW h per kg H_2
Losses per 1000 km	0.5	%[b]
Pressure	70–100	bar[c]
Min. annual capacity (208 d of operation, 900 mm)	69	TW h a^{-1d}
Max. annual capacity (350 d of operation, 900 mm)	115	TW h a^{-1d}

[a] Ref. 5. [b] Ref. 38. [c] Ref. 35. [d] 900 mm diameter, own calculation.

frame is included in the analysis. However, since the leakage is relatively small, it does not significantly contribute to the FU GWP. The main assumptions for the baseline scenario of hydrogen transport *via* pipeline are listed in Table 2.

4. Results

Emissions from sources in the hydrogen supply chain can be classified into the following two main categories:

• Emissions from the production of hydrogen: emissions occur indirectly through manufacturing and operation of electrolyzers (PV electricity for electrolyzer operation, electrolyzer production, conditioning of hydrogen…).

• Emissions from transport of hydrogen: transportation-related emissions – emissions associated with the operation of various transport sources, including tanks and transfers into transmission or distribution pipelines (compression of hydrogen during transport, pipe manufacturing…).

4.1 GWP of FU in the baseline scenario for the production of hydrogen

Two different operation scenarios were modeled for each country: a "high energy demand scenario" with 57.5 kW h and a "low energy demand scenario" with 55 kW h. Increasing the efficiency of the electrolyzer results in a lower GWP according to a linear correlation.

However, the emissions associated with the input of electricity dominate the GWP. The primary source of emissions here is the electricity supply along the entire value chain of PV production. A variation of the GWP of PV electricity used to power the electrolyzer between 15 and 45 g CO_2-eq per kW h is shown in Fig. 5.

4.2 GWP of FU of pipeline transport

Thanks to higher irradiation, PV-powered electrolysis in Africa will have a lower impact on global warming than in Germany. The question is, however, whether the GWP of hydrogen produced with PV electricity in Germany would still be lower when considering the GWP due to transportation, *i.e.* imports from Africa. To answer this question, a scenario of German domestic production was analyzed and compared to the supply chain from Africa to Germany. The GWP results associated with the production, operation, and deposition of the pipeline are presented in this section.

Table 3 gives an overview of the GWP of hydrogen transport for the baseline scenario of compressor consumption for different supply routes. Similar to the production of hydrogen, the primary source of emissions for hydrogen transport is the electricity supply. The most substantial consumption can be attributed to the operation of the pipeline compressor stations (see Fig. 6 and 7).

4.3 Compression efficiency and PV emissions

Due to the increased research interest in hydrogen infrastructure, it can be assumed that efficiencies will be optimized in the near future. However, it is difficult to predict precise figures. The sensitivity analysis in this section is conducted to gain a better understanding of the influence of the different

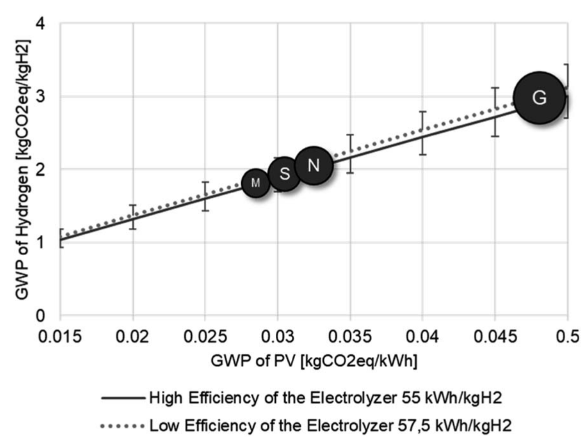

Fig. 5 GWP of hydrogen production based on different PV electrolysis efficiencies and PV electricity emissions. Germany (G), Nigeria (N), Senegal (S), and Morocco (M).

Table 3 The life cycle GWP results of hydrogen imports (excl. production)

Production region	High flow rate[b]	Low flow rate[a]	Unit
Morocco	0.07	0.11	kg CO_2-eq per kg H_2
Senegal	0.18	0.26	kg CO_2-eq per kg H_2
Nigeria	0.27	0.38	kg CO_2-eq per kg H_2

[a] GWP of the baseline scenario for the flow rates, 69 TW h a^{-1}. [b] GWP of the baseline scenario, 115 TW h a^{-1}.

Table 4 Life cycle inventory of the onshore pipeline

Material onshore pipeline	Volume	Value
Water	187	m^3
Diesel, burned in construction machinery and vehicles	3.31	TJ
Steel X52, seamless pipeline	630	t
Epoxy powder, at the plant	1.36	kg
Polyethylene, LDPE, granules, at the plant	4.64	t
Transport, helicopter	26	h
Transport, truck 32 t	219 000	t km
Transport, freight, rail	77 500	t km

Table 5 Life cycle inventory of the offshore pipeline

Material offshore pipeline	Volume	Value
Water	805	m^3
Diesel, burned in construction machinery and vehicles	2.53	TJ
Steel X52, seamless, pipeline	1015.61	t
Concrete	361	m^3
Aluminum	3.32	t
Zinc for coating	175	kg
Transport, truck 32 t	76 100	t km
Transport, freight, rail	122 000	t km
Transport, transoceanic cargo ship	182 000	t km

Table 6 Life cycle inventory of the compression stations

Material	Value	Unit
Steel profiles	12 100	t
Concrete	172 000	t
Reinforcing steel	8500	t
Transport, trucks 32 t	54 750	tkm
Diesel, trucks, and construction machinery	827 500*	MJ

Table 7 Import distances from Africa to Germany

Pipeline type	Distance [km]
Onshore pipeline Europe–Germany	2400
Offshore pipeline Europe–Africa	40
Onshore pipeline Africa (Morocco)	560
Onshore pipeline Africa (Senegal)	3060
Onshore pipeline Africa (Nigeria)	4260

compression efficiencies on the GWP of PV-based hydrogen supply. The energy demand for previously described pipeline routes is varied until the worst-case scenario (compressor demand of 1.5 kW h per kg H_2 per compressor station) is achieved. Additionally relevant is the origin of the PV panels used to run the compressors. Therefore, minimum and maximum values for the GWP of PV electricity, as described in the previous section, are applied. Fig. 8 shows the GWP of hydrogen imports based on different PV emissions and the energy demand of the compression stations. For the best-case scenario, renewable electricity is assumed for PV production ("low emission PV" – 0.015 kg CO_2-eq per kW h). In the worst case, Chinese PV production is based on coal electricity ("high emission PV" – 0.045 kg CO_2-eq per kW h).[40]

The results of low-efficiency compressors in combination with the high GWP of PV electricity can only achieve up to 5.5 kg CO_2-eq per kg H_2 for transport from Nigeria to Germany, 3.9 kg CO_2-eq per kg H_2 for Senegal, and 2.0 kg CO_2-eq per kg H_2 for the shortest distance from Morocco.

4.4 GWP of hydrogen supply chains for Germany

For the holistic results on the hydrogen supply chains, the production and distribution of hydrogen are included in the model in this section (see Fig. 8). The mass flows described earlier were evaluated for two scenarios: lower efficiency electrolyzers with a demand of 57.5 kW h for producing 1 kg of

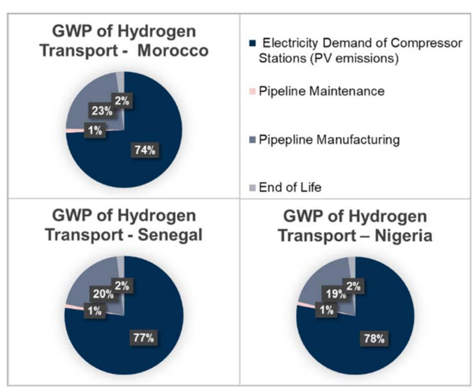

Fig. 6 The life cycle GWP contribution of hydrogen transport from Morocco, Senegal, and Nigeria to Germany. The GWP of hydrogen transport is demonstrated excl. the GWP of hydrogen production.

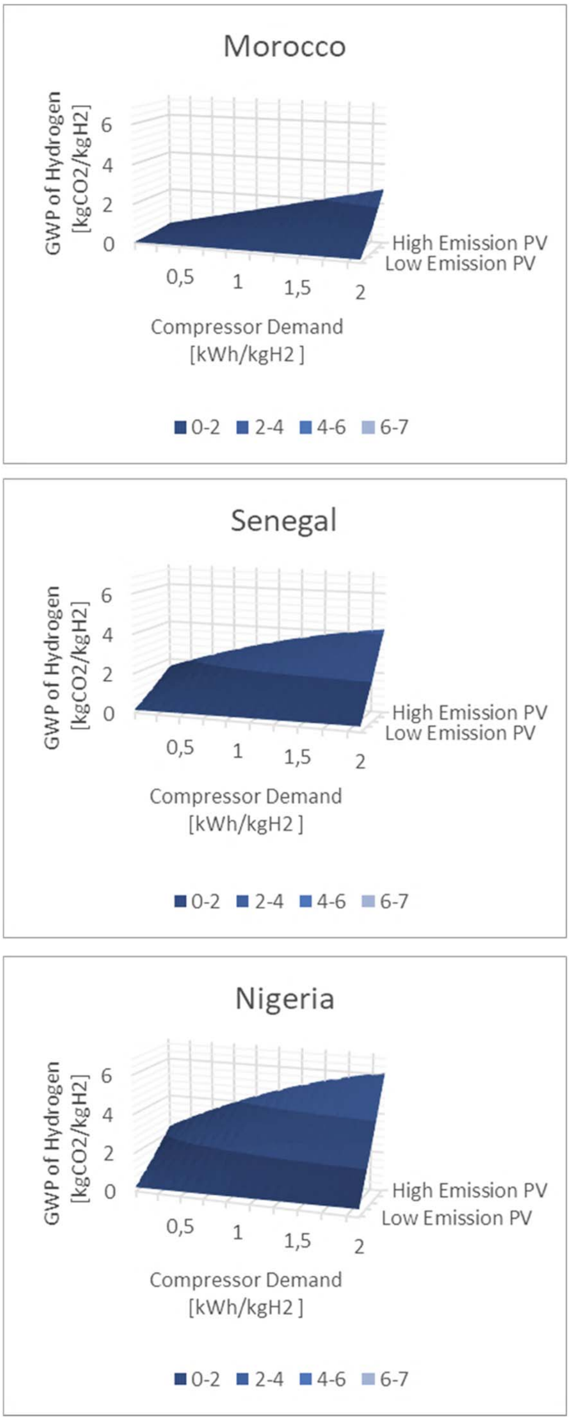

Fig. 7 GWP of hydrogen transport (excl. production) from Morocco, Senegal, and Nigeria depending on the efficiency of the compression and origin of PV electricity. For the best-case scenario, renewable electricity is assumed for PV production ("low emission PV" – 0.015 kg CO_2-eq per kW h). The worst case involves Chinese PV production based on coal electricity ("high emission PV" – 0.045 kg CO_2-eq per kW h).

hydrogen and higher efficiency electrolyzers that only need 55 kW h per kg H_2. For the German supply chain, a distribution distance of 300 km was assumed. The pipeline infrastructure was modeled according to the assumptions described previously in this paper.

Additionally, a scenario of a grid-connected PEM electrolyzer in Germany was evaluated. The GWP of the German grid in this study was assumed to be 0.251 kg CO_2-eq per kW h, which is the GWP of the grid in 2030 after the phasing out of coal. The GWP of hydrogen production *via* electrolysis using the average grid electricity for 2030 in Germany is 14.5 kg CO_2-eq per kW h. The current share of renewable electricity in the German electricity grid is lower. The GWP of the German grid in 2021 is 0.428 kg CO_2-eq per kW h. Based on the current grid, the hydrogen supply would lead to significantly higher emissions of 24.2 kg CO_2-eq per kg H_2. Fig. 8 shows the results of this comparison. The results show that the import of renewable hydrogen can outperform domestic production in the baseline scenario, where the efficiency of the compressors is estimated at an average of 0.1 kW h per kg H_2. The GWP of the domestic production sites is dominated by the power supply, with more than 90% of emissions resulting from electricity emissions.

4.5 Limitation of the study

There are several limitations to application of the study in the context of current energy systems:

• An LCA study requires a significant amount of data of future energy systems. However, the availability and reliability of such data is limited, particularly for emerging technologies and processes. The increased share of renewable electricity in the grid will influence the GWP for all future supply chains covered in the study. For instance, the GWP of electricity required for PV cell production will probably drop in the future, leading to reduced GWP per kW h of PV energy production.

• GWP results are subject to uncertainties and variability due to the data used and assumptions applied for the future energy system that doesn't exist yet in reality in 2023. These uncertainties can arise from various sources, such as assumptions about the technological performance and operation profiles of components in the system considered (*e.g.*, compression stations). In this study, for instance, we assume ideal performance of the compression stations under non-stationary operation (as if operated under base load conditions) with oversized grid-connected PV systems. This simplified approach was applied due to a lack of information available about operation profiles for hydrogen compressors in scientific literature. Probably further future research on practical experiences with demonstrations of (parts of) the hydrogen infrastructure will close this gap.

• Defining the boundaries of this study was challenging, as different stages of the life cycle of parts the investigated system may occur in different geographical locations and involve different actors. In general, it is known that the choice of system boundaries can significantly affect the results of an LCA study and limit its scope. We decided not to include island systems with batteries in the study, since their sizing depends on several unknown factors as desired level of reliability of system operation, project budgets, system autonomy and load profiles of the electrolyzers.[11,26]

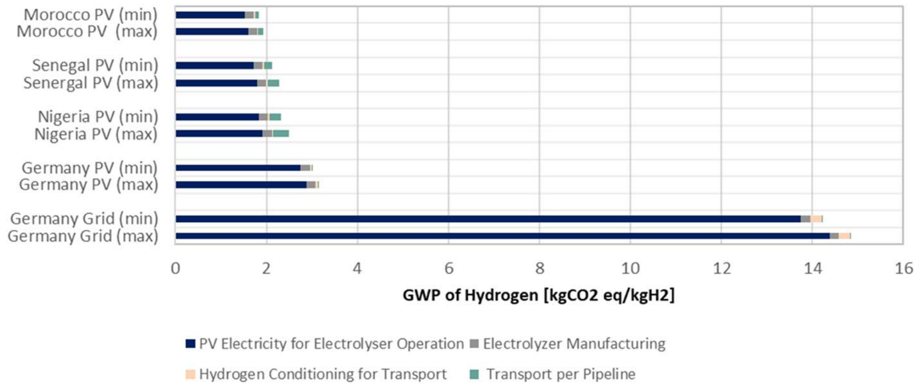

Fig. 8 Scenario analysis for different insolation levels and electrolyzer consumption. GWP of PV-powered hydrogen production by country with high-efficiency scenario (power consumption: 55 kW h per kg H_2) and low-efficiency (electricity demand of 57.5 kW h per kg H_2). Blue – GWP caused by PV electricity, grey – GWP of plant manufacturing, beige – GWP of compression and conditioning, and mint – the pipeline transport.

• Different energy systems' LCA results may be hardly comparable, due to differences between the chosen system boundaries, functional units, and environmental impact categories. The outputs of an LCA have thus to be evaluated only in the framework given through the specific LCA study. The performance of PV systems, for instance, can vary based on several factors, such as location, irradiance conditions, module technology, and installation quality. The location of a PV production site can impact the amount of solar radiation it receives, which affects its energy output. Production sites located in areas with high levels of solar irradiance, such as southern Germany, may perform better than those in areas with lower levels of irradiance as central Germany. It is essential to carefully consider these factors when discussing the results of the study.

• This LCA focused only the GWP, and may not capture other aspects of sustainability, such as social and economic impacts. The GWP results represent just a few of the many outputs of the LCA, which are, however, based very centrally on the expected usage of hydrogen in the energy and transport sectors. Additional impact categories that may be addressed in future research considering hydrogen application fields include acidification potential, eutrophication potential, and photochemical ozone creation potential.[22] The results of this and future studies might be relevant to policymakers, investors, researchers, and stakeholders in the EU and Africa. More data from actual hydrogen pipeline structures are needed for future research to extend the system boundaries and validate the LCA models.

5. Discussion

The results for domestic and import supply chains of solar PV-based hydrogen range from 2 to 3 kg CO_2-eq per kg H_2 in the baseline scenario. The GWP results in our study are within the range of existing life cycle studies. The GWP of hydrogen from PV electrolysis is usually reported to be around 2–7 kg CO_2-eq per kg H_2.[17,41,42] The sensitivity analyses demonstrated that the GWP could significantly increase with the emissions of PV, which explains the gap between the GWPs.

However, even from the high energy demand scenario in this study, the GWP of hydrogen still has a lower GWP than any fossil-dominated alternative production methods. According to the certification of hydrogen by CertifHy, production by steam methane reforming (SMR) of natural gas causes 10.9 kg CO_2-eq per kg H_2 without distribution. A review by Bhandari *et al.*[43] indicated a range of 8.9–12.9 kg CO_2-eq per kg H_2. Even higher values for the SMR production of hydrogen (up to 17.5 kg CO_2-eq per kg H_2) can be found in the literature.[44] The combination of SMR with CCS technologies for producing "blue" hydrogen results in a lower total GWP of 6.87 kg CO_2-eq per kg H_2.[45] The emissions resulting from the entire transport supply chain are not additionally analyzed and are therefore unknown. Domestically produced hydrogen from PV in Germany also shows a higher GWP than liquid hydrogen imports.[13]

The GWP of hydrogen per kg of this study can be recalculated to kW h using a lower heat value of 33.3 kW h per kg H_2 in order to compare it to other fossil fuels such as natural gas. The GWP of 0.04–0.050 kg CO_2-eq per kW h for the Moroccan export to Germany and 0.06–0.07 kg CO_2-eq per kW h for German domestic production is concluded for the baseline scenario of this research after recalculation of the FU. Based on the literature, the GWP of natural gas transported by pipeline to Germany ranges between 0.5 kg CO_2-eq per kW h and 0.95 kg CO_2-eq per kW h, depending on the export region and transport quality (*e.g.*, leakage). For instance, a higher GWP is considered for Russian natural gas *via* the TurkStream pipeline to Southeast Europe, caused by a higher leakage rate and a longer pipeline transport distance.[46] The GWP of natural gas is thus higher than the GWP of imported hydrogen in the baseline scenario of this study.

Since the Russian invasion of Ukraine in February 2022, sales of liquefied natural gas (LNG) to Europe have been increasing rapidly.[47] However, the value chain of LNG is even more complex than gaseous natural gas, which causes an even higher GWP.[48]

The security of hydrogen pipelines is a critical issue that needs to be addressed to ensure the safe transportation of hydrogen. One of the major challenges is the potential for hydrogen embrittlement, which can lead to the degradation of pipeline materials and ultimately result in pipeline failure. The selection of appropriate pipeline materials, proper maintenance and inspection, and the installation of effective leak detection systems are all critical components of ensuring the security of hydrogen pipelines. In our study an ideal operation without security or safety issues is assumed, but in real life a comprehensive security plan that addresses the potential risks of terrorism must be developed and implemented to safeguard the integrity of the pipeline network and protect public safety.[49]

The export of hydrogen would most likely have a positive impact on the local energy supply, the labor market, local education, and health in Africa. However, alongside these benefits, the import also harbors risks, which must also be highlighted. For instance, the provision of sufficient pure water is a challenge in Africa. The H_2Atlas-Africa shows that sufficient water to produce green hydrogen would be available in many regions of Africa.[8] The availability of fresh water for electrolysis is an essential factor that must be considered when choosing a production site. The results of the atlas indicate that the cost of desalination would not significantly increase the price of hydrogen. Another option would be to produce hydrogen directly from seawater. However, this technology is still being developed.[50] A stable political and economic framework is as significant as the choice of location. It is crucial to fostering the benefits of international cooperation and ensuring the initiation of renewable production. International standards are needed to speed up a fair energy transition in Africa and Europe in order to guarantee economic development, new business and job opportunities, and better living conditions.

6. Conclusions

This study provides a comprehensive evaluation of the life cycle performance of hydrogen imports from Africa in comparison to domestic PV – powered hydrogen production. By analyzing various supply chain parameters in different scenarios, we identified hot spots and potential sources for future reduction of emissions.

Our results reveal that hydrogen produced by electrolysis and imported *via* pipelines from Africa has a total GWP ranging from 1.9 to 2.5 kg CO_2-eq per kg H_2. On the other hand, PV-powered German domestic hydrogen production results in a GWP of 3.0 to 3.1 kg CO_2-eq per kg H_2 in the baseline scenario, while the use of electricity from the German electricity mix after 2030 instead of PV leads to a GWP increase of up to 14.5 kg CO_2-eq per kg H_2. These emissions are highly dependent on the flow rate of hydrogen, the GWP of PV electricity used to power the compressors along the way, transport distance and compression efficiency. Our findings suggest that the impact of transport *via* pipeline on the GWP is negligible when compared to the production of hydrogen by PV electrolysis. Moreover, the results indicate that in the GWP associated with PV electricity is contributing up to 78% of the GWP of hydrogen transport and up to 91% of the total GWP of the hydrogen supply chain depending on the scenario analyzed.

In conclusion, our life cycle assessment highlights the importance of considering the entire supply chain when assessing the environmental performance of hydrogen. As hydrogen becomes increasingly important in the fight against global warming, investigating potential supply chains is essential. Future studies should examine the potential of alternative transportation methods, such as liquid hydrogen (LH_2) and liquid organic hydrogen carriers (LOHCs).

Author contributions

Conceptualization – AR, UR, KD, KB, FB; methodology – OK, AR; software and validation – OK; formal analysis – KB; writing (original draft preparation) – OK; writing (review and editing) – AR, KB, KD, and UR; supervision – AR. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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