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How Green is Green Hydrogen – a Life-Cycle Approach to Hydrogen Production in Namibia

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1 Abstract

Hydrogen is considered green when it is produced from renewable electricity via electrolysis or other renewable-based pathways, such as direct water splitting or biogenic production. However, all technical processes show environmental impacts over their life time that are related to the use of technical materials, resources (including water) and energy.
In this study, an evaluation on the environmental impacts and particularly of the greenhouse gas (GHG) emissions of hydrogen value chains are presented taking Namibia and the site of the Daures Green Hydrogen Village project as a case study in context with other worldwide hydrogen production sites. A life-cycle assessment (LCA) according to DIN ISO 14040/44 is pursued, taking the global warming potential (GWP) as the main impact category. The analysis considers the specific impacts of the weather conditions at the Daures site on electricity generation from solar and wind power and the technical layout of the first project phase.
First results are presented and compared with standard values, emission levels from literature and other hydrogen projects worldwide.

2 Objectives of the study

The objective of this study is to evaluate the role of green hydrogen produced in Namibia within international standards and competing hydrogen value chains. For this, the definitions and emission levels of green hydrogen are assessed on an international level and a life-cycle based analysis of hydrogen production in Namibia and particularly at the site of the Daures Green Hydrogen Village (DGHV) project is analyzed. The values are then compared with other prominent production sites such as Chile, Europe or China. The analysis also shows the value of a standardized life-cycle assessment (LCA) methodology for securing accurate and adequate results.

3 Green Hydrogen Standards and Regulations

Hydrogen is set to play a major role in the global energy transition, in accordance with the 1.5 °C target set in the Paris Agreement (IEA, International Energy Agency, 2023). Many countries have developed hydrogen strategies, aiming to enable a transition on a national level. One major challenge in building a hydrogen economy remains securing a low-carbon supply of hydrogen on a large scale. While hydrogen at present is mainly produced from natural gas *via* steam reforming that is associated with considerable greenhouse gas (GHG) emissions of around 11.3 kg of carbon dioxide per kg of hydrogen produced ($kgCO_2eq/kgH_2$) and future hydrogen production will need to deliver hydrogen at much lower carbon intensities to align with net-zero targets (European Commission, 2023/1185). Producing hydrogen *via* electrolysis using renewable energies is the promising pathway to deliver low emission green hydrogen.

International Renewable Hydrogen Standards

The ramp-up of green hydrogen production is linked to standardization and certification schemes, that ensure investments into really “green” projects. For this the maximum allowed carbon intensity of green hydrogen is an important threshold within such standards.

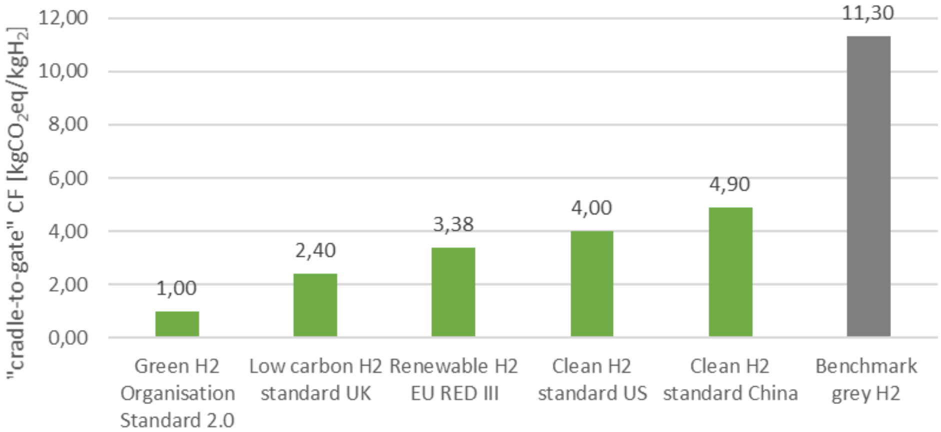

Figure 1: Comparison of CO_2-emission levels of hydrogen standards and certification schemes for low carbon or green hydrogen (DESNZ, 2023; European Commission, 2023/1185; GH2, 2023; Liu et al., 2022; U.S. DoE, 2021).

LCA is a common approach to evaluate the environmental impacts such as the carbon footprint, i.e. global warming potential (GWP) of hydrogen production pathways. Figure 1 shows carbon thresholds set in standards established by governments, such as the UK, US, China and the EU, as well as a non-governmental scheme by the Green Hydrogen Organisation. The comparison shows that the values for green or low-carbon hydrogen vary between 1.0 and 4.9 $kgCO_2eq/kgH_2$, depending on the respective standard and region. Standards vary in terms of the actual threshold that can be attributed to the methodology used to develop the standards. The Renewable Energies Directive III (RED III) by the EU and the Chinese Clean Hydrogen Standard (CCHS) require a direct reduction of emissions compared to a fossil reference, which are steam methane reforming for RED III and coal gasification for CCHS (European Commission, 2023/1185; Liu et al., 2022). The US and UK standards refer to typical emission-intensities for green H_2 production pathways from LCAs and also recommend a procedure to facilitate an environmental assessment accordingly (DESNZ, 2023; U.S. DoE, 2021). The Green Hydrogen Organisation chooses a different approach, setting the standard for green hydrogen in line with net-zero ambitions for 2050 (GH2, 2023).

Worldwide LCA emission levels of Green Hydrogen

Figure 2 shows GHG emission results assessed via LCA with a “cradle-to-gate” approach for H_2 production pathways for North America (including Canada), Central Europe, the UK, and South America.

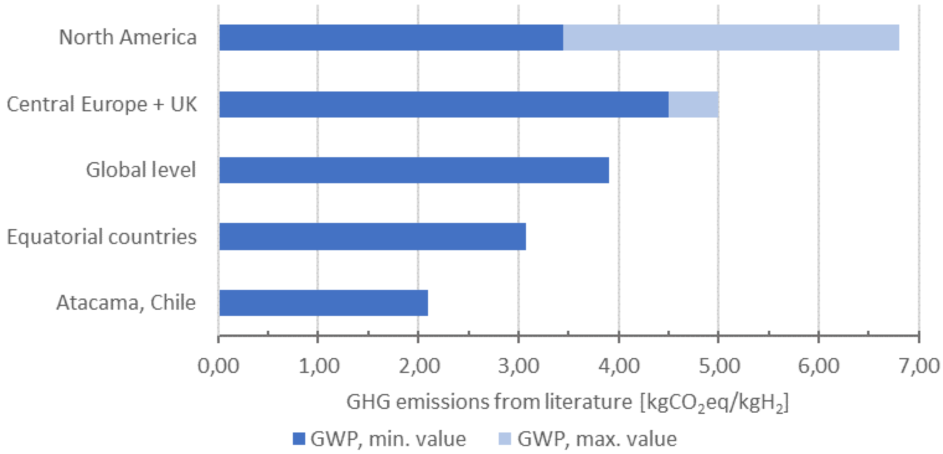

Figure 2: LCA-based GHG emission levels for H_2 produced via electrolysis using PV-electricity. Comparison of sites/regions worldwide. Based on (Al-Qahtani et al., 2021; Aydin & Dincer, 2022; Freire Ordóñez et al., 2022; Hermesmann & Müller, 2022; Kolb et al., 2022; Schmidt Rivera et al., 2018; Weidner et al., 2023)

Additional results from a study on a global level are included (Weidner et al., 2023). GHG emission levels vary between 2.1 and 6.3 $kgCO_2eq/kgH_2$, depending on the location (Al-Qahtani et al., 2021; Aydin & Dincer, 2022; Freire Ordóñez et al., 2022; Hermesmann & Müller, 2022; Kolb et al., 2022;

Schmidt Rivera et al., 2018; Weidner et al., 2023). The relation of GHG-emissions with the production sites is mainly due to the different solar irradiation levels and subsequent different efficiencies of renewable electricity generation. In locations with higher solar irradiation the environmental impacts per unit produced energy of the entire system is lower, culminating also in a lower specific global warming potential (GWP).

4 Methodology – Assessment of Green Hydrogen

To compare the different hydrogen emission levels and identify potential entry points and hotspots for improvements a literature review on reference data was conducted.

Life Cycle Assessment

The life cycle assessment (LCA) was conducted according to ISO 14040/44 (DIN 14040:2006) and the IPCC method (IPCC 2021 GWP100 V1.02) using the SimaPro 9.5.0 tool. The scope of the study includes the manufacturing of components for the photovoltaic (PV) plant and electrolyzer, as well as their installation and operation. The decommissioning of the system is not considered. For the Life Cycle Inventory (LCI) the Ecoinvent 3.9.1 database was used when component data were available. The specific carbon emissions for hydrogen are given for the electrolyzer output, expressed in kg CO_2 per kg H_2. The study places particular emphasis on the detailed calculation of emissions per unit of energy produced (Kolahchian Tabrizi et al., 2023), as it is well documented that electricity production is one of the largest contributors to the carbon footprint of hydrogen. For assessing this, PV solar energy generation was analyzed, considering modules, inverters, generic electronic devices, and mounting systems. A 1 MW PV plant was modeled using JA Solar JAM72S30 MR modules (Peak power: 550 Wp, area: 2.583 m², weight: 2.73 kg, efficiency: 21.85 %) and ABB central PVI 500.o-CN inverters (Maximum AC power: 500 kW).

Renewable Electricity Generation

The System Advisor Model (SAM) (NREL, 2024) was employed to design the 1 MWp PV plant and calculate the annual energy yield. The lifespan of the PV plant is assumed to be 30 years and number of modules and inverters and their respective weights were considered in the LCA model in SimaPro. The location of the plant was also considered to calculate transport efforts from the manufacturing site in Shanghai port (for PV modules and inverters) to the destination country's port by ship, followed by 200 km of road transport

(truck). The GWP100 result represents the total CO_2 emissions required to manufacture and transport a 1 MW PV plant, expressed in kg CO_2.
To estimate the values for the hydrogen produced at the Daures Project site (Namibia), the PV plant was scaled to 739 kWp. Consequently, both the SAM and SimaPro models were downscaled to match this size. The specific carbon emissions of photovoltaic energy for a 739 kWp PV plant were calculated as shown in equation 1:

$$S_{PV} = specific\ CO_2\ emissions\ of\ PV\ electricity = \frac{total\ CO_2\ emissions}{total\ energy\ yield\ over\ lifespan} \left[\frac{kgCO_2}{kWh}\right]$$

The 260 kW PEM electrolyzer used in the Daures project (stack and balance-of-plant components) was modelled with the LCI from (Bareiß et al., 2019) to model the electrolyzer (Bareiß et al., 2019). Since the LCI data provided by the authors is for a 1 MW PEM electrolyzer, it was downscaled to 260 kW. Due to the lack of references the analysis does not include the energy required to assemble the electrolyzer or to operate and maintain the devices.

Hydrogen Production

The specific carbon emissions per unit of hydrogen produced depend on the equivalent operating hours of the electrolyzer. If the electrolyzer is used for more time, each unit of hydrogen produced accounts for a lower fraction of the electrolyzer's carbon footprint. Therefore, the annual equivalent operating hours of the electrolyzer were calculated from the hourly electric output of the PV plant. No batteries were considered, meaning the electrolyzer will operate only during daylight hours. The minimum threshold to start electrolyzer operation is 30 % of the nominal power, i.e., 78 kW. The efficiency rate of the electrolyzer, i.e., the energy consumed to produce 1 kg of hydrogen, is obtained from the Clean Hydrogen Strategic Research and Innovation Agenda 2021–2027, ranging from 55 to 48 kWh/kgH_2 (CHP, 2022). With the hourly hydrogen production, the annual hydrogen production is obtained. Assuming a lifespan of 30 years, the total hydrogen production and electricity consumption for the project is calculated.

Water Use

The carbon footprint of water provision for the electrolysis process was calculated with a reverse osmosis process from seawater over 30 years of operation (source: Ecoinvent), that gave a value of 0.00231 kgCO_2/kgH_2O.
The specific carbon emissions per unit of hydrogen (SH_2) were calculated as:

$$S_{H2} = \frac{C_{EL} + S_{PV} \cdot T_{PV} + S_{H2O} \cdot T_{H2O}}{T_{H2}} \left[\frac{kgCO_2}{kgH_2}\right]$$

Where, C_{EL} is the total carbon footprint to manufacture and install the electrolyzer [$kgCO_2$],
S_{PV} is the specific carbon emissions for PV electricity [$kgCO_2/kWh$],
T_{PV} is the total electricity consumed over the lifespan of the project [kWh],
S_{H2O} is the specific carbon emissions for desalinated water [$kgCO_2/kgH_2O$],
T_{H2O} is the total water consumed over the lifespan of the project [kgH_2O],
T_{H2} is the hydrogen produced over the lifespan of the project [kgH_2].

Sites and Regions

Four locations were selected for comparing the carbon footprint of green hydrogen: Daures, Namibia; Atacama Desert, Chile; Qinghai, China; and Stuttgart, Germany. Additionally, six cases were defined for each location to perform a sensitivity analysis. Four cases focused on the electrolyzer's efficiency in converting electricity to hydrogen, with parameters based on existing literature. The worst-case scenario assumes 60 kWh/kgH_2 (case 1), followed by three efficiency rates from the Strategic Research and Innovation Agenda 2021–2027: 55 (case 2), 52 (case 3), and 48 (case 4) kWh/kgH_2 (CHP, 2022).

Using case 3 as a reference, since it represents the target efficiency for 2024, a second parameter for the sensitivity analysis was the water consumption of the electrolyzer (only for hydrogen production, excluding water used for PV plant cleaning, refrigeration, or other purposes). Cases 1 to 4 assume a water consumption of 10 kgH_2O/kgH_2, while the other two cases assume 20 kgH_2O/kgH_2 (case 5) and 30 kgH_2O/kgH_2 (case 6), based on treated water.

5 Namibia’s Green Hydrogen Potential

Namibia has abundant solar resources, with around 10 hours of sunlight per day for 300 days a year. The country also has significant wind energy potential with highest wind speed in the southern and northern coastal areas. Due to the abundance of these natural resources, Namibia can produce green hydrogen at low cost rates compared to other regions in the world by 2030 (SYSTEMIQ, 2022). The country’s onshore wind energy potential between 2020-2050 is 5,050.35 TWh/yr and open-field PV energy potential is 9,513.51 TWh/a (Forschungszentrum Jülich, 2024).

The country has ambitions to develop three green hydrogen valleys: the Northern Valley, Central Valley, and Southern Valley (Ministry of Mines and Energy Namibia, 2022). The Northern Valley will be located in the Kunene Region, the Central Valley in the Erongo Region where the country's green hydrogen pilot project hub will be. This area will have the necessary infrastructure to enable future industrial-scale sizes of these projects and their applications (Government of the Republic of Namibia, 2024). The Southern Region is located at Karas. These valleys will form a green fuel ecosystem within the country that will aid in the country becoming a leading exporter of green hydrogen in Africa to support the global transition to net zero.

With the aid of the production potential of the different valleys within the country, Namibia is targeting green hydrogen production (hydrogen equivalent) values of 1-2 Mt/a in 2030, 5-7 Mt/a in 2040 and 10-15 Mt/a in 2050 (Ministry of Mines and Energy Namibia, 2022). This target represents about 5-8% of the projected global hydrogen trade volume.

The Daures Green Hydrogen Project is one of the pilot projects located within the Central Valley. It is located in the heart of the Erongo Region in the Daures Constituency, close to the Brandberg Mountain. The site is located at latitude: -21.14S and longitude: 14.16E. The project's objectives are to sustainably produce green hydrogen and green ammonia for research, local use cases, and regional and international export.

The project is divided into phases. During its pilot proof of concept phase, it only consists of solar (739 kW) and battery as power sources to produce green hydrogen (and subsequently, green ammonia). During the industrial scale phases, wind will be used to complement the solar power generation on site.

The yearly global horizontal irradiance on site was 2445 kWh/m^2 and preliminary desktop wind studies found that the average wind speed on site was 7 m/s (Geo-Net Umweltconsulting GmbH, 2024; Solargis, 2024). With these irradiance levels and an available land size of 15,000 hectares, the project could potentially generate 5.13 GW of solar power and 427 MW of wind power further at its industrial scale.

6 Results

The global warming potential (GWP 100) for hydrogen produced on PV electricity at four different locations worldwide including Namibia and the GWP for PV electricity at the Daures project site is shown in Fig. 3.

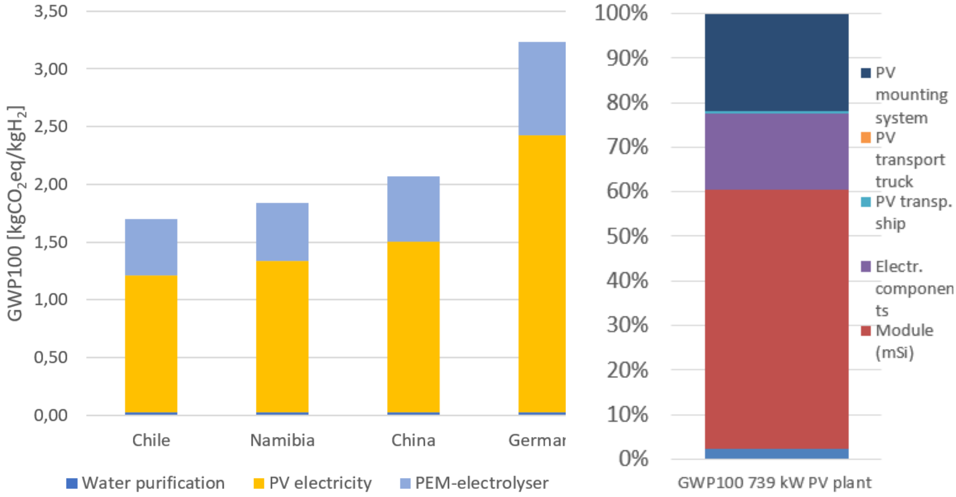

Figure 3: Comparison of the global warming potential (GWP 100) for hydrogen production at four different locations worldwide (left) and the shares of GWP for PV solar electricity production at the Daures project site in the first project phase (739 kW PV plant as only source of electricity).

The GWP is dominated by the share of electricity production in the PV panels (Fig. 3 left). The share of the PEM electrolyser is less than half of electricity production. Compared to these shares water purification is only a small fraction of the overall emission levels. The GWP of hydrogen produced in Namibia is among the lowest in worldwide comparison and is at the same level than that of hydrogen produced in Chile, which is known for its good conditions for hydrogen production.

The GWP for solar PV electricity production is dominated by the share for the PV module production. Also, the electronic components and the mounting system contribute to the overall GWP. The shares for the transport of the PV-panels to the project site (international via ship and national via truck) represent only a negligible portion of the overall GWP.

The comparison of GHG emissions for hydrogen production with data from worldwide projects (Fig. 4) demonstrates the strong relationship with the solar resource. As higher the solar irradiance as lower are the GWP values. This comparison shows the advantage of projects sites with a high solar irradiance for hydrogen production.

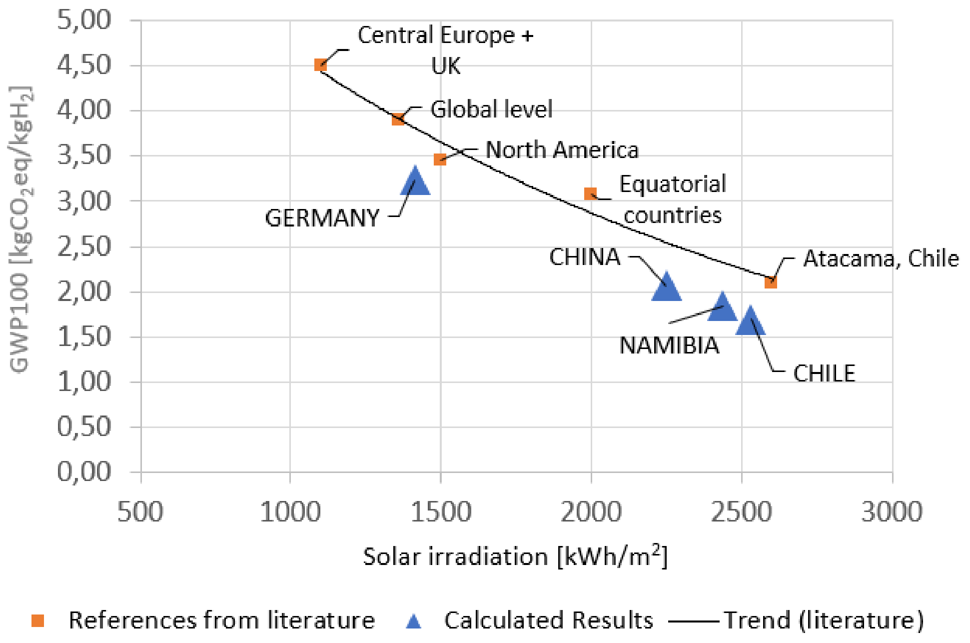

Figure 4: The GWP of hydrogen production versus solar irradiation compared for different sites world-wide. Data from own analysis (blue triangles) and reference values from literature (orange rectangles).

The values at sites in Namibia and Chile are in the range of 1,5-2,0 kg CO_2/kg H_2, whereas for sites in Germany these values are more than double and in the range of 3.0 to 3.5 kg CO_2/kg H_2.

Many parameters affect the GWP values. Among those heavily debated are the emissions for the electrolyzer and for water use, although these are not the largest contributors for the overall GWP. Because of this high attention the variation of the GWP due to different parameter was tested in the sensitivity analysis and is shown in Fig. 5.

The results show that for the overall GWP for hydrogen production decreases almost linearly with the electrolyzer efficiency that was decreased from 60 to 48 kWh electricity per kg of hydrogen (Fig. 5 left). Compared to the reference level at 52 kWh/kg H_2 the overall GWP at the lower efficiency of 60 kWh/kg H_2 increased from 1.8 to 2.1 kg CO_2/kg H_2 and decreased to around 1.65 kg CO_2/kg H_2 at the higher efficiency level of 48 kWh/kg H_2.

The sensitivity analysis for water use for the electrolyser has only a minor impact on the overall GWP. Increasing the water use from 10 to 30 l/kg H_2 increased the GWP level from 1.82 to 1.88 kg CO_2/kg H_2.

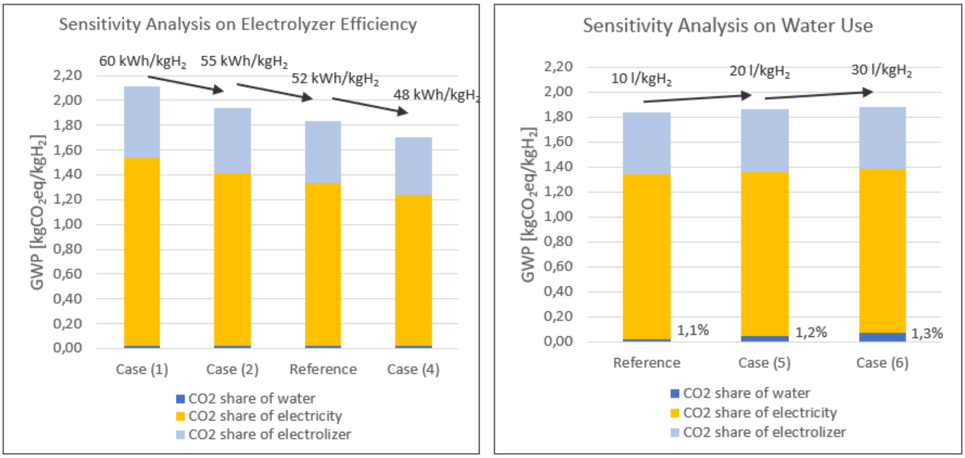

Figure 5: Sensitivity analysis for the GWP of hydrogen production for electrolyzer efficiencies (left) and for water use (right).

7 Conclusions and outlook

The results of the analysis show that hydrogen production in Namibia and at the Daures GHV project site can be highly competitive with respect to the greenhouse gas emission levels (GWP100). They are – compared to other locations and regions in the world – very low and in accordance with technical and regulatory standards. Thus, this hydrogen can be considered really “green hydrogen”!

The analysis has confirmed that the GWP level is dominated by the production conditions for the electricity used in the electrolysis. The LCA based analysis also shows that the PV module production has a major impact for the overall GWP. In the case of PV modules produced in China the GWP levels are fairly high as long as fossil electricity (e.g. from coal power plants) is used. Assuming that the production of PV panels is done with renewable electricity the GWP of PV-modules and consequently also that of hydrogen production can be reduced considerably.

For the future it can be expected that PV and also hydrogen production can be improved through learning effects (e.g. electrolyzer efficiencies) and that consequently also emission levels can be reduced still. Other effects like transport (of the PV panels to the site) or water use are of minor importance with respect to the overall GWP level.

For the GWP evaluation of hydrogen production and the option to introduce this hydrogen in international trade it is important that the assessment is done according to internationally accepted rules and standards (such as ISO 14040/44 for LCA). For a holistic assessment of environmental impacts of hydrogen production also other impact categories than the GWP, e.g. land use or social acceptance, are important impact categories. Similarly, the system boundaries for the life-cycle assessment of hydrogen production should be extended to a „cradle-to-grave“ approach that also includes end of life aspects. In that way green hydrogen can receive more public acceptance and may be a real environmental alternative to existing high emission fossil energy and gas provision pathways.

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