HYPAT

H2 Potential

Global Atlas of H_2 Potential

Sustainable locations in the world for the green hydrogen economy of tomorrow: technical, economic and social analyses of the development of a sustainable global hydrogen atlas

HYPAT Working Paper 01/2022

Background paper on sustainable green hydrogen and synthesis products

Authors:

Jana Thomann, Frank Marscheider-Weidemann (Fraunhofer ISI)

Andreas Stamm (DIE)

Ludger Lorych (GIZ)

Christoph Hank, Friedrich Weise, Lucas Edenhofer (Fraunhofer ISE)

Zarah Thiel (Ruhr-Universität Bochum)

Fraunhofer ISI

Fraunhofer ISE

RUHR UNIVERSITÄT BOCHUM RUB

d·i·e Deutsches Institut für Entwicklungspolitik

German Development Institute

giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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Project lead

Prof. Dr. Martin Wietschel
Fraunhofer-Institut für System- und Innovationsforschung ISI
Breslauer Str. 48, 76139 Karlsruhe
martin.wietschel@isi.fraunhofer.de

Project website

www.hypat.de

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The information was compiled to the best of our knowledge in accordance with the principles of good scientific practice. The authors assume that the information in this report is correct, complete and up-to-date, but do not accept any liability for any errors, explicit or implicit.

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1 Introduction

There is currently much debate about the sustainability of green hydrogen and its synthesis products. This working paper addresses this discussion and serves as a basis for developing a common understanding of the sustainability of hydrogen and its synthesis products in the HYPAT (Global Hydrogen Potential Atlas) research project. The HYPAT project develops a global hydrogen potential atlas and identifies potential partner countries of Germany for cooperative development of a future green hydrogen economy. The importance of a secure, economic and ecologically sustainable supply in the production regions is also analyzed.[1] The criteria developed in this document serve as background information for evaluating potential, and for economic and model calculations within HYPAT. They are the result of literature research, participation in workshops, interviews and, most importantly, discussions within the HYPAT work package "Sustainability Criteria for Green Hydrogen" (3.2.1). Since these results are relevant for the ongoing development of the green hydrogen economy, publishing this paper aims to make them available to a wider range of users.

The HYPAT project is based on the objectives of the National Hydrogen Strategy (NHS) of the German government (Bundesministerium für Wirtschaft und Energie 2020), which is why there are frequent references to specifications from the NHS in this paper.

Green hydrogen is defined in the NHS as hydrogen produced by the electrolysis of water using electricity from renewable energy sources (RES). Other definitions in current or proposed labels allow for different energy sources from any renewable energy sources through to energy sources with low greenhouse gas (GHG) emissions or with net zero CO_2 emissions via carbon capture and storage (CCS) (Velazquez Abad et al. 2020). A few well-chosen and currently up-to-date definitions are presented in Table 5 in Section 10.1. A brief overview of the corresponding "color theory" of hydrogen is given in section 10.2.

According to the definition of the NHS, however, even green hydrogen would not necessarily be sustainable. In addition to the use of renewable electricity for electrolysis, the NHS stipulates that no incentives for investment in fossil energy sources should be created in the partner countries in the case of hydrogen cooperation, and that the energy transitions in these countries should also be supported. Thus, the focus of the NHS for assessing the sustainability of hydrogen is on the energy sources used for hydrogen production and the energy system as a whole. In the European hydrogen strategy (European Commission 2020), the focus is on power generation. It also states that the raw material needed, especially the demand for critical raw materials, must be taken into account and life cycle considerations are necessary to minimize the negative climate and environmental impacts of hydrogen production. For a comprehensive assessment of sustainability, other criteria should be included in addition to energy sources, such as water supply, land use, or labor standards, see also: and Sachverständigenrat für Umweltfragen (German Advisory Council on the Environment) (2021), Nationaler Wasserstoffrat (2021), Heinemann et al. (2021), Piria et al. (2021).

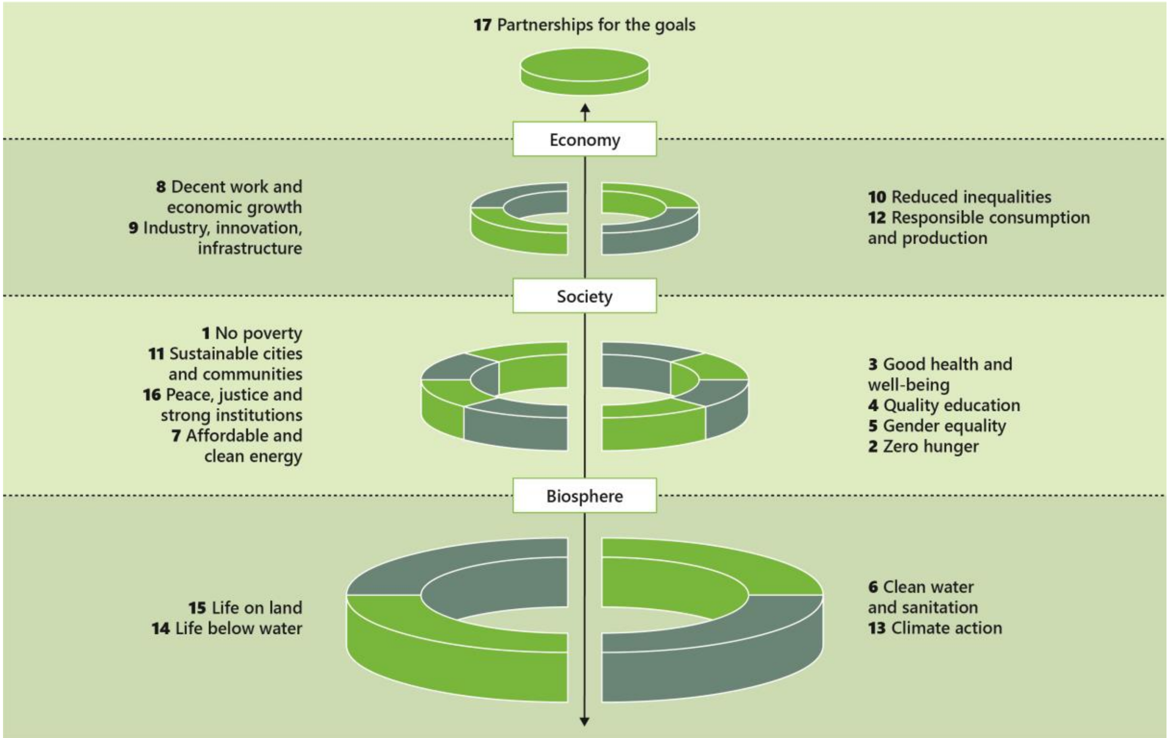
In some cases, other criteria are already being taken into account (see, for example, German Energy Agency/World Energy Council – Germany (2022)). The discussion on these criteria is currently (02/2022) well underway, with new contributions on the subject being published almost monthly from the scientific and political communities. The issue of water sourcing, for example, is taken into

1 See https://hypat.de/hypat-en/.https://hypat.de/hypat/

account in atmosfair's seal of approval for the production of CO_2-neutral kerosene (atmosfair 2021). This also includes criteria concerning human rights and the CO_2 sources for the production process.

In addition to energy sources, HYPAT also considers other criteria, such as water demand, land use, CO_2 sources, and social concerns along the lines of the Sustainable Development Goals (SDGs) of the 2030 Agenda (see Figure 1 from Brockhage et al. (2021)).

Figure 1: Integration of the 17 SDGs within the 3-pillar model of sustainability according to Brockhage et al. (2021)



In addition to the processes for the production of hydrogen and synthesis products, HYPAT also considers upstream and downstream processes. Upstream processes include, for example, the mining of raw materials, as well as the production and construction of the necessary infrastructure, such as electrolysis plants or tankers for transporting the products. Downstream processes include emissions from the use of the products and the dismantling of the production plants. In this way, HYPAT aims to consider the entire life cycle of hydrogen and synthesis products, see Figure 2 (based on "whole life cycle greenhouse gas (GHG) emissions" in Velazquez Abad et al. (2020)).

In other hydrogen atlases presented in the following, although sustainability criteria are reflected in socio-economic indicators, these indicators are not included in estimating the potential for hydrogen production.

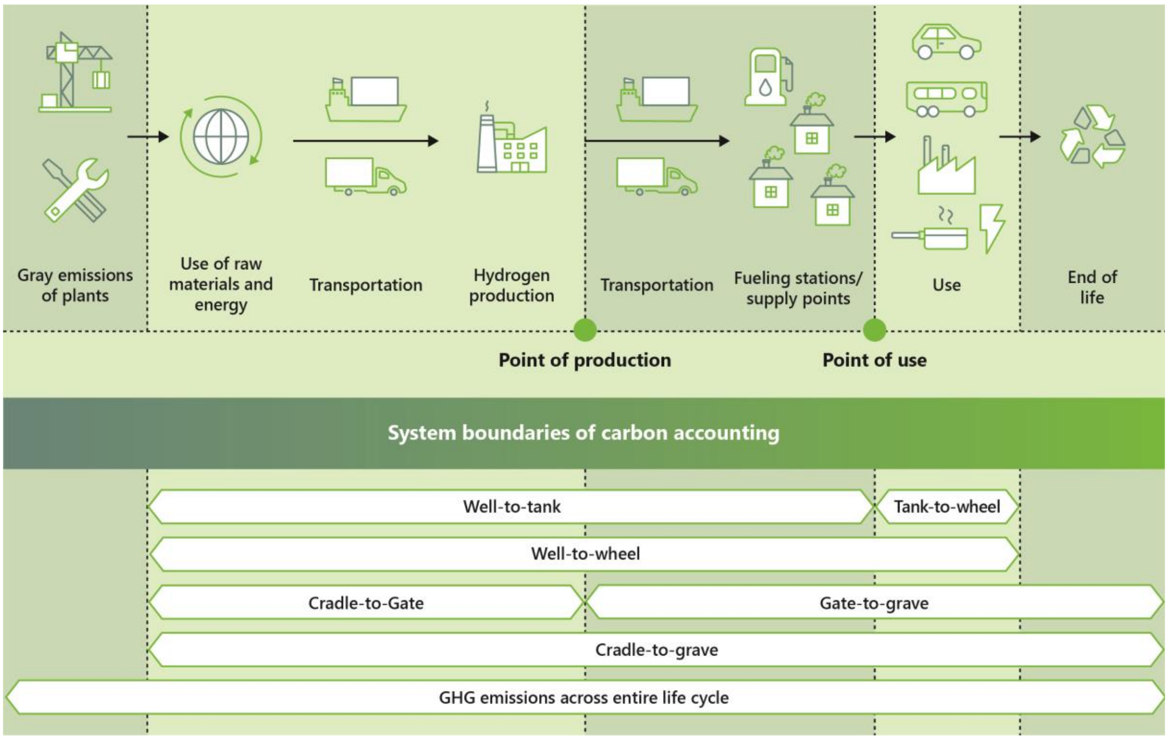
As part of the research project DeV-KopSys (Decarbonization Transport - Feedback Energy System, led by Fraunhofer IEE, funded by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection), a PtX atlas[2] [3] was created showing the simulation results for a non-European PtX volume scenario and country-specific location analyses for the production and costs of PtX products. A socio-economic analysis was carried out based on the method described on the corresponding website and the interim report provided. Various economic,

[2] PtX (Power-to-X) is the term used for the production of synthetic fuels and basic materials from electricity.

[3] See https://devkopsys.de/ptx-atlas/.

societal, political, technological and natural indicators were taken into account, as well as the proximity to Germany. For example, water availability, types of land use (the exclusion of nature reserves incl. buffer zones/spacing and forest land, agricultural land), macroeconomic indicators (incl. gross domestic product, investment climate, import and export of goods and services), societal aspects (incl. healthcare systems, educational qualifications, energy demand) and political aspects such as rule of law or legislation to reduce emissions are taken into account. This analysis is regarded as preliminary, as its results will not be taken into account when determining the suitability of possible PtX generation in a country.

Figure 2: Analysis scope for the production of hydrogen and synthesis products according to Velazquez Abad et al. (2020)



The project 'H2 Atlas of Africa' (BMBF, FZJ)[4] is researching the potentials of green hydrogen production in Africa. Its results for West Africa are already available via the online atlas tool. This atlas also considers additional indicators apart from water availability, such as; 1. social indicators (e.g., access to electricity, poverty, unemployment), 2. indicators relating to the energy system and political indicators (energy sector framework and policies indicator) and 3. indicators relating to social framework conditions (political and regulatory framework indicator). The five levels (from very high to very low) of these three indicators are represented by different colors in the atlas. Publication of the exact composition and weighting of these indicators is planned, but this information is not yet available. Therefore, it is unclear whether these three indicators are included as part of the Atlas's calculations of potentials. In addition, environmental, socio-political and physical constraints are used to exclude areas with regard to hydrogen production (e.g., nature reserves and settlement areas).

The BMBF funding guidelines[5] for international hydrogen projects stipulate that only projects that support the production of green hydrogen or the subsequent processing, storage, transport and

4 See https://www.h2atlas.de/en/.

5 See https://www.bmbf.de/bmbf/shareddocs/bekanntmachungen/de/2021/10/2021-10-04-Bekanntmachung-Wasserstoff.html.

integrated applications of hydrogen and its synthesis products are eligible for funding. As well as requirements for the procurement of renewable electricity (no incentives for generation plants using fossil fuels, promoting the energy transition, proof of electricity source or of power purchase agreements), there are also requirements for the procurement of carbon for the production of synthesis products and for the procurement of water. Carbon may be acquired by means of air capture or sequestration of unavoidable process-related industrial emissions, and biogenic CO_2 may also be used. The procurement of water must be sustainable, i.e., there must be no local shortage or increase in the price of water. In addition, the management of waste and pollutants must be outlined (ISO 14001) and a societal and environmental impact assessment must be carried out. Likewise, the international labor standards of the ILO (International Labor Organization) must be complied with at the very least.

The NHS currently reports the production of 55 TWh of gray hydrogen in Germany, and estimates a demand of about 90 to 110 TWh of hydrogen by 2030. Of this, 14 TWh is to be produced as green hydrogen in Germany, meaning that 5 GW of electrolysis capacity must be installed in Germany by 2030 including the necessary renewable energies.[6] [7] However, this also means that approx. 21 to 41 TWh (about 37%, corresponding to 0.6 to 1.2 million tons) at least of green hydrogen will have to be imported in 2030, or more if parts of the current fossil fuel production are to be substituted by green hydrogen. The challenges become clear if we consider that the "world's largest electrolysis plants" are currently being built on the scale of 10 to 24 MW, and that an expansion to the GW scale in the medium term appears to be difficult.[8] [9]

This document is structured as follows: In section 2, different ways of producing hydrogen are examined with regard to their sustainability. In section 3, criteria for energy sources (electricity, heat) are discussed. Relevant aspects of the additional processes required for the production of hydrogen and synthesis prodcuts are explained in section 4. In section 5, impacts on the environment, such as water requirements and land use, are discussed and, in section 6, criteria related to the societal impacts of the hydrogen economy are presented and discussed. Based on the examples of a few countries, section 7 illustrates the implications of considering nature reserves for the potential generation capacity of RE installations. Finally, section 8 summarizes the sustainability criteria relevant for the model calculations within HYPAT and section 9 presents a general summary.

6 Assumption in NHS: 4,000 full-load hours and an average efficiency of the electrolysis plants of 70 percent.

7 The German government's coalition agreement doubles this target to 10 GW by 2030, see https://www.spd.de/koalitionsvertrag2021/.

8 Shell/Wesseling 10 MW: https://www.shell.de/ueber-uns/projects-and-sites/shell-rheinland/aktuelles/shell-startet-europas-groesste-pem-wasserstoff-elektrolyse.html.

9 Linde/Leuna 24 MW: https://www.linde.com/news-media/press-releases/2021/linde-to-build-own-and-operate-world-s-largest-pem-electrolyzer-for-green-hydrogen.

2 Hydrogen production

There are numerous other technical possibilities for the production of hydrogen besides the conventional production of so-called gray hydrogen by means of natural gas steam reforming.

A study of the chemical industry suggests that only electrolysis for the production of green hydrogen and methane pyrolysis for the production of turquoise hydrogen are regarded as sufficiently mature and able to be carried out at industrial scale by the year 2050 (Bazzanella et al. 2019). Blue hydrogen (methane steam reforming with CCS technology) is also considered to have significant potential; the federal government discuss it in the NHS as a possible means of production, along with water electrolysis and turquoise hydrogen (Bundesministerium für Wirtschaft und Energie 2020). The European hydrogen strategy (European Commission 2020) also regards production pathways with CCS technology as important transitional solutions. However, due to the lack of sufficient long-term final storage capacity for the captured CO_2, there is still a significant hurdle to introducing this approach. GHG emissions in the upstream production chain during natural gas extraction and its transport are also not negligible and, depending on the country of origin, may continue to make a significant contribution (Deutscher Bundestag 2014).

There are a few pilot-scale plants for the production of hydrogen from biomass by means of reforming, gasification or pyrolysis. According to Bazzanella et al. (2019), biomass gasification should reach TRL 9 (Technology Readiness Level) in 2030. With regard to the biomass used, a distinction must be made between biomass grown directly for hydrogen production and biogenic residues. As in the case of biofuels, the cultivation of biomass for the sole production of hydrogen is in direct competition with food production. This could be problematic given the limited amount of land available for agriculture, a growing world population, and increasing biodiversity loss. Land use in future should therefore focus more on renaturation and less on its use for energy purposes. If biomass is to be used as an energy source (e.g., for electricity generation), the aim should be to only use those parts of the plant that cannot be used for food. For the reasons mentioned above, HYPAT does not consider biomass as a potential source for hydrogen.

In addition to the processes mentioned here, there are a number of other processes for generating hydrogen, such as (in-)direct (bio)photolysis or solar thermal water splitting. Some of these are being intensively researched, but will most likely only reach a rather low level of technological maturity (TRL < 6), even in the medium term (Bazzanella et al. 2019; Roeb et al. 2020).

In the context of this background paper, the focus is on producing hydrogen by using electrolysis to split water. The parameters for water electrolysis in terms of water and electricity consumption are shown in Table 7 in section 10.3.

3 Energy sources

As explained in section 2, the focus of the HYPAT research project is on the production of hydrogen by means of water electrolysis. In this context, the energy sources used to power the electrolysis process are an important aspect when assessing the sustainability of the hydrogen produced. A key criterion is that only production methods with low environmental and societal impacts should be used. The German government considers only renewable energy to be sustainable, not nuclear power or energy from fossil sources (Bundesministerium für Bildung und Forschung 2021; Bundesministerium für Wirtschaft und Klimaschutz 2022).

Nuclear power is considered too expensive for cost-efficient hydrogen production. Moreover, from a sustainability point of view, the far-reaching effects of possible nuclear accidents and the unsolved problem of radioactive waste disposal preclude it from use (Pistner et al. 2021; Schrems et al. 2020; Wealer et al. 2021).[10] Although, from an economic point of view, fossil fuels could be a large-scale production option in the short term, their GHG emissions and other related environmental impacts, some of which are severe, make them unsuitable for the sustainable production of hydrogen. Therefore, this production pathway is not considered further in this background paper.

In this and the following sections, different criteria regarding sustainable green hydrogen production are discussed. These are the result of discussions within HYPAT, which drew mainly on the following sources: Bundesministerium für Wirtschaft und Energie (2020), Heinemann et al. (2021), Nationaler Wasserstoffrat (National Hydrogen Council) (2021) and Sachverständigenrat für Umweltfragen (German Advisory Council on the Environment) (2021). The deliberations of the EU in the context of the amendment of RED II have also been taken into account.

3.1 Electricity generation

As explained in the previous section, only renewable energy sources can be considered for the generation of electricity for sustainable green hydrogen, which is also a NHS stipulation. Due to their global availability, the focus is generally on photovoltaics (PV) and wind power. However, HYPAT also investigates the use of hydropower[11], geothermal energy, solar thermal energy and ocean energy (tidal, wave energy, etc.).[12] In doing so, it must be ensured that

[10] In the current draft of the EU taxonomy (31.12.2021), nuclear power is classified as climate neutral; it is seen as a relevant technology to facilitate the transition to renewable energy due to its low CO_2 emissions, see https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2 . This assessment is controversial, see for example https://www.base.bund.de/SharedDocs/Stellungnahmen/BASE/DE/2022/base-fachstellungnahme-taxonomie.html.

[11] Excess production of existing large hydropower plants can be used in HYPAT calculations, but the sustainability of these plants must be verified when doing so.

[12] For model calculations in HYPAT, energy from biomass is not considered since producing biomass solely for hydrogen production is regarded as problematic because of the competition with food production. However, there may be individual regional cases where biomass can be a relevant energy source for hydrogen projects. For example, the expansion of sugar cane production in South Africa increases the amount of biomass which can be used as a waste material (Souza et al. 2016). Large amounts of biomass are also produced through forest management (thinning) when large reforestations are carried out as CO_2 sinks (Forster et al. 2021). In principle, it must be verified in each case that there is no local demand for electricity from this biomass.

1) the power plants used have a low negative impact on the environment. For example, the destruction of biotopes (large-scale hydropower plants[13]) or damage to marine mammals (offshore wind power plants established without noise protection measures) would not be acceptable,
2) the renewable electricity is generated in plants that have been built specifically for hydrogen production. This criterion of "additionality" is regarded as an important prerequisite for supporting the energy transition in partner countries and implementing hydrogen projects in a socially responsible manner.

Electricity is also required for processes other than water electrolysis. In the manufacture of synthesis products, for example, electricity is needed for air separation to produce the nitrogen for ammonia synthesis (cf. Table 8 in section 10.3). For ancillary services, such as heating and lighting, the electricity used should also come from renewable sources, however small these amounts of electricity may be compared to the main processes.

For an ecological but also economical and socially responsible implementation of large-scale hydrogen projects in the respective target countries, a balancing act is required between the maximum utilization of electrolysis capacities on the one hand, and the use of one hundred percent renewable energies as far as possible on the other hand. To meet these requirements, additional renewable energy capacity needs to be installed to supply future electrolysis and synthesis capacities. However, this does not mean that electrolysis plants with RE systems must be planned and built as stand-alone facilities without connection to the local power grid. Being connected to the grid also allows any additional RE capacity to be used in the connected power system (e.g., as balancing power). In the case of drawing electricity from the grid, power purchase agreements or guarantee of the origin of the electricity in accordance with the REDII draft are necessary. This means it is necessary to monitor the electricity fed into and purchased from the grid to ensure that only renewable energies are used for hydrogen production. Otherwise, the electrolyzers would have to be shut down. In accordance with the NHS, it must be ensured that the local energy transition is being supported by the production of hydrogen. Therefore, electrolyzers are not allowed to create incentives for the use of fossil sources.

Stand-alone concepts are conceivable in exceptional cases. However, these concepts require a well-developed regulation and (intermediate) storage concept (e.g., batteries) in order to be able to react to fluctuations in RE and hydrogen generation. Furthermore, it is advisable for electrolyzers to be operated in close geographical proximity to the point of production of renewable electricity in order to minimize any losses and additional grid congestion (Sachverständigenrat für Umweltfragen 2021). If there is a necessity or practical benefit to geographically separating renewable energy facilities and electrolyzers, the use of the existing power grid should be critically evaluated and the construction of dedicated transmission lines should be considered.

The use of grid-connected electrolyzers can be assessed from different perspectives. On the one hand, the focus may be on the producer's perspective and the aim to produce as much hydrogen as possible. On the other hand, system efficiency in relation to the power grid may be the main focus, which leads to a different mode of operation: the electrolyzer can be used here as a variable load that is switched on if there is a high RE power supply in the grid. This can prevent the curtailment of RE generation plants but can also adversely affect the economic efficiency of electrolyzers due to a potentially limited operating time. It has long been suspected that dynamic

[13] Common negative impacts of large hydropower plants are summarized in Moran et al. (2018): Drop in available freshwater, seasonal changes to runoff, loss of downstream freshwater habitats, flooding, coastal erosion due to sediment retention, and changes in salinity. Negative consequences for the ecosystem structure and composition include habitat fragmentation, loss of aquatic and terrestrial biodiversity and reduction of fish populations.

operation with frequent startups and shutdowns results in increased degradation, but this has not been verified in recent studies. More research is needed to further clarify the various degradation processes (Frensch et al. 2019; Siracusano et al. 2020).

There is another technical challenge for production routes that go beyond hydrogen production and aim to generate synthesis products. Here, the fluctuating supply of RE and variable hydrogen production contrast with the hydrogen demand of the synthesis processes, which is normally constant. This can be managed by separating hydrogen production and demand using an intermediate hydrogen storage facility (e.g., in suitable underground geological formations). Additional investments are required for this, however. It is therefore essential that the local RE supply is considered when designing and dimensioning all the components of the PtX system in a comprehensive, cost-optimal way.

In the model calculations in HYPAT, an optimization of the entire energy system is performed, with domestic needs taking priority over hydrogen production. As a result, the aspect of grid efficiency is always taken into account.

3.2 Heat

Some of the processes for producing hydrogen and synthesis products require heat as well as electricity. For example, solid oxide electrolysis requires steam. This technology operates at approx. 700-850 °C with current levels of overall efficiency of 45-55 %, however, this is expected to be increased to approx. 80 % through the use of external heat sources (Marscheider-Weidemann et al. 2021). The parameters mentioned in 3.1 for electricity also apply with regard to the use of heat.[14]

3.3 Promoting the energy transition

With all the criteria regarding energy sources, consideration must also be given to developing a hydrogen economy in alignment with the local energy transition. This has to be ensured particularly by the "additionality of RE plants".

According to NHS, it is important to ensure that local markets and local energy transitions are supported by the production of hydrogen. In particular, the climate-neutral and sustainable supply of energy, sufficient for all, must not be restricted by any such hydrogen project at any time. There must be no incentives to use fossil fuels, either directly or indirectly (Bundesministerium für Wirtschaft und Energie 2020). Indirect incentives would arise, for example, if shortfalls in the RE power supply for electrolysis led to the expansion of fossil fuel power plants. Another critical aspect results from using favorable RE locations exclusively to produce hydrogen for export, which would be needed in the long term to implement the local energy transition.

It is important to maximize the synergies between a national energy transition and hydrogen project cooperation. These synergies include, among others, cost reductions of RE plants due to the development of hydrogen production. Possible synergies should be identified based on a more detailed analysis of the energy systems involved.

[14] The proton exchange membrane electrolysis (PEM) electrolyzer technology and the alkaline electrolysis (AEL) technology do not require heat.

Assessing the progress of the energy transition[15] in a country is not easy. The following criteria could be used for this purpose:

a) The partner country has energy policy goals for transforming the national energy system in line with the 2030 Agenda and the Paris Agreement on climate change.

b) To achieve the energy policy goals, the partner country has an up-to-date energy strategy with appropriate intermediate goals, steps for implementation and means of monitoring.

c) The development of the GHG emissions of a country (total amount, only in the electricity sector, relative amount in tons of GHG per produced kWh of electricity or similar).[16]

d) How the capacity of fossil fuel power generation plants develops.[17] [18]

e) How the capacity of RE plants develops.[19]

f) If applicable, Nationally Determined Contributions (NDCs): these national climate protection targets are often difficult to compare between countries, as there are no binding requirements for their design (including for the production of hydrogen) (Heinemann et al. 2021).

g) The overall potential of renewable energy (e.g., Enertile Model[20]).

h) The projected electricity and energy demand.

It should be noted that many developing countries need to massively expand their energy systems in order to implement the 2030 Agenda. This is especially true for large parts of sub-Saharan Africa and parts of Southern Asia. According to the International Energy Agency (IEA), in 2019, approximately 580 million people in Africa and 155 million people in Asia were without reliable access to electricity.[21] These are also those countries whose per capita GHG emissions are low by international standards. In Ethiopia and Malawi, for example, per capita GHG emissions in 2018 were about 1.9 t GHG and 1.5 t GHG, respectively, and in relatively developed Ghana, about 0.7 t GHG. Industrialized nations have a much higher level; in 2018, for example, emissions were 17.7 t for the U.S., 20.6 t for Canada, 13.8 t for Russia, and 9.4 t GHG per capita for Germany.[22]

Particularly in the least developed countries, the energy transition means first and foremost providing all sections of the population with more reliable sources of energy in a way that is compatible with the climate and the environment, also in order to reduce the amount of energy that is often generated from firewood (resulting in deforestation).

[15] "Energy transition refers to the transformation and, if necessary, expansion of an energy system in line with the 2030 Agenda and the Paris Climate Agreement. It addresses a climate-neutral and sustainable supply of energy that is sufficient for all." Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (2021).

[16] However, a continuous expansion of renewable energy sources and the reduction of specific CO_2 emissions in the past, for example, would have to be sustained into the future.

[17] The share of coal in the electricity mix as an indicator of an energy transition is the subject of controversial scientific debate: If there is a large potential for CO_2 savings, there is also the possibility that the country in question will remain with this generation (lock-in) due to its investments in energy from fossil fuels.

[18] The construction of new fossil-fuel power plants is fundamentally critical (since power plants, once commissioned, are rarely decommissioned within the calculated operating time for political/economic reasons).

[19] However, if a country has only limited or expensive potentials of base-load capable renewables and does not take action in time for a climate-neutral full supply (e.g., through electricity storage, grid expansion), the construction of fossil power plants (or nuclear power plants) would at some point be almost unavoidable even in the case of a continuous expansion trend of renewables in the past.

[20] See https://www.enertile.eu/enertile-en/index.php.

[21] See https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity.

[22] See https://www.climatewatchdata.org/ghg-emissions.

4 Additional processes for the production of synthesis products and their transportation

GHG emissions can also be generated in other processes besides electricity and hydrogen production. Therefore, as mentioned in section 1, HYPAT looks at GHG emissions along the entire life cycle of hydrogen and its synthesis products. In HYPAT, the synthesis products ammonia (NH_3), methanol and Fischer-Tropsch hydrocarbons are examined. The latter were chosen following an internal consultation based on the assumption that they can be produced economically on a large scale in the next 10 years. Synthetic methane was excluded from further investigation, partly because of its potential for greenhouse gas emissions.

4.1 Processes for the production of synthesis products: Energy requirements and CO_2 utilization

In addition to hydrogen, other precursors such as carbon dioxide or nitrogen (N_2) are also required to produce synthesis products. Thus, stoichiometrically 0.8 t of N_2 is required per ton to produce NH_3. This is usually separated using an air separation unit. The actual reaction to produce NH_3 requires energy (is endothermic, i.e., the enthalpy of formation is positive, $\Delta H > 0$):

(1) $N_2 + 3\ H_2 \rightleftharpoons 2\ NH_3$ $\Delta H = +\ 92.1$ kJ/mol

The principal chemical reactions for methanol (CH_3OH), see (2) and (3), and for Fischer-Tropsch hydrocarbons (4) are exothermic (i.e., $\Delta H < 0$) and consequently release thermal energy. However, the steam produced is usually used to purify the synthesis product.

(2) $CO + 2\ H_2 \rightleftharpoons CH_3OH$ $\Delta H = -\ 90.8$ kJ/mol
(3) $CO_2 + 3\ H_2 \rightleftharpoons CH_3OH + H_2O$ $\Delta H = -\ 49.6$ kJ/mol
(4) $n\ CO + 2n\ H_2 \rightleftharpoons (CH_2)_n + n\ H_2O$ $\Delta H = -\ 158$ kJ/mol

It is possible to synthesize methanol directly from CO_2, whereas CO is required as a reactant for the production of Fischer-Tropsch synthesis products.

Nowadays, CO is generally obtained from fossil sources (5). This is of course not possible for sustainable synthesis products. Theoretically, Fischer-Tropsch syntheses can also be operated with CO_2 and H_2 as inputs, where the necessary CO is obtained from CO_2 by a reverse water-gas shift (RWGS) reaction (6).

(5) $CO_2 + C \rightleftharpoons 2\ CO$ $\Delta H = +172.5$ kJ/mol
(6) $CO_2 + H_2 \rightleftharpoons CO + H_2O$ $\Delta H = +\ 41.2$ kJ/mol

However, the level of technology maturity (TRL) of RWGS is not yet sufficient for large-scale application. Nevertheless, Fischer-Tropsch products such as synthetic diesel or synthetic kerosene are of great economic and political interest because they can supply existing infrastructure and applications, some of which would also be difficult to electrify. Therefore, Fischer-Tropsch synthesis is also examined in HYPAT. For the initial market ramp-up of the syntheses, limited CO sources can also be used for a transitional period. In the long term, it may be technically feasible to achieve Fischer-Tropsch synthesis on a large scale based on CO_2. This can be achieved by improvements to the aforementioned reverse water-gas shift reaction or by further development of co-electrolysis and high-temperature electrolyzers.

4.2 Carbon sources for the production of synthesis products

According to the SRU (German Advisory Council on the Environment) (Sachverständigenrat für Umweltfragen 2021), synthetic products can only be considered "green" if the CO_2 is extracted from ambient air by means of DAC (Direct Air Capture) or from sustainable biomass. This is intended to achieve the sustainability goal of a closed carbon cycle. However, in the REDII draft, all sources of carbon are allowed as long as the use of carbon does not entail an "additional operation" in the fossil source process (so-called "non-elastic" C source).

If the synthesis product derived by means of DAC is used as a fuel, only CO_2 is released, which was already part of the atmosphere. However, energy, raw materials, land and water are needed along the entire production chain of synthesis products. This leads to varying levels of CO_2 and other GHG emissions, depending on the use of fossil fuels. This also applies to the operation of DAC plants. [23] The use of biomass to produce large amounts of renewable CO_2 as well as its use to produce hydrogen must be weighed up carefully, as sustainable biomass is limited (see also section 2).

4.3 Transport emissions

Another important aspect is the GHG emissions generated during the transportation of hydrogen and its synthesis products. A sample listing of GHG emissions for various transportation options can be found in Table 9 in section 10.3.

The transportation of hydrogen and synthesis products by ocean-going vessels will play an important role. These are currently powered primarily by heavy fuel oil containing sulfur and this would significantly increase the carbon footprint of hydrogen and its synthesis products, which have very low GHG emissions during production.

Alternative propulsion systems that use methanol[24], hydrogen[25] or ammonia[26] as fuel are still the subject of research and development and have so far only been tested in a few pilot projects.

In road-based freight transport, there are pilot projects featuring e-trucks (trolley trucks[27], trucks with fuel cell drive[28], battery electric trucks[29]). However, in the coming years, it can still be assumed that transport will be predominantly by trucks with combustion engines using conventional fuel. Consequently, any GHG emissions resulting from this should be taken into account and attributed to the hydrogen or the synthesis products.

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[23] See https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal.

[24] For example, MAN with the ME-LGI series: since 2019, seven 50,000 DWT ships have been in use here. Also one of the largest car ferries in the world runs on 100% methanol:
https://www.methanex.com/about-methanol/methanol-marine-fuel
https://www.stenaline.de/supergreen/treibstoff-der-zukunft.

[25] For example, in 2014, Kawasaki HI submitted concept studies for two LH_2 carriers (180 & 11,000 t H2). The smaller of the two carriers is currently powered by diesel. The larger carrier is planned to be powered by a H_2 gas engine. However, this has not yet been implemented.

[26] For example, MAN has developed large fuel engines (ME-LGIP dual fuel engines), which previously ran on LPG, LNG, methanol, or ethane in initial operations. Now ammonia is following suit. In 2018, MAN indicated a development time of 2-3 years and a target of 50% engine efficiency.

[27] See, for example https://www.isi.fraunhofer.de/de/competence-center/energietechnologien-energiesysteme/projekte/bold.html.

[28] See, for example https://www.bmvi.de/SharedDocs/DE/Anlage/G/MKS/teilstudie-brennstoffzellen-lkw.pdf.

[29] See, for example https://www.srf.ch/news/schweiz/elektro-mobilitaet-riesige-batterie-fuer-erste-e-40-toenner.

In the long term, transportation by pipeline would also have to be designed in such a way that no GHG emissions are released, for example by using natural gas at the compressor stations. This also applies to trucks and the loading and unloading processes at storage tanks.

5 Other environmental impacts

5.1 Demand for water

Water is an important input for electrolysis in addition to electricity. Stoichiometrically, 8.9 t H_2O are needed to produce 1 t H_2 (Bazzanella et al. 2019; Geres et al. 2019). Research is still being conducted on electrolyzers that can use seawater.[30] So far, the only systems that can be used are those that require fresh water as an input. Either freshwater sources (rivers, lakes, groundwater) are used for this purpose or seawater desalination plants are used.

Some RE technologies also require water. For example, CSP (Concentrated Solar Power) currently requires a total of about 4.3 m^3 H_2O/MWh for mirror cleaning, thermodynamic cycling and cooling. If dry cooling systems are used, however, this can be reduced by up to 90%. Photovoltaic systems also require fresh water for cleaning the solar panels, whereby the demand depends strongly on the size of the system. The data in the literature vary greatly, the median value is 0.022 m^3 H_2O/MWh (Zelt et al. 2021).

There should be no negative effects on local water supply (e.g., shortage, price increase) and no conflicts of use as a result of the hydrogen production chain. The demand along the entire value chain should therefore be taken into account.

There are a large number of indicators for assessing water availability. The World Resources Institute (WRI) already provides 13 indicators for the topic of "Water Risk" (Hofste et al. 2019).[31] In addition, there are other indicators, e.g., from the Food and Agriculture Organization of the United Nations (FAO)[32] or from the United Nations SDG 6 Data Portal.[33]

In the case of groundwater and surface water, scarcity and seasonality must always be taken into account. Here, there can be large regional differences within a country, which is why a site assessment should be carried out. For example, the WRI indicators "Baseline Water Stress," which indicates the ratio of withdrawals to available renewable surface and groundwater, "Drought Risk," which indicates the risk of drought, or "Seasonal Variability," which indicates the variability of water availability within a year, can be used for site assessment and site selection. The data are available broken down into geographical regions.[31]

Depending on the location, the use of drinking water from existing drinking water networks can be unproblematic or very critical. If there is already a water shortage in an area, this should not be exacerbated by the additional demand of electrolyzers. To assess a country's water supply, the Falkenmark indicator or "Water Stress Index" (WSI) (Damkjaer et al. 2017) is widespread, but not uncontroversial (White 2012).[34] It defines the following thresholds:

- Water scarcity:
  Water resources < 1,700 m^3 per person and year

[30] See, e.g., https://www.nature.com/articles/s41560-020-0550-8.

[31] See https://www.wri.org/data/aqueduct-water-risk-atlas and https://www.wri.org/applications/aqueduct/country-rankings/.

[32] See http://www.fao.org/aquastat/statistics/query/index.html?lang=en.

[33] See https://www.sdg6data.org/ , Indicator «Renewable water resources > Total».

[34] The Falkenmark indicator measures water scarcity only at country level and thus neglects regional differences in water availability. Water demand or use also differs from country to country and/or from region to region (urban agglomerations, areas of agricultural use, areas with low population density, etc.). These differences can also not be taken into account using this indicator. (White 2012).

- Water stress:
  Water resources < 1,000 m^3 per person and year
- Absolute water stress:
  Water resources < 500 m^3 per person and year

If hydrogen generation plants (or associated plants that need water, such as PV or CSP) are constructed in areas with water scarcity, extra seawater desalination plants should be constructed to meet their demand. Existing plants should not be used, since these are needed to supply local drinking water and the water required for hydrogen production could reduce supply and increase prices. If they are not used exclusively for hydrogen production, newly constructed seawater desalination plants could also improve the local drinking water supply and thus contribute to the acceptance of hydrogen projects.[35]

In HYPAT, the requirements within countries for hydrogen projects are examined in an initial general country analysis. Water availability is also taken into account. Countries that are facing water scarcity according to the Falkenmark indicator, have a drought risk according to WRI (Drought Risk indicator > 60%) and are landlocked are excluded from the HYPAT analyses.

A more detailed investigation is carried out in the modeling. Water availability is not only considered at country level, but also in a regional breakdown. The WRI indicator "Baseline Water Stress" mentioned above is used for this purpose. In areas where there is a more than 40% risk of water stress according to this indicator (risk categories "high" and "very high"), the water demand (similar to atmosfair (2021)) for hydrogen production must be covered by seawater desalination plants.

5.2 Environmental impacts of seawater desalination plants

The additional energy demand generated by seawater desalination must also be taken into account (cf. Table 9 in section 10.3), which, like the energy demand for the electrolyzers, should be covered by renewable energies. Furthermore, there can be negative environmental impacts on coastal marine ecosystems. Marine organisms (fish eggs, fish larvae, algal spores, phytoplankton, zooplankton, etc.) are drawn in with the seawater used, which can affect ecosystem populations. In addition to the high salinity, the resulting wastewater also contains auxiliary substances such as biocides, anti-lime agents and anti-foaming agents, as well as metals from corrosion processes. It has a higher temperature and density than seawater (risk of stratification, chemocline) and can damage local marine ecosystems (Lattemann 2010).

The detrimental effects of brine have been investigated in various studies and can still occur up to 4 km away from the point of discharge (Roberts et al. 2010). Therefore, a minimum distance of 4 km from marine protected areas should be maintained.

Currently, international standards for the site selection of seawater desalination plants and the handling of wastewater are still lacking, cf. Heinemann et al. (2021). However, the environmental impacts of such a facility should be assessed on a site-specific basis prior to construction. There are some suggestions for this (Lattemann 2010; UNEP/MAP/MED POL 2003). For example, desalination plants should be located along coastlines with strong currents and sufficient water circulation to ensure that the injected brine can be well diluted and distributed to mitigate any adverse impacts. Another recommendation is to give preference to sites located close to energy generation facilities and consumption points in order to minimize the impact of the transportation infrastructure. An

[35] atmosfair (2021) demands that, in the case of a planned site with a water shortage of more than 40 %, the production water must be obtained, for example, via seawater desalination. In the case of a water shortage of over 60 %, an appropriate amount of desalinated water must be produced for the public at socially acceptable prices in addition to the production water.

overview of the possible environmental impacts and recommendations to avoid them is given in section 10.4.

5.3 Land requirements and land use

Like the need for water, the need for land, especially for RE plants or for DAC plants, can also lead to competition for its use. Most importantly, land that can be used for agriculture should not be converted, and cultural sites should not be encroached upon. In addition, hydroelectric power plants and their related facilities should not be built on land that is needed for the local energy transition, e.g., for the expansion of wind and PV plants.

However, it is possible to enable combined use, for example through the use of agro-photovoltaics. This involves using the land underneath PV systems to cultivate agricultural products. A list of the land needed for various systems in the value chain of hydrogen and synthesis products is given as an example in Table 10 in section 10.3.

In order to avoid any adverse effects on specific terrestrial and aquatic protected areas, they should in principle be excluded from use for power generation, hydrogen and PtX infrastructure, see for example Bundesamt für Naturschutz (2020). The IUCN protected area classification can be used for this purpose (International Union for Conservation of Nature and Natural Resources). Not only areas with such a protected status, but also areas with high biodiversity (e.g., primary forests) or high carbon content (e.g., wetlands, peatlands) should be excluded as sites for electrolyzers and their related facilities (seawater desalination, processing plants for synthesis products, DACs, etc.)[36]

Furthermore, it is expected that more areas within the EU will be designated as (strictly) protected areas in the coming years. These include, above all, areas with or with the potential for very high biodiversity. Currently, 26% of EU land and 11% of EU marine areas have a protected area status, and 3% of EU land and less than 1% of EU marine areas are strictly protected. However, according to the EU Biodiversity Strategy for 2030, at least 30% of EU land and 30% of EU marine areas should be protected. One third of these protected areas should be strictly protected, i.e., 10% each of EU land and marine areas, including all remaining primary and virgin forests in the EU.[37]

5.4 Particulate matter, eutrophication, acidification due to ammonia as a synthesis product

In HYPAT, ammonia is considered as a synthesis product of hydrogen and is being discussed in general for various applications, as it has a high techno-economic potential. However, ammonia is by no means unproblematic: not only is it toxic, it is also an air pollutant that forms secondary inorganic aerosols (SIA) and is a source of particulate matter, therefore contributing to the tens of thousands of deaths per year in Germany caused by particulate matter.[38]

Although ammonia has no greenhouse gas potential like methane, it has a high eutrophication and acidification potential. The German reduction target for ammonia emissions is 29% for 2030 in

[36] Also see, for example, «Key Biodiversity Areas» http://keybiodiversityareas.org/kba-data or «Critical Habitats» https://data.unep-wcmc.org/datasets/44 according to IFC PS6 (International Finance Corporation`s Performance Standard, Definition, see https://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/sustainability-at-ifc/policies-standards/performance-standards/ps6).

[37] See EU Biodiversity Strategy for 2030: https://eur-lex.europa.eu/resource.html?uri=cellar:a3c806a6-9ab3-11ea-9d2d-01aa75ed71a1.0002.02/DOC_1&format=PDF.

[38] See for example https://publications.iass-potsdam.de/rest/items/item_1602896_5/component/file_1602901/content.

comparison to 2005.[39] Currently, emissions are mainly from agriculture and have only decreased slightly, so additional industrial ammonia emissions from leakage or unburned gases must be viewed as highly critical. Therefore, HYPAT focuses on possible leakages and emissions in the transportation and further processing chain of ammonia. The impacts on the environment will be examined in more detail in the LCA (life cycle assessment) work within the scope of the HYPAT project.

[39] See NEC-Guidelines https://www.umweltbundesamt.de/sites/default/files/medien/1410/dokumente/luftreinhalteprogramm_bericht_bf.pdf.

6 Social impacts

6.1 Social criteria

Negative impacts on the local population should be avoided along the entire production chain of hydrogen and synthesis products, such as those related to the supply of energy and drinking water, food situation and health. This is closely related to the explanations in section 3 on energy supply and those in section 5 concerning the use of water and land. As well as avoiding negative impacts, possible synergies should be fostered. For instance, desalination plants can contribute to improving water supply in general, or expanding the local power grid can stabilize the availability of electricity for residential areas connected to it.

Furthermore, fundamental guidelines such as the core labor standards of the International Labour Organization (ILO) on the abolition of child labor, the elimination of forced labor and of discrimination in employment and occupation, the freedom of association and the recognition of the right to collective bargaining[40] should be complied with along the entire value chain. Equally fundamental are the UN Guiding Principles on Business and Human Rights, which include guidelines to protect human rights for governments and for companies.[41]

This should also consider the ILO Convention 169 on the protection of the rights of indigenous peoples.[42] To date, this has only been ratified by 24 nations (as of 18.02.2022), but these include Germany since 15.04.2021. Articles 6 and 7 of the convention are of particular relevance. They define consultation and participation procedures intended to ensure that indigenous peoples are heard and involved in projects that affect them.

In addition, the development of a hydrogen economy should create local value added and as many jobs as possible that are filled with skilled local workers. Knowledge transfer should also take place and the further training and education of the local workforce, so that long-term sustainable development in climate and environmental protection takes place in the exporting countries. However, it must also be ensured that local content clauses are not in conflict with free trade rules.

Foreign investors buying up valuable land must be ruled out. According to the SRU (Sachverständigenrat für Umweltfragen 2021), the risk of "land grabbing" exists primarily in countries with weak institutions, where the rights of the local population to land and water are not formalized or are not enforced. In some countries, this also affects indigenous peoples.

6.2 Discussion: Sustainability requirements and acceptance

Acceptance in the countries producing and consuming the hydrogen must be considered in all the requirements regarding sustainability criteria.

In principle, the more consistently sustainability criteria are taken into account, the more complex and costly the production and export of hydrogen and synthesis products will be. Such requirements must be factored into the costs of green and sustainable hydrogen and synthesis products by potential investors. The resulting higher prices would increase the financial flows to the

[40] See fundamental principles ILO and their elaboration in eight conventions («Core labor standards»): https://www.ilo.org/berlin/arbeits-und-standards/kernarbeitsnormen/lang--de/index.htm.

[41] See https://www.business-humanrights.org/en/big-issues/un-guiding-principles-on-business-human-rights/text-of-the-guiding-principles/.

[42] See https://www.ilo.org/wcmsp5/groups/public/---ed_norm/---normes/documents/normativeinstrument/wcms_c169_de.htm.

partner countries – which could also be used to foster local energy transitions. In any case, importing countries must be willing to pay fair prices.

On the other hand, Germany and Europe are not the only potential partners for countries exporting hydrogen, so that strict stipulations for sustainability standards could hinder cooperation projects. For example, China's influence has grown over the past few years, especially in Africa (Hansen et al. 2018), and areas of East Africa (as well as Asia and the Middle East) are part of the "New Silk Road". It is possible that China's interest in imported green hydrogen will grow, and that it will have less stringent demands, e.g., with regard to reliable guarantees of origin for the electricity used in production.

It is not desirable for capital-intensive enclaves to be formed without significant spillover effects to the local economies, i.e., that international investors construct large hydrogen production facilities using technology and know-how from abroad that create hardly any local jobs or jobs that are only filled with specialized foreign workers. In this case, there would be very few synergies with local transformation processes (such as coupling effects with existing RE generation plants). Even if national elites might be interested in such development models, acceptance among the population would remain limited. The profit margins are not large for financing development projects. Various studies currently indicate that there are no clear cost advantages to producing hydrogen in Africa compared to production in Germany (Merten et al. 2021).

To achieve a win-win situation, it must be clear and certain to what extent potential partner countries can benefit from hydrogen cooperation, and the impact such cooperation has on local value creation. Up to a certain point, these win-win situations can be achieved by subsidies, but simply exporting hydrogen is not enough. Even if attractive prices were paid for exported hydrogen, there would still be risks in the exporting countries such as "Dutch Disease" [43] or "rentier economy"[44].

These and other acceptance problems on both the demand and the supply side are addressed in more depth in other parts of the HYPAT research project. Table 1 shows the different viewpoints of importing and exporting countries concerning hydrogen cooperation and possible areas of conflict.

Within an energy and hydrogen partnership, importing industrial nations can use many types of cooperation instruments to make entering the hydrogen economy attractive to developing countries. This can also prevent having to pay excessive prices over and above those that are fair. Developing countries should be put in a position where they can use hydrogen technologies to overcome domestic problems as well. Germany has a broad and recognized portfolio of instruments to strengthen knowledge capacities in developing countries, ranging from supporting vocational training and sending out skilled workers as part of development collaborations through to science cooperation in the context of scientific and technological cooperation.

[43] «Dutch Disease» is the term used to describe the effect that strong growth in one raw material sector can have negative impacts on other sectors, such as manufacturing, for instance, because of substantial appreciation of the national currency as the result of a raw material boom.

[44] Since the 1970s, economics has used the term "rentier economy" to describe the structural deficits in resource-rich countries and their exploitation by domestic elites. The structural deficits concern the economic (low competitiveness of industrial sectors) and political (weak institutions, clientelism) dimensions of development (analogous to the example of many oil-exporting countries).

Table 1: Differences in the perspectives of importing/exporting countries

Interests of an importing country	Interests of an exporting country
• Specialized workers needed for smooth construction and operation of plants.	• Creation of local jobs. • Education and specialization of domestic workforce.
• Population and government should share basic acceptance of the local energy transition (in the exporting country). • Increasing local acceptance is targeted, e.g., through creating employment and sustainable investments.	• Creation of employment and income opportunities, e.g., also through capital-intensive large-scale projects, which are closely linked with the local economy. • Acceptance in the exporting country through integration in the global H_2 economy. • Avoidance of "White Elephants" (investment projects with negative social surplus), as they question the ability to govern (and can lead to or enhance social tensions).
• If strict sustainability criteria in exporting countries cannot be implemented immediately (acceptance, costs), then as a compromise, e.g., transitional periods with blue H_2. For Germany as an importing country, the funding guidelines exclude gray, red, blue and turquoise hydrogen in international cooperation projects.[45]	• Possible lowering of political interest in and social acceptance of H_2 economy if strict sustainability standards are formulated, .e.g., when climate justice is questioned (if the exporting country has low CO_2 emissions, lack of understanding for demands for high percentage GHG savings by importing country).[46]
• Germany: NHS as the framework for sustainability standards.	• Sustainability standards geared toward importing country with the "weakest" standards (e.g., reliable guarantee of origin certificates, additionality of RE installations)
• Import country: affordable, sustainable H_2 to manufacture its industrial products. • Helping to prevent national economic crises like "Dutch Disease" in exporting countries is also in the importing country's own interests (Hanisch et al. 2016).	• Strong self-interest of exporting countries necessary, so that they provide parts of their renewable energy resources to produce H_2 for Germany and Europe and are involved in co-designing relevant investment projects. • Economic risks like "Dutch Disease" and "rentier economy" are possible, even if attractive prices are paid for exported H_2. • Industry in the exporting country would have to be co-developed at the same rate as the H_2 economy
• Avoidance of "green" competing products from exporting countries.	• Industry in the exporting country should also produce higher value products based on green H_2.

[45] See https://www.bmbf.de/bmbf/shareddocs/bekanntmachungen/de/2021/10/2021-10-04-Bekanntmachung-Wasserstoff.html.

[46] For example, Germany emits about 8 t CO_2 per person per year; many countries in sub-Saharan Africa < 1 t CO_2 per person per year (see https://www.climatewatchdata.org/ghg-emissions). «Non-Annex I Countries» of the UNFCCC (United Nations Framework Convention on Climate Change) are not obligated to rapidly reduce their GHG emissions.

7 Example of calculating the influence of protected areas on RE potentials

The potentials for hydrogen production in HYPAT decrease if sustainability criteria are taken into account. In order to be able to classify the magnitude of this decrease and to illustrate the procedure for doing so in the HYPAT project, the example of protected areas is presented below.

When calculating RE potentials in HYPAT, areas are classified as certain land-use types and assigned land-use factors. For instance, settlement areas are not usable for RE technologies due to the selected land-use factors. This also applies to protected areas: Excluding the IUCN protected area categories Ia, Ib and II, see also section 5.3, also reduces the area that can be used for renewable energies. For the total RE potential, distances to settlement areas, roads, railway tracks and airports are also taken into account, which leads to the exclusion of additional areas.

To illustrate the impact of protected areas on potential RE generation capacities, several countries are considered here as examples. The calculation results are shown for ground-mounted PV, CSP and onshore wind. The impact of protected areas on these three types of generation is very similar, however, which is why the results are illustrated using ground-mounted PV.

Figure 3 shows the potential PV capacity in 2050 in MW/km^2 for Namibia. The left-hand map shows the potential capacity of ground-mounted PV installations without excluding protected areas, and the right-hand map the result of excluding the IUCN protected area categories. Table 2 lists the RE potentials for PV, CSP and onshore wind in TWh for both calculations. This example clearly shows that considering protected areas which cover large areas of land significantly reduces the potential generation capacities for PV as well as CSP and onshore wind energy (by 22 % for PV and CSP and 17 % for onshore wind energy).

Figure 3: Potential PV capacity (in MW/km^2) in Namibia in 2050 without excluding protected areas (left) and excluding protected areas up to IUCN category II (right)

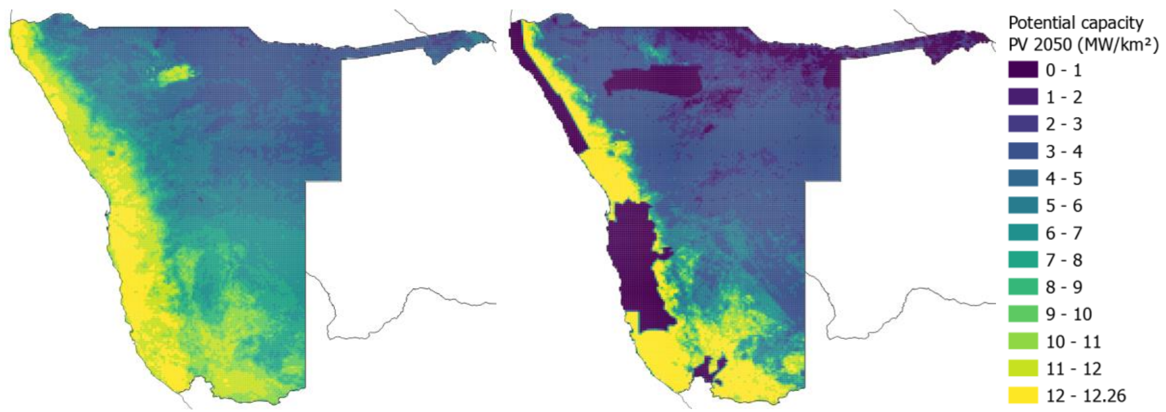

Table 2: Calculated RE potentials in Namibia (preliminary)

RE technology	Without excluding protected areas	Excluding protected areas	Effect of protected areas on RE potentials
Ground-mounted PV	8,490 TWh	6,660 TWh	-22 %
CSP	11,180 TWh	8,770 TWh	-22 %
Onshore wind energy	1,870 TWh	1,550 TWh	-17 %

Table 3 shows the effect of considering protected areas on PV potentials in other countries (selected examples). While the effect in Botswana is similar to that in Namibia with a reduction by 21 %, excluding protected areas in Algeria and Germany has a much lower impact on energy generation using PV. A detailed description of the RE potentials of different generation technologies and all the factors considered can be found in Franke et al. (2022 - in preparation).

Table 3: Effect of excluding protected areas on PV potentials

Country	Effect of protected areas on RE potentials
Namibia	-22 %
Algeria	-5 %
Botswana	-21 %
Germany	-1 %
Mongolia	-15 %

8 Key criteria for the modeling in HYPAT

The following criteria result from the aspects discussed in this paper for hydrogen and PtX value chains in HYPAT. These criteria are summarized in the following checklist and refer to the sections indicated.

Table 4: Criteria for HYPAT work packages and modeling of green and sustainable hydrogen

2. Hydrogen production	
Only electrolysis, no other production process	✓
3. Energy sources	
Only RE plants installed additionally for hydrogen production, no bioenergy, no non-sustainable large hydropower	✓
RE plants able to provide baseload power (hydropower, geothermal) only if these are not needed for domestic energy transition	✓
Consideration of the entire energy system, hydrogen production integrated into entire energy system	✓
Generally, electrolysis plants connected to power grid	✓
Monitoring of RE generation and RE supply if electrolysis plants connected to the power grid	✓
If no connection to the power grid (stand-alone solution): well-developed control and (intermediate) storage concept is required (fluctuations in RE and hydrogen production)	✓
4. Other process to produce synthesis products	
Electricity for auxiliary processes (synthesis, producing N_2, CO_2, buildings, desalination) also from RE sources as specified in 3.	✓
CO_2 from DAC or point sources: according to draft of REDII, all carbon sources are allowed as long as the carbon use does not initiate “additional operation” of fossil source process (so-called non-elastic carbon source)	✓
5. Additional environmental impacts	
Exclusion of countries if: 1) Water scarcity measured using the Falkenmark indicator (available water < 1,700 m^3/(person*year)), 2) Drought risk according to WRI (Indicator “Drought Risk” > 60 %) and 3) landlocked.	✓
Regional analysis in modeling using WRI’s “Baseline Water Stress“ indicator: Water required for hydrogen production must be provided by desalination plants if BWS ≥ 40 %	✓
Min. 4 km distance from marine protected areas (Roberts et al. 2010)	✓
No protected areas Ia, Ib or II according to IUCN for installations	✓
In general: no negative environmental impacts such as, e.g., destruction of biotopes, species or damage to marine life	✓

9 Summary

This working paper takes up the existing debate on the sustainability of hydrogen and synthesis products and creates a basis for a common understanding of this topic within the HYPAT research project. This project aims to create a global atlas of hydrogen potential by identifying possible countries for producing hydrogen and synthesis products based on it, and countries importing these products. As the result of literature reviews, participation in workshops, interviews and above all discussions among the institutions participating in HYPAT work package 3.2.1, criteria have been developed to assess the sustainability of hydrogen and synthesis products for export.

From the viewpoint of sustainability, electrolysis is seen as the only option to produce green and sustainable hydrogen in the medium and long term (section 2). According to Germany's National Hydrogen Strategy (NHS), the electricity used for this must come from renewable energy (RE) sources, and the use of fossil fuels or nuclear power must be ruled out (section 3). Additional RE plants should be constructed for the production of hydrogen (as close as possible to the point of hydrogen production both geographically and in terms of the time). In principle, according to the NHS, the energy transition of the country producing hydrogen must be supported. This includes the local population's access to electricity supply in the producing countries.

Greenhouse gas (GHG) emissions should be taken into account and reduced along the entire life cycle of hydrogen and synthesis products (section 4). This includes auxiliary processes, CO_2 extraction processes, and transportation.

Section 5 identified the water and land required for hydrogen production as additional relevant environmental impacts. There should be plenty of water available in locations producing hydrogen; no plants should be constructed in designated protected areas. The conservation of biodiversity should also be observed. Of the synthesis products, ammonia, in particular, is problematic from an environmental viewpoint due to its high potential for eutrophication and acidification as well as being a source of particulate matter. For these reasons, and against the backdrop of existing international reduction agreements, the use of ammonia should be reviewed in a comprehensive environmental assessment.

Under social aspects (section 6), it is emphasized that there should not be any negative impacts on the population, e.g., with regard to the supply of energy and drinking water, food situation and health. A win-win situation should be achieved, which balances the conflicting priorities of exporting and importing countries. Skilled jobs should be created in the exporting countries in compliance with the core labor standards of the International Labour Organization ILO and the level of acceptance in exporting countries must remain high in the face of the strict guarantees of sustainable green hydrogen demanded by importing countries.

References

atmosfair (Hrsg.) (2021): atmosfair fairfuel - Kriterienkatalog. Gütesiegel für grünes, synthetisches Kerosin.

Bazzanella, A.; Geres, R.; Kohn, A.; Lenz, S.; Ausfelder, F.; Möller, A. (2019): Roadmap Chemie 2050. Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland.

Brockhage, F.; Lüsse, M.; Pietzner, V.; Beeken, M. (2021): Nachhaltigkeit in Gesellschaft, Wissenschaft, Politik und Schule. In: Chemie in unserer Zeit, 55 (2), S. 125–129.

Bundesamt für Naturschutz (Hrsg.) (2020): Erneuerbare Energien Report. Die Energiewende naturverträglich gestalten. Bonn, Bad Godesberg.

Bundesministerium für Bildung und Forschung (2021): Bekanntmachung der Förderrichtlinie für internationale Wasserstoffprojekte im Rahmen der Nationalen Wasserstoffstrategie. Online verfügbar unter https://www.bmbf.de/bmbf/shareddocs/bekanntmachungen/de/2021/10/2021-10-04-Bekanntmachung-Wasserstoff.html, zuletzt geprüft am 15.02.2022.

Bundesministerium für Wirtschaft und Energie (Hrsg.) (2020): Die Nationale Wasserstoffstrategie.

Bundesministerium für Wirtschaft und Klimaschutz (Hrsg.) (2022). *EU-Taxonomie: Statement von Bundesminister Habeck*. Online verfügbar unter https://www.bmwi.de/Redaktion/DE/Meldung/2022/20220101-atomenergie-als-nachhaltig-zu-labeln-ist-falsch.html.

Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (Hrsg.) (2021): BMZ-Kernthemenstrategie. Verantwortung für unseren Planeten - Klima und Energie. BMZ.

China Hydrogen Alliance (2020): Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen. Online verfügbar unter http://www.fuelcellchina.com/cnt_143.html, zuletzt geprüft am 04.03.2022.

Damkjaer, S.; Taylor, R. (2017): The measurement of water scarcity: Defining a meaningful indicator. In: Ambio, 46, S. 513–531.

Deutscher Bundestag (2014): Erdgasverluste bei der Erdgasförderung. Daten zu den USA, Russland und Europa. Online verfügbar unter https://www.bundestag.de/resource/blob/416930/808896c1723c80eba8d9621ad2a7e49a/wd-8-095-14-pdf-data.pdf, zuletzt geprüft am 02.03.2022.

European Commission (Hrsg.) (2020): Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A hydrogen strategy for a climate-neutral Europe. Brussels.

Forster, E. J.; Healey, J. R.; Dymond, C.; Styles, D. (2021): Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. In: Nature Communications, 12.

Frensch, S. H.; Fouda-Onana, F.; Serre, G.; Thoby, D.; Araya, S. S.; Kær, S. K. (2019): Influence of the operation mode on PEM water electrolysis degradation. In: International Journal of Hydrogen Energy, 44 (57), S. 29889–29898.

Geres, R.; Bazzanella, A.; Kohn, A.; Lenz, S.; Ausfelder, F.; Möller, A. (2019): Roadmap Chemie 2050. Auf dem Weg zu einer treibhausgasneutralen chemischen Industrie in Deutschland. DECHEMA e.V. /FUTURECamp Climate GmbH.

German Energy Agency/World Energy Council – Germany (Hrsg.) (2022): Global Harmonisation of Hydrogen Certification. Overview of global regulations and standards for renewable hydrogen. Berlin.

Hanisch, A.; Sattelberger, J. (2016): Rohstoffreichtum: Vom Fluch zum Segen.

Hansen, S.; Bauer, B.; Buitenhuis, A. (2018): Chinas Aufstieg. Mit Kapital, Kontrolle und Konfuzius. TAZ.

Heinemann, C.; Mendelevitch, R. (2021): Sustainability dimensions of imported hydrogen.

Hofste, R.; Kuzma, S.; Walker, S.; Sutanudjaja, E.; Bierkens, M., Kuijper, M., Sanchez, M., Van Beek, R.; Wada, Y.; Rodríguez, S.; Reig, P. (2019): Aqueduct 3.0: Updated Decision-Relevant Global Water Risk Indicators. Washington, DC: World Resource Institute.

International Union for Conservation of Nature and Natural Resources: Protected Area Categories. Online verfügbar unter https://www.iucn.org/theme/protected-areas/about/protected-area-categories, zuletzt geprüft am 11.10.2021.

Lattemann, S. (2010): Development of an environmental impact assessment and decision support system for seawater desalination plants. Doctoral thesis, Delft University of Technology (Hrsg.). Online verfügbar unter http://resolver.tudelft.nl/uuid:fe9c27c4-6329-4314-9ae3-5d2e5fc11e28, zuletzt geprüft am 30.08.2021.

Marscheider-Weidemann, F.; Langkau, S.; Baur, S.-J.; Billaud, M. (2021): Rohstoffe für Zukunftstechnologien 2021. Berlin.

Merten, F.; Scholz, A. (2021): Vor- und Nachteile von Wasserstoffimporten versus heimische Erzeugung: Teil 1: Kostenunterschiede, Realisierungsunsicherheiten und Reboundeffekte in Lieferländern. In: Energiewirtschaftliche Tagesfragen, 71 (1-2), S. 33–37.

Moran, E. F.; Lopez, M. C.; Moore, N.; Müller, N.; Hyndman, D. W. (2018): Sustainable hydropower in the 21st century. In: Proceedings of the National Academy of Sciences of the United States of America, 115 (47).

Nationaler Wasserstoffrat (2021): Nachhaltigkeitskriterien für Importprojekte von erneuerbarem Wasserstoff und PtX-Produkten.

Piria, R.; Honnen, J.; Pfluger, B.; Ueckerdt, F., Odenweller, A. (2021): Ariadne-Analyse. Wasserstoffimportsicherheit für Deutschland: Zeitliche Entwicklung, Risiken und Strategien auf dem Weg zur Klimaneutralität.

Pistner, C.; Englert, M.; Küppers, C.; Hirschhausen, C. von; Wealer, B.; Steigerwald, B.; Donderer, R. (2021): Sicherheitstechnische Analyse und Risikobewertung einer Anwendung von SMR-Konzepten (Small Modular Reactors). Online verfügbar unter https://www.base.bund.de/SharedDocs/Downloads/BASE/DE/berichte/kt/gutachten-small-modular-reactors.html, zuletzt geprüft am 15.02.2022.

Roberts, D. A.; Johnston, E. L.; Knott, N. A. (2010): Impacts of desalination plant discharges on the marine environment: A critical review of published studies. In: Water research, 44 (18), S. 5117–5128.

Roeb, M.; Brendelberger, S.; Rosenstiel, A.; Agrafiotis, C.; Monnerie, N.; Budama, V.; Jacobs, N. (2020): Wasserstoff als ein Fundament der Energiewende. Teil 1: Technologien und

Perspektiven für eine nachhaltige und ökonomische Wasserstoffversorgung. Online verfügbar unter https://www.dlr.de/content/en/downloads/2020/hydrogen-research-study-part-1.pdf, zuletzt geprüft am 22.11.2021.

Sachverständigenrat für Umweltfragen (Hrsg.) (2021): Wasserstoff im Klimaschutz: Klasse statt Masse. Stellungnahme.

Schrems, I.; Fiedler, S. (2020): Gesellschaftliche Kosten der Atomenergie in Deutschland. Eine Zwischenbilanz der staatlichen Förderungen und gesamtgesellschaftlichen Kosten von Atomenergie seit 1955. Online verfügbar unter https://foes.de/publikationen/2020/2020-09_FOES_Kosten_Atomenergie.pdf, zuletzt geprüft am 15.02.2022.

Siracusano, S.; Trocino, S.; Briguglio, N.; Pantò, F.; Aricò, A. S. (2020): Analysis of performance degradation during steady-state and load-thermal cycles of proton exchange membrane water electrolysis cells. In: Journal of Power Sources, 468.

Souza, S. P.; Horta Nogueira, L. A.; Watson, H. K.; Lynd, L. R.; Elmissiry, M.; Cortez, L. A. B. (2016): Potential of Sugarcane in Modern Energy Development in Southern Africa. In: Frontiers in Energy Research, 4.

UNEP/MAP/MED POL (2003): Sea Water Desalination in the Mediterranean: Assessment and Guidelines.

Velazquez Abad, A.; Dodds, P. E. (2020): Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges. In: Energy Policy, 138.

Wealer, B.; Breyer, C.; Hennicke, P.; Hirsch, H.; Hirschhausen, C. von; Klafka, P.; Kromp-Kolb, H.; Präger, F.; Steigerwald, B.; Traber, T.; Baumann, F.; Herold, A.; Kemfert, C.; Kromp, W.; Liebert, W.; Müschen, K. (2021): Kernenergie und Klima.

White, C. (2012): Understanding water scarcity: Definitions and measurements. Online verfügbar unter https://globalwaterforum.org/2012/05/07/understanding-water-scarcity-definitions-and-measurements/, zuletzt geprüft am 11.01.2022.

Zelt, O.; Kobiela, G.; Ortiz, W.; Scholz, A.; Monnerie, N.; Rosenstiel, A.; Viebahn, P. (2021): Multikriterielle Bewertung von Bereitstellungstechnologien synthetischer Kraftstoffe. Teilbericht 3 (D2.1) an das Bundesministerium für Wirtschaft und Energie (BMWi). Wuppertal, Stuttgart, Saarbrücken: Wuppertal Institut, DLR, IZES.

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List of abbreviations

AEL	Alkaline electrolysis
BMBF	Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung)
C	Carbon
CCS	Carbon Capture and Storage
CH_3OH	Methanol
CO	Carbon monoxide
CO_2	Carbon dioxide
CSP	Concentrated Solar Power, solar thermal power stations
DAC	Direct Air Capture
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GW	Gigawatt, 1 GW = 10^6 kW = 10^9 W
H_2	Hydrogen
H_2O	Water
IEA	International Energy Agency
IFC	International Finance Corporation’s Performance Standard
ILO	International Labour Organisation
IUCN	International Union for Conservation of Nature and Natural Resources
kWh	Kilowatt hour, 1 kWh = 10^3 Wh
LCA	Life Cycle Assessment
MW	Megawatt, 1 MW = 10^3 kW = 10^6 W
MWh	Megawatt hour, 1 MWh = 10^3 kWh = 10^6 Wh
N_2	Nitrogen
NDC	Nationally Determined Contributions
NH_3	Ammonia
NHS	Germany’s National Hydrogen Strategy (Nationale Wasserstoffstrategie) (Bundesministerium für Wirtschaft und Energie 2020)
PEM	Proton Exchange Membrane/Polymer Electrolyte Membrane
PtX	Power-to-X, term for the production of synthetic fuels and basic materials from electricity
PV	Photovoltaic
RE	Renewable energies
REDII	Renewable Energy Directive, Directive (EU) 2018/2001, Directive promoting energy from renewable sources
SDGs	Sustainable Development Goals der Agenda 2030
SIA	Secondary inorganic aerosols
SRU	German Advisory Council on the Environment (Sachverständigenrat für Umweltfragen)

TRL	Technology Readiness Level
TWh	Terawatt hours, 1 TWh = 10^9 kWh = 10^{12} Wh
UNFCCC	United Nations Framework Convention on Climate Change
WRI	World Resource Institute
WSI	Water Stress Index

10 Annex

10.1 Green hydrogen labels

Table 5: Overview of existing labels and definitions of green hydrogen, adapted from Velazquez Abad et al. (2020)

Organi-zation	Type	Focus	Benchmark	Observed values and criteria	Process	System boundary
TÜV Süd (Germany)	National standard Green Hydrogen	Renewable energies / GHG emissions	GHG potential of biofuels from REDII	GHG reduction potential of at least 70 % compared to the reference value for biofuels (Annex V REDII) i.e., GHG value of 28.2 gCO_2eq/MJ + basic requirements[47]	In principle, no restrictions, CCS and CCU only under specific conditions	Point of produc-tion
TÜV Süd (Germany)	National standard Green Hy-drogen+	Renewable energies / GHG emissions	GHG potential for biofuels from REDII	GHG reduction potential of at least 70 % compared to reference value for biofuels (Annex V REDII) i.e., GHG value of 24 gCO_2eq/MJ + basic requirements of green hydrogen met + additional requirements[48]		Point of use
CERTIFHY (EU)	Guarantee of origin	Renewable energies/ GHG emissions	Hydrogen from steam reforming natural gas	< 60 % of the emissions from steam reforming	All renewable pathways meeting the threshold with 99.5 % purity	Point of produc-tion

[47] Basic requirements of green hydrogen: Proof of RE electricity (on-site installation or direct line without using the general power grid or guarantees of origin or comparable certification); proof for biogas/biomethane (via national register for renewable gases or equivalent proof); sustainability certification in terms of the REDII for biogas/biomethane and other biomass; mixed production possible (use of renewable and non-renewable resources, certification only for correspondingly produced share); GHG accounting for hydrogen in accordance with ISO 14040, ISO 14044 and Annex V (biofuels, liquid biofuels and their fossil fuel comparators) and Annex VI (biomass fuels and their fossil fuel comparators) of REDII (applied analogously to hydrogen); LCA requirements (met if GHG accounting conducted according to GHG protocol ISO 14067 or PAS 2050, system boundary for accounting is well-to-gate).

[48] Additional requirements of Green Hydrogen+: exclusion of legally supported electricity from RE, which receives increased remuneration per kWh fed into the grid (exception: purchase as part of a nationally regulated auction as defined in REDII); RE electricity generation plant for electrolysis must be a new installation (start-up at the earliest 11 months before or after electrolyzer start-up); simultaneity (quarter of an hour) of power generation and consumption when purchasing power from the grid; regionality (no grid congestion in power grid between RE plant and electrolyzer at time of start-up, same bidding zone, exceptions possible); mass balanced system proof of sustainability as defined in REDII for material use of biomethane, biomass, glycerin; mass balanced supply (hydrogen and certified property of GreenHydrogen+ must be marketed together at all times).

Organi-zation	Type	Focus	Benchmark	Observed values and criteria	Process	System boundary
AFHYPAC (FR)	Proposal WG	CO_2 reduction	-	100 % renewable	All renewable pathways, incl. electrolysis powered by waste (with renewable electricity or biomethane with guarantee of origin)	Point of produc-tion
California Low Carbon Fuel Standard	Regulation	Air quality and CO_2 reduction	WTW emissions from new gasoline vehicles	30 % lower GHG and 50 % lower NOx emissions (on WTW per kilometer basis) for FCV	Renewable electrolysis, catalytic cracking of SMR of biomethane or thermo-chemical conversion of biomass (incl. municipal waste)	Point of use
China Hydrogen Alliance	Standard for low-carbon hydrogen, Clean Hydrogen and Renewable Hydrogen[49]	GHG emissions		Low-carbon H_2: GHG emissions ≤ 14.51 kg CO_2e/kgH_2 Clean H_2, Renewable H_2: GHG emissions ≤ 4.9 kg CO_2e/kgH_2	Renewable H_2: Energy demand covered by RE	Point of produc-tion
atmosfair	Quality label for green, synthetic kerosene "fairfuel gold"	CO_2-free aviation fuel	Transitional period for non (and conditionally) sustainable C-sources	100 % RE electricity. Not from RE that is subsidized under EEG. Only newly constructed RE, PPA and short distances. CO_2 from 2050 100 % DAC. For "fairfuel silver" label, use of up to 50 % bio-based CO_2	Not limited to a prescribed process to produce the kerosene.	Point of produc-tion

49 See China Hydrogen Alliance (2020).

10.2 Colors of hydrogen

Table 6 provides an overview of the color classifications of hydrogen according to Bundesministerium für Wirtschaft und Energie (2020), Sachverständigenrat für Umweltfragen (2021) and the Institute for Climate Protection, Energy and Mobility e.V.[50]

Table 6: Colors of hydrogen

Gray, brown or black	Gray: Use of fossil hydrocarbons, mainly steam reforming of natural gas Brown: produced using gasification of lignite (brown coal) Black: produced using gasification of hard coal (black coal)
Blue	If production is combined with carbon capture and storage (CCS), hydrogen is CO_2-neutral, since CO_2 is not released into the atmosphere
Green	Produced via electrolysis of water using electricity from renewable energies; CO_2-free production as CO_2-free electricity
Dark green	Hydrogen produced in accordance with environmental and social criteria yet to be defined more precisely (according to SRU)
Turquoise	Produced by thermally splitting methane (methane pyrolysis), is CO_2-neutral if the heat required is covered by CO_2-neutral energy sources and the carbon produced is permanently bound
Orange	Produced using bioenergy
Red, pink or yellow	Produced via electrolysis of water using electricity from nuclear power or TWS processes (using high-temperature wastewater from nuclear power generation)
White	Naturally-occurring deposits

10.3 Examples of process data along the value chain

Table 7: Parameters of water electrolysis (Bazzanella et al. 2019)

Water demand (stoichiometric) [tH_2O/tH_2]	8.9
Electricity demand [MWh/tH_2]	51.6

Table 8: Parameters for synthesis products from electrolysis-based hydrogen and nitrogen from air separation (Bazzanella et al. 2019)

Reference: 1 t Ammonia	
Electricity demand electrolysis [MWh/t] (for 1 t NH_3, based on 4.3 kWh/Nm^3 H_2)	9.17
Electricity demand utilities [MWh/t]	1.72
Reference: 1 t Methanol	
Electricity demand electrolysis [MWh/t] (for 1 t MeOH, based on 4.3 kWh/Nm^3 H_2)	9.52
Electricity demand utilities, without supplying CO_2 [MWh/t]	1.5

[50] IKEM (2020) Short study "Wasserstoff - Farbenlehre", https://www.ikem.de/wp-content/uploads/2021/01/IKEM_Kurzstudie_Wasserstoff_Farbenlehre.pdf.

Table 9: Examples of GHG emissions in the process chain

Process step	GHG emissions	Energy use
Transport via ocean-going vessels[51]	0.00785 kg CO_2 per 1 t*km transported good	0.00252 kg heavy fuel oil per 1 t*km transported good
Transport via HGV[52]	0.0575 kg CO_2 per 1 t*km transported good	0.0192 kg diesel per 1 t*km transported good
Transport of natural gas via pipeline[53]	$1.5*10^{-5}$ kg CO_2 per 1 t*km transported good	0.0725 kWh electricity (medium voltage) per 1 t*km transported good
Desalination: reverse osmosis[54]	$3.25*10^{-5}$ kg CO_2 per 1 kg drinking water produced	0.00369 kWh electricity (low voltage) per 1 kg drinking water produced

Table 10: Examples of area required (Zelt et al. 2021)

Installation	Required area (average/assumption)	Example (Nominal capacity/hydrogen production rate and area)
CSP (Main share: mirrors)	40,000 m^2/MW	50 MW and 120 ha (24,000 m^2/MW) 50 MW and 130 ha 50 MW and 200 ha 392 MW and 1,457 ha
PV	20,000 m^2/MW	70 MW and 137 ha (19,571 m^2/MW) 300 MW and 600 ha 800 MW and 1,600 ha 1,650 MW and 3,720 ha
Onshore wind[55]	200,000 m^2/MW	300 MW and 100 km^2 (333,333 m^2/MW) 580 MW and 43 km^2 (74,138 m^2/MW)
DAC, low-temperature	0.1 m^2 per 1 t (CO_2, year)	No information
DAC, high-temperature	16 m^2 per 1 t (CO_2, year)	No information
Electrolysis, low-temperature	Variable: 0.39 – 0.92 m^2 per 1 t (H_2, year)	3,880 standard cubic meters H_2 per hour and 770 m^2 (AEL) 485 standard cubic meters H_2 per hour and 225 m^2 (AEL) 400 standard cubic meters H_2 per hour and 160 m^2 (PEM)

51 Ecoinvent 3.7.1, dataset «transport, freight, sea, container ship» (GLO).

52 Ecoinvent 3.7.1, dataset «transport, freight, lorry > 32 metric tons, EURO6» (GLO).

53 Ecoinvent 3.7.1, dataset «transport, pipeline, onshore, long distance, natural gas» (GLO).

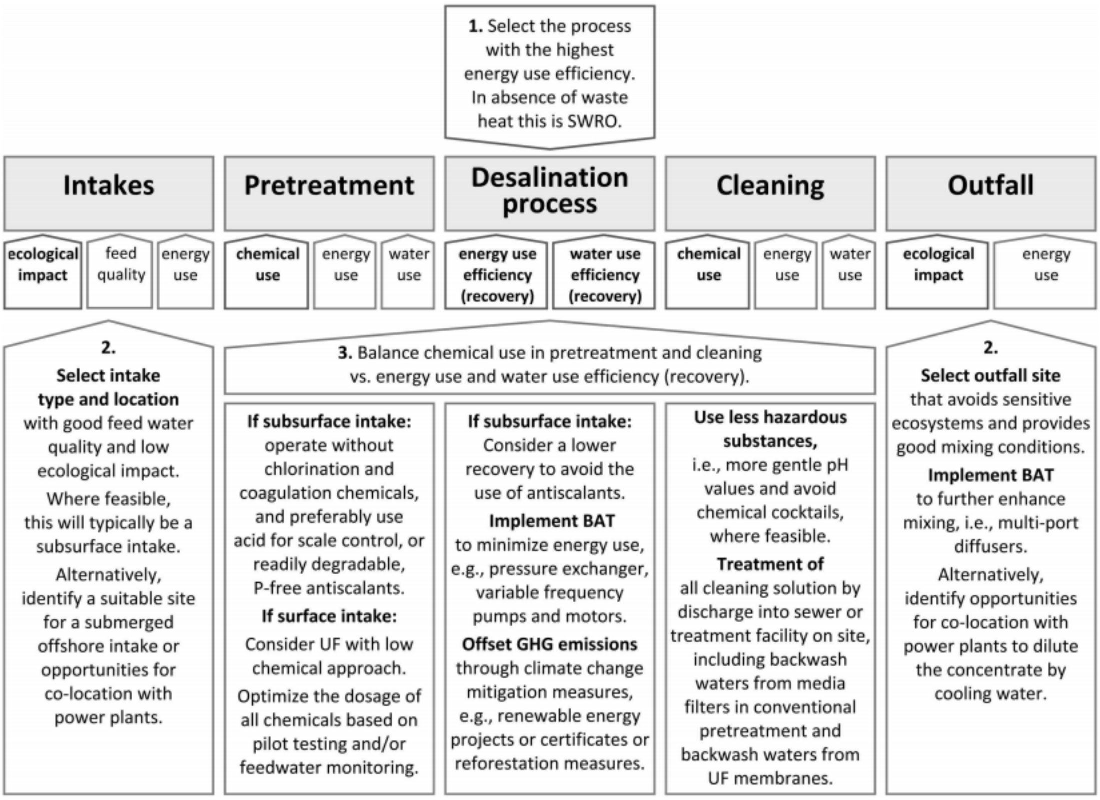
54 Ecoinvent 3.7.1, dataset «tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage» (GLO).

55 Different definitions of the land required are available in the literature; the most commonly used metric is the area required by the overall project.

10.4 Environmental impacts of desalination plants and recommendations for site selection

More detailed studies and analyses of the possible environmental impacts of desalination plants are found in (Lattemann 2010). This section presents an overview of the impacts and recommendations given there with regard to site selection. Figure 4 (Figure 24 in Lattemann (2010)) provides an overview of the most important aspects concerning "green" or "sustainable" desalination.

Figure 4: Roadmap to 'green' or 'sustainable' desalination (Figure 24 in Lattemann (2010))



The most important environmental effects of desalination plants are summarized in Table 11 (based on Table 35 in Lattemann (2010)).

Table 11: Environmental effects of high priority for impact mitigation (Table 35 in Lattemann (2010))

Receptors	Environmental effects
Landscape properties and natural scenery	• visual, aesthetic impacts due to the discharge of reddish-brown backwash water from media filters (specific to the reverse osmosis process) that may cause a discoloration of the water column in the mixing zone or may be transported to nearby beaches • acoustic impacts caused by noise emissions from plant operation
Air quality and climate	• any significant impairments of local air quality due to emissions of air pollutants (NO_X, SO_X, PM_{10})

Receptors	Environmental effects
	• significant emissions of carbon dioxide (CO_2) and other greenhouse gases
Groundwater quality and hydrology	• any changes in flow directions and groundwater salinity • any pollution from spills and seepage
Marine sediments	• changed erosion and sedimentation patterns locally and in downdrift locations which may be caused by artificial breakwaters • increases in pore water salinity which may be caused by the concentrate discharge • the accumulation of coagulant material in sediments near the outlet potentially caused by the discharge of media filter backwash water • the risk of heavy metal accumulation in sediments if present in the discharge, e.g., copper from corroding plant materials
Seawater quality and hydrology	• significant changes in salinity and temperature in the mixing zone of the effluent plume • sinking of the discharge plume and formation of a dense bottom water layer, which may have a strengthening effect on density stratification of the water column and which may impede reoxygenation of bottom waters • increases in turbidity and decreases in light penetration in the mixing zone potentially caused by the filter backwash plume
Terrestrial fauna and flora	• effects that may cause a long-term to permanent loss of habitat • noise emissions that may scare away sensitive wildlife within acoustic range • prominent features that could preclude linkages and movement corridors of wildlife, and which could strengthen the effect of habitat loss
Benthic macrofauna and -flora	• salinity or temperature increases in the mixing zone that may cause a decline of algae stands and seagrass meadows, or that may be harmful to benthic invertebrate species, depending on exposure and species sensitivity • any toxic effects of chemicals, e.g., from residual chlorine, chlorination by-products, or heavy metals, alone or in combination with other effects, e.g., synergetic effects between increased temperature and chlorine • avoidance reactions, which may cause a lasting change in species abundance and diversity in the discharge site • a harmful blanketing of sessile species potentially caused by the filter backwash plume
Marine mammals, reptiles or bird species	• loss of haul-out sites, nesting grounds or important feeding grounds, for example caused by noise emissions and general disturbance within visible and acoustic range

Recommendations and criteria when selecting sites for desalination facilities are summarized in Table 12 (based on Table 36 in Lattemann (2010))

Table 12: Criteria for site selection of desalination projects (Table 36 in Lattemann (2010))

Criteria	If possible, the selected site(s) should:
• Geologic and land area requirements	• provide stable geologic conditions, with no risk of affecting the stability of soils and sediment, or buildings and pipelines • be planar or easily allow for initial earthwork activities (site grading, excavation) or the laying of below-ground intakes, outfalls and pipelines

Criteria	If possible, the selected site(s) should:
	• where relevant, have a permeable substratum that allows for the use of beachwells, infiltration galleries or horizontally drilled drains as intakes • be sufficiently elevated above sea level with no risk of flooding • be able to accommodate the intakes and outfalls and all facilities of the plant in terms of area size and geometry • have no risk of aquifer pollution in the case of spills and seepage
• Biologic resources	• be devoid of ecosystems or habitats that are: • unique within a region (e.g., riffs on a mainly sandy shoreline) • worth protecting on a global scale (e.g., coral reefs, mangroves) • important in terms of productivity or biodiversity • inhabited by protected, endangered, rare species, even if temporarily • important feeding grounds or reproductive areas for a larger number of species or certain key species within a region • important for human food production
• Oceanographic conditions	• provide sufficient capacity to dilute and disperse the salt concentrate, as well as any residual chemicals discharged along with the waste water. In this regard, provide sufficient water circulation and exchange rate as a function of currents, tides, surf, water depth and bottom/shoreline morphology. In general, exposed rocky or sandy shorelines with strong currents and surf may be preferred over shallow, sheltered sites with limited water exchange
• Concentrate discharge area	• be close to the concentrate disposal area to avoid pumping and to minimize the risk of land and groundwater contamination from pipelines • provide a discharge area that is located in sufficient distance from the intake or that is separated from the intake by natural or artificial features (headlands, jetties) in order to avoid recirculation of the waste
• Proximity to consumers	• be close to existing distribution networks and consumers to avoid construction and land-use of pipelines and pumping efforts for water distribution. However, impairment of communities by visual effects, noise, air pollution or other environmental health concerns should be avoided
• Proximity to energy supply	• be close to the power grid for SWRO plants • provide access to low-cost heat for distillation plants
• Other infrastructure	• allow for easy connection to other relevant infrastructure, such as access roads or communication networks • be co-located to power plants to make use of: • the existing intake/outfall structures (no new construction impacts) • the cooling water, resulting in a reduced energy demand of the SWRO process because of a higher membrane permeability at higher water temperature; a lower feedwater intake than for two separate plants with lower impingement/entrainment effects; and a lower discharge salinity if the concentrate is blended into the cooling water
• Raw water quality and proximity	• facilitate an intake location that provides a good and reliable water quality, taking seasonal changes into account, with minimum danger of pollution or contamination, in order to avoid performance problems of the plant or impacts on product water quality • be close to the sea to minimize land use for pipelines and to avoid passage of pipes through agricultural land, settlements, etc. However, in some cases it may be more appropriate to locate the plant further inland, e.g., when construction on the shore is not possible for certain reasons (e.g., use of beaches, nature reserves, geological instability, etc.

Criteria	If possible, the selected site(s) should:

Regional planning	• be classified as an industrial area or designed for industrial development in conformity with regional and land area plans
	• have the acceptance of neighboring communities and provide as little conflict as possible with other existing or planned uses and activities, especially recreational uses, commercial uses including shipping, nature conservation efforts, or cultural resources
	  • Recreational conflicts may occur if the project has the potential to reduce the recreational value of the area for residents or tourists by changing the natural scenery through emissions of noise, glare, etc., or by restricting access to beaches, hiking trails, fishing sites, etc.
	  • Commercial conflicts may occur if the project is to be located within existing urban boundaries, where it could reduce the price for land or the value of adjacent residential properties, or if it interferes with maritime structures, navigation, access to harbors or other marine activities like commercial fishing or aquaculture.
	  • Nature conservation conflicts may occur if the project significantly reduces the ecological value of the project site as a habitat for terrestrial and marine species. The decision to protect or open an area for development should therefore consider the presence or absence of rare and endangered species or biological communities. By changing the ecological value of a site, it may lose its present protection status or may no longer be eligible for becoming a protected area in the future.
	  • Archaeological conflicts may occur if archaeological, paleontological or human remains are located in or near the project site, which may be accidentally uncovered or disturbed during construction.