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Working Paper

Sustainability dimensions of imported hydrogen

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Synthesis

To achieve the climate neutrality target in Germany for 2045, large quantities of hydrogen will have to be imported from regions outside the EU. This report analyses the expected far-reaching and multi-layered impacts on exporting countries. It focuses on the production of hydrogen based on renewable electricity (green hydrogen) and its import into the EU. Ambitious and clearly defined sustainability criteria avoid negative effects of hydrogen production abroad, provide investment security for companies and are the basis for a long-term recognition of imported hydrogen as a climate protection instrument. This report presents a first set of criteria that could help secure sustainability in the emerging international market for green hydrogen.

There is more to sustainable green hydrogen than just using renewable electricity

The impact of bulk hydrogen production on the exporting countries[1] is significant (see Figure 1-1): for the import of around 170 TWh of hydrogen, around 50 million cubic metres of water must be provided in these countries and around 260 TWh of electricity must be generated from renewable energies. This corresponds roughly to a capacity of 85 GW of onshore wind turbines. By comparison, wind turbines installed in North Africa at a capacity of 3 GW generated around 8 TWh of electricity in 2020. Currently, the policy focus is on the use of green electricity to produce green hydrogen. Due to the far-reaching and diverse sustainability impacts of hydrogen production on exporting countries, we propose to work towards imports of sustainable green hydrogen[2]:

- Electricity is the main input into the electrolysis but is also needed for other processes within the hydrogen value chain such as seawater desalination or when producing derivatives from hydrogen. Electricity supply from renewable energy sources can conflict with the decarbonisation of the domestic energy system. Especially when sourcing electricity from the electricity grid, hydrogen production can cause additional GHG emissions or contribute to bottlenecks.
- Water is needed as feedstock for the electrolysis but also for cleaning PV panels. Even though the amount of water needed for hydrogen production is low compared to other uses (such as agriculture), local water stress is a serious issue for many countries with high hydrogen export potential. Risks relate both to the physical availability of water and the economic pressure on scarce water resources.
- Land is mainly needed for renewable electricity production. Land-use change can interfere with biodiversity or local (sometimes informal) land rights.
- Socio-economic impacts will accompany the build-up of a hydrogen export value chain. Human rights could be particularly at risk when it comes to land-use change as well as in work processes along the whole value chain. In addition, there can be a lack of (economic) participation of local people related to local jobs or transfer of technology and know-how.
- CO_2 is needed as an additional input to produce derivatives from hydrogen. If fossil CO_2 is used that results from burning fossil fuels, the decarbonisation of the economy might be delayed.
- Transport of hydrogen or derived products can be dangerous for workers and the environment in case of accidents (for example if ammonia is being transported).
- Raw materials are needed to produce electrolysers and renewable power plants. Some of these materials are mined under unacceptable working conditions, mines contribute to pollution and are

[1] There are multiple trading partners in debate, for example: North African countries; Gulf Cooperation countries and Chile.
[2] See also SRU (2021); Oeko-Institut (2021).

a risk to health. Iridium is used in some electrolysers and could be a limitation to the uptake of hydrogen production due to its low availability.

Sustainable green hydrogen needs a clear set of criteria building on existing frameworks

Ambitious and clearly defined sustainability criteria avoid negative effects of hydrogen production abroad, provide investment security for companies and are the basis for long-term recognition of imported hydrogen as a climate protection instrument. We suggest differentiating between criteria for a minimum standard and for additional support of sustainable development. If possible, existing criteria sets should be used to keep the hurdle for complying with sustainability criteria in hydrogen production low. Options for specific criteria are the following (see Figure 1-2).

- At country level, we propose to ask hydrogen trading partners to develop a decarbonisation strategy that also takes hydrogen production into account. This strategy should be analysed through a Strategic Environmental Assessment (SEA). If major concerns are identified in this SEA, the trading partners' strategy should be adjusted.
- At the project level an Environmental Impact Assessment should be carried out. This could be complemented by a Sustainability Impact Assessment that also includes socio-economic dimensions. Consultation of local stakeholders and suitable grievance mechanisms should be implemented.
- Electricity input to hydrogen production should be based on additional renewable energy sources. In case of sourcing electricity from the grid, provisions of the RED addressing system integration and grid bottlenecks should be considered. Additional instruments should make sure that the allocation of dedicated renewable sites for hydrogen production does not impede domestic decarbonisation. Additional investment in local infrastructure (such as renewable electricity generation, energy grids, electricity storage systems) could support local sustainable development.
- Water should be sourced from additional seawater desalination plants, sourcing from ground or surface water should be limited to areas with high water availability. Local water prices should be monitored, and countermeasures should be taken if prices increase due to hydrogen production. Desalination plants should fulfil ecological standards and should be powered by renewable energy. Investment in improved local water infrastructure to reduce losses and evaporation, and additional water production through seawater desalination could support local sustainable development.
- Land-use change for hydrogen production and especially renewable electricity production should not take place in ecological protected areas. Local stakeholder consultation should make sure that local and sometimes informal land rights are not violated. Economic participation of the local population and enabling co-benefits (such as shading local agricultural areas by agri-PV systems) could be options to further support local sustainable development.
- Socio-economic risks need to be mitigated by following the due diligence procedures (definition of sector-specifc risks and adequate measures to mitigate those risks) and human rights violations should be prevented. In addition, corruption should be prevented through initiatives that define standards for economic participation and make the flow of money transparent. Socio-economic participation could be supported by guaranteeing a certain share of local workforce, establishing a local supply chain for technology, direct investments in R&D and local capacity building initiatives.

- CO_2 use should be limited to those sources that create a short-term carbon-cycle with the atmosphere. Therefore, we suggest to only use CO_2 from Direct Air Capture (DAC) or from waste streams from industrial processes based on sustainable biomass.
- Raw materials and transport were not in the focus of our research. However, we suggest specifying that compliance with due diligence and international labour safety standards is mandated for the whole value chain. Concerning transportation, the higher the losses the more hydrogen needs to be produced in the first place with all the sustainability dimensions to be considered described in the sections above. Therefore, the most efficient transport mode should be considered to keep overall sustainability impacts in the exporting country low.

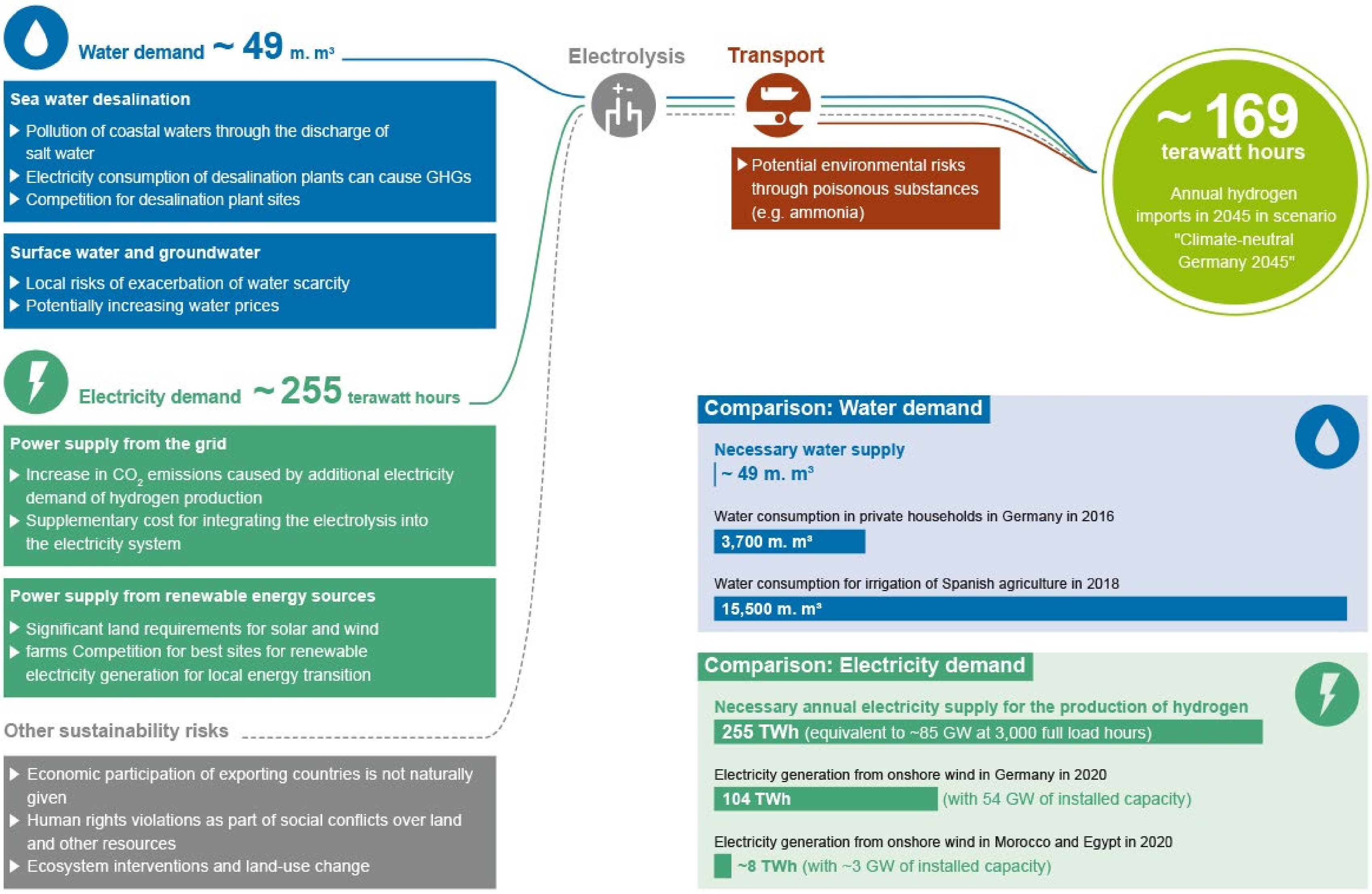
The next steps for an early uptake of sustainable green hydrogen consist in agreeing on criteria, setting ecological standards, building up institutions and cooperating with future exporting countries

The uptake of sustainable green hydrogen requires the definition and international agreement on respective criteria and standards. If an international agreement on sustainability criteria leads to weak criteria, more ambitious specifications for the European hydrogen market should be provided. Standards relate to sustainability dimensions but also to the way certain assessments are carried out at the project level (such as the Environmental Impact Assessment). Also, an international standard securing a low ecological impact of seawater desalination is missing and should be developed.

The uptake also requires institutions to be established that act as the backbone of securing compliance with sustainability standards. On the one hand, local institutions are needed for the implementation of certification systems and for robust monitoring and auditing. On the other hand, a private/public initiative could foster socio-economic standards and monitor them.

Close cooperation with exporting countries will ensure that the way sustainability dimensions are defined and addressed can be aligned between exporting and importing countries. This way a clear pathway towards the uptake of sustainable green hydrogen can be supported.

Figure 1-1: Sustainable production of hydrogen needs action – Expected environmental and socio-economic impacts



Source: Oeko-Institut 2021, CC BY-SA 2. | Further explanations and sources are documented in Annex I

Figure 1-2: Possible criteria for sustainable green hydrogen

Country specific
- National decarbonisation strategy (NDC) should include hydrogen production
- Perform a Strategic Environmental Assessment (SEA)
- Work towards Hydrogen strategy addressing sustainability dimensions (power, water, land-use, socio-economics, transport, CO2-feedstock)

Project specific
- Environmental Impact Assessment
- Sustainability Impact Assessment (SIA)
- Consultation of local stakeholders
- Grievance mechanisms
- No significant harm to SDGs (especially SDG 6 to 9)

Minimum standard

Electricity
- Exclude Biomass and Nuclear power plants
- If sourcing from direct connection to dedicated RES-E capacity:
  - RES-E should be additional
- If sourcing from electricity grid:
  - RES-E should be additional
  - Temporal correlation to RES-E
  - Geographical correlation to RES-E
- Address competition for RES-E sites between exports and local decarbonisation

Water
- Exclude surface and ground water in areas with regional water stress
- If sourcing from Sea Water Desalination (SWD):
  - SWDs should be powered by RES-E
  - SWDs water supply need to be additional
  - Compliance with yet to be developed international environmental standard for brine disposal
  - Monitoring and securing existing water prices

Land use
- Exclude protected areas
- Respect local (informal) land rights

Socio-economics
- Comply with due diligence
- Secure human rights
- Prevent corruption and enable monitoring local economic participation (Transparency Initiative)

support of sustainable development

Electricity:
- Additional RES-E capacity to decarbonize local energy system
- Provisions for additional (funds for) infrastructure
  - Flexibility
  - Grid

Water:
- Additional water production exceeding the needs for hydrogen production
- Improve existing water infrastructure

Land use:

Enable co-benefits, for example:
- Shading from "Agri-PV"
- Local economic participation

Socio-economics:
- Capacity Building (R&D)
- establishing and operating a local supply chain for technology
- Secure a share of local work force

SWD: sea water desalination | RES-E: renewable energy sources electricity | "Additional", refers to the principle of additionality: In practice this needs further specifications such as developing a baseline projection and taking into account interference with other parallel developments.

Source: Oeko-Institut, own graphic

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List of abbreviations

AIB	Association of Issuing Bodies
CCS	Carbon Capture and Storage
CSP	Concentrated Solar Power
DAC	Direct Air Capture
DNSH	Do no significant harm
EITI	Extractive Industries Transparency Initative
EU	European Union
FCH & JU	Fuel Cell and Hydrogen Joint Undertaking
GHG	Greenhouse gas
GO	Guarantee of origin
GW	Gigawatt
IEA	International Energy Agency
IFC	International Finance Corporation
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LOHC	Liquid organic hydrogen carriers
MJ	Megajoule
MRV	Monitoring, reporting and verification
MW	Megawatt
MWh	Megawatt hours
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
PEM	Polymer electrolyte membrane
PV	Photovoltaics
R & D	Research and Development
RED II	Renewable Energy Directive of the European Union
RES-E	Electricity from renewable energy sources
RFNBO	Renewable fuels of non-biological origin
SDGs	Sustainable Development Goals
SEA	Strategic Environmental Assessment
SG-H_2	Sustainable green hydrogen
SIA	Sustainability Impact Assessment
SWD	Seawater desalination
TWh	Terawatt hours
UNEP-WCMC	UN Environment Programme World Conservation Monitoring Centre
WFD	Water Framework Directive
WTO	World Trade Organisation

1 Our motivation: Why is sustainability an issue for hydrogen imports?

Why do we need hydrogen?

Decarbonising the energy system and reducing greenhouse gas emissions mainly builds on renewable electricity. Only a few years ago GHG emission reduction goals for 2050 of only 80% compared to 1990 implied that some energy demand could have been covered with fossil fuels. Now, with higher ambitions of 95% to 100% GHG emission reductions, fossil fuels are not an option anymore for 2050. In addition, there is a lack of sustainable biomass potential, which otherwise could also replace fossil fuels. Moreover, there is energy demand, demand for basic chemicals and demand for chemical agents in industrial processes in our economy that cannot be substituted by direct electrification, and hence cannot use renewable electricity directly. The largest demands are projected in the following sectors (Oeko-Institut 2021):

- Chemical industry which needs hydrogen and its derivatives as a feedstock for their processes;
- Industrial processes that need hydrogen or hydrogen-based fuels for high-temperature processes or as reducing agent (such as steel making without coal);
- Long-distance transportation, in particular aviation, and long-haul maritime transport will require hydrogen-based fuels;
- As a seasonal electricity storage option in times of low electricity generation from PV and wind.

The overall hydrogen demand resulting from the sectors and processes mentioned above have been quantified in a recent scenario analysis. For Germany, a demand of about 265 TWh_{hu} is expected in the year 2045 (Agora Energiewende; Stiftung Klimaneutralität; Agora Verkehrswende 2021). Scenarios that expect a significant use of hydrogen in additional sectors to the ones mentioned above (like for domestic heating or in fuel-cell cars), show even higher demands of up to 500 TWh_{hu} in 2050 (Oeko-Institut 2021). The hydrogen demand in all European countries is expected to be around 1,500 TWh_{hu} in 2050 (compare EC 2018).

Why do we need imports of hydrogen?

From today's perspective, it is hard to predict the exact size of the share of hydrogen imported to Europe to meet local demand. However, there are two main drivers why many scientific studies modelling the future energy system[3] assume significant amounts of imported hydrogen by 2050:

- Europe is quite densely populated and therefore there is limited space available for deployment of RES-E generation (which is the main energy input to produce hydrogen). Taking into account that the RES-E share in the European electricity generation was only 33% in 2018 (BMWi 2020b) and demand is rising due to electric mobility and heat production, the European potential to produce hydrogen from RES-E is assumed to be not sufficient to cover demand. Other countries outside the EU are assumed to be able to provide sufficient space for deployment of RES-E generation.

- The generation costs of hydrogen are assumed to be lower in some countries outside the EU. The overall production costs of hydrogen strongly depend on costs for the electricity input into the electrolysis, and generation costs of renewable electricity based on PV and wind are lower in countries with high solar radiation and higher windspeeds.

[3] Examples are: Fraunhofer ISE (2020); FZJ; RWTH Aachen (2019); Agora Energiewende; Stiftung Klimaneutralität; Agora Verkehrswende (2021).

This indicates that imports of hydrogen are very likely to be relevant in the future. However, not all hydrogen is assumed to be imported. Most studies with the focus on Germany assume that some part of the hydrogen needed will also be produced within German borders (Oeko-Institut 2020, p. 84). In some recent studies, such as Consentec; Fraunhofer ISI; TU Berlin Fachgebiet E&R; ifeu (2021), the potentials for European RES-E generation are assumed to be higher, resulting in larger hydrogen production in Europe.

Why are sustainability criteria relevant?

The main goal for the use of hydrogen and its derivatives should be the long-term reduction of GHG emissions. Therefore, it is crucial that the production of hydrogen itself does not lead to GHG emissions. Hydrogen can be produced using different production routes, which are referred to as hydrogen of different colours (Oeko-Institut 2020). Here we focus on hydrogen produced through electrolysis (hereafter referred to as green hydrogen) which requires electricity as the major energy input. This implies that first and foremost the electricity used must come from RES. However, there is a range of possible pitfalls. One example is the following: When there is a fixed amount of RES-E generation and an increase in electricity demand for hydrogen production, the share of RES-E generation withdrawn from the electricity system for hydrogen production must be replaced by fossil generation to meet the total demand. In this case hydrogen production would lead indirectly to additional GHG-emissions. But even hydrogen based on additional RES-E can have a negative impact on other sustainability dimensions. Examples are competition for water (especially in arid regions with high and low-cost PV potentials) and land conflicts. Hence, socio-economic dimensions must be considered, too.

The history of mass biomass imports for energetic use has taught us: If sustainability criteria are too weak or not defined early enough, imports of hydrogen could lead to negative impacts in exporting countries, undermining global GHG reductions and resulting in low public acceptance. Correspondingly, investors need clear sustainability criteria to be able to develop future-proof projects and process chains for hydrogen production in exporting countries. Sustainable development goals (SDGs) are relevant in all aspects of sustainability addressed within the report. They will be related to in various sections but will not define the structure of the report.

Based on this motivation we strive to give answers to the following questions within this report:

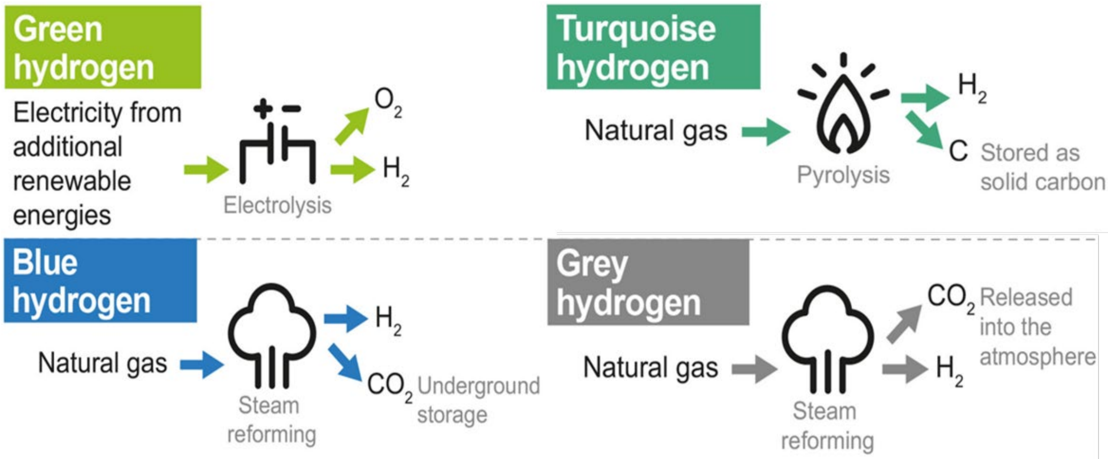
- Which resources are needed for hydrogen production and what are the respective sustainability dimensions that need to be looked at?
- Based on an analysis of possible future exporting countries; which sustainability dimensions arise from their hydrogen strategies and economic (such as their current energy system and economic system) and natural conditions (such as RES-E potentials)?
- Which international minimum requirements should be set for hydrogen to “do no harm” and which goals should be strived for to “support sustainable development” in exporting countries?
- How can sustainability requirements be put into operation, i.e. implemented into certification systems and regulation?

Our methodology to address the questions above was based on a literature review, detailed research in countries expected to be relevant exporters of hydrogen in the future (we have chosen Morocco, Chile, South-Africa, Saudi-Arabia, Spain) including interviews with stakeholders from these countries and workshops and interviews with experts in the field of hydrogen, water stress, land use as well as related topics such as sustainability dimensions of biomass exports.

2 An introduction to the production of hydrogen

Different processes can be used to produce hydrogen. Currently, the generation processes shown in Figure 2-1 are in the focus of the discussion (see (Oeko-Institut 2020), for a detailed explanation and discussion of different technologies, their respective technology readiness level and current and future techno-economical parameters). These processes are based on natural gas or electricity as the main energy inputs.

Figure 2-1: Production pathways of hydrogen: The colours of hydrogen



Source: Oeko-Institut 2020

This report focuses on the production of hydrogen based on electricity using the electrolysis process. Other options to produce hydrogen such as steam reforming of natural gas and underground storage of CO_2 emissions (blue hydrogen) or pyrolysis of natural gas and storing the solid carbon (turquoise hydrogen) are not in the focus of this report. The reason is the following: Blue and turquoise hydrogen are produced from natural gas and therefore rely on limited fossil resources. Moreover, extraction and transportation of natural gas causes methane emissions which add to global warming and are in conflict with a climate neutral energy system. Therefore, we focus on green hydrogen based on electrolysis of water using renewable electricity. Green hydrogen is expected to cover the hydrogen demand in the long term according to the current German and European hydrogen strategies (BMWi 2020a; EC 2020).

With a view to future imports of hydrogen, this report focuses on green hydrogen based on electricity from renewable sources. Electrolysis (the splitting of water) mainly requires water and electricity. Instead of using electrolysis other options that use electricity as an input can become relevant in the future (e.g. plasmalysis of wastewater) to produce hydrogen. However, the main sustainable dimensions are similar.

3 Analysis of relevant sustainability dimensions in hydrogen production

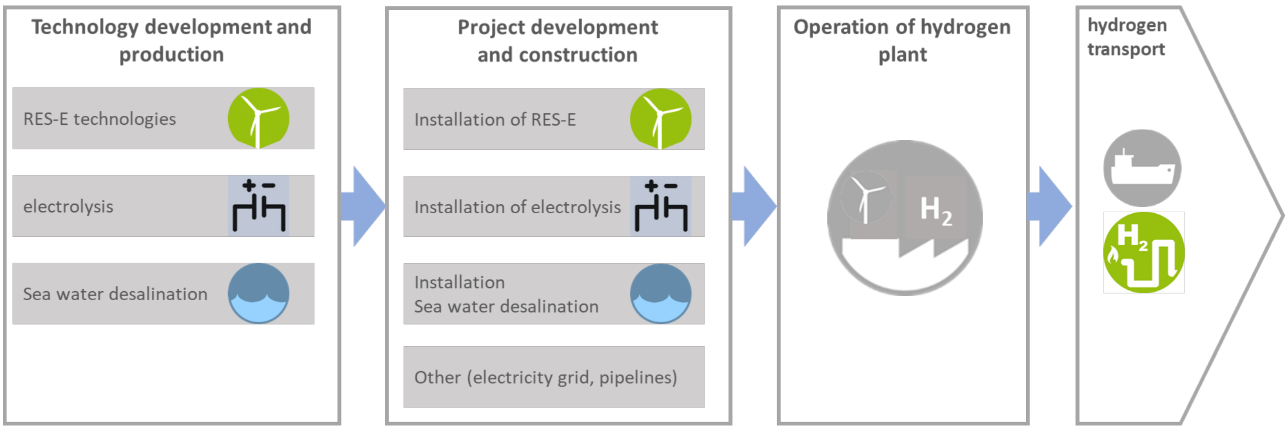
The debate on sustainability in green hydrogen production mainly focuses on the electricity input for the electrolysis. Hence, the importance of using electricity from renewable sources is stated in current hydrogen strategies (BMWi 2020a; EC 2020). This focus on renewable electricity input is driven by a European perspective as within the European Union most other relevant sustainability dimensions are addressed by other regulations. However, as future hydrogen exporting countries will be located outside the EU and in countries with potentially weaker environmental, ecological and social governance standards, considering just the electricity input is not sufficient.

Early studies on green hydrogen production potentials have solely looked at the technical potential of hydrogen production based on the availability of low-cost RES-E generation (e.g. Fasihi et al. 2016). In recent studies and ongoing projects these potentials have been further investigated and limited by taking into account for example water stress, protected areas and the distance of RES-E plants to other land uses (e.g. Fraunhofer IEE 2021).

It is important to look at the whole value chain to make sure most sustainability dimensions that could arise are considered. Figure 3-1 shows the value chain of hydrogen production which consists of the following parts:

- the development (R&D) and production of the technology (such as RES-E production plants, electrolysis, seawater desalination plants and other technologies in case derivatives from hydrogen are being produced);
- the construction and interconnection of the different components forming a hydrogen production plant (engineering and construction work);
- the operation of the hydrogen plant (and refining of derivatives if these are to be exported) and
- the transport of hydrogen or derived products.

Figure 3-1: Value chain of hydrogen production based on electrolysis and RES-E

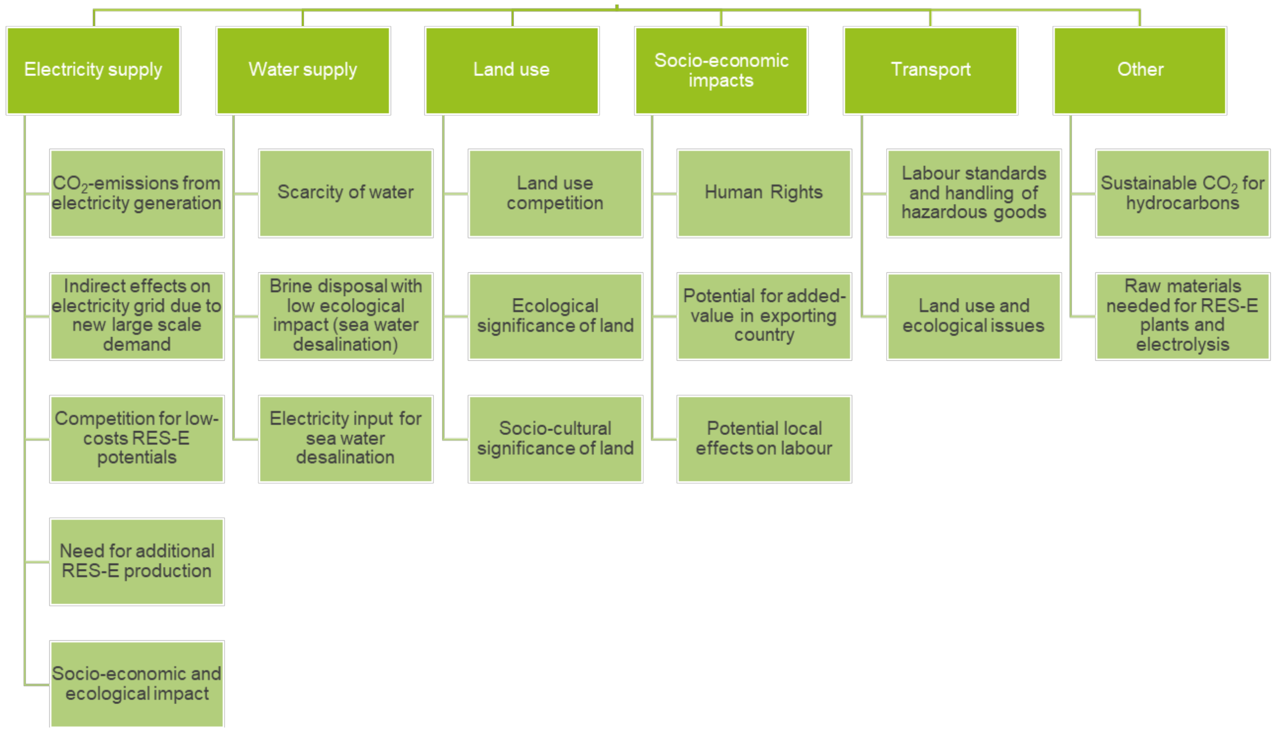


Source: Oeko-Institut, own graphic

It is important to note that we have not carried out a conclusive life cycle analysis. Instead, we intend to focus on the sustainability dimensions that are especially relevant for imported hydrogen and that differ from a domestic hydrogen production in Europe. Therefore, within the scope of our underlying project, we do not look specifically into sustainability issues arising with the production of electrolysis or RES-E technologies.

In this light we have assessed the hydrogen value chain with support from the current literature and our own research. Figure 3-2 shows the main sustainability issues which will be addressed in more detail in the following chapters.

Figure 3-2: Sustainability dimensions in hydrogen production



Source: Oeko-Institut, own graphic

3.1 Electricity supply

Electricity supply is one of the key dimensions affecting the sustainability of hydrogen production. The main reason is that using electricity from the grid with high specific CO_2 emissions would lead to high additional CO_2 emissions. In most countries, CO_2 emissions associated with hydrogen production using the average grid mix would be higher than producing hydrogen from natural gas via steam-reforming (Oeko-Institut 2019, p. 6). Countries with large-scale low-cost RES-E potentials close to Europe such as Northern African states show single-digit RES-E shares and high shares of coal and natural gas within their current electricity grid mix.

However, the impact of electricity supply does not only relate to GHG emissions but can be grouped into three major areas:

- The electricity used in hydrogen production determines its qualification as **"green" hydrogen** but also determines the real GHG emissions that will be caused additionally due to hydrogen production.
- There can be a competition for the use of **limited RES-E potentials** between hydrogen exports and national decarbonisation strategies.
- The choice of location and type of generation technology has an impact on further conflicts in the use of resources such as water and land, and accompanying economic, human rights and biodiversity considerations, hence on the **socio-economic and ecological impact** of the hydrogen production.

One must differentiate between hydrogen production that uses renewable electricity from a dedicated source (also called off-grid; such as a wind farm with a direct connection to the hydrogen plant) and that one which uses renewable electricity from the grid. Defining a sustainable electricity supply when sourcing electricity from the electricity grid comes with additional sustainability dimensions as summarised in Table 3-1.

Table 3-1: Sustainability dimensions in electricity supply

Sustainability dimensions that need to be considered	Electricity supply from the grid	Off-grid electricity supply
CO_2 footprint of hydrogen production due to specific CO_2 intensity of electricity	✓	
Energy system integration of electrolysis	✓	
Competition for low-cost RES-E potentials	✓	✓
Additionality of RES-E plants to cover demand for hydrogen production	✓	✓[4]
Socio-economic and ecological footprint	✓	✓

Source: Oeko-Institut, own compilation

How much **electricity and capacity is needed to produce hydrogen**? Depending on the employed electrolysis technology and the timeframe, electricity input to produce 1 TWh of H_2 varies between 1.14 TWh for future high-temperature electrolysis, and 1.54 TWh for alkaline or PEM electrolysis, at current efficiency levels. Assuming an electrolysis efficiency of 70%, about 1.4 TWh of electricity would be needed to produce 1 TWh of hydrogen. The following additional capacities of RES-E plants would be needed to provide this electricity:

- 410 to 720 MW of onshore wind (assuming 3,500 to 2,000 full-load hours of production)
- 570 to 1,430 MW of PV (assuming 2,500 to 1,000 full-load hours of production)

Additional options to increase full-load hours of hydrogen production such as combining PV and wind plants or making use of energy storage systems would lower the RES-E capacity needed for hydrogen production.

3.2 Water supply

The water demand to produce hydrogen is determined by three main drivers:

- With the current state of the art of electrolysis plants, fresh water is needed as input. Depending on the electrolysis technology, different qualities of water can be used.
- If electricity is generated based on PV systems or Concentrated Solar Power (CSP) systems, additional water is needed for cooling the systems (in the case of CSP) or cleaning the systems (in the cases of CSP and PV) (Cerulogy 2017).
- For large electrolysis plants, water is needed for cooling. However, the quantity needed has not been stated in the literature so far.

[4] This also covers the option that existing RES-E plants will be disconnected from the grid to produce electricity solely for a specific hydrogen production plant.

Water demand can be met from four sources: groundwater, surface water, seawater from desalination plants, and freshwater from the existing network. Additional water demand for hydrogen production can lead to competition for water at a local scale. Therefore, national-level water potentials are not a solid basis for the sustainability assessment of hydrogen producing plants. Sustainability dimensions for water supply vary greatly between groundwater and surface water on the one hand and water from seawater desalination plants on the other. We have summarised the main differences in Table 3-2.

Table 3-2: Sustainability dimensions in water supply

Sustainability dimensions that need to be considered	Groundwater / surface water	Seawater desalination
General scarcity of water	✓	
Seasonality of water availability	✓	
Additionality of water supply	✓	✓
Brine disposal harms maritime flora and fauna and contains chemicals		✓
Electricity demand can lead to additional CO_2 emissions		✓
Competition for input water		✓

Source: Oeko-Institut, own compilation

How much **water is needed to produce hydrogen**? The International Energy Agency (IEA) calculated a water demand of about 0.27 litres per kWh of hydrogen (2019, p. 43)[5]. If the hydrogen is further processed on site into downstream products (e.g. methane or synthetic fuels), it can be assumed that about half of the water input can be recirculated within a closed system (Fasihi et al. 2017). If electricity is generated based on PV systems or concentrated solar power (CSP) systems, additional water consumption is incurred for cooling the systems (CSP) or cleaning the systems (CSP and PV) (Cerulogy 2017). Hernandez et al. (2014) assume 20 litres of water per MWh of electricity in the case of PV plants for regular cleaning of the panels. For CSP plants, the water requirement can be many times higher if water is needed for cooling (approx. 3,000 litres of water per MWh of electricity). Converting these water quantities to one kilowatt hour of hydrogen and assuming a 70% efficiency of electrolysis, we can assume a water demand (additional to the needs of the electrolysis) of about 0.03 litres per kWh_{hu} hydrogen (in the case of electricity generation by PV plants) and up to 4.29 litres per kWh hydrogen (in the case of electricity generation by CSP plants with water cooling).

3.3 Land use

The production of hydrogen requires land for three parts of the value chain:

- the hydrogen production plant itself which consists of the electrolysis and periphery modules (including a seawater desalination plant if needed);
- the production of electricity which can be based on different RES-E technologies;

[5] These calculations correspond to the orders of magnitude from Cerulogy (2017); LBST; Bauhaus Luftfahrt (2016), which estimate the water requirement per litre of synthetic diesel and also from Fasihi et al. (2017).

- the direct air capture (DAC) in case the hydrogen is processed into other products requiring CO_2.

Land can have very different values (socially, economically, ecologically). Competing land uses can vary on a very small scale. For example, while valley floors are being used culturally and for agriculture the adjacent mountain ridges might not be used at all. However, this picture can change entirely if those mountain ridges have a cultural significance.

In general, many countries with low-cost hydrogen production potentials are semi-arid and show vast landscapes of low biodiversity, population density and economic value at first sight. This is significantly different from the production of biomass for energy use in tropical regions. However, due to water needs for electrolysis the locations for hydrogen production plants and their respective RES-E generation technologies could mainly be located close to the coastlines where typically population density and agricultural use is higher (Fraunhofer IEE 2021). However, land that is occupied by RES-E generation plants such as wind power or PV can still be used for agriculture or livestock farming[6].

How much land is needed to produce hydrogen? The literature indicates for example 0.048 to 0.095m²/kW for the electrolysis plant depending on the exact technology being used (Patel 2020). For onshore wind farms, a space requirement of 48 m²/kW was assumed for onshore wind turbines based on (Enevoldsen und Jacobson 2021). For ground-mounted PV systems, Deutsche Energie-Agentur (dena); Energiewirtschaftliches Institut an der Universität zu Köln (EWI) (2018) assume 20 m²/kW. The land requirements of RES-E generation plants are assessed differently. This has to do with the fact that wind turbines, for example, allow land to be used for other purposes such as agriculture, pasture farming or forestry (except for the space required for foundations and access roads). Land use for the generation of electricity from PV systems or wind turbines therefore does not necessarily exclude additional uses. For example, pilot projects are being carried out to test intensive agricultural use (e.g. field crops) underneath ground-mounted PV systems[7]. Disadvantages of a lower machinability of the land are offset by advantages of shading by the PV plants and thus lower water needs for irrigation.

Land-use in terms of areas occupied is dominated by the RES-E generation plants. However, as the social, economic and ecological value of land cannot be described by a quantitative parameter such as square-metres, project specific analysis and stakeholder involvement are necessary.

3.4 Socio-economic impacts

Apart from ecological impacts, the development of hydrogen production facilities may affect the local people and their economy. The following section describes potential human rights infringements as well as possible economic effects. While human rights are regulated in Germany via the due diligence law, the importance of economic effects can be derived from the UN Sustainable Development Goals.

3.4.1 Human rights

While the nature of the hydrogen value chain determines specific human rights risks, a first step in assessing them would be an analysis of a country’s more general human rights situation. If e.g., a country has an autocratic regime, levels of corruption tend to be higher and rule of law tend to be

[6] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/infomaterial/brochures/photovoltaik/20_en_ISE_Flyer_Agrar-PV.pdf accessed on 08.12.2021

[7] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/infomaterial/brochures/photovoltaik/20_en_ISE_Flyer_Agrar-PV.pdf accessed on 08.12.2021

weaker, hence, and the probability that human rights will be adequately considered in hydrogen production is low. Another overarching issue are workers' right. Here, the International Labour Organization (ILO) core labour standards are the globally relevant norm. To assess specific risks, the entire value chain of hydrogen needs to be assessed.

- ***Attacks on human rights and environmental defenders***: Activists are an important safeguard for human rights and protection of the environment when states fail to protect either of them. Attacks on defenders range from frivolous lawsuits, arbitrary arrests and detentions to death threats, beatings and even killings. In 2019 the renewable energy sector was the industry with the fourth highest number of allegations of attacks on defenders globally.[8]

- ***Land rights***: Since RES-E tend to occupy large stretches of land there is a high risk of conflicts around property rights and land use. However, the risk level will be different according to the kind of RES-E production. As described above, with PV and wind co-use of land might be possible and even provide co-benefits. In all cases assessment is needed on whether the use of the land conflicts with the needs of the local population. With hydroelectric power human rights risks regarding land are very likely, since they often involve resettlements schemes.

- ***Right to water***: Local access to water for the local population, either for drinking and sanitary use or for irrigation might be at risk. Whether additional water demand negatively affects local population highly depends on the respective region's water supply scheme.

- ***Right to livelihood***: Whenever the afore-mentioned rights are infringed the right to livelihood may be threatened as well, especially when communities depend on their land and sufficient water supplies for subsistence.

- ***Access to energy***: Access to energy is not a human right. However, in the modern world the realisation of several other human rights is closely linked to the availability of energy. Large industrial developments may limit the chances for local communities to install a RES-E infrastructure that benefits them, because the land that promises the highest RES-E yields is already occupied.

- ***Indigenous rights***: Indigenous populations are often affected by all the above-mentioned risks to human rights, because large RES-E projects are routinely installed on their territories[9]. Furthermore, their livelihood often depends disproportionately on the natural resources on their land.[10] And lastly, the communities often do not possess full legal ownership of their land.

3.4.2 Economic effects in the exporting country

Building a new hydrogen economy with international trade will lead to economic effects in the exporting as well as the importing countries. To evaluate possible economic effects in export countries, we have conducted desk research and interviews in possible exporting countries such as Chile, Morocco, South Africa, Spain and Saudi Arabia.

[8] https://dispatches.business-humanrights.org/hrd-january-2020/index.html

[9] One reason for this is that in the past indigenous communities were often driven from their fertile ancestral lands to mountainous and arid areas that are now well suited for the generation of wind and solar power.

[10] https://ssir.org/articles/entry/respecting_the_rights_of_indigenous_peoples_as_renewable_energy_grows#

At the **state level,** direct and indirect income for the exporting country can be generated through very different channels. In the following we list several options which can be combined to make up the hydrogen business model of a country. It must be noted that developing hydrogen production and exports in a country with an existing fossil fuel exporting business model can provide new business opportunities to an industry in decline and provide a better starting point in building up respective technological and skilled workforce capacities. At the same time, these two business models and their proponents might get into conflict over government resources, infrastructure use and business shares.

- Selling hydrogen or derivatives (e.g. through state-owned companies): with this business model income at the state level would be generated from most parts of the hydrogen value chain. The income would be even higher if derivatives are sold, as converting hydrogen into derivatives would add value to the exported product. However, this could also increase competition with producers in the importing countries.
- Licensing/Lending land for RES-E generation: with this business model constant revenues would be generated. However, only a minimum part of the value chain would generate income for the exporting country. The lack of formal land rights or violation of informal rights might lead to conflicts on the right beneficiaries from the lease/lending.
- Benefiting from infrastructure build-up (excess electricity grid or pipeline capacity, additional RES power plants, additional water supply): Exporting countries could gain from a build-up of a hydrogen economy for exports if infrastructure primary dedicated to serve the hydrogen export supply chain provides excess capacities that can be used for other purposes. Examples would be that parts of the capacity of pipelines or electricity grids remain free for domestic use, new ports including infrastructure are build or additional water from seawater desalination plants is made available to cover domestic demand.
- Other forms of economic participation at the state level include financial instruments such as export taxes or taxes on added value in the country.

At a **regional level** the economic effects can be expected in the following fields:

- Employment of local people: Effects on local labour can be expected to be high for the construction phase but low in the operational phase. Local workforce is needed for the construction phase of the overall hydrogen export project. However, during construction as well as in the operation phase, a significant share of highly skilled and specialised workforce is needed.
- Revenues from lending land if land rights are formally documented.
- Profiting from additional water or electricity if local participation is part of the hydrogen project. This is especially relevant in countries where access to energy, electricity and/or water is still low.
- Literature on the possibility for economic participation of **local companies** and local people in the build-up of a hydrogen export industry and the potential for local value added is very sparse[11]. Economic participation can occur for all parts in which local companies can deliver know-how, technology, and workforce. However, our stakeholder interviews indicate that most countries with large-scale low-cost hydrogen production potentials lack industries for large-scale technology needed within the hydrogen value chain (PV panels, wind turbines, electrolysis, desalination plants, power lines, etc.).[12] Therefore, without additional efforts, economic participation could be

[11] However, first indications can be drawn from Wuppertal Institut; DIW Berlin (2020).

[12] However, there are some companies that deploy new production plants for RES-E technologies in countries of the global south that could be relevant hydrogen producers in the future. An example is the

mainly limited to the building sector. Some countries which have an established natural gas export industry could be able to transfer this know-how and allow a deeper technological and hence economic participation in the build-up of a supply chain for exporting hydrogen or derivatives.

3.5 CO_2 feedstock

Hydrocarbons such as methanol, diesel, petroleum or kerosine require carbon as a molecular component if they are to be produced from renewable hydrogen. When burned, carbon is released again, mainly in the form of CO_2, unless the CO_2 is captured and stored for the long term (CCS[13] or storing solid carbon). For this reason, the essential prerequisite for a potentially climate-neutral production and use cycle of such hydrocarbons is that the CO_2 used for production has been previously removed from the atmosphere, thus creating a closed short-term carbon cycle with the atmosphere[14]. In addition to the direct capture of CO_2 from the air, the use of waste streams from industrial processes based on sustainable biomass is also a possible sustainable source of CO_2.

3.6 Transport

No international hydrogen shipping or pipeline infrastructure is currently in place. However, converting existing natural gas pipelines into regional hydrogen pipelines or building new regional hydrogen pipelines is taking place, already[15]. Also, the first ships have been developed to transport liquified hydrogen[16].

Today, international shipping is based on fossil fuels. Therefore, imported hydrogen would account for CO_2 emissions as long as international shipping is not decarbonised. If other chemicals are used as an energy carrier to transport hydrogen (such as ammonia), risks in handling exist for workers as well as for ecosystems in the case of leakages. For shipping and for pipeline transport, land will be used for ports or pipelines. This can result in ecological impacts or land conflicts.

For transportation, hydrogen needs to be compressed (pipeline transport), liquified (shipping) or even converted into other chemicals such as ammonia (shipping). Each option incurs certain conversion (and possibly reconversion) losses. In addition, there might be losses during transport, for example boil-off losses when shipping liquified hydrogen. The higher the losses due to transportation the more hydrogen needs to be produced in the first place with all the sustainability dimensions to be considered described in the sections above. Therefore, the most efficient transport mode should be considered to keep overall sustainability impacts in the exporting country low.

3.7 Raw materials

Raw materials are needed throughout the hydrogen value chain to produce the technologies required. Renewable power plants and electrolysis plants require rare earths and critical raw materials. Some of these materials are mined under unacceptable working conditions, mines

new production site for blades for wind turbines in Morocco https://www.siemensgamesa.com/newsroom/2017/10/siemens-gamesa-inaugurates-the-first-blade-plant-in-africa-and-the-middle-east.

13 Carbon Capture and Storage.

14 If relevant amounts of products such as methane with a higher GHG impact than CO_2 are produced during use, or if the hydrocarbon is burned at high altitudes in aviation, for example, with the corresponding higher GHG impact, the carbon cycle is not climate-neutral but associated with an additional negative GHG effect.

15 https://www.get-h2.de/projekt-lingen/.

16 https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487.

contribute to pollution and are a risk to health for local communities. Iridium is used in some electrolysers and could be a limitation to the uptake of hydrogen production due to its low availability (Fraunhofer ISE; E4Tech; Fraunhofer IPA 2018).

As this report focuses on sustainability dimensions associated with the import of hydrogen, we did not focus on the raw materials needed for the technology base. In principle the resources and materials needed are the same if hydrogen is produced in Europe or elsewhere. However, due to higher capacity factors (meaning the utilisation of the technologies and therefore more hydrogen production per unit of technology) in the countries that possibly export hydrogen in the future, less technology is needed to produce the same amount of hydrogen and hence, the socio-ecological impact due to mining of raw materials could be lower.

However, the question remains how sustainable green hydrogen must also build on technologies based on raw materials with low ecological impact that are mined with high working standards. Further research is required in this field.

4 Guardrails and goals for hydrogen production

The main sustainability dimensions identified were substantiated and put into perspective by the country analysis carried out within the project. Assessing the sustainability impact of hydrogen imports goes far beyond analysing the electricity input for the electrolysis:

- While **“green” hydrogen** is defined by electricity supplied from RES-E, its sustainability impact crucially depends on additional dimensions.
- Hence, we suggest using the term “**sustainable green hydrogen (SG-H_2)**” if the following sustainability dimensions are addressed in the hydrogen supply chain: **electricity supply, water supply, land use, human rights, economic effects,** and **transportation.**

In this section we define overarching “guardrails” and “goals”, which address two different levels of ambition:

- We define **“guardrails”** that ensure that hydrogen supply does not have a negative sustainability impact and follows the “do no significant harm” principle. Hence, guardrails constitute minimum requirements that must be fulfilled so that the local ecological and socio-economic situation is not worsened. For example, guardrails on the water input ensure that access to water for the local population is not reduced or gets more expensive due to hydrogen production in the country.
- We define **“goals”** that link hydrogen supply to improving local ecological and socio-economic circumstances. For example, a goal in the field of water supply is to increase fresh water supply in the respective communities. Additional fresh water could be supplied by additional saltwater desalination capacities as part of the hydrogen supply project.

4.1 Electricity supply

Guardrails: Electricity input for hydrogen production needs to be produced in a way that makes sure that additional electricity demand does not lead to additional CO_2 emissions within the energy system. To produce green hydrogen, electricity needs to be generated by RES-E plants. As a guardrail, electricity input for hydrogen production must come from additional renewable electricity sources. This way RES-E generation is not withdrawn from the existing electricity system.

As a source for RES-E only technologies with high generation potentials and low ecologic and social impact should be considered. We therefore suggest focusing on wind and PV. Sustainable biomass potentials are limited and available potentials should be reserved for uses in the decarbonisation of the energy system that require heat or CO_2 input. New hydropower projects come with a large-scale ecological impact and local land-use change leading to various conflicts in the past[17].

The use of RES-E resources must not slow down local uptake of RES-E in the transformation of the energy system or increase the future cost of the local energy transition. However, this criterion needs a baseline which lacks a proven methodology and comparable goals for RES-E development. Verifying additionality of RES-E supply for on-grid projects[18] requires established registers, functioning certification, and monitoring, reporting and verification (MRV) schemes (see Oeko-Institut 2021).

[17] https://ejatlas.org
[18] Hydrogen production plants that source electricity from the grid.

Goals: Local hydrogen projects could be used to support local energy transition and electricity access. The choice of the concrete measures needs to be discussed with the exporting countries and local communities which instrument (for example a fund or concrete infrastructure) is the most suitable one. For projects that source electricity from the grid, contributions to decreasing energy transition costs (such as electricity storage or grid development) should be a goal.

4.2 Water supply

Guardrails: The production of hydrogen must not lead to additional pressure neither on short-term, nor on seasonal or long-term water availability. This guardrail ensures that no negative effects arise for the ecosystem and biodiversity. Also, water scarcity for local communities and water cost must not increase. As high potentials for low-cost hydrogen production exist in (semi-)arid regions with increasing demand for freshwater, we conclude that in most cases hydrogen production will lead to additional pressure on water resources. Therefore, using seawater desalination (SWD) seems to be the more sustainable option. However, criteria must make sure that seawater desalination plants meet high ecological standards regarding brine disposal, efficiency and the use of RES-E for power supply. To date, no international standards are available to ensure this, but they must be developed to allow for sustainable green hydrogen production. In addition, SWD plants should be new and additional, providing all the water needed for the whole value chain (including cooling, electrolysis and PV cleaning) of hydrogen production.

Goals: In terms of the Sustainable Development Goals, projects should aim at increasing local water availability. The goal could be to increase total volumes or improve the seasonal water availability balance. Excess freshwater from SWD plants could be supplied to local communities and water storage facilities could be deployed. Moreover, efficiency of local water infrastructure in terms of losses and evaporation could be increased through dedicated investments.

4.3 Land use

Guardrails: As a baseline, formal and informal land rights must not be violated by any part of the hydrogen value chain. In addition, we suggest that investors must prove that land use does not have a significant residual impact on biodiversity, agricultural land and cultural land. Interference with biodiversity and cultural land is addressed in existing criteria (such as IFC World Bank). Criteria for hydrogen plants should build on these existing standards. Involving local communities seems to be crucial, as land rights and cultural value are not always formally described.

Goals: Wind and PV plants do not lead to an exclusive use of the land. Extensive farming can be carried out underneath wind farms and PV panels can even shade agricultural areas. This leads to win-win situations which should be aimed at. Another issue is the financial participation of local communities in revenues from land use. This issue is also often discussed in EU Member States. Communities hosting parts of the hydrogen value chain or those that are in visible distance to RES-E plants should participate in respective financial gains involved. This might secure the long-term acceptance of hydrogen plants.

4.4 Socio-economic impacts

Human rights: Human rights must be respected in the whole value chain of hydrogen imports. To guarantee respect of human rights, the due diligence approach, based on the UN Guiding Principles on Business and Human Rights, should be applied. Following best practice in the application of due diligence in other sectors we suggest that an internationally accepted body (e.g. the OECD or EU) defines sector-specific risks and adequate measures to mitigate these risks. As the value chain for hydrogen imports does not exist yet, defining the crucial aspects of human rights can only be done based on plausibility and criteria used for example by the International Finance Cooperation (World Bank Group) or the European Investment Bank to assess renewable energy projects. The risk assessment should address the country, technology and project level. Moreover, criteria need to be fulfilled not only in the project planning and construction phase but also during the operation phase (especially for water input, electricity input, transport of hydrogen). The full due diligence cycle must be observed, including the installation of non-judicial grievance mechanisms and reporting requirements.

Economic participation: Economic participation in the exporting country should be ensured on two levels: hydrogen projects should increase local employment, and substantial shares of the value-added should be generated within the exporting country. However, data is missing on expected added value for any part of the value chain. Our own research has indicated that operating hydrogen plants will not be labour-intensive and we expect that the main workforce will be highly skilled workers. In the short term, most of the technology components will not be produced within the exporting countries and must be imported. Based on these findings, local education and research centres should be aimed at, as a stepping stone to long-term economic participation. We also expect tough political negotiations on which parts of the hydrogen value chain should be located in the exporting countries. Sustainable development in exporting countries can partly conflict with geopolitical and economic interest in importing countries. It could be a goal to link the deployment of hydrogen plants to Sustainable Development Goals (SDGs). Hydrogen projects could be embedded into local SDG programs. Relevant SDGs in relation to the hydrogen value chain are:

- SDG 6 (clean water)
- SDG 7 (affordable and clean energy)
- SDG 8 (decent work and economic growth)
- SDG 9 (industry, innovation, and infrastructure)

4.5 CO_2 feedstock

We see two sustainable options to provide CO_2 as a **guardrail in the long term**:

- Direct Air Capture (DAC) and
- waste streams from industrial processes based on sustainable biomass.

However, Direct Air Capture comes with high energy (electricity) demand and some technologies require significant space for which all guardrails addressed in the previous sections on electricity and land use should apply.

Because DAC is very expensive to date and sustainable biomass is limited, the **short-term guardrail** could be the use of unavoidable process emissions (cement production, glass production) with a robust phase-out strategy towards DAC.

4.6 Transport

Shipping or pipelines are the options for long-distance transport of hydrogen or derivatives. The following **goals** could be aimed at to reduce the impact of transport on sustainability dimensions:

- Pipeline transport should be preferred to shipping as long as there are no “zero-emission” ships in operation.

- Existing natural gas pipelines should be retrofitted to be used for hydrogen. This will keep impact on land use, ecosystems and use of resources low.
- Conversion of hydrogen (e.g. into ammonia or LOHC) only for transport reasons and recovering hydrogen at the destination should be kept at a minimum due to conversion losses. The more losses that occur during transport the higher the impact on all sustainability dimensions (more space needed for RES-E, more water use, etc.) in the exporting country.
- The use of hazardous substances should be limited if possible, for the sake of labour security and possible harm to the environment.

5 Suggesting specific criteria: Minimum standards and options for additional support of sustainable development

Based on the guardrails and goals described in the section above, concrete options for criteria are suggested in the following. We differentiate between minimum standards and options that further support sustainable development for each sustainability dimension. The options presented in this section must be interpreted as a suggestion for future criteria but are not a detailed definition of criteria to be used in a certification process.

- The **minimum standard** should make sure that no harm is done by producing and exporting hydrogen. These criteria could be used for **defining green and sustainable hydrogen** in legislation such as quota systems for hydrogen in the importing countries.
- The **options for additional support of sustainable development** suggest additional criteria that support a sustainable development within the exporting countries. These criteria could for example be used by private certification schemes or by publicly funded projects.

In order to operationalise the criteria, it is necessary to further specify the level on which they should be applied and verified (e.g. at the country level, at the project level) and the verification time and frequency (e.g. prior to project approval or continuously).

In Figure 5-1 we give an overview of the suggested criteria and options. The elements of this figure are described in more detail in the sections following it. We have not mentioned “transport”, “CO_2 sourcing” and “raw materials” in Figure 5-1 as these dimensions were not in the focus of our research. However, we do address a few issues related to “transport”, “CO_2 sourcing” and “raw materials” in the sections following the figure.

Figure 5-1: Possible criteria for sustainable green hydrogen

Country specific

- National decarbonisation strategy (NDC) should include hydrogen production
- Perform a Strategic Environmental Assessment (SEA)
- Work towards Hydrogen strategy addressing sustainability dimensions (power, water, land-use, socio-economics, transport, CO2-feedstock)

Project specific

- Environmental Impact Assessment
- Sustainability Impact Assessment (SIA)
- Consultation of local stakeholders
- Grievance mechanisms
- No significant harm to SDGs (especially SDG 6 to 9)

	Electricity	Water	Land use	Socio-economics

Minimum standard	• Exclude Biomass and Nuclear power plants
	• If sourcing from direct connection to dedicated RES-E capacity:
	  ◦ RES-E should be additional
	• If sourcing from electricity grid:
	  ◦ RES-E should be additional
	  ◦ Temporal correlation to RES-E
	  ◦ Geographical correlation to RES-E
	• Address competition for RES-E sites between exports and local decarbonisation
		• Exclude surface and ground water in areas with regional water stress
		• If sourcing from Sea Water Desalination (SWD):
		  ◦ SWDs should be powered by RES-E
		  ◦ SWDs water supply need to be additional
		  ◦ Compliance with yet to be developed international environmental standard for brine disposal
		  ◦ Monitoring and securing existing water prices
			• Exclude protected areas
			• Respect local (informal) land rights
				• Comply with due diligence
				• Secure human rights
				• Prevent corruption and enable monitoring local economic participation (Transparency Initiative)

support of sustainable development	• Additional RES-E capacity to decarbonize local energy system
	• Provisions for additional (funds for) infrastructure
	  ◦ Flexibility
	  ◦ Grid
		• Additional water production exceeding the needs for hydrogen production
		• Improve existing water infrastructure
			Enable co-benefits, for example:
			• Shading from "Agri-PV"
			• Local economic participation
				• Capacity Building (R&D)
				• establishing and operating a local supply chain for technology
				• Secure a share of local work force

SWD: sea water desalination | RES-E: renewable energy sources electricity | "Additional", refers to the principle of additionality: In practice this needs further specifications such as developing a baseline projection and taking into account interference with other parallel developments.

Source: Oeko-Institut, own graphic

Country-specific risk assessment

Countries aiming at exporting green hydrogen and its derivatives should provide a decarbonisation strategy which includes hydrogen production. This could be done as part of the Nationally Determined Contributions (NDCs). Moreover, a Strategic Environmental Assessment (SEA)[19] should be mandatory. Suggestions for improvements unveiled by the SEA should be integrated in decarbonisation and hydrogen policies. In addition, exporting countries could work towards a hydrogen strategy addressing the main sustainability dimensions like electricity, water, land use, socio-economics, transport and CO_2 feedstock.

Project-specific risk assessment

Project-specific risk evaluation should not tolerate any substantial risk in the following assessments: Environmental Impact Assessment based on current frameworks[20] and socio-economic impact assessments such as Sustainability Impact Assessments (SIA)[21]. Also, due diligence needs to be reported throughout the whole value chain. Further, at the local or regional level stakeholders should be consulted and involved during the whole project planning process and grievance mechanisms need to be implemented.

In general, the project should not do any significant harm to any SDGs, relevant SDGs include SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation and infrastructure). In a further step concrete actions to support these SDGs could be implemented by the hydrogen project.

Electricity supply

Obviously, green hydrogen can only be sustainable when the electricity is sourced from RES-E. Electricity based on biomass and nuclear power should be excluded. Hydropower could be accepted in accordance with the European minimum requirements of the Water Framework Directive (WFD). We suggest making use of the existing definitions of the current European Renewable Energy Directive (REDII). All provisions of RED II Recital 90 and future Delegated Act should be applied and further specified such that the requirement can be fulfilled by exporting countries:

- In case of electricity supply from the grid, additional and new RES-E plants that produce the amount of electricity needed for hydrogen production should be installed in the same grid area. The sourcing of green electricity must be certified and proven by Guarantees of Origin (GOs). The operation of the electrolysis should follow the current RES-E production or grid needs (flexible operation). Furthermore, the siting of the electrolysis plants should consider implications on the grid and avoid worsening grid bottlenecks.
- In case the hydrogen production plant is directly connected to dedicated RES-E, these renewable energy sources should be new and additional.

Instruments should be provided to make sure that export of hydrogen does not impede the decarbonisation of the local energy sector. This could be the case if best sites for RES-E production are mainly used to produce hydrogen for exports. We see the following options to address the

[19] Based for example on the OECD recommendations OECD (2006).
[20] Based for example on Guidance of the European Commission EC (2017).
[21] Based for example on the European guidelines EC (2016).

competition between RES-E sites being used for hydrogen exports versus domestic decarbonisation:

- Exporting countries could prove how developing a certain number of RES-E sites for hydrogen production is compatible with a mandatory national decarbonisation strategy (for example NDCs[22]).
- Alternatively, areas for RES-E development for hydrogen production could be designated that do not interfere with the RES-E deployment needed for domestic decarbonisation. This could be sites that are far away from electricity demand centres.
- To support further sustainable development within the exporting country, more RES-E capacity could be installed that exceeds the capacity needed to generate electricity for hydrogen production and is embedded in a local decarbonisation strategy. Moreover, excess investments in the local grid infrastructure or additional flexibility for balancing the grid like battery storage could further support SDGs.

Water supply

Groundwater and surface water are to be excluded in areas with water stress[23]. It is important to ensure that a negative impact on local water prices is prevented and that no price distortion occurs.

Using seawater desalination facilities (SWD) to produce freshwater is another option. These plants should fulfill minimum efficiency standards and yet to be developed international environmental standards on brine disposal to avoid negative environmental impacts. Also, these plants should be additional to the existing ones so that no competition of water or price distortions occur. To ensure sustainability SWD plants should be operated with RES-E.

Options to add to sustainable development could be the production of additional (fresh) water for the local population and the support of local projects for water supply efficiency, e.g. infrastructure to reduce leakage or evaporation.

Land use

As regards the location of hydrogen production facilities and especially the deployment of RES power plants, it is important to respect local land rights including informal rights. Here, it is helpful to refer to the SIA and consult local stakeholders. Moreover, no parts of the hydrogen value chain (including RES-E and production) should be developed in protected areas (e.g. UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC)).

Additional (co-)benefits for local communities could improve sustainable development. Options are local economical participation (such as payments to the effected local community) or to use shading from PV modules for agriculture.

[22] Nationally determined contributions are national goals concerning climate protection in relation to the Paris Agreement.

[23] A source could be the World Resource Institute's Water Risk Atlas. Applicable water stress levels must be defined.

Socio-economic impacts

We suggest following the due diligence procedure (incl. publication and contact points[24]). Sector-specifc risks should be defined and adequate measures to mitigate those risks should be reported. Also, corruption must be prevented, for example based on an international initiative like The Extractive Industries Transparency Initiative (EITI) but with a focus on hydrogen.

Sustainable development could further be supported by the following actions:

- investments in local capacity building, which could be Research and Development or trainings;
- establishing and operating a local supply chain for hydrogen production and RES-E technology;
- prescribing a certain share of local workforce to be employed during construction as well as operation of the hydrogen production plant.

CO_2 feedstock

CO_2 is needed to produce hydrocarbons. Only CO_2 that originates from sources that create a closed short-term carbon cycle with the atmosphere should be used. Therefore, we suggest to only use CO_2 from Direct Air Capture (DAC) or from waste streams from industrial processes based on sustainable biomass.

Transport and raw materials

For transport and raw materials we do not suggest specific criteria as these areas were not in the focus of our research. However, international labour safety standards are crucial for the whole value chain. The due diligence approach could help to secure acceptable labour safety.

[24] For example based on the OECD Due Diligence Guidance for responsible Business Conduct OECD (2018).

6 Existing sustainability criteria for hydrogen production

There are several sets of criteria for hydrogen production that have been published to date. Table 6-1 shows a selection of existing sets of criteria and the sustainability dimensions addressed. The following sections give further insights into the selected sets of criteria.

Table 6-1: Existing sets of criteria addressing various sustainability dimensions

	Electricity	Water	Land Use	Human Rights	Economic effects	Transport	CO_2 sources for derivative
REDII	✓						
EU Taxonomy	✓	✓					
IPHE Methodology	✓						
atmosfair	✓	✓		✓			✓
CertifHY	✓						

Source: Oeko-Institut, own compilation

Renewable Energy Directive (RED II, Directive EU 2018/2001)

The RED II states criteria for the use of electricity from the grid to produce renewable fuels of non-biological origin (RFNBOs) in Recital 90. According to this recital, the following issues must be addressed: renewability of power purchase, additionality of RES-E sources and both temporal and geographical correlation between hydrogen production and RES-E generation. The delegated act is still pending. The RED II thus focuses on the electricity input and the system integration of the electrolysis. For hydrogen (and other synthetic fuels) to be used in the transport sector, Article 25(2) furthermore provides a minimum GHG reduction threshold of 70% compared to the fossil comparator. Other sustainability dimensions in the hydrogen supply chain such as water input, land use and socio-economic issues are not addressed in RED II.

EU taxonomy

"*The EU taxonomy is a classification system, establishing a list of environmentally sustainable economic activities. It could play an important role helping the EU scale up sustainable investment and implement the European green deal. The EU taxonomy would provide companies, investors and policymakers with appropriate definitions for which economic activities can be considered environmentally sustainable.*"[25]

The current Annex II to the Commission Delegated Regulation 2020/852 sets standards to "do no significant harm ('DNSH')" relating to the following sustainability dimensions:

- Electricity input: In accordance with the provisions made in the REDII (EU 2018/2001) hydrogen production must comply with "[…] *the life cycle GHG emissions savings requirement of 70% relative to a fossil fuel comparator of 94g CO_2e/MJ* […]".This implies that hydrogen production must not emit more than 102 g CO_2e/MWh. Hence, in countries with a very low emission factor

[25] https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en, accessed 18.11.2021

within the grid (e.g. Norway) an electrolysis sourcing electricity from the grid can comply with the provisions set by the taxonomy.

- Water input: The taxonomy requires an EIA. Criteria is met if risks identified have been addressed.
- Biodiversity: The taxonomy requests an EIA, and the required mitigation and compensation measures for protecting the environment must be implemented. Biodiversity-sensitive areas (such as Natura 2000) are not excluded but must carry out an appropriate assessment.

IPHE Methodology

The IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) is an international partnership of governments aiming at promoting and accelerating the uptake of hydrogen in the economy[26]. The IPHE published a “Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen”. This methodology takes a well-to-gate approach in determining GHG emissions associated with hydrogen production, covering all possible types of hydrogen production and electricity sources. Hence, there is a strong focus on the electricity input as well as upstream emissions for grey and blue hydrogen (such as methane emissions). Other relevant sustainability dimensions such as water input, land use, transport and social economic issues are not considered. Also, because the methodology only focuses on hydrogen, CO_2 to produce derivatives is not part of the methodology.

fairfuel standard by atmosfair

The company atmosfair published a set of criteria for the production of CO_2-neutral kerosine in 2021 (atmosfair 2021). This set of criteria addresses the sources of CO_2, electricity input, water and social standards as well as governance. The issues of land use, transport and economic effects are not explicitly addressed. The standard set by atmosfair is explicitly not to be used for fuels used in road transport. This shows how standards can foster specific uses of hydrogen and its derivatives. It also addresses specific sources of CO_2. Private standards have the option to define such technology-specific provisions.

CertifHy

The CertifHy project is a project at the European level which aims at developing and implementing a certification system for hydrogen in Europe. It is currently in its third phase (until 2023) and is funded by the Fuel Cell and Hydrogen Joint Undertaking (FCH 2 JU), a public-private partnership initiated by the European Commission. In the previous phases of the project (phase 1 and phase 2) a definition of criteria for “CertifHy green hydrogen” and for “CertifHy low-carbon hydrogen” were developed. These are applied in test applications in order to issue tradable CertifHy guarantees of origin for hydrogen. In the third phase CertifHy is currently working on the development and implementation of hydrogen certification systems in line with RED II in Europe in the period up to 2023. With the collaboration of the Association of Issuing Bodies (AIB), a market-compatible[27] hydrogen proof of origin system is to be developed and implemented and applied at least in individual pilot countries. The focus is on green hydrogen according to the requirements of RED II, but the development of a tracking system for non-renewable hydrogen (blue hydrogen) should also be included in the system, if possible. In addition, a certification system is to be developed that ensures

[26] https://www.iphe.net/
[27] In practice, this means that the guarantees of origin should be in line with the European Energy Certificate System (EECS), which is established and maintained by the AIB.

compliance with the requirements of RED II for RFNBOs and, in this sense, is to be recognised by the Commission as a voluntary verification system.

CertifHy focuses on the definition of green hydrogen from renewable sources and “low-carbon hydrogen” from non-renewable sources by setting criteria for the electricity input. General GHG emissions thresholds are defined for the hydrogen production based on requirements defined in RED II, and for the overall performance of the hydrogen production device. Other sustainability dimensions are not under consideration (CertifHy 2019, p. 7).

7 A pathway for the uptake of sustainability criteria for hydrogen

Several steps must be taken to facilitate the uptake of sustainability criteria for sustainable green hydrogen. In the following section we focus on two main questions:

- Where can and should sustainability criteria be incorporated?
- What are the next steps to be taken for policy makers and regulatory bodies?

7.1 Where can and should sustainability criteria be incorporated?

Sustainability criteria for hydrogen production and transport can be incorporated in various regulatory frameworks established at the international, EU, national or private entities' level (see Figure 7-1).

Figure 7-1: Options for placement of sustainability criteria for hydrogen imports

Source: Oeko-Institut, own graphic

International trade regulations for energy goods (such as those established under the World Trade Organization (WTO) or under the Energy Charter Treaty) currently mainly focus on non-discriminatory market access and investor security. However, these institutions can also provide an established and accepted platform to define minimum sustainability criteria that could be accepted and shared by all partners. New financing guidelines such as the EU taxonomy for sustainable activities already set specific criteria following a "do no harm" approach and formulate criteria addressing sustainability dimensions, mainly focusing on biodiversity, socio-economic effects and ecological impact. Expanding this regulation to include financing of hydrogen imports and incorporating additional sustainability criteria would be a natural extension to the EU's attempt to direct investments towards sustainable projects and activities. At the EU level, standards set out in the Renewable Energy Directive (RED II) will have a major impact on potential hydrogen imports by defining eligibility criteria to meet targets set out in the directive. However, up to now only GHG emissions and the electricity input have been addressed. These standards are currently designed with a view on European markets, technology levels, existing institutions and regulations. They need to be specified and adapted to become operational and effective for hydrogen imports. Private initiatives such as CertifHy and TÜV Süd are already working to operationalise current standards for voluntary labels defining standards for "low-carbon" and "green" hydrogen. These initiatives can become key players in building capacities and defining procedures to operationalise sustainability criteria and initiating the build-up of required entities and institutions.

Given different underlying financing mechanisms and different users of the final products, we see two main types of hydrogen projects that are driven by different levels of sustainability ambitions:

1. **Projects aiming at lowest cost hydrogen production** will have two major drivers for criteria: on the one hand the financing guidelines (EU taxonomy) and on the other hand the European regulatory framework, mainly RED II. The combination of both will lead to hydrogen based on additional renewable electricity sources and will follow the "do no harm" principle concerning socio-economic issues, water sourcing and ecological issues.
2. **Projects with high sustainability ambitions** could follow higher standards in some sustainability dimensions (referred to "additional options to support SDGs" in section 4.6 of this report). These higher standards should be incentivised by criteria defined to receive financial support. Examples could be cases of state procurement of hydrogen (such as the German H_2 global initiative) or specific project support schemes. A second option to set higher standards could be to implement private labels for hydrogen (such as atmosfair fairfuel, see section 6).

7.2 What are the next steps?

Although the process to develop certification systems has started already (for example CertifHY) sustainability criteria have not been incorporated yet. We see the following issues that must be addressed at the regulatory or political level:

Work towards a set of sustainability criteria at an international level

We suggest defining a set of sustainability criteria for hydrogen production and transport at an international level. This could make sure that at least the most relevant sustainability dimensions are addressed when a worldwide hydrogen market evolves. A lack of international standards could lead to a "race to the bottom" because hydrogen production with low sustainability standards will also result in low production costs for hydrogen.

In addition, an international set of sustainability criteria will add to the security of investment especially for early hydrogen projects. If there is no specific set of criteria, investors will hesitate to invest into hydrogen projects as they do not know if their hydrogen will be eligible under yet to be defined criteria in the future. At a minimum, common criteria will need to be defined at the European level, otherwise common climate protection targets and subordinate targets could be undermined. Standards do not only include certain sustainability dimensions (such as water sources) but also consider how certain assessments at a project level are to be carried out (such as the Environmental Impact Assessment).

Foster the uptake of certification systems for sustainable hydrogen and resolve open questions

For all sustainability dimensions and each specific criterion an international standard for auditing and monitoring is needed. This could for example be provided by the Association of Issuing Bodies (AIB)[28]. Also, an international standard for a project fact sheet providing the necessary data for certification is needed.

For the electricity input a GO system must be developed and implemented in the exporting countries. These domestic systems could be based on the existing EU certification regulation. However, national regulators must implement the schemes. Robust monitoring and audit systems need to be implemented as many criteria must be monitored and audited each year.

How can existing (European) criteria that rely on data and comparability that is not available in all countries be met by other countries? An example is that provisions of RED II (Recital 90) ask for temporal and geographical correlation between hydrogen production and RES-E generation. However, data for temporal correlation and definitions for market areas and grid congestion are not defined and available in many countries. As a result, criteria based on RED II might not be applicable in some countries. Hence, criteria need to be specified and adapted to allow importing countries to meet the respective standards.

Set sustainability standards for Seawater Desalination (SWD)

An international standard for sustainable seawater desalination, addressing energy consumption and brine disposal, is missing. This could be provided by international collaboration schemes and developed into an ISO standard.

Establish initiatives that set standards and monitor socio-economic effects

Just like the Extractive Industries Transparency Initiative (EITI) an initiative could be established to make sure the hydrogen sector and its export is beneficial to the local population within the exporting country. This initiative could set standards, provide transparency, and monitor socio-economic effects. Beside the industry and governments, the local population and non-governmental organisations should be part of such an initiative.

Cooperate closely with possible exporting countries

Sustainability standards should be discussed with possible exporting countries and their public from the very beginning. This is important for two reasons: For one thing, additional country-specific sustainability dimensions can be addressed appropriately. For another, this will add to transparency to which criteria will be relevant in the future so that strategies of exporting and importing countries can be aligned.

[28] https://www.aib-net.org/

Annex I. Explanations and sources for Figure 1-1

The calculation procedure and the corresponding sources are described below, starting from the top right and working clockwise to the bottom left.

Hydrogen demand: 169 TWh

- For the year 2045, an annual hydrogen import demand of 169 TWhhu is forecast for Germany. (Agora Energiewende; Stiftung Klimaneutralität; Agora Verkehrswende 2021, 25 (Abb. 12))

Transport

- For the calculations, transport by pipeline was assumed. This would be conceivable for imports from Morocco, for example, since there is geographical proximity and at least one natural gas connection already exists here. Pipeline transport requires additional energy. In the area of the natural gas network, the energy for the compressor stations is usually provided by natural gas. For the calculations, it is assumed that the energy required for the compressor stations in the hydrogen network is also provided by hydrogen. The compressor has an electricity demand of 0.02 kWhel/kWh H2hu. If an efficiency of 35% is assumed for an OCT gas turbine running on hydrogen, this results in an additional hydrogen demand of about 6%. To satisfy this additional demand, a total of 179 TWh Hu must be produced.

Water demand: 49 m. m^3

- *Water consumption for electrolysis*: The International Energy Agency (IEA) estimates the water consumption for electrolysis at 0.27 litres per kWh of hydrogen (2019, p. 43). If electricity is to be generated exclusively via PV systems, this results in an additional water requirement of 0.02 l/kWhel (Hernandez et al. 2014) for cleaning the PV panels. In the case of the use of Concentrated Solar Power (CSP) for electricity generation, the water demand can increase further (Hernandez et al. 2014).

Electricity demand: 255 TWh

- Efficiency of the electrolysis plant: 70%; this assumes PEM electrolysis in the GW range. The efficiency refers to the entire plant including ancillary plants for control and operation. The value corresponds to the average of values for 2040 and 2050.[29]

Comparison: electricity demand

- *255 TWh with 85 GW installed capacity*: To generate 255 TWh per year, an installed capacity of onshore wind power plants of around 85 GW is required. It is assumed here that the plants are fully utilised in around 3,000 hours per year due to the wind supply (fullloadhours for Morocco: (Fraunhofer IEE 2021))
- *104 TWh with 54 GW installed capacity*: In 2020, electricity generation from onshore wind turbines in Germany amounted to around 104 TWh. At the end of 2020, the installed capacity of onshore wind turbines in Germany was around 54 GW. (BMWi 2021)
- *8 TWh with 3 GW installed capacity*: In the area of African countries in the Mediterranean region, only Morocco and Egypt had relevant amounts of onshore wind energy plants in 2020. In 2020,

[29] Douma, J., Vos, M. (2020): Database with techno-economic data for the import of liquid renewable energy carriers. DNV GL. https://www.gie.eu/wp-content/uploads/filr/2599/2020-09-09%20-%20DNV%20GL%20-%20GIE%20database%20Liquid%20Renewable%20Energy%20(draft%20final).xlsx Zuletzt aufgerufen am 12.11.2021.

electricity generation from onshore wind turbines in these countries amounted to around 8 TWh. At the end of 2020, the installed capacity of onshore wind turbines here was around 3 GW.[30]

Comparison: water demand

- *3,700 m. m³:* In 2016, each person used an average of 123 litres of drinking water per day. With 365.25 days per year and a population of 82.349 million, the water demand for private households is around 3,700 million m3 of drinking water.[31]
- *15,500 m. m³:* In 2018, 15,500 million m3 were used in the Spanish agricultural sector.[32]

[30] IRENA (2021): RENASTAT Online Data Query Tool. http://pxweb.irena.org/pxweb/en/IRENASTAT . Zuletzt aufgerufen am 12.11.2021.

[31] UBA (2020): Wassernutzung privater Haushalte. https://www.umweltbundesamt.de/daten/private-haushalte-konsum/wohnen/wassernutzung-privater-haushalte#direkte-und-indirekte-wassernutzung . Zuletzt aufgerufen am 12.11.2021.

[32] Instituto Nacional de Estadística (2020): Distribution of water to agricultural holdings by Autonomous Community, types of crops/irrigation techniques and period https://www.ine.es/jaxi/files/_px/en/xls/t26/p067/p03/serie/l1/02003.xls?nocab=1 . Zuletzt aufgerufen am 12.11.2021.

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