Comparing sustainability of RES- and methane-based hydrogen

Sustainability dimensions, blind spots in current regulation and certification, and potential solutions for hydrogen imports to Europe

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Abbreviations

ATR	Autothermal reforming
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Use
CH_4	Methane
CO_2	Carbon dioxide
DAC	Direct Air capture
GO	Guarantees of Origin
H_2	Hydrogen
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
LCFS	Low carbon fuel standard
NG	Natural gas
NO_x	Nitrogen oxide
RED	European Renewable Energy Directive
RES	Renewable energy source
RES-E	Renewable energy source electricity
SDG	Sustainable development goals
SMR	Steam methane reforming

1 Setting the scene

The regulatory landscape for hydrogen sustainability in the EU can be compared to a complex building site at an early stage of development, where the overall goal is clear, some foundations and cornerstones have been or are in the process of being erected, but a number of important elements is still being designed by teams that must consider partly conflicting interests as well as exogenous enfolding events. This paper aims at shedding light on parts of this complexity.

Achieving climate neutrality by 2050 is one essential reason for the EU to pursue its hydrogen strategy. Therefore, the GHG emission intensity of hydrogen production and transport is crucial. However, EU policy makers must also consider a number of other goals, such as the security and resilience of the energy supply system, its affordability, geopolitical issues, industrial policy, the integrity of the internal market, development policy goals as well as other sustainability issues. This paper focuses on sustainability including its environmental, economic, social, and governance dimensions. While there is a growing literature on the sustainability of hydrogen from renewable electricity (for example World Energy Council; DENA (2022), Oeko-Institut (2021), ILF; LBST (2021), Nationaler Wasserstoffrat (2021)), this paper adds a view on the sustainability issues associated with methane-based hydrogen.

Based on the identified sustainability dimensions of hydrogen from renewable electricity and from methane (CH_4), the report performs a screening of the main elements of selected existing and proposed regulations and certification schemes in the EU and in some non-EU countries as well as of selected literature in the surrounding debate. The focus is on highlighting possible gaps or shortcomings in the existing and planned regulatory framework regarding sustainability criteria and on identifying areas where the EU needs to act to prevent “a race to the bottom” as well as best practice initiatives that can serve as blueprints for more general (international) standards.

The emerging EU policy framework is currently set to distinguish between three main types of hydrogen:

- Renewables-based hydrogen, either from biomass or from electrolysis based on renewable electricity, as defined by the EU Renewables Directive 2018/2001 (RED II). Concerning the electrolysis, the detailed criteria will be specified in a delegated act, which, at the time this text has been concluded, has not yet been tabled by the European Commission.
- Low-Carbon hydrogen: according to Article 2 (10) of the proposal for a Directive “on common rules for the internal markets in renewable and natural gases and in hydrogen” presented by the Commission on 15 December 2021, ‘low-carbon hydrogen’ “means hydrogen the energy content of which is derived from non-renewable sources, which meets a greenhouse gas emission reduction threshold of 70%”. The same principle is valid for synthetic fuels based on hydrogen (‘low-carbon fuels’). Article 8 (2) of the proposal states that, for the purpose of demonstrating that the 70% threshold is fulfilled, gas market players shall use a mass balance system according to the rules of RED II. Article 8(4) of the proposal specifies that the 70% threshold shall apply both to low carbon fuels (i.e. hydrogen and derivatives) produced in the EU and to those imported. Art 8 (5) of the proposal determines that the Commission will adopt delegated acts by 2024 to specify

the methodology for assessing GHG emission savings. Otherwise, the proposal does not specify the exact benchmark against which the 70% reduction shall be calculated.[1]

- Grey hydrogen, i.e. hydrogen that does neither fulfil the criteria for renewable nor for low-carbon hydrogen. Sustainability criteria are applied only as long as they are included in general legislation, such as the EU Water Framework Directive and the EU Groundwater Directive in the field of water pollution or the EU Habitat Directive and the EU Marine Strategy Framework Directive in the field of biodiversity.

The EU regulatory landscape regarding hydrogen sustainability will also be affected by two further ongoing EU legislative processes. The proposed Regulation “on methane emissions reduction in the energy sector”, when adopted and implemented, will lead to a much stricter monitoring, measurement, and reduction of CH_4 emissions. By doing so, it will increase the price and decrease the GHG impact of hydrogen based on methane. However, if not modified in course of the legislative process, the rules of the EU methane emission regulation will only apply within the EU borders, and not to the upstream CH_4 emissions associated to the very large share of imported CH_4. Second, the future EU Carbon Border Adjustment Mechanism (CBAM) might be applied also to imported hydrogen (and its related CO_2 emissions), if the relative amendment of the European Parliament’s rapporteur, MEP Mohammed Chahim, will be adopted (EP 2021).

Interaction of the three types of hydrogen in the market

Besides its stated or certified sustainability attributes, hydrogen is a homogenous product: each molecule is identical, regardless how it has been produced. Therefore, the three hydrogen sustainability types mentioned above will interact with each other in the market, with an impact on their relative market volumes, market prices, emissions, as well as more broadly on the market development of hydrogen technologies, their political and market acceptance and more in general the energy system.

For example, the stricter and the more ambitious the delegated act defining under which conditions hydrogen produced via electricity taken from the grid qualifies as renewable (as mentioned in recital 90 RED II) will be, the more expensive and scarcer will probably be the offer of renewable-based hydrogen, at least in the short and in the medium term.

Therefore, assuming any level of hydrogen demand at a given point in time, additional sustainability criteria for renewable hydrogen and for low-carbon hydrogen could lead to a higher demand for grey hydrogen. On the other hand, an unambitious definition of “renewable” and of “low-carbon” hydrogen can lead to investments not in line with the EU’s climate neutrality targets and to delegitimating the market deployment of hydrogen technologies. The level of ambition, or strictness, of the definitions of, respectively, “renewable” and “low-carbon” hydrogen will have a strong impact on the competitiveness of the technologies behind the relative production processes. For instance, a soft definition and a broad market acceptance of “low-carbon” hydrogen would slow down the market deployment of electrolysers, and thus also the achievement of economies of scale in this crucial field. On the other hand, a very strict definition of “low-carbon” hydrogen could postpone investments to switch e.g. industrial production to hydrogen or, in other cases, lead to higher market shares of

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[1] cf. https://fsr.eui.eu/a-first-look-at-the-eu-hydrogen-and-decarbonised-gas-markets-package/, accessed 23 February 2022

grey hydrogen, if the growth of renewable hydrogen production is not as quick as the increase in demand.

In some EU countries, such as Germany, a debate is unfolding about the potential impact of large-scale green hydrogen production for export purposes on the sustainability of the development of exporting countries and regions. This important discussion is reflected in this paper. Before looking at it in detail, it is important to note that, if higher sustainability standards are applied to green hydrogen imports than to traditional fossil fuel imports, the unintended consequence is a regulatory privilege for the latter.

Interaction between imported and domestic hydrogen

Similarly, the sustainability standards applied within and outside the EU will have an impact on the market interaction between domestic hydrogen production and imported hydrogen. On one hand, ambitious sustainability requirements implemented in the EU could trigger a virtuous circle, inspiring the adoption of comparable standards in other parts of the world, as frequently happened in the past in other fields. On the other hand, if no effective mechanisms to prevent social and environmental dumping are applied, a significant gap in the level of ambition concerning the sustainability of hydrogen supply might simply lead to a regulatory privilege for less sustainable hydrogen imports.

2 Conceptual screening of sustainability dimensions in the field of hydrogen

To define criteria for sustainable hydrogen, various sustainability dimensions need to be considered along the entire hydrogen value chain and with respect to different hydrogen production routes. The focus of this section is to screen the existing literature on sustainability dimensions that should be evaluated across the value chain and across the different types of hydrogen.

2.1 The hydrogen value chain

Table 2-1 shows the main steps of the hydrogen value chain and gives examples of technologies or process steps that need to be considered when evaluating its sustainability. The hydrogen value chain consists of primary energy supply, hydrogen production, hydrogen storage, CO_2 transport and storage (where relevant), production of derivatives (where relevant) and hydrogen transport.

Table 2-1: The main steps of the hydrogen value chain

Main Steps of value chain		Examples of technologies or actual process steps
Primary energy supply (upstream)	Energy production: Production and installation/construction of equipment	Production of • PV panels, wind turbines • Gas conveyor towers • Drilling equipment • Hydro dams
	Energy production: Operation	Extraction of methane, coal, uranium Operation of methane wells, wind turbines, solar plants, nuclear reactors

	Transport of energy carrier: Production of equipment, right of way, installation of infrastructure	Electricity grid Gas pipelines LNG infrastructure
	Transport of energy carrier: Operation of infrastructure	Infrastructures own consumption of energy Leakages/losses in infrastructure
Hydrogen production	Production of the equipment for the conversion into hydrogen	Steam Methane Reforming (SMR) facilities Electrolysers Carbon capture equipment (where applicable)
	Operation	SMR/ autothermal reforming process: Carbon Capture and Sequestration Electrolysis
CO_2 transport and storage (where applicable)	Production and construction of CO_2 transport and storage infrastructure	CO_2 compressing stations, pipelines or ships.
	Operation of CO_2 transport and storage	Compression, injection underground; in case of enhanced oil recovery, GHG footprint of additional oil production
Hydrogen storage	Production, construction (or adaption) of storage facilities	Construction of (underground) facilities and auxiliary installations
	Operation	Pre-treatment: compression and injection Pressure management and boil-off
Production of derivatives (where relevant)	Production of the equipment	Fischer-Tropsch synthesis or other technologies CO_2 Capture plants (DAC)
	Conversion of hydrogen into derivatives	Production of CO_2 (e.g. for synthetic CH_4) or nitrogen (e.g. ammonia) needed as input Production and operation of facilities
Transport	Production of the equipment	Pipelines, ports, ships, compression
	Conversion/Compression	Liquefaction of hydrogen Conversion into ammonia Conversion into hydrocarbons
	Transportation	Shipping; Pipeline
	Reconversion	Regasification of liquid hydrogen Reconversion from ammonia to hydrogen

Source: own

2.2 Sustainability dimensions in the hydrogen value chain

To arrive at a comprehensive set of sustainability dimensions that need to be considered, we perform a literature review on selected recent reports and papers assessing sustainability along the hydrogen value chain.

Our main sources take different approaches to identify relevant sustainability dimensions. Oeko-Institut (2021) takes a bottom-up approach based on studies about potential hydrogen exporting countries as well as on expert interviews. As most existing studies, they focus on renewables-based hydrogen from electrolysis. ILF; LBST (2021) develop their set of relevant sustainability dimensions based on a two-sided approach: on the one hand, they perform a comprehensive review of existing certification schemes and regulations on renewables-based hydrogen and low-carbon hydrogen. On the other hand, they scan other existing certification schemes (not focused on hydrogen) to identify additional or missing dimensions. In particular, they draw from certification schemes for sustainable biomass, forest management, extraction, trade and manufacture of raw materials, and international fair trade and labour organizations. Nationaler Wasserstoffrat[2] (2021) suggests a two-level approach: one set of dimensions applying to the national level, and one that is relevant on the project level. On the national level, they identify relevant SDGs that needs to be considered for international cooperation and by national bodies during project development. This includes the system level perspective considering potential resource and target conflicts. They suggest adhering to existing frameworks from OECD, UN and World Bank[3]. “Project level dimensions” cover most issues that are also raised in other studies on sustainability of hydrogen. World Energy Council; DENA (2022) take an approach similar to one of the sides in the approach taken by ILF; LBST (2021). They examine existing regulations, certification schemes and selected funding programmes for renewables-based and low-carbon hydrogen. Their set of sustainability dimensions is made up by all criteria that come up in at least one of them. A different approach has been taken by Norouzi (2021). The paper compares hydrogen production technologies or routes using the sustainability index assessment method. The paper looks into five main dimensions: environmental, social, energy, exergy and economic. For all those dimensions, specific factors including specific quantitative units are defined. Based on those parameters they conclude which technologies are most sustainable. While the approach seems very comprehensive, there is a lack of documentation of production routes, the parameters used for the assessment and the methodology to calculate specific and total scores. Therefore, this source was not included in the further assessment of sustainability criteria.

The results of the literature review are summarized in Table 2-2. Based on this review, we structure the sustainability dimensions into three overarching categories: While the **environmental sustainability** and **socio-economic sustainability** refer to the impacts of an individual project on the local and regional level, **system level sustainability** considers second order effects on the electricity, energy, and economic systems. The dimensions are listed in Table 2-2. Further explanation on the respective dimensions can be found in the detailed assessment in section 2.3 further below.

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[2] The German National Hydrogen Council appointed by the German government

[3] E.g., OECD Due Diligence Guidance for Responsible Business Conduct: https://www.oecd.org/investment/due-diligence-guidance-for-responsible-business-conduct.html The UN Guiding Principles on Business and Human Rights: https://www.business-humanrights.org/en/big-issues/un-guiding-principles-on-business-human-rights/ ; Worldbank Environmental and Social Framework (ESF): https://www.worldbank.org/en/projects-operations/environmental-and-social-framework

Table 2-2: Sustainability dimensions considered in the hydrogen value chain – Literature review

		ILF; LBST 2021	Oeko-Institut 2021	Nationaler Wasserstoffrat 2021	World Energy Council; DENA 2022
Type of hydrogen considered					
	RES-E-based H_2	X	X	X	X
	RES-based H_2: biomass and others				
	Low carbon H_2 (of fossil origin)				X
Sustainability dimension					
Environmental sustainability	GHG emissions	X	X	X	X
	CO_2 source	X	X	X	X
	Water	X	X	X	X
	Air quality	X			
	Critical resources		X		
	Biodiversity	X	X	X	
	Soil	X			
Socio-economic sustainability	Community development	X	X	X	Social Impact
	Economic participation	X	X	X	
	Labour conditions	X	X	X	
	Respect and fostering of right	X	X	X	
System level sustainability	Electricity system perspective	X	X	X	X
	Energy system perspective	X	X	X	
	Economic system perspective		X	X	

Source: own

The following insights can be drawn from this literature review:

- Most of the research has focussed on the sustainability of green hydrogen based on renewable electricity and electrolysis. Biomass based and fossil-based hydrogen have generally not been considered. This paper contributes to closing the gap concerning hydrogen produced from methane.
- In terms of environmental sustainability, criteria for green hydrogen (and derivates), GHG emissions, CO_2 sourcing, water input and biodiversity are covered in most studies and can be considered as standard criteria. The impact on soil is covered less frequently, however, in some cases it is subsumed when considering land-use change. Impacts on air quality and requirement

of critical resources are hardly considered, yet. In terms of socio-economic sustainability, the reviewed studies are very similar. However, the concrete certification schemes existing today cover these criteria to a very different extent, leaving much room for diverse interpretation and operationalization (World Energy Council; DENA 2022).

- Current literature usually focuses on the level of individual projects, while the sustainability in a broader sense, e.g. looking at the overall hydrogen strategy of a country, is covered only in two of the studies. The limitation to individual projects may lead to relevant blind spots: for example, if the low-cost renewable energy potential of a certain country is used mainly for hydrogen exports, the decarbonisation of the local energy system might be postponed or even made impossible.
- The system level perspective is equally important for low carbon hydrogen production. Here, it will perpetuate the current fossil fuel extraction-based economic model and might create new economic inertia for the transition of the global energy systems. We highlight the respective challenges in the analysis below.

2.3 Sustainability dimensions for the main hydrogen production routes

This section outlines the main elements of the sustainability dimensions identified in section 2.2 on the bases of the hydrogen value chain as described in section 2.1, thus providing an insight into the relevant sustainability challenges for the two hydrogen production pathways considered in this paper.

Due to limitations in the scope of this paper, we analyse two main production routes of hydrogen. We focus on electrolysis based on renewable electricity and on steam methane reforming (SMR) based on natural gas with or without CCS. These two production routes are those likely to be most used in the coming years.

2.3.1 Environmental sustainability

Production of equipment and infrastructure

To produce technical equipment and infrastructures for the hydrogen value chain, raw materials and energy are required.

Within the different pathways of the hydrogen value chain, significant amounts of steel are essential to produce for example wind power plants, drilling equipment, ships, pipelines and electricity grids. Moreover, rare earths and critical minerals are of relevance (e.g., for PV, electrolysers, SMR equipment and CCS technologies). Mining of those raw materials has an impact on the environment during the mining and refinement processes as well as after the lifespan of the technical equipment during the recycling or disposal phase.

Besides the raw materials, also the energy intensity to produce the equipment should be considered. The production of PV panels and steel for example are highly energy intensive.

The mining of raw materials as well as the production process of the equipment has an impact on almost all dimensions of environmental sustainability that are addressed within this section such as water, GHG-emissions, soil, biodiversity etc. However, within the scope of this paper we cannot cover those environmental impacts in much detail. While several studies performed lifecycle analysis for specific elements of the hydrogen value chain, literature explicitly analysing the hydrogen value chain and comparing different pathways of hydrogen production is scarce and mostly focus only on the GHG emissions of hydrogen production (DECHEMA 2021; Valente et al. 2017; Delpierre et al. 2021; Bauer et al. 2021).

This paper highlights some of the most outstanding sustainability issues related to the production of equipment and infrastructure.

2.3.1.1 GHG emissions

GHG emissions can occur in almost all steps of the hydrogen value chain and include all relevant greenhouse gases (besides CO_2, in particular CH_4, GHG effects of land-use change as well as, indirectly, hydrogen itself to a certain extent[4]). The assessment of GHG emissions needs to consider both the respective hydrogen (and derivatives) value chain and the fossil comparator, which is often referenced in regulations and certification schemes.

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[4] cf. https://www.euractiv.com/section/energy/news/scientists-warn-against-global-warming-effect-of-hydrogen-leaks/, accessed on 23 February 2022

Table 2-3: Sustainability challenges – GHG emissions

Value chain step[5]	Renewable hydrogen - electrolysis	SMR-based hydrogen (with CCS)
Primary energy supply (upstream)		
Energy production: Production of equipment	Emissions[6] from the production of PV panels, wind turbines etc.	Emissions from construction of CH_4 extraction and processing infrastructure (drilling wells, pipelines, processing plants, etc.)
Energy production: Operation	No significant emissions if electricity production based on renewables Emissions if electricity is produced from fossil fuels	Emissions from energy used to drive CH_4 extraction and processing Fugitive CH_4 emissions from CH_4 extraction (drilling, fracking, etc.) On-purpose emissions from venting and flaring (at CH_4 extraction or processing plant)
Transport of electricity/energy carrier: Operation of infrastructure	Losses within electricity grid can increase specific emissions from energy production	Emissions from CH_4 leakages in pipeline infrastructure Emissions from energy used to operate transport infrastructure (pipelines, distribution centres, LNG terminals etc.)
Hydrogen production		
Operation	Emissions from energy used for ancillary systems and water production	Emissions from energy used to operate SMR and carbon capture processes Emissions from the SMR reaction (if not captured and stored)
CO_2 transport and storage (where applicable)		
Operation		Leakages of CO_2 during transport Long-term leakages during storage and leakages during compression into underground storage
Productions of derivatives (where applicable)		
Operation	Production of hydrocarbons using CO_2 can cause additional CO_2 leakages Secondary effects causing additional CO_2 emissions if the use of fossil CO_2 sources (e.g. from industry processes) results in prolonging a phaseout of fossil fuels	
Hydrogen storage		
Operation	Hydrogen leakages and boil-off	
Transport of hydrogen		
Conversion/Compression	Emissions if energy demand is not covered by RES-E	
Transportation	Relevant if energy demand is not covered by RES-E, for example if e-fuels would be shipped with standard tankers run with heavy fuel oil	
Reconversion	Relevant if energy demand is not covered by RES-E	

Source: own

Renewable hydrogen – electrolysis: In this case, no significant GHG emissions occur in the electricity generation process nor in the electrolysis process. Emissions mainly are related to the energy needed to produce the equipment. If it is based on fossil fuels, CO_2 and other greenhouse gases are emitted. This is especially relevant, if PV panels are produced in regions with high GHG-emissions in the electricity mix (Yıldız et al. 2020). If the equipment production is based on renewable energy, GHG emissions within the whole value chain can be limited. In addition, GHG emissions can occur in adjacent processes, such as compression for transport or sea water desalination if fossil fuels are used instead of renewable energy sources. If the hydrogen plant is connected to the electricity grid,

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[5] Only most relevant upstream effects from mining and energy use for production of technical equipment are mentioned in the table.

[6] The term “emissions” within this table refers to greenhouse gas emissions in any form.

it is hard to track the actual effects of the additional electricity demand on the whole energy system and potentially resulting increased CO_2-emissions.

The main challenges related to GHG emissions are:

- How to report and reduce the GHG footprint of the production of equipment.
- How to report and reduce the GHG footprint of electricity sourced from the grid.
- How to make sure that all adjacent processes (compression for transport, sea water desalination, etc.) do not add emissions, e.g. by running them based on renewable energy.

Steam Methane Reforming: In the hydrogen value chain based on steam methane reforming, significant levels of CO_2 and CH_4 emissions occur in the extraction and processing of the CH_4 as well in the SMR process itself. CCS can reduce but not eliminate the CO_2 emissions. Different CCS processes achieve very different shares (from ca 56% up to more than 90%, see Bauer et al. 2021).Most of the CH_4 emissions are upstream, i.e. they are embedded in the CH_4 extraction and transport, rather than occurring during the SMR process itself. Comparably minor emissions are associated with the production and construction of the SMR (and CCS) equipment.

The main challenges related to GHG emissions are:

- Monitoring and in many places heavily reducing upstream CH_4 emissions
- Implementing and monitoring high (>90%) shares of CO_2 capture with permanent underground CO_2 sequestration
- Minimising the energy required for the SMR process
- If an ambitious level of CCS is implemented, the emission intensity can be reduced, but not eliminated.

2.3.1.2 Water consumption and pollution

This sustainability dimension includes local and regional impacts on the quality of groundwater and surface water, water supply and balances, as well as second order impacts of water supply, like energy supply and brine disposal from saltwater desalination plant, and impacts on water prices (ILF; LBST 2021; Oeko-Institut 2021).

Table 2-4: Sustainability challenges – water

Value chain step[7]	**Renewable hydrogen - electrolysis**	**SMR-based hydrogen (with CCS)**
Primary energy supply (upstream)		
Energy production: Production of equipment	Water use in countries where mining for raw materials (e.g. silicon for PV) takes place water pollution in mining countries	Water use for construction of CH_4extraction infrastructure (drilling wells, etc.)
Energy production: Operation	Water use in countries where electricity generation takes place for cleaning of PV	Large water use in CH_4 extraction (drilling, fracking) and processing

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[7] Only most relevant upstream effects from mining and energy use for production of technical equipment are mentioned in the table.

	panels and cooling of CSP plants Large impacts on water systems in case of hydro power	Water pollution due to drilling, fracking, and wastewater disposal
Transport of electricity/energy carrier: Production of equipment, installation of infrastructure	Water use in countries where mining for raw materials takes place Water pollution in mining countries	
Transport of electricity/energy carrier: Operation of infrastructure	No water use	Water use for cooling in LNG infrastructure
Hydrogen production		
Production of the equipment for the conversion into hydrogen	Water use in countries where mining for raw materials takes place Water pollution in mining countries	
Operation	Water use for input into electrolysis, cooling of electrolysis, and water pre-treatment in producing countries Maritime pollution due to brine disposal in case of sea water desalination	Water use for SMR (reaction, cooling, and water pre-treatment) and carbon capture process Maritime pollution due to brine disposal in case of sea water desalination
CO_2 transport and storage (where applicable)		
Operation		Potential water pollution due to CO_2 injection processes and CO2 leakages (when stored underground)
Hydrogen storage		
	No relevant additional water use or water pollution	
Productions of derivatives (where applicable)		
	No relevant additional water input[8] if most water needed to produce hydrocarbons can be reused[9]	
Transport of hydrogen		
Conversion/Compression	No relevant additional water use or water pollution	
Transportation	No water demand, however, water pollution risks in case of maritime transport of hazardous goods (e.g., Ammonia)	
Reconversion	No relevant additional water use or water pollution	

Source: own

Renewable hydrogen – electrolysis: Water is used for the electrolysis process itself as well as to produce electricity for example for cleaning of PV panels or cooling of CSP-plants (Cerulogy 2017). For the electrolysis process, the water needs to be especially clean and, in some cases, even deionized. Large electrolysers may require water for cooling purposes. Many countries with outstanding low-cost RES-E potentials show high water stress levels[10], which can be aggravated by even small amounts of additional water consumption. Water pollution is mainly relevant if water is sourced from sea water desalination, as brine disposal can cause significant damage to the local

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[8] 10th International Renewable Energy Storage Conference, IRES 2016, 15-17 March 2016, (2016), p. 253.

[9] LUT (2017).

[10] https://www.wri.org/applications/aqueduct/water-risk-atlas/#/?advanced=false&basemap=hydro&indicator=w_awr_def_tot_cat&lat=30&lng=-80&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scenario=optimistic&scope=baseline&threshold&timeScale=annual&year=baseline&zoom=3

maritime ecosystem. The mining and refinement of metals used in electrolysis, electricity grid and RES-E power plants can cause substantial water pollution at mining sites (Duncan 2020; Tutu 2012).

The main challenges related to water are:

- Reducing overall water use within the process of electricity production and electrolysis, especially in regions with water stress
- Limit brine disposal in case of sea water desalination
- Limit water pollution related to the mining and refinement of metals

SMR-based hydrogen (with CCS): The upstream CH_4 production leads to significant local water demand and often also water pollution, mainly due to drilling, fracturing, and wastewater disposal processes. This is especially the case, when unconventional extraction methods, such as fracking, are used (EPA 2016; EIA 2021; Scanlon et al. 2020). In the midstream SMR process, water is used as a feedstock, for cooling, and for water pre-treatment (Lampert et al. 2016). In case of CCS, water pollution can result from the CO_2 injection processes (Bundesregierung 2018; World Bank Group 2017) and from mining of metals used in the CCS and SMR technology components (e.g., nickel) (Duncan 2020; Tutu 2012).

The main challenges related to water are:

- Reduce water use and water pollution resulting from upstream CH_4 production processes, such as fracking and wastewater disposal
- Reduce water pollution resulting from mining of raw metals used in current SMR and CCS technologies

Challenges associated with both production pathways:

- The lifecycle water consumption of renewable hydrogen production (from wind and solar PV) and SMR-based hydrogen production from CH_4 (with/without CCS) is in the same order of magnitude (Blanco 2021; Mehmeti et al. 2018; Elgowainy et al. 2016). However, especially production potentials for low-cost renewable hydrogen are to a large share located in countries with high water stress.
- Both hydrogen production pathways (can) lead to significant pollution of drinking water resources at different points of the value chain, e.g., due to hydraulic fracturing in case of hydrogen from CH_4 and mining processes for rare earths and minerals relevant for both pathways (EPA 2016; Scanlon et al. 2020; EIA 2021).
- Location-specific assessments of the effects of hydrogen production on water resources (including availability, consumption, degradation, and pollution) are needed, even though the expected water demand for hydrogen production often seems small in comparison to the total available water resources on a broader perspective.
- The water footprint of relevant hydrogen production pathways and its effects on local water resources need to be considered in hydrogen strategies, hydrogen standard setting and energy system planning, in general, to avoid exacerbating local water stress and resulting acceptance problems for the energy transition.

2.3.1.3 Biodiversity

The sustainability dimension of biodiversity includes the ecological impact on natural habitats and high conservation value areas (ILF; LBST 2021; based on UN 1992 and on SDG 15) due to land use change. Both for renewable hydrogen and for SMR-based hydrogen, there are general challenges concerning biodiversity that occur for all large-scale infrastructure developments, such as the clearing and levelling of relatively undeveloped areas. Especially hydrogen transport infrastructure and large underground storage sites for CO_2 or hydrogen can have negative effects on biodiversity (EIA 2021; Bundesregierung 2018). In case of sea water desalination used to produce fresh water, maritime ecosystems can be negatively affected by the disposal of the brine.

The main sustainability challenges for both production pathways are:

- Reduction of negative effects of CH_4 production and transport as well as of RES-E generation on biodiversity and integration of biodiversity conservation into CH_4 and hydrogen development
- Standardization and monitoring processes for sustainable CO_2 and hydrogen storage activities are needed
- Vulnerable areas and locations need to be excluded from use for hydrogen production, transport and storage.

2.3.1.4 Critical resources

Critical resources are required to produce the technology needed within the hydrogen value chain. Critical raw materials are often related to human rights violations in the mining process as well as to some geochemical risks. (Oeko-Institut 2021; Wuppertal Institut 2014)

Renewable hydrogen – electrolysis: Iridium, a critical raw material, is used in PEM electrolysers. Permanent magnets in generators of wind turbines require rare earths, photovoltaics contain the conflict mineral tin and other toxic substances. Besides production processes, the environmental impact of equipment can be significant at the disposal of the materials after the end of the lifetime. Recycling (for example of PV panels, Strachala et al. 2017) can reduce the overall consumption of those critical resources as well as the waste disposal issues.

Steam Methane Reforming: Current SMR and CCS technologies require substantial quantities of critical minerals, such as nickel and manganese, as reaction catalysts. For the deployment of large-scale blue hydrogen capacities, a significant expansion of mining activity for such minerals would be required, which often leads to negative environmental impacts (World Bank 2017; Carbon Brief 2018; Chen et. al. 2020).

The main sustainability challenges for both production pathways are:

- Long-term reduction of critical resources in the technology needed.
- Uptake of high recycling quotas aiming at a circular economy for all metals and rare earths.
- Sustainable mining and sourcing of critical resources.

2.3.1.5 CO_2 source

To produce hydrocarbons (such as e-fuels or methanol) from hydrogen, a carbon source is needed. Most carbon sources are based on the use of CO_2. The CO_2 source itself must be assessed based on its lock-in potential and alternative use (ILF; LBST 2021; Nationaler Wasserstoffrat 2021; Oeko-Institut 2021). As the production of hydrocarbons does not affect the production process of hydrogen in the first place, the sustainability challenges do not differ between renewable or low-carbon hydrogen.

The main sustainability challenges are:

- How to ensure that CO_2 used form a cycle with the atmosphere so that this path does not lead to additional CO_2 emissions.
- How to ensure that using CO_2 from fossil sources does not lock in the use of unabated fossil fuels
- How to ensure that CO_2 from biogenic origin does fulfil sustainability criteria for biomass sourcing

2.3.1.6 Air quality

Air quality is mostly impacted by particle matters and potential release of toxic gases (e.g. ammonia) (ILF; LBST 2021; Oeko-Institut 2021). It can be a temporary issue in the construction phase of the respective infrastructures and facilities. Depending on the final good (hydrogen or derivates like ammonia) and means of transport (i.e., for road transport and conventional shipping) it also might be an issue in the operational phase.

Table 2-5: Sustainability challenges – air quality

Value chain step[11]	Renewable hydrogen - electrolysis	SMR-based hydrogen (with CCS)
Primary energy supply (upstream)		
	Not relevant	Air quality can be negatively affected by fugitive CH_4 emissions and other emissions related to CH_4 extraction, especially when combined with oil extraction
Hydrogen production		
	Not relevant	Criteria air pollutant emissions from SMR process (e.g., CO, NO_x, PM10)
CO_2 transport and storage (where applicable)		
	Not relevant	Air quality can be negatively affected by amine emissions resulting from the CCS process and accidental CO_2 emissions from the storage site
Hydrogen storage		
	Not relevant	
Productions of derivatives (where applicable)		

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[11] Only most relevant upstream effects from mining and energy use for production of technical equipment are mentioned in the table.

	In case of leakages of gases such as ammonia, CH_4 or others
Transport of hydrogen	
	In case of shipping with fossil fuels or leakages from transport in form transport of toxic gases, e.g., ammonia gases

Source: own

SMR-based hydrogen (with CCS): Air quality can be negatively affected by criteria air pollutant emissions from SMR processes and toxic emissions resulting from CCS processes (e.g., amine emissions). Additionally, hydrogen shipping can have negative effects on air quality, if fossil fuels are being used and/or toxic ammonia emissions occur (Sun et al. 2019; Bundesregierung 2018; Oeko-Institut 2021).

The main sustainability challenges for both production pathways are:

- Reduce or mitigate air pollutant emissions from SMR and carbon capture processes, as well as potential fugitive CO_2 emissions from carbon storage sites.
- Decrease energy-related air pollutant emissions and prevent potential fugitive ammonia emissions during shipping processes.
- To make sure that mining does not substantially affect air quality.

2.3.1.7 Soil and seismicity

This sustainability dimension includes the assessment of ecological impacts aiming at protection from soil erosion, as well as protection from reduced fertility and other types of deterioration caused by over usage, acidification, salinization or other chemical soil contamination (ILF; LBST 2021; based on JRC 2021 and on SDG 15).

Renewable hydrogen – electrolysis: In the case of renewable hydrogen production, the ecological impacts on soil are relevant in two steps of the value chain: Firstly, the mining of minerals and metals and secondly, during the construction of all infrastructure needed such as RES-E plants (e.g. windparks or hydro dams). Specific risks concerning erosion or deterioration are not reported in the literature. SMR-based hydrogen (with CCS): In addition to the potentially negative effects on soil from mining and infrastructure construction mentioned before (see renewable hydrogen), induced seismicity and earthquakes can be caused by unconventional and conventional CH_4 extraction processes, such as underground wastewater disposal and hydraulic fracturing, as well as by CO_2 injection and storage processes. In the US, for example, the number of earthquakes has increased significantly in areas with oil and gas operations in the years of the so-called shale gas boom (Rubinstein n.d.; Rubinstein und Mahani 2015). Furthermore, CH_4 extraction and underground CO_2 storage can lead to soil contamination, e.g., when wastewater spills or CO_2 leakages occur.

The main sustainability challenges for both production pathways are:

- Reduce or mitigate potentially negative effects on soil from mining of minerals and metals and infrastructure construction needed for hydrogen production
- Reduce or mitigate induced seismicity from CH_4 extraction processes, e.g., by reducing the rate of wastewater injections (Hager et al. 2021)

- Reduce or mitigate soil contamination, e.g., by using modern wastewater treatment and reuse processes in CH_4 production (Pichtel 2016) and preventing potential leakages at CO_2 storage sites.

2.3.2 Socio-economic sustainability

A thorough assessment of relevant socio-economic sustainability dimensions is out of the scope of this study. For RES-E based hydrogen it was already assessed in detail in the existing literature (LBST 2021, Oeko 2021). Therefore, we only summarize dimensions and assessments for RES-E based hydrogen production and add a brief overview of socio-economic sustainability dimensions of SMR-based hydrogen (with CCS).

The main sub-dimensions of socio-economic sustainability identified in the literature are:

- community development, including effects on local infrastructure (e.g., access to energy and clean water, transport, and education),
- economic participation, including impacts on local businesses, energy and water prices as well as sourcing of technology, materials and workers,
- labour conditions, including health and safety issues, wages and contract design,
- and respect and fostering of rights, including individual, community and indigenous rights, as well as land and water rights and potentially also rights to other impacted resources.

Renewable hydrogen – electrolysis: Communities can benefit from local infrastructure development. This is especially relevant in countries where access to energy, electricity and/or water is still low. First indications on the possibility for economic participation of local companies and people in the build-up of a hydrogen export industry and the potential for local value creation can be drawn from Wuppertal Institut; DIW Berlin (2020). Economic participation can occur in all parts of the value chain where local companies can deliver know-how, technology, and workforce. However, countries with large low-cost hydrogen production potentials often lack industries for the large-scale technology needed within the hydrogen value chain (PV panels, wind turbines, electrolysis, desalination plants, power lines, etc.).[12] Thus, in the short term, most of the technology components will often not be produced within the hydrogen exporting countries but must be imported. Furthermore, it can be expected that operating hydrogen plants will not be labour-intensive and the main workforce will be highly skilled workers. Therefore, without additional efforts, economic participation could be mainly limited to the building sector. As a stepping stone to long-term economic participation, local education and research centres should be aimed at. Moreover, with a business model of lending or licensing of land for RES-E production constant revenues would be generated. However, still only a small 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 regarding the correct beneficiaries from the lease/lending. Some countries with an established fossil fuel export industry could be able

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

to use 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.

The main sustainability challenges are:

- Community development needs to take place in a collaborative manner, by consulting with local communities and addressing their needs and concerns.
- Economic participation is highly desirable but might need a ramp-up phase in terms of skilled workers and local content in technology supply. Education and production sites could be established with the first installations and local content can be increased for a subsequent phase of a larger project.

SMR-based hydrogen (with CCS): If CH_4 supply for this hydrogen production pathway will come from already developed CH_4 production sites, then there will likely be limited potential for a positive impact in terms of socio-economic sustainability dimensions. New community development cannot be expected, if no new infrastructure is built. Hence there is a lack of potential for co-development in terms of infrastructure access (electricity, road, water, education). It is likely that economic participation will not gain additional traction and existing business models will stay in place. If strong elite building, low levels of local content and strong societal inequality are prevailing in the gas industry, then they will likely be perpetuated. The same holds true for labour conditions and the respect and fostering of rights. If the domestic value chain includes CO_2 capture, transport and storage, then co-development of such infrastructure might occur in the areas along the CH_4 transport routes and at the storage hubs. In terms of economic participation, it is not likely that this will bring a strong impulse for changing socio-economic patterns. Again, highly specialized equipment and respective workers are required, however, both are similar to those employed in CH_4 production. With some exceptions (USA, Canada, Russia, China, EU, Norway) CH_4 producers in multiple countries rely on imported equipment and do not employ high shares of local worker in their CH_4 industries. This will also apply to an integration of CO_2 transport and storage into the value chain. Except for some potential for co-development of infrastructure, the above-mentioned holds true, for the case of developing new CH_4 reserves in countries with an established CH_4 industry. Nevertheless, assuming that there will be less demand for CH_4-only production in the future due to climate change, methane-based hydrogen production with CCS could offer current CH_4 producers the opportunity to (partly) maintain their economic activities, at least for some time, and thereby potentially reduce their resistance against decarbonization efforts in general.

In case countries develop a methane-based hydrogen industry (with CCS) from scratch, the situation regarding socio-economic sustainability is similar to the one with RES-E-based hydrogen. Regardless whether a new industry is developed or an established industry expands further, the impacts of methane-based hydrogen on biodiversity, air pollution and soil can be significant (see above) and can also have implications on the heath and livelihood for local communities.

The main sustainability challenges are:

- Ensure stakeholder and community consultation and approval for CO_2 transport and especially for CO_2 storage.
- Ensure respect of community and human rights and health protection for established CH_4 operations.

- Fostering economic participation in the value chain in countries with an existing gas industry will be difficult to achieve, in particular, if the same actors develop the new industry along their established business models.

2.3.3 System level sustainability

This dimension reflects the second order impacts of hydrogen production, e.g., effects on the electricity grid coming from additional electricity demand. They take a system-wide view in contrast to the project-specific sustainability impacts examined in the other categories.

2.3.3.1 Electricity system perspective

Electricity is the core input factor into RES-E based hydrogen from electrolysis. Saltwater desalination (SWD) plants, if needed, supplying freshwater as the second core input factor, do also come with a significant electricity demand. However, this demand is much smaller than the former and highly depends on the SWD technology. CH_4-based SMR also comes with non-neglectable electricity demand, but on-site electricity generation from excess heat exceeds this demand in standard configurations. SMR facilities are net electricity producers. Additional electricity demand is induced, if the CO_2 is captured for subsequent transport and storage. This can change the balance towards net electricity demand for SMR with carbon capture. The impact of this additional power demand on the local power system and related conflicts with the domestic decarbonization of the electricity mix needs to be taken into account. (ILF; LBST 2021; Nationaler Wasserstoffrat 2021; Oeko-Institut 2021)

Renewable hydrogen – electrolysis: Within the hydrogen value chain, especially the step “Energy production” – in this case the use of existing or deployment of new RES-E generation plants – affects the electricity system. If electricity from existing RES-E plants is used (no additionality), the extra fossil generation needed to balance the system may result into additional GHG emissions. If additional RES-E plants are deployed, they might use the RES-E sites with lowest LCOE, thus limiting the potential needed to decarbonise the electricity system. As a large single-point electricity consumer, grid-connected electrolysers can have a strong impact on grid bottlenecks. Depending on their locations and on how they are operated, electrolysers can have positive of negative effects on the grid.[13] The same arguments in terms of flexibility and siting apply to SWD plants. If CO_2 for hydrogen derivates is sourced from Direct Air Capture (DAC), then electricity demand for air fan can also add a significant new consumer. Elaborations on dispatch and location described above for the electrolyser are also true for the DAC unit.

The main sustainability challenges are:

- How to ensure the electricity is sourced from additional RES-E plants.

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[13] If the electrolyser is located before a grid bottleneck, its additional demand can help to reduce grid congestion. Vice versa, if it is located behind a bottleneck, it will increase congestion. If the electrolyser operates flexibly and follows the fluctuating RES-E supply, it will not increase grid congestion and possibly use renewable electricity that would be to stored or even curtailed. If the electrolyser is operated inflexibly, or even round the clock, electrolysis constitutes new inflexible demand and thereby increase gird stress and emissions.

- How to ensure that additional electricity demand does not create new congestions in the electricity grid.
- How to make sure that electrolysers are operated flexibly, especially during the hours when the grid features lower emissions (e.g. lower shares of GHG intensive generation)
- How to make sure that hydrogen production does not postpone decarbonisation of the domestic electricity system.

SMR-based hydrogen (with CCS): The production of hydrogen via SMR (with CCS) will not have major impacts on the electricity system, given the high shares of on-site self-generation, and comparably low additional demand from compression for transport and storage. The additional natural gas demand impacts the gas system. In locations relying on LNG supply, it also adds emissions linked to the additional energy consumption related to the LNG cycle. In regions relying on gas imports, SMR-based hydrogen production increases possible security of supply issues.

2.3.3.2 Energy system perspective

Hydrogen can play an important role for domestic decarbonization. Infrastructure development for hydrogen export should consider needs for domestic decarbonization. This relates to the dimensioning and location of the infrastructure (e.g. hydrogen pipeline routing, auxiliary facilities, routing of CO_2 delivery and or waste streams) and to the usage of RES resources that might be needed for domestic decarbonization and to the technological compatibility with a RES-based energy system (e.g., conversion of pipelines, auxiliary facilities etc. to RES-based energy supply. Moreover, the use of scarce resources like land, biomass, and sustainable CO_2 needs to be coordinated on the system level (ILF; LBST 2021; Nationaler Wasserstoffrat 2021; Oeko-Institut 2021).

Renewable hydrogen – electrolysis: Exporting countries could gain from a build-up of a hydrogen economy for exports if infrastructure primarily dedicated to serve the hydrogen export supply chain also provides excess capacities that can be used for other purposes. This could for example be the case where parts of the capacity of pipelines, electricity grids, ports infrastructure or desalination plants remain available for domestic use of or the import/export of other goods. If hydrogen derivates are exported, system level coordination for the CO_2 input streams is necessary. Both biomass, and CO_2 from DAC might be needed also for the decarbonization of the domestic energy system.

The main sustainability challenges are:

- Reaping economies of scale from infrastructure build-up (excess electricity grid or pipeline capacity, additional RES power plants, additional water supply) and coordination with future export and local demand when considering infrastructure location.
- System level coordination is needed for scarce resources like land, and biomass, in particular, if hydrogen derivates are exported.

SMR-based hydrogen (with CCS): The EU climate neutrality goal will require a phase out of most CH_4 applications during the next few decades, especially space heating than can be substituted by thermal insulation and direct use of renewables, including RES-E based heat pumps. In the medium and long term, large parts of the methane distribution grid will need to be dismantled, as the methane demand should be reduced to a smaller number of consumers, usually larger ones than can apply CCS. In this context, even if CCS is applied to the SMR process to achieve a low carbon hydrogen supply, the expansion of SMR capacities can produce a lock-in effect of and/or stranded assets in CH_4 infrastructure, which is co-used by other current small scale CH_4 applications, which shall be electrified during the coming decades. This lock-in effect can have a negative impact on decarbonisation, if new SMR facilities are located in areas where the CH_4 network could otherwise be dismantled during their planned lifetime.

Where CCS is applied to SMR, there may be co-benefits if the CO_2 transport infrastructure can also be used for transporting CO_2 emissions from unavoidable sources, e.g. from cement production to storage sites. On the other hand, SMR with CCS will be in competition for scarce CO_2 storage resources, which may be needed for those unavoidable CO_2 emissions.

In contrast to electrolysis, fossil fuel-based hydrogen production infrastructure and equipment comes with significant residual emissions, even when CCS is applied. In the long term, in a climate neutral world, hydrogen production based on fossil fuels would only be acceptable if it is accompanied by a sufficient amount of negative emission technologies. Therefore, while the massive expansion of infrastructure for renewable energy supply (electricity grid, RES-based electricity generation) is indisputably a no regret choice, hydrogen based on SMR is rather to be seen as a possibly useful temporary solution.

The main sustainability challenges are:

- How to avoid lock-in of and/or stranded assets in CH_4 infrastructure
- How to plan the location of new SMR facilities in a way that is on one hand compatible with the necessary, gradual dismantlement of large parts of the methane grid infrastructure over the next two or three decades and on the other makes best use of potential co-benefits in terms of sharing CO_2 transportation infrastructure with unavoidable CO_2 sources
- How to avoid that SMR with CCS prevents unavoidable CO_2 emissions sources from having access to scarce CO_2 storage resources

2.3.3.3 Economic system perspective in exporting countries

Due to the projected size of hydrogen exports, they can become an important economic factor for the export country’s economy. Direct and indirect income for the exporting states can be generated through various channels, including selling hydrogen or derivatives (e.g. through state-owned companies), licensing or lending of land, positive local side effects of infrastructure build-up, or different forms of taxation. The structure of the value chain is well comparable with highly automated extractive industries, such as oil and gas production. It is characterized by high technology intensity and low labour intensity in the operation of centralized production systems (Oeko-Institut 2021). Establishing such an industry can create economic structures known as the Dutch disease (Corden 1985) and inhibit sustainable economic growth and equal economic participation (resource course hypothesis, Sachs and Warner 2001). They might also create competition for infrastructure, financial and human resources with established extractive industries (e.g., oil, CH_4, copper) and business models (Nationaler Wasserstoffrat 2021; Oeko-Institut 2021).

It must be noted that steering projects towards contributing to sustainable economic development on the country level is a challenge. Criteria are difficult to formulate and to operationalize, because they touch upon areas of national sovereignty and require cooperation on the international level. Higher valued added and the export of hydrogen derivates (e.g., ammonia or methanol) can put pressure on business models and producers in the importing countries. While shifting production to countries with large low-cost hydrogen production potentials can be very beneficial from a sustainability point of view (increasing energy and resource efficiency), economic and geopolitical motives of importing countries might prevent further value chain integration in exporting countries.

Renewable hydrogen – electrolysis: Building up a new RES-E based hydrogen export industry comes with the opportunity of establishing new economic structures and new economic actors. While opening up this new income source comes with the opportunity of economic development and social redistribution, it is not a self-fulfilling prophecy. By contrast, establishing a new export-oriented industry has often come with a negative impact on the overall medium-term socio-economic development of countries (see above).

SMR-based hydrogen (with CCS): The economic impact of this production pathway depends on two factors:

In general, SMR-based hydrogen is being considered in countries with an established gas industry. In several countries, SMR-based hydrogen production is being discussed to maintain (parts of) the economic structures and actors already active in CH_4 extraction, making their business model more compatible with the climate policy agenda. Wherever these industries did not so far manage to establish sustainable and socio-economically viable business models, the challenge will be to improve those structures while also extending the value chain to include also SMR (and CCS).

If the SMR-based hydrogen production should be based on developing new fossil reserves, it is highly questionable whether this can be compatible with achieving the Paris climate goals. Research strongly suggests emissions from already developed fossil fuel reserves exceed the budget for 1.5°C target (Trout et al. forthcoming).

The second factor deals with the CO_2 transport and storage value chain. (1) Exporting countries can stay simple exporters of CH_4, if the reforming process and subsequent CO_2 transport and storage happens at the import destination (e.g., CH_4 transport to Germany, reforming at a location at the German coast, CO_2 transport and storage in North Sea saline aquifers), (2) they can provide CH_4 and store CO_2 (e.g., CH_4 transport to Germany, reforming at a location at the German coast, CO_2 transport and storage in saline aquifers in source country), or (3) they can integrate all process steps in their country and export hydrogen or derivates. In the first case there is no change to the established CH_4 exporting business model, while the second and the third come with establishing one (second case) or even two (third case) new industries. The latter two cases extend the product portfolio of a country and can allow to establish transition pathways from fossil fuel-based industries to (RES-E)-based hydrogen exports and the provision of CO_2 storage capacities, which will likely become a scarce commodity in future with climate-neutral energy systems.

The main sustainability challenges for both production pathways are:

- Good governance, institutional trust, long-term perspectives and a strive for value chain integration are needed to enable positive effects on the long-term economic development of a hydrogen exporting country.
- In countries with existing fossil fuel exporting business models, RES-E-based and SMR-based hydrogen production (with CCS) 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 new business models and their proponents might get into conflict over government resources, infrastructure use and business shares with existing ones.

- New infrastructure investments for CH_4 production can have high lock-in or stranded asset potential.

While RES-E based hydrogen comes with the economic opportunities of establishing a new industry, if potential pitfalls are addressed, fossil fuel-based hydrogen allows to extend the lifetime of an existing industry. In the latter case, it cannot be expected that any change in the extraction-based business model will be initiated by SMR-based hydrogen production (with CCS). It will rather perpetuate existing economic structures and create new economic lock-ins that might oppose a sustainable economic development.

3 Screening of existing or proposed international schemes including criteria for hydrogen

Over the last three years several schemes and regulations have been developed that address criteria for hydrogen production and derivatives. Most of those schemes and regulation address the transport sector and aim at the reduction of GHG emissions compared to a fossil comparator (World Energy Council; DENA 2022, 25f). Schemes and regulation can be found worldwide, however, most of them in Europe, Asia and North Amerika.

There has been recent literature published on how those schemes compare to each other with a focus on hydrogen from renewable electricity. While World Energy Council; DENA (2022) focus on how schemes can be harmonized, ILF; LBST (2021) look into the sustainability dimensions that are covered by those schemes.

However, there is a lack of information firstly on schemes and regulations for hydrogen based on fossil fuels and secondly on addressing the shortcomings within the regulations and schemes. With this focus, we describe and analyse selected schemes and regulations and show which sustainability dimensions are addressed to which extend. This way we show how the schemes compare to each other and which sustainability dimensions are hardly addressed.

3.1 Sustainability dimensions in selected schemes and regulations

We selected the following schemes, regulations and methodologies for the following reasons:

- EU Taxonomy: The EU Taxonomy defines environmentally friendly technologies and might be a relevant document to steer future investments into different types of hydrogen production in the future.

- Renewable Energy Directive II and Delegated Acts: For the EU the RED II sets the scene for defining renewable hydrogen production. Pending delegated acts will further specify especially the electricity input into the electrolysis.

- IPHE: The IPHE methodology defines how to calculate GHG emissions for hydrogen production and is supported by many states that are likely to play a major role in the future hydrogen market.

- CertifHy & TÜV SÜD: Both voluntary certification standards aim at implementing REDII-compatible H_2 certification schemes on a pan-European level.
- H2Global: Is a form of state procurement of hydrogen that has been implemented by the German federal government to foster the market uptake of hydrogen. Specific criteria have been published recently.
- California’s Low Carbon Fuel Standard: This is one of the first standards to address reducing GHG emissions from transportation fuels and it includes emissions intensity benchmarks for different hydrogen production pathways.
- Hydrogen Guarantee of Origin (GO) scheme of the Australian Government: While not fully implemented yet, the proposed scheme closely aligned to the IPHE methodology aims to accelerate the country’s development to become a major hydrogen exporter.
- China Hydrogen Alliance’s Standard and Evaluation of Low Carbon Hydrogen, Clean Hydrogen and Renewable Energy Hydrogen: This is the first hydrogen standard established in China and it could likely become the basis for a future official government standard, since relevant state-owned enterprises and other large hydrogen companies active in China participated in its development.

3.1.1 EU Taxonomy

The EU Taxonomy Climate Delegated Act offers a list of environmentally sustainable economic activities. This way it provides companies, investors and policymakers appropriate definitions which activities can be classified as environmentally sustainable.[14] Annex II to the Commission Delegated Regulation 2020/852[15] defines standards to “do no significant harm” (‘DNSH’). Provisions are made for GHG emissions, water input and biodiversity.

- GHG Emissions: In accordance with the requirements set in the Renewable Energy Directive II (EU 2018/2001) hydrogen production must be conform with “[…] *the life cycle GHG emissions savings requirement of 70% relative to a fossil fuel comparator of 94g* CO_2*e/MJ* […]”. This implies a threshold for hydrogen production of 28.2 gCO2eq/MJ. System boundaries are yet to be defined in a delegated act which defines the methodology referred to in Article 28(5) of Directive (EU) 2018/2001. Reference to ISO standard 14067:2018 suggests, however, that a well-to-gate boundary will be aimed at which includes upstream emissions from energy input but excludes emissions from production of capital goods.
- Water: Regarding water use, the EU taxonomy requires an Environmental Impact Assessment (EIA) and risks identified in this EIA must be addressed.
- Biodiversity: Biodiversity is also included in the EIA. For biodiversity-sensitive areas (such as Natura 2000) the investor must carry out appropriate assessments.

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

[15] https://eur-lex.europa.eu/resource.html?uri=cellar:d84ec73c-c773-11eb-a925-01aa75ed71a1.0021.02/DOC_3&format=PDF

3.1.2 Renewable Energy Directive (RED-II)

The Renewable Energy Directive (RED-II) defines criteria for the production of Renewable liquid and gaseous transport fuels of non-biological origin (RFNBO). It therefore aims at hydrogen and fuels that are used in the transport sector. Recital 90 of the RED II defines four criteria for the electricity that is used to produce such fuels: Renewability of power purchase, additionality of RES-E sources, temporal correlation, and geographical correlation. The delegated act on specific definitions is still pending (Article 27(3)).

- GHG emissions: According to Article 25(2) the "[…] *greenhouse gas emissions savings from the use of renewable liquid and gaseous transport fuels of non-biological origin shall be at least 70 % from 1 January 2021.*". [16] System boundaries are yet to be defined in a delegated act which defines the methodology referred to in Article 28(5) of Directive (EU) 2018/2001.
- Electricity sources: Eligible sources for renewable electricity are defined in Article 2(36): "[…] *renewable liquid and gaseous transport fuels of non-biological origin' means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass* […]". This indicates that all renewable electricity sources can be used other than biomass.

The RED II is the starting point for other schemes and regulations on European level.

3.1.3 IPHE

In October 2021, the IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) published a Working Paper with the title "Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen[17]. This Working Paper has been prepared by the Hydrogen Production Analysis Task Force of the IPHE. The process was open to all IPHE member countries, but several of them did not actively participate in the analysis and in the production of the report. As the title suggests the methodology focusses exclusively on GHG-emissions.

- GHG-emissions: The Working Paper does not set any thresholds, it only provides a methodology for determining the GHG emissions. An analysis carried out by the same team who is authoring the present report (adelphi; Oeko-Institut (2021)) suggests that the methodology proposed by the IPHE Task Force is likely to significantly underestimate GHG emissions, both from SMR-based hydrogen and for renewable hydrogen based on electrolysis. System boundaries include upstream energy related emissions, however no emissions associated with the production of capital goods. The scope is well-to-gate. Therefore, emissions occurring during hydrogen transport are not reflected upon.

The methodology does not consider any other sustainability dimensions as described in section 2.3 of this report.

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[16] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=fr

[17] https://www.iphe.net/_files/ugd/45185a_ef588ba32fc54e0eb57b0b7444cfa5f9.pdf

3.1.4 CertifHy

The CertifHy project (CertifHy 2019) has been initiated by the European Commission and is funded by the Clean Hydrogen partnership. It is currently in its 3rd project phase until 2023 and aims at developing and implementing REDII-compatible H_2 certification schemes on a pan-European level. In collaboration with the Association of Issuing Bodies (AIB) a system of certificates shall be developed which is compatible with the European Energy Certificate System (EECS) and the requirements as imposed by the RED II for guarantees of origin. According to the RED II requirements, the focus is on green hydrogen based on production from renewable electricity, but it is also planned that hydrogen produced with non-renewable sources shall be covered. Furthermore, a certification system shall be established which ensures compliance with the RED II requirements for RFNBOs and which aims to be recognised by the European Commission as a voluntary verification system in that sense. Within its first two project phases, CertifHy has developed criteria for two different types of hydrogen, being "*CertifHy Green hydrogen*" and "*CertifHy Low-carbon hydrogen*". The respective criteria cover the following aspects:

- Electricity (only applicable for *CertifHy Green hydrogen*): Hydrogen production must be based on renewable electricity as defined in the RED II, Art. 2. This energy sourcing must be proven by means of cancelled RES GOs[18]. In multi-fuel plants, only the hydrogen produced from renewable sources (as calculated based on its energy content and documented by RES GOs) qualifies as *CertifHy Green hydrogen*.

- GHG Emissions: CertifHy defines an eligibility benchmark for the hydrogen production device in total, currently referring to state-of-the-art steam reforming of CH_4 in large installations with a GHG footprint of the H_2 produced of 91 gCO_{2eq}/MJ.[19] The GHG footprint of hydrogen production by the respective plant which neither qualifies as *CertifHy Green hydrogen* nor as *CertifHy Low-carbon hydrogen* has to be below the respective value. Otherwise, the production device is not qualified to produce *CertifHy green hydrogen* or *CertifHy Low-carbon hydrogen* at all.
  With respect to the GHG footprint of a specific production batch to qualify for *CertifHy Green hydrogen* or *CertifHy Low-carbon hydrogen*, CertifHy refers to GHG footprint methodologies as defined by ISO 14044 and 14067 as well as by Annex V (biofuels, bioliquids and their fossil fuel comparators) and Annex VI (biomass fuels and their fossil comparators) of the RED II[20] by applying them analogously to hydrogen. The applicable system boundary shall include all life-cycle stages from cradle to gate[21], assuming a hydrogen purity of at least 99.9% and a gauge pressure of at least 3MPa. System boundaries include upstream energy related emissions, however no emissions associated with the production of capital goods.

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[18] Guarantees of Origin for Renewable Energy Sources.

[19] MJ of hydrogen using the lower calorific value.

[20] CertifHy currently aims at updating the criteria in order to also refer to the corresponding Delegated Acts on greenhouse gas calculation.

[21] i.e. from extraction and processing of raw materials up to production of a marketable product, but excluding
- Building of the capital goods
- Transport and supply of the hydrogen to the consumers
- Use of the hydrogen; and
- Product end of life

3.1.5 TÜV Süd CMS 70

The TÜV Süd CM 70 standard (TÜV Süd 2021) is a voluntary certification standard which only covers hydrogen from renewable sources. It aims to be compatible with CertifHy, but it also imposes further criteria. The *Green Hydrogen* certificate which fulfils the function of a guarantee of origin is applicable for hydrogen if the hydrogen production is based on eligible renewable sources and GHG emission thresholds are met.[22] The scope of the certification is well-to-gate, assuming a purity of at least 99.9% and an achieved pressure of at least 3 MPa. The *GreenHydrogen+* certificate requires further criteria to be fulfilled, including aspects like mass balance tracking of the hydrogen transport, details on electricity supply and the use of certified electricity. Thus, the system boundary GreenHydrogen+ certification does also include transport (according to mass balance principles) and any conversions up to delivery to the customer.

The CMS 70 specifications generally refer to RED II/RED III and CCS Directive as well as to EN ISO 14067:2018, DIN EN IO 14040 and to DIN EN ISO 14044. Besides the criteria themselves, the CMS 70 standard also describes on a detailed level the verification procedures and certification process, which has to be performed by TÜV Süd as certification body.

- Electricity: The electricity supply to produce hydrogen has to be renewable. This must be either on-site generation, RES-E being supplied by direct line, or be documented by cancelled GOs (or similar instruments in non-EU-MS).

  For certification according to the *GreenHydrogen+* standard, further criteria apply. In principle, the renewable production must be unsupported. If it is supported, the support scheme must apply a competitive mechanism (auctioning). Furthermore, the following criteria are defined with respect to additionality and to temporal and geographical correlation:

  1. The renewable electricity production plant shall be not older than the electrolyser, meaning that the start of production of electricity shall have taken place not more than 11 months before the start of production of hydrogen by the respective electrolyser.

  2. Electricity taken from the grid shall be used within the same quarter of an hour as it is produced by the supplying RES-E plant; or it has to be demonstrated that more RES-E is generated in the same bidding zone in the same quarter of an hour as compared to the average annual generation of the respective country two years before the production period.

  3. At the time of commissioning of the electrolyser, there shall be no grid congestions between the contracted RES-E plant and the electrolyser. Both installations shall be in the same bidding zone. If it can be demonstrated that there are neither bottlenecks nor price differences, the installations may also be located in neighbouring bidding zones.

- Energy system: Certified hydrogen may only be used in the mobility sector, for material use or as a storage medium. For use in steam, heat or cold applications, a minimum GHG emission reduction has to be fulfilled (see below).

- GHG Emissions: The GHG emission reduction potential of certified hydrogen must be at least 70% compared to the reference value for biofuels according to Annex V RED II of 94g CO_2eq/MJ.

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[22] If countries have implemented operational GO systems according to Art 19 of RED II (or analogously in Non-EU-MS), the GreenHydrogen standard aims to be used as an independent criteria scheme as additional information item on official GOs.

This corresponds to a GHG value of 28.2 g CO_2eq/MJ. For use in steam, heat or cold applications, a minimum GHG emission reduction of at least 70% as compared to a fossil fuel benchmark of 80g CO_2eq/MJ must be achieved by the certified hydrogen, corresponding to a GHG value of 24 g CO_2eq/MJ_{Hi}. The scope of the certification is well-to-gate. Hydrogen production which takes place outside the accounting periods for *GreenHydrogen* has to fulfil a GHG emission value of being not larger than 91 gCO_2eq/MWh as a prerequisite that the plant is eligible for the production of *GreenHydrogen*.

3.1.6 H2Global

H2Global has been developed as a form of state procurement of hydrogen and other derivatives to foster the market uptake of hydrogen. A company will function as intermediary between hydrogen off-takers (e.g., Industry) and hydrogen producers. The system will be based on long-term contracts (10 years) on the production side and short-term (1-2 years) sell contracts. Financial losses of the intermediary will be covered by the German federal government. H2Global started a market consultation late 2021 on criteria for hydrogen production that should be part of the off-take contracts[23]. Only “green PtX-Products” will be contracted, therefore criteria relate to green hydrogen.

- Electricity: Criteria will be based on REDII (201872001/EU) including the pending delegated act for Article 27. This includes use of renewable electricity, additionality of RES-E, temporal and geographical correlation.
- GHG emissions: The criteria are suggested to be based on the RED II, where GHG reductions must be 70% compared to the fossil comparator. The balancing must include scope 1, scope 2 and scope 3 emissions and should include all steps of the hydrogen value chain up until delivery in Germany.
- CO_2 source: It is suggested to allow CO_2 from Direct Air Capture (DAC), process-related emissions of industries that cannot be avoided in the long-term and biogenic CO_2 which fulfils the European standards for biofuels. CO_2 from fossil fuelled power plants is excluded.
- Water: Use of water must be sustainable, which addresses the quality of water as well as the availability of water. In arid regions the use of fossil waterbodies as well as drinking water is excluded. In case of sea water desalination, the handling of brine disposal is to be reported.
- Land use change: Conflicts over land use is to be prevented, protected areas are excluded, ecological damages need to be excluded and only sustainable biomass is to be used. They suggest performing a “social and environmental impact assessment”.
- Waste and pollutant management: Must be conform with a suitable UN environmental standard (ISO 14001).
- Social and work standards: Minimum must be the ILO standards. Those standards must also be respected by subcontractors.
- Local participation: Participation of local people (especially woman) and companies must be proven.

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[23] https://www.bmwi.de/Redaktion/DE/Downloads/W/marktkonsultation-H2Global.html

3.1.7 California's Low Carbon Fuel Standard (LCFS)

The LCFS was introduced in 2011 to reduce the GHG emissions intensity of the transportation fuel pool used in California through annually decreasing technology-neutral benchmarks for any fuels including hydrogen. Fuel retailers must meet the GHG emissions intensity benchmark on average for each year by either procuring low-emission fuels themselves or by purchasing LCFS credits from others to balance their deficits resulting from fuels with higher emissions intensity, e.g., Diesel (CARB 2020a; 2020b). With regards to the included hydrogen production pathways, the LCFS regulation addresses the following sustainability dimensions:

- GHG emissions: Predefined emissions intensity benchmarks are set by the California Air Resources Board (CARB) based on well-to-wheel full life-cycle analyses, including upstream emissions from feedstock production and transport as well as indirect emissions from land use change, amongst others. These are for renewable hydrogen from RES-E 10.51 gCO2eq/MJ, for compressed hydrogen from SMR 117.67 gCO2eq/MJ, and for liquified hydrogen from SMR 150.94 gCO2eq/MJ. Blue hydrogen from SMR with CCS is not yet included, since no such production project exist so far in California (CARB 2018). The 2022 LCFS emissions intensity benchmark for the overall fuel pool stands at 89.50 gCO_{2eq}/MJ (CARB 2022).

- Electricity (in case of renewable hydrogen from electrolysis): Needs to come from renewable energy resources (excluding biomass, biomethane, geothermal, and municipal solid waste) and can be either directly supplied or indirectly through the electricity grid ("book-and-claim accounting"), if additionality of RES-E, temporal and geographical correlation requirements are met (CARB 2019).

3.1.8 Hydrogen Guarantee of Origin (GO) scheme for Australia

The Government of Australia is currently developing a GO scheme based on a certificate approach for hydrogen production in Australia. The scheme will be very closely aligned to the IPHE methodology and process, since the government expects the IPHE methodology to progress into a formalised international standard over time, which would then maximise international trade opportunities for Australian hydrogen producers. The GO scheme includes the GHG emissions intensity over a well-to-gate boundary of three production pathways "most relevant to Australia": electrolysis, coal gasification with CCS, and SMR with CCS. Additionally, the possibility to use carbon offsets for indirect hydrogen emissions reductions is discussed as part of the scheme. The Australian government currently tests the application of the proposed GO scheme through trial projects to settle the remaining question and determine the robustness, before it becomes fully operational (DISER 2021a; 2021b). The following sustainability dimensions are included in the GO scheme as of now.

- GHG Emissions: The scheme includes GHG emissions over a well-to-gate system boundary, such as upstream emissions (e.g., fugitive and combustion emissions from extraction, processing and delivery of the coal or CH_4), direct hydrogen production emissions from SMR and coal gasification processes, and indirect emissions from electricity/energy used for the hydrogen production and CCS processes. Apart from that carbon capture emissions removals, and co-product emissions are also considered. For CCUS, it is proposed that it should be limited to emissions permanently stored in geological formations until robust international accounting provisions are developed for other forms carbon storage/usage. Predefined emissions intensity thresholds for hydrogen production pathways to be counted as low-carbon or renewable are not yet discussed as part of the scheme.

- Electricity: A so-called market-based method is proposed, which allows to purchase of renewable electricity through contractual arrangements, e.g., the existing large-scale generation certificates (LGCs) under the Renewable Energy Target (RET) scheme. The use of such certificates shall mitigate the risk of double counting for the renewable electricity used. If also electricity is for hydrogen production that is not covered by renewable energy certificates or supplied from directly-connected renewables, then its emissions will be calculated based on the emissions intensity of the local grid (through a so-called residual mix factor) (DISER 2021a; 2021b).

3.1.9 China Hydrogen Alliance Standard and Evaluation of Low Carbon Hydrogen, Clean Hydrogen and Renewable Energy Hydrogen

The China Hydrogen Alliance, a government-supported industry group, has published this first Chinese hydrogen standard in December 2020, distinguishing between “low-carbon hydrogen”, “clean hydrogen” and “renewable hydrogen” based on a life-cycle assessment approach largely aligned to the CertifHy project in Europe. It is likely that the technology-neutral standard will be the basis for (or at least have a significant influence on) a future governmental hydrogen standard, which may be currently under development as part of China’s hydrogen strategy (Fuel Cell China 2020; Liu et al. 2021) . The following sustainability dimension are included in the standard as of February 2022:

- GHG emissions: The scope of the scheme is well-to-gate (with a “point of production” system boundary to reduce the calculation and administrative cost). Emissions from upstream activities, such as coal and CH_4 production and transport are included. Excluded are downstream GHG emissions from hydrogen storage, transportation, supply, boil-offs and leakages as well as from the construction of hydrogen plant and transportation infrastructure.

  The scheme sets two emissions intensity thresholds for hydrogen production, instead of one threshold like in CertifHy, to account for the Chinese situation and ensure a smooth transition. Since most hydrogen in China is currently produced from coal, the GHG emissions intensity of hydrogen produced via coal gasification (242 g/CO_2eq/MJ H_2) is used as the benchmark for the adopted the “low-carbon”, “clean” and “renewable hydrogen” thresholds. “Low-carbon hydrogen” is defined with a threshold of 121 g/CO2e/MJ H2 (14.51 kgCO_2eq/kgH_2) based on the expected emissions intensity of hydrogen produced via coal gasification with CCS. “Clean” and “renewable hydrogen” are defined with a threshold of 40.8 g/CO_2/MJ H_2 (4.9 kgCO_2eq/kgH_2) based on a 65% emissions reduction compared to “low-carbon hydrogen” and as expected in China’s “Energy Supply and Consumption Revolution Strategy 2016–2030”. The difference between clean and renewable hydrogen is that the latter specifically requires to be produced based on renewable energy (including wind, solar, hydro, biomass, geothermal, and ocean energy) (Liu et al. 2021).

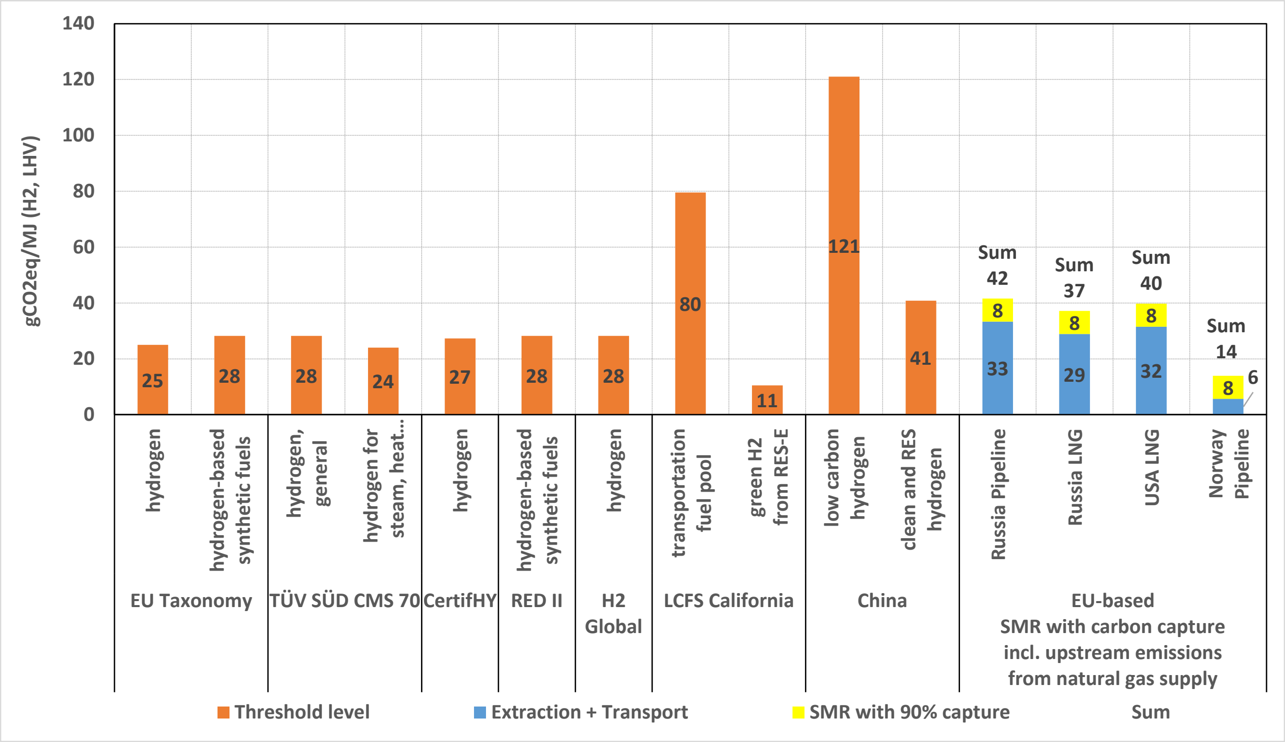
- Electricity: In case of renewable hydrogen from electrolysis, hydrogen producers can either use renewable electricity directly supplied to the electrolysis plants or purchase recognised renewable electricity certificates. When non-renewable electricity is used, the emissions intensity of hydrogen will be based on power grid emissions intensity in the area. Specific provisions regarding the principles of additionality, temporal and geographical correlation of renewable electricity generation were not found by the authors (Fuel Cell China 2020; Liu et al. 2021) .

3.2 Overarching results and shortcomings

All analysed schemes and regulations in this section define specific thresholds and criteria for **GHG-emissions**. There is a divergence in the ambition levels between EU-based schemes and regulation and those tailored to the US and China (see Figure 1): The threshold for GHG-emissions for e-fuels and hydrogen for different end-uses in European schemes and regulations are streamlined between 24 and 28 gCO_{2eq}/MJ, which corresponds to a 70% reduction to the fossil fuel-based. The threshold for hydrogen is 27 gCO_{2eq}/MJ. LCFS California with a target of about 80 gCO_2eq/MJ is not directly comparable, as it represents a transportation fuel pool target where individual production routes with respective emission intensities contribute to the overall target. According to the underlying LCFS methodology, RES-E-based green hydrogen has an emissions intensity of 11 gCO_2eq/MJ. The Chinese scheme uses a different reference system. Coal gasification is the reference for “low carbon hydrogen”, i.e., while the threshold refers to coal-based hydrogen with CCS. The Chinese “clean and RES-based standard” is broadly aligned via CertifHy to the ambition levels of the former EU reduction target of 60%, which, however, has been increased to 70% in current EU policies.

Figure 1 provides a comparison between the different threshold levels of the schemes and indicative estimated GHG emissions from EU-based hydrogen production from SMR with CO_2 capture, where the GHG balance includes upstream emissions evaluated from a 100 years Global Warming Potential (GWP) perspective (calculations based on FOEN 2021b; 2021a and IEAGHG 2017. See footnote 24 for further details). For EU-based SMR with carbon capture, it highlights that CH_4 supply is limited to short distance transport and conventional production to comply with the thresholds, if upstream emissions are included into the GHG emission balance. If SMR with carbon capture is performed in the CH_4 producing country (potentially implying a reduction in transport related emissions), then conformity with EU standards will critically depend on additional emissions from CO_2 transport and storage and whether the GHG footprint of the hydrogen transport is also included into the GHG balance.

Figure 1: Thresholds for GHG-emissions in different European and international schemes compared to a scenario of EU-based SMR with carbon capture based on indicative data.



Source: own illustration based on various sources provided in the text.[24]

System boundaries are at least well-to-gate in all schemes and regulations analysed. Some schemes also include the transport of hydrogen to the point of demand (see Table 3-1). GHG-emissions of the technical equipment are not addressed in schemes or regulations. However, the wording used in official documents describing the H2Global suggested criteria set could be interpreted that those emissions are to be considered. There is also considerable divergence in terms of the **scopes and time horizons**. These aspects are important, given that upstream emissions make up a significant portion of the overall GHG emissions balance, especially if SMR, long distance transport and fracking gas are involved.

Even if upstream GHG-emissions are generally covered by the schemes and regulations, the specific quality of data on how to determine those emissions can lead to deviating results. The IPHE working paper considers upstream GHG-emissions, yet the methodology could lead to underestimation of those (compare section 3.1.3).

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[24] The sources of the thresholds are provided in the description of the respective schemes and regulations. Figures on GHG emissions from NG extraction taken from FOEN (2021b). Figures take into account GHG emissions from emitted NG, flared NG, NG, heavy fuel oil and diesel burned and from other sources, Figures on GHG emissions from CH_4 transport are calculated based on transport distances, leakage rates, and additional energy demands given in FOEN (2021a). The GWP100 from AR6 is applied to CH_4 leakage. Total energy demand for SMR with 90% CO_2 capture (1.32 MWh/MWh H_2 LHV) from process and flue gases is taken from IEAGHG (2017).

Table 3-1: System boundaries for GHG-Emissions in schemes and regulations

Scheme / Regulation	hardware	Energy production	Energy transport	Hydrogen production	Transport of hydrogen	supply
EU Taxonomy	None of the schemes and regulations include emissions from CAPEX	▨	▨	▨		
RED-II		▨	▨	▨		
IPHE Task Force		▨	▨	▨		
CertifHy		▨	▨	▨		
TÜV Süd CMS 70		▨	▨	▨	▨ for GreenHydrogen+	▨
LCFS		▨	▨	▨	▨	▨
China H₂ Alliance		▨	▨	▨		
H2Global	▨ No clear definition	▨	▨	▨	▨	▨

Source: own

Other environmental sustainability dimensions such as water, biodiversity, critical resources, CO_2 sources, air quality and soil are mainly not covered by the schemes and regulations and if so, in much less detail. Especially **water use and water pollution** can be relevant for both pathways of hydrogen production under consideration within this paper (see section 2.3.1). However, only the EU taxonomy and proposed criteria by H2Global define tangible standards. **Electricity sources** for renewable hydrogen are defined in most analysed schemes and regulations. For European schemes it is defined according to the provisions of REDII. However, some international schemes do not (yet) specifically define electricity sources. Also, provisions for the electricity input such as additionality, temporal correlation and geographical correlation are missing or defined differently. **CO_2 sources** to produce hydrocarbons from hydrogen are only addressed in the criteria proposed by H2Global, which suggests to only use CO_2 from Direct Air Capture (DAC), process related CO_2 from industry, or sustainable biogenic CO_2. However, schemes and regulations that only cover hydrogen production may not be expected to address CO_2 sources needed to produce derivatives.

Sustainability dimensions on the system level (compare section 2.3.3) are not covered at all in the schemes and regulations analysed. The system level is especially relevant for imports of hydrogen and derivatives as decarbonisation goals in exporting countries might interact with exporting hydrogen.

Socio-economic sustainability dimensions are also not considered by the schemes and regulations analysed.

4 Most relevant challenges for sustainability in hydrogen imports and discussion of potential solutions

Challenges are identified by analysing issues that arise at the intersection of the different viewpoints and sections of this paper: along the hydrogen value chain, along the sustainability dimensions, for different types of hydrogen and from different existing regulations and certification schemes.

4.1 Application of RED II provisions to electricity systems in third countries

The REDII and pending delegated acts do and will define detailed provisions for electricity input to produce hydrogen eligible to be defined as renewable according to EU law. These provisions will also be relevant for hydrogen based on electrolysis imported into the EU.

4.1.1 Description of the challenge

The RED II defines three options to prove that electricity input into the electrolysis is from renewable electricity generation. Each of them involves specific challenges for hydrogen production and certification in third countries.

- **Fulfilment of GHG threshold by use of average CO_2-emissions of grid mix**: The option of using the grid mix to define renewable hydrogen production is stated in Article 27(3)[25]. Article 25(2) aims at a GHG emissions reduction of 70% comparing the hydrogen-based e-fuel to a fossil comparator fuel in the transport sector. The exact methodology is to be defined in a separate delegated act that is still pending.
    - The main challenge will be to define comparable datasets for third countries providing CO_2-emissions of the average grid mix.
- **Proving renewable electricity input by direct connection of electrolysis to RES-E plants**: Article 27(3) a and 27(3)b define that electricity obtained from direct connection may be fully counted as renewable if the RES-E plant comes into operation at the same time or after the hydrogen production plant and the RES-E plant is not connected to the grid or it is proven that electricity from the grid is not used.
    - Those provisions need strong verification and monitoring systems in place with regular audits.
- **Claiming renewable electricity from the grid**: This is based on provisions from pending delegated act on Article 27 and Recital 90: Renewability of power purchase, additionality of RES-E sources, temporal correlation, and geographical correlation. The challenge is to define criteria that can be fulfilled in third countries, especially those with integrated monopolies:
    - The **definition of a “bidding zone”** has been used in drafts of the delegated act to secure a geographical correlation between the hydrogen production installation and the electricity generating installation. However, in many countries of the world the concept of “bidding zone” cannot be defined at all, especially if there is no unbundling in the electricity market and electricity generation and transmission is not organized on a market platform but by vertically integrated utilities. In countries and power systems with nodal pricing (e.g., large parts of the US and several other countries) bidding zones are very small. There, the application of this principle might lead to unintended consequences: for instance, if an electrolyser is adjacent to a hydro power plant, it appears as if it is running 100% on renewable electricity, although in the broader region the renewable share might be low

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[25] *“For the purposes of this paragraph, where electricity is used for the production of renewable liquid and gaseous transport fuels of non-biological origin, either directly or for the production of intermediate products, the average share of electricity from renewable sources in the country of production, as measured two years before the year in question, shall be used to determine the share of renewable energy.”*

- **National systems for Guarantees of Origin** (GOs) for electricity, which should rule out double counting of renewable energy, are not in place in several countries.
- **Data availability** to prove temporal correlation between hydrogen production and RES-E generation is not given in all countries.

4.1.2 Options for solutions

Table 4-1: REDII provisions – Challenges and options for solutions

Challenge	Options (not mutually exclusive)	Pro	Con
Data availability of specific CO_2 grid mix	• IEA Datasets • Optional with correction for net imports	• Availability of worldwide data • Established methodology and reporting channels	• Country data might substantially deviate from emissions within the relevant bidding zone or region for hydrogen production • Data standards might differ between countries • Data unrealistic in countries with high imports from other countries • No independent verification • Data is available with 2-3 years time lag
Implementing institutions for verification and monitoring of technical provisions and data	Private institutions to verify hydrogen production in exporting country based on European verification regulation	• Private actors are flexible; approach is easy to implement and applicable for all countries	• Might lack access to country level statistical information • Increased challenge of comparability of audit results and independency of auditors
	Central European Verification Authority	• Establish new independent agency that provides independent expertise and acquires important knowledge and experience base	• Lead time to build up such agency in terms of knowledge and work force • Might lack access to country level statistical information • Might get in conflict with local government competencies
	Verification based on governmental regulation in exporting country (e.g. associated with national H_2 GO system)	• Establishment of competent national authority with direct access to information and resources • Possibly improved synergies with other national verification systems	• Comparability and transparency of verification results might be restricted • Approach possibly not applicable in all exporting countries (if those have not established such a verification scheme)
Definition of “bidding zone”	Bidding zone could be defined as country borders if no bidding zones exist	• Clear definition • Electricity system and grid often correlated to countries borders	• not feasible for countries with nodal pricing • Data unrealistic in countries with high imports from other countries • Data unrealistic in countries with grid bottlenecks between regions
	Bidding zone = zone under one transmission system operator	• Clear definition • One contact point	• TSOs zone can have historical origins and not correspond to physical flows and system boundaries
National systems for Guarantees of origin for	Integration into European scheme	• Can build on established practices	• different regulatory basis between EU and exporting countries to build on

Challenge	Options (not mutually exclusive)	Pro	Con
electricity including auditing and verification	Use of national scheme in exporting country	• Co-benefits with use of the system with other domestic decarbonization efforts	• Lead time for build-up of knowledge base, data access, etc. might slow down the market uptake of hydrogen imports to EU
Data availability to prove temporal correlation	Use of data from local transmission grid operator If not available, built up to data collection	• Data can be helpful for other purposes in terms of decarbonization of the domestic energy systems	• Lead time for build-up of knowledge base, data access, etc. if such a system is not in place or does not provide data with the required quality

Source: own

Remarks on grid integrated hydrogen production in third countries:

- Especially when using electricity from the grid the fulfilment of provisions such as additionality, temporal and geographical correlation as well as renewability comes with substantial challenges. Missing institutions, missing data and mismatching definitions in electricity systems that substantially differ from the European electricity system will at least cause a time lag for the uptake of hydrogen exports.
- Therefore, it could be an option to foster off-grid hydrogen production with direct connection to the RES-E plant at least for a market uptake phase. This production layout might be the safeguard for investors anyhow.
- Grid-integrated hydrogen production that complies with European regulation according to RED-II could be fostered by direct support of exporting countries in:
  - Building up institutions that establish and run a national GO system for electricity
  - Building up institutions for data collection and provision processes including regular verification

4.2 Accounting of upstream methane emissions

4.2.1 Description of the challenge

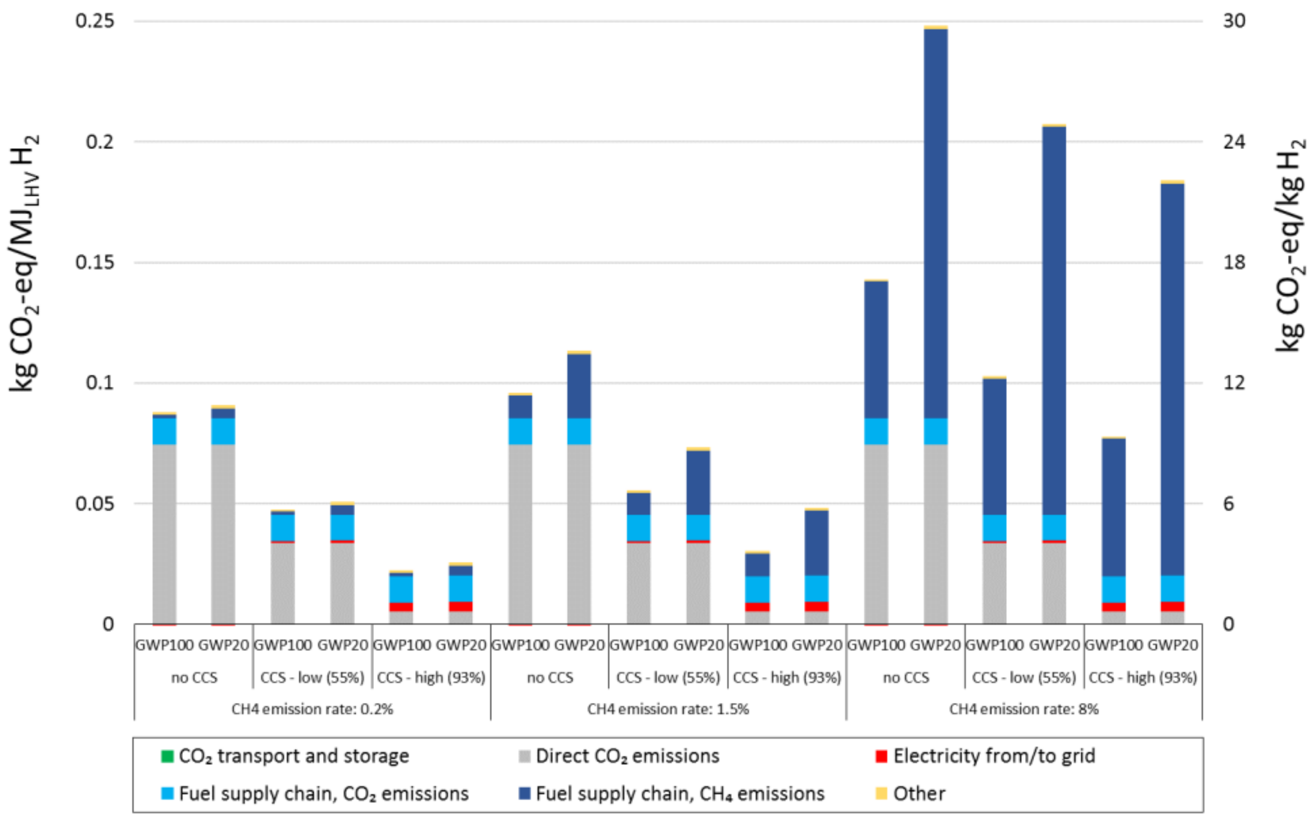
After CO_2, methane (CH_4) is the second most important greenhouse gas. While the largest source of CH_4 emissions at global level is agriculture including animal breeding, CH_4 emissions from the energy sector have been rapidly rising during the last two decades, largely driven by production increases from the so-called shale-gas revolution (Saunois et al. 2020). CH_4 emissions from the energy sector can occur deliberately (e.g. venting or incomplete flaring in the oil and gas industry, mainly in extraction areas) or unintentionally (e.g. diffuse emissions at gas fracking extraction sites, emissions from coal mines, leaks along CH_4 pipelines and in the distribution networks, at compressing stations, storage sites or due to incomplete combustion at the consumption point).

Upstream CH_4 emissions play no significant role for hydrogen produced by electrolysis based on electricity exclusively generated from renewable energy. If a part of the electricity used in the electrolysis is taken from a power system with significant shares of gas-powered generation, they can play a more or less important role, especially depending on factors such as the way how electrolysers are operated and how this correlates with the dispatch of gas-fired units.

The rate of upstream CH_4 emissions has a fundamental impact on the GHG emission intensity of fossil-based hydrogen production based on SMR with or without CCS (Bauer et al. 2021), as shown in the following figure, where the methane emissions are depicted in dark blue. Decreasing the CH_4 emission rate from 8% (a level probably occurring only in association with super emitters) to 1.5% (a level in line with rather optimistic assumptions) reduces the GHG emission intensity of hydrogen from SMR with best practice CCS (with a 93% capture rate) by a factor of circa 3, with reference to the global warming potential over 100 years.[26]

Comparing SMR with best practice CCS to SMR without CCS, the relative difference is smaller (slightly less than factor 2), but the absolute difference remains similarly high.

Figure 2 - Impact of CH_4 emission rate and other factors on the GHG emission intensity of H_2 from SMR



Source: Bauer et al. (2021)

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[26] Alvarez et al. (2018) estimate a methane leakage rate of 2.3% for the U.S. oil and gas supply chain, similarly, Howarth (2022) estimate fugitive methane emissions in terms of percentage of methane that is produced at the well site and from processing as 0.3% to 2.4% for conventional gas and as 2.6% for shale gas production in the US. Such average values are the result of many facilities with rather low or very low emissions in association with so-called super-emitters, e.g. major leaks that remain unaddressed over longer time. As one might expect, the figure also shows the strong impact of the CCS level (none, low or high) on the emission intensity of hydrogen from SMR.

The large variation of CH_4 emissions and their impact on the GHG emission intensity of hydrogen produced via SMR are a challenge for international trade with hydrogen. An effective monitoring of CH_4 emissions based on procedures recognized at global level will be necessary. Without that, there would be neither a reliable basis to determine the value of hydrogen in terms of climate mitigation nor a level playing field for the competition between hydrogen from renewables and from SMR or between different countries. Therefore, a main challenge is how to ensure that the upstream CH_4 emissions embodied in hydrogen produced by SMR with or without CCS are properly accounted for, as a decisive step for being able to compare and price the GHG emissions of different hydrogen production paths. As most of the CH_4 consumed in the EU is imported, it is crucial that the emerging EU regulatory framework on CH_4 emissions is applied also to imported CH_4, including the parts of the value chain outside the EU borders.

CH_4 is odourless and not visible to human eyes. Traditionally, CH_4 emissions could only be monitored in direct proximity of the facilities. Besides its cost, on-site measurement is difficult or impossible to implement without the collaboration of the governments of the relative countries as well as of pipeline and facilities operators. In the past, public authorities have referred to operators' assessments without independent verification. However, recent studies have shown that industry data in the US were often massively underestimated (Alvarez et al. 2018; Parkinson et al. 2019), which may be true also for other parts of the world. A game changer (Columbia SIPA Center on Global Energy Policy; TNO 2020) emerged during the last few years is the data flow from satellites dedicated to monitoring CH_4 emissions, notably from the European Space Agency[27]. Further innovation consists of monitoring via air drones. Satellite based monitoring enables the detection of both individual leaks and diffuse CH_4 emissions, independently from the collaboration of the infrastructure operators or of the authorities of the state where the emissions occur. If the monitoring is linked with sufficiently deterring sanctions, satellite-based monitoring can be a decisive means to reduce CH_4 emissions.

Traditionally, CH_4 emissions have been regulated in terms of health and safety (explosion risk), but not in terms of their climate impact. The proposal for the EU methane emissions reduction regulation adopted by the European Commission in December 2021 is a pioneering effort to establish detailed standards for measuring, reporting and verifying CH_4 emissions from the energy sector. The proposal also includes an intentional ban on natural gas venting and flaring and makes leak detection and repair mandatory.

4.2.2 Options for solutions

Table 4-2: Upstream methane emissions – challenges and options for solutions

Challenge	Options (not mutually exclusive)	Pro	Con
Ensure proper accounting for upstream CH_4 emissions embodied in SMR-based	Rapid adoption and implementation of the EU methane emissions regulation	• Reduction of CH_4 emissions • Higher transparency of GHG emission intensity, enabling a level playing competition between different hydrogen pathways	• Implementation costs for the gas industry and the public sector

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[27] https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P

Challenge	Options (not mutually exclusive)	Pro	Con
hydrogen (with or without CCS)	Application of EU methane regulation requirements to entire value chain of imported CH_4, including the substantial segments outside the EU (if possible in a legally binding form, or least in a voluntary form, i.e. enabling importers to demonstrate their compliance)	• Reduction of CH_4 emissions • Avoidance of an inappropriate competitive advantage in favour of hydrogen production paths that are more CH_4 emissions intensive	• Binding application might require foreign policy efforts and have WHO implications (not examined in this paper) • Higher costs for CH_4 consumers (including SMR-based hydrogen producers) if monitoring and avoidance costs are passed through
	Deepening of public investment in monitoring infrastructure	• Possibility and incentive for operators to repair and possibly prevent CH_4 leaks • Provide CH_4 and hydrogen customers as well as civil society with the data needed to exercise pressure on the providers to reduce CH_4 emissions	• Cost of the potential support programs

4.3 Diverging definitions of “blue / low carbon hydrogen”

4.3.1 Description of the challenge

The terms blue / low carbon hydrogen usually refer to methane-based hydrogen using SMR including capture and storage of CO_2. However, an analysis of hydrogen strategies and public documents in third countries suggest that this term “is used in various ways, which partly deviate from EU regulations in force or in course of being adopted. The deviation mainly concerns the CCS or CCU process. Especially countries with a strong fossil gas and oil extraction industry often include in the definition of low carbon hydrogen also CO_2 storage in operating oil or gas fields for enhanced oil or gas recovery as well as CO_2 used in the chemical industry to produce for example methanol or plastics. However, ff those products are burnt later (as plastics or as fuels) the CO_2 is finally emitted into the atmosphere.

However, the current “*Commission Implementing Regulation (EU) 2018/2066 on the monitoring and reporting of greenhouse gas emissions*”[28] states in Article 49 that CO_2 emissions can only be subtracted from process emissions if

- stored in a long-term geological storage or
- used to produce precipitated calcium carbonate, in which the used CO_2 is chemically bound.

Concerning carbon capture and usage (CCU), the Proposal for a “DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757”[29] states that

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[28] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02018R2066-20210101&from=EN

[29] https://eur-lex.europa.eu/resource.html?uri=cellar:618e6837-eec6-11eb-a71c-01aa75ed71a1.0001.02/DOC_1&format=PDF

- For carbon capture and utilisation "*[…] surrender obligations do not arise for emissions of CO_2 that end up permanently chemically bound in a product so that they do not enter the atmosphere under normal use*."
- Also, Recital 13 states that: "*Greenhouse gases that are not directly released into the atmosphere should be considered emissions under the EU ETS and allowances should be surrendered for those emissions unless they are stored in a storage site in accordance with Directive 2009/31/EC of the European Parliament and of the Council13, or they are permanently chemically bound in a product so that they do not enter the atmosphere under normal use.*"

4.3.2 Options for solutions

There is a strong need to clearly describe which CCS and CCU options are suitable for GHG-reductions in line with European legislation. Those definitions need to be made transparent to possible hydrogen export countries that aim at exporting methane-based hydrogen with CCS or CCU.

4.4 Clear definition of sustainability criteria beyond GHG-emissions

As analysed in section 3.2, the schemes and regulations currently existing or in the pipeline mainly focus on the GHG-emissions intensity of hydrogen production. Other sustainability dimensions with respect to environmental, socio-economic and system-level sustainability are hardly covered. While the focus on emission intensity is important for compliance with GHG reduction targets, the implementation of sustainability standards besides GHG-emissions is relevant to ensure

- that hydrogen production does not lead to negative socio-economic and environmental effects on the project level as well as on the energy and economic system level, hence ensuring compliance with the Sustainable Development Goals,
- long-term public acceptance for (imported) hydrogen as a (publicly funded) decarbonisation instrument
- security of investments and desired technology development to foster technological learning and decreasing technology and transformation costs in the long-term.

4.4.1 General consideration: Achieving a consistent and accepted set of standards

Even though individual schemes or regulations do address some sustainability dimensions besides GHG-emissions, they are in general not yet sufficiently specified nor operationalizable. How can definition and implementation of sustainability dimensions be streamlined, and should those be addressed in regulation or solely be left to regulation under private schemes? We suggest considering the following approaches to tackle this challenge:

- Adopt mandatory sustainability standards that are required to be allowed to sell or consume hydrogen in the EU: Aim at setting standards on the European level (based on a multi-stakeholder process) for a chosen set of sustainability criteria for hydrogen production. However, standards will touch upon very different topics and can most likely not be streamlined for the entire value chain of hydrogen production.

- Adopt sustainability standards that are required for hydrogen investments or hydrogen as a commodity to be eligible for support via public policies, such as qualifying for the EU Taxonomy, or being accepted as “renewable” or “low carbon” or being eligible for other support schemes intended to promote the market uptake of hydrogen. However, this will firstly still not cover all relevant sustainability dimensions and secondly will – in the case of ambitious criteria set by funding schemes – set higher standards in the market uptake phase than in later phases of the hydrogen economy when funding and hence its criteria are less relevant. In general, the development of a “one stop shop” defining all relevant criteria within the hydrogen value chain with reference to the various regulations could be helpful for investors aiming at a market uptake in the short term.
- Phase-in of criteria with lower sustainability standards to start-off with. This can lower costs for first movers and create a learning curve. Still criteria need to set the right incentives concerning future proof technology development and the phase-in criteria should not act as a lock-in for future criteria sets.

4.4.2 Selected individual dimensions

Water

The challenge: Total water demand is quite similar between production routes based on RES-E- and those based on SMR. As described in section 2.3.1.2, one must still differentiate between water withdrawal and effects on water quality. The configuration of the hydrogen supply chain (how is primary energy sourced, where is hydrogen production located, are water input, consumption and wastewater discharge tailored to local conditions etc.) is a key factor in the assessment of the water footprint and the relevance of this sustainability dimension.

However, the focus in the discussions and the coverage in current regulation and certification schemes is very different for different hydrogen production routes. Sustainable water sourcing and water treatment needs to be defined for all routes and analysed on project level. We suggest considering the following approaches to tackle this challenge:

- Certain regions with water stress could be excluded from water sourcing for certain types of hydrogen production. This can act as a strong safeguard, however, defining “regions” and choosing the right indicators to assess those would be difficult. On the other hand, some worldwide datasets are already available from sources such as the World Resource Institute[30].
- Water sourcing from sea water desalination could be mandatory for certain areas that show water stress. This option could be merged with option I above. This would certainly reduce pressure on fresh water sources; however, sea water desalination generates sustainability challenges itself such as brine disposal and competition with other usages of desalinated water in densely populated areas. Moreover, this option would also need to rely consistent and robust datasets for defining respective areas.

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[30] https://www.wri.org/applications/aqueduct/water-risk-atlas/#/?advanced=false&basemap=hydro&indicator=w_awr_def_tot_cat&lat=30&lng=-80&mapMode=view&month=1&opacity=0.5&ponderation=DEF&predefined=false&projection=absolute&scenario=optimistic&scope=baseline&threshold&timeScale=annual&year=baseline&zoom=3

- Reliance on project based Environmental Impact Assessments. This option can reduce risks from single projects. However, it tends to neglect the broader impact of a large-scale uptake of hydrogen production within a certain area. Hence, the first projects might be feasible within some regions, but an uptake of hydrogen production in large scale must rely on other sources of water in the long run. Also a standard for Environmental Impact Assessments needs to be defined.

CO_2 source

CO_2 is needed to produce synthetic hydrocarbons from hydrogen such as methanol or e-fuels. As shipping of pure hydrogen comes with additional losses due to liquification or conversion and reconversion (e.g. into ammonia), it can be expected that synthetic hydrocarbons will play a significant role in international trade of low-carbon fuels. Sources with high density of CO_2 in the exhaust gas flows can be found mainly in industries burning fossil fuels. However, while this production cycle allows for a reutilization of the CO_2, it is not climate neutral: after their second useful application in the synthetic hydrocarbon, the CO_2 molecules of fossil origin are eventually emitted into the atmosphere. Moreover, using those CO_2 streams will generate a value for CO_2 which might lead to a lock-in of the fossil-based CO_2 cycle and thus to a postponement of the decarbonisation of those industries.

In view of achieving climate neutrality, in the long-term synthetic hydrocarbons need to be produced from sustainable, climate neutral CO_2 sources. Fully climate neutral options are biogenic CO_2 from sustainably produced biomass, and direct air capture (DAC). Another relevant option, although not climate neutral are unavoidable process emissions from partly irreplaceable industrial processes, such es calcination (e.g., from cement production).

However, DAC is currently very expensive and energy intensive, and sustainable biomass is scarce. Therefore, a gradual phase-in of such sustainable CO_2 sources should be considered. If CO_2 from fossil fuels is used during the first part of the lifetime of a facility to produce synthetic hydrocarbons, the transformation towards sustainable CO_2 sources should be enshrined in the project outline in terms of timelines but also physical infrastructure. For instance, reserving sufficient space for the later implementation of DAC. Moreover, correct, and full accounting of the GHG footprint should not leave the CO_2 input as a blind spot but make the fossil-based input transparent for monitoring and in terms of correct GHG accounting.

Socio-economic sustainability

None of the regulations or schemes analysed for this report specifically addresses socio-economic sustainability dimensions. However, especially when considering the prospect of large-scale hydrogen production in developing countries for export purposes, the socio-economic dimension is very relevant to ensure progress towards the achievement of the Sustainable Development Goals. Yet, some socio-economic sustainability dimensions cannot easily be expressed in quantitative indicators and therefore, cannot easily be integrated into measurable criteria and verified in audits.

- Approach I: Build upon standard for Environmental and Social Impact Assessments and incorporating them into the entire project lifecycle.

- Approach II: An initiative could be established[31] to make sure that 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. This would include the chance to address specific risks and chances related to the hydrogen value chain.

System level sustainability

Electricity system level: Ensuring sustainability on the electricity system level (for green hydrogen) requires a set of institutions (GO system, certification etc.). Several potential exporting countries outside the EU do not have such systems and institutions in place. We suggest considering the following approaches to tackle this challenge:

- Definition transition pathways and joint efforts between EU and potential exporting countries are necessary
- Limit support on dedicated RES-E generation with off-grid H_2 plants at least until institutions and processes to prove renewable electricity input from the grid are in place.

Energy system level & Economic system level: Criteria for those levels are difficult to formulate and to operationalize, because they touch upon areas of national sovereignty and require cooperation on the international level (e.g., IPCC). However, if not addressed, the global GHG effect could be mitigated and long-term decarbonization pathways could be at risk. We suggest considering the following approaches to tackle this challenge:

- Hydrogen strategies could be explicitly part of trade agreements and integrate certain criteria for system level.
- Specific support in decarbonisation strategies for countries or regions that export hydrogen could be implemented. This could range from financial support for RES-E investments over knowledge sharing to support in transformation of infrastructures.
- Thresholds related to NDC targets or other official documents could be formulated. However, this might interfere with international trade regulation. Therefore, this option might only be feasible for directly supported hydrogen projects.

4.5 The sustainability versus renewable hydrogen uptake dilemma

Since climate mitigation is the main reason why the EU, its Member States and many other countries promote the uptake of hydrogen, the verification of the GHG emission intensity of hydrogen production and transport and, more broadly, of its sustainability is of essential importance. In this paper, we have shown that sustainability standards and certification procedures for hydrogen production have not been fully established in any of the relevant fields. On GHG emissions there is more progress, but essential elements are still missing. In other fields, such as water, CO_2 sources and the socio-economic dimension, the debate is still at an early stage.

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[31] Such an initiative has been established for extractive industries: Extractive Industries Transparency Initiative (EITI)

4.5.1 Description of challenge

It is worth to consider arguments in favour or against implementing sustainability criteria for hydrogen production. However, it is to be noted that sustainability criteria can relate to various dimensions and can be set at different levels of ambition. Defining sustainability standards for hydrogen is not a simple “yes” or “no” decision.

The calls for defining and implementing sustainability criteria for hydrogen production comes from civil society organisations and scientists and is largely based on four main arguments:

- The high interest of policy makers and investors for hydrogen might lead to a lower attention for alternatives that are less energy and resource intensive and therefore in general more sustainable, such as energy sufficiency, energy efficiency, and the direct use of renewable electricity and renewable heat. In the case of hydrogen from SMR or from electrolysers connected to a power system with low shares of renewables, hydrogen production can even be associated with higher GHG emissions and worse environmental impacts than the fossil fuels it substitutes. Taking this into account, strict sustainability standards e.g., on additionality of RES-E plants can avoid a net negative impact of the hydrogen uptake.
- When considering large scale hydrogen production in developing countries for export purposes, there is a concern about the risk that the best renewable resources are used to produce and export hydrogen, thus hampering the energy transition and decarbonisation of the exporting country.
- Since the hydrogen uptake is largely driven by public policies (ranging from CO_2 pricing, to dedicated support schemes and infrastructure investments), the legitimacy of public policies supporting non-sustainable hydrogen production is questionable.
- Finally, as a new value chain for renewable hydrogen and partly for hydrogen based on SMR is about to be created, the chance of setting it up right from scratch, also from the point of view of sustainability, is attractive and should be taken.

On the other hand, the drive to define strict sustainability rules for hydrogen imports might end up having unintended consequences or even turn out to have an opposite effect than intended. When looking at the competition between hydrogen and fossil fuels, strict sustainability criteria for hydrogen, e.g. from electrolysis, might end-up creating an unfair competitive advantage for fossil fuels and nuclear energy, on which analogous criteria are not applied. Such an advantage might hinder the market uptake of hydrogen technologies needed in the long-term to decarbonise hard to abate sectors. A similar dynamic can arise in the competition between hydrogen from renewable, “low carbon” hydrogen from fossil fuels and grey hydrogen: if sustainability criteria are applied only or more strictly to hydrogen from renewables than to fossil fuel-based hydrogen, the result is an unintended competitive advantage for fossil fuel-based hydrogen.

4.5.2 Options for solutions

We suggest considering the following approaches to tackle this challenge:

- Cost-benefit analysis for different sustainability dimensions and ambitions levels: Dimensions and ambition level could be assessed with respect to their contribution to sustainable development, GHG reduction, technological development and diffusion targets and other targets.

Such an assessment would need to be carried out for the different hydrogen production routes (methane-based, RES-E-based, other RES-based) but also for fossil fuel and biogenic alternatives to analyse how sustainability criteria influence the uptake and cost curves for the different routes and alternatives.

  - Pros: Understanding expected price differences will allow to quantify financial support that would be necessary to support the implementation of certain sustainability criteria and ambition levels. It would be the basis for a staged approach that balances different targets. In addition, detailed analysis of cost curve intersections of blue, green hydrogen and other fossil or biogenic gases and fuels also helps to understand what the expected price differences will be and which financial support is necessary to support the implementation of sustainability criteria.
  - Cons: The inherent problem with cost-benefit analysis, i.e., the monetarization of non-monetary items would prevail also in this case. This might happen within individual dimensions of sustainability, but will certainly happen when comparing different dimensions. Establishing minimum threshold levels could be a remedy to this caveat if these levels can be based on solid ground.

- Phase-in approach: Low standards in specific categories with later ratcheting up. Most important and beneficial criteria (referring to dimensions yet to be defined) could be made obligatory from the beginning, while others could be added at a later stage. Such an approach would require provisions to safeguard investments made under existing standards while standards are ratcheting up.
  - Pros: Such an approach would focus on the most important dimensions in a setup phase and allow to start the build-up of the industries and supply chains without sacrificing important sustainability concerns. This way, costs for first movers can be lowered facilitating progress along learning curves. The most ambitious criteria could be made obligatory only for hydrogen production receiving public financial support. This way, sustainability standards could directly be supported by public funding in the market uptake phase.
  - Cons: Adjustment points could be prone to lobbing etc. Moreover, they may create artificial limits (for example for certain thresholds or for the definition of phase transitions) or new unintended incentives. Different parallel and similar standards would require additional administration and increase costs and complexity in accounting towards target levels.

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