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The sustainability of green hydrogen: An uncertain proposition

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HIGHLIGHTS

- Production and export of GH raise questions of sustainability and climate justice.
- Land and freshwater availability are key risks for local communities.
- Community engagement is needed to mitigate local environmental risks factors.
- International standards for governance of hydrogen projects are key to sustainability.
- Climate-related risks should be included in sustainability standards.

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ABSTRACT

Green hydrogen is increasingly considered a vital element for the long-term decarbonization of the global energy system. For regions with scarce land resources, this means importing significant volumes of green hydrogen from regions with abundance of renewable energy. In producing countries, this raises significant sustainability questions related to production and export. To assess these sustainability-related opportunities and challenges, the authors first present a review of renewable energy deployment in the electricity sector, and then extend it to the foreseeable opportunities and risks of green hydrogen production in exporting countries. The paper finds that questions of freshwater and land availability are critical from an environmental and a socio-economic point of view, and that the development of international standards for the governance of hydrogen-related projects will be crucial. These should also address potential conflicts between the deployment of renewable energy for the decarbonization of local power grids, and the export of green hydrogen.

Introduction

While the production and use of hydrogen is not a new phenomenon, there is a consensus emerging, which points to its importance for the achievement of national and international GHG emission targets in so-called hard-to-abate sectors [1,2]. The International Energy Agency (IEA) describes hydrogen as a "versatile energy carrier," with diverse range of applications in sectors that still rely heavily on fossil fuels such as transport, industry, and heating [3,4]. In order to support the transition to climate neutrality, however, it is crucial that hydrogen production is emissions-free. While it is possible to produce low-carbon hydrogen from natural gas, combined with carbon capture and storage technologies or so-called methane pyrolysis, these processes cannot fully eliminate greenhouse gas

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List of abbreviations

GHG	Greenhouse gas
REE	Renewable energy electricity
TWh	Terawatt hour
GH	Green hydrogen
SDG	Sustainable Development Goals
RE	Renewable energy
PV	Photovoltaic panels
KW_p	Kilowatt power
WSF	Water Scarcity Footprint
MWh	Megawatt hour
SOEC	Solid oxide electrolyzer cells
PEM	Polymer electrolyte membrane
CSP	Concentrating Solar Power
PPA	Power purchase agreement
CF	Capacity factor
GWP	Global warming potential
IPPs	independent power producers
IPPPP	Independent Power Producers Procurement Programme
INDCs	Intended National Determined Contributions
PA	Paris agreement

emissions. Hence, they do not offer a long-term solution for reaching climate-neutrality targets. Only so-called green hydrogen (GH), which involves the extraction of hydrogen from water molecules via electrolysis using renewable electricity (henceforth REE), offers such a prospect.

To meet climate-neutrality targets by mid-century, it is recognized that a rapid ramp-up of GH will be needed. Demand for hydrogen in Europe is projected to reach 481 (business as usual scenario) to 665 TWh (ambitious scenario) by 2030 [5]. This equates to approximately half of the current renewable power generation on the continent. To reach its decarbonization goals, the German government estimates a demand of 90 to 110 TWh of GH by 2030. This translates into approximately 130 and 160 TWh of renewable power, more than half of Germany's current REE generation. Given the constraints of renewable power deployment in Germany, the government only aims to produce approximately 20 TWh domestically [6]. It is therefore clear that Germany and the EU will rely heavily on hydrogen imports to meet the projected demand [7,8,1].

The production of hydrogen to meet this demand represents an important prospect for value creation in countries with abundant renewable energy resources, including opportunities to become net exporters of GH. This represents a tangible opportunity to contribute to the economic development and diversification of exports. Moreover, compared to conventional fossil-based energy, it has been demonstrated that renewable energy offers a range of advantages, due to lower environmental and health-related impacts [9,10]. However, it also comes with risks, in particular when developed primarily as an export-oriented commodity. Similar to other export commodities, it is far from certain whether GH exports will indeed enhance socio-economic development and promote the well-being of producing regions. Conversely, increased pressure on local resources, like land or water, and other environmental impacts also may have detrimental impacts on local populations. In this vein [11], note that most of the social risks associated with the hydrogen economy will be "imported social risks" (p. 3042). In other words, these risks will largely materialize in regions of GH production, while countries aiming to import large quantities of hydrogen will largely avoid these local effects. This, in turn, raises important climate and environmental justice issues, in particular when it comes to potential production of GH in low-income countries. Compared to industrialized countries, low-income countries have contributed only a small share of global CO_2 and other GHG emissions, but are disproportionally burdened by environmental and climate change impacts [12]. At the same time, a number of low-income countries, especially in Africa, may be well-positioned to become exporters of GH to enable the decarbonization of European industry (Nweke-Eze & Quitzow, 2022). In this respect, the identification and mitigation of potential risks and impacts of GH production is also relevant to avoid exacerbating these injustices.

For the development of a future GH economy, it is therefore crucial to consider conditions under which production activities can take place without compromising the well-being of current and future generations, in particular, but not only, in low-income countries. In this vein, this paper represents a first attempt to provide a holistic perspective on the sustainability of GH. In doing so, the paper also includes normative aspects of equity and justice, as these are integral both to the concept of sustainable development and the challenges related to GH production and trade. More specifically, the paper reviews the potential opportunities, challenges, and implications of GH production activities with a particular emphasis on the socio-economic and environmental sustainability dimensions in prospective exporting countries. It does not consider questions of economic viability of GH production at the project level, as these questions have been covered in great detail by other publications. Rather, it explores conditions under which GH could support a net-positive contribution towards achieving sustainable development (such as the SDGs) and to minimize potential risks and impacts. Frequently, it is precisely these risks and unintended impacts that are ignored in conventional cost-oriented analyses. The paper thereby provides an important contribution to the discussions of GH, which have been dominated by economic considerations to date.

Moreover, it is critical to raise these issues at this early stage of development to ensure that they can be accounted for from the onset and help place the GH economy on a sustainable development pathway. Indeed, since the sector is still at an early stage of development, there is little empirical evidence that can be drawn on. However, GH production is directly linked to the production of renewable energy, needed for powering electrolyzers. Hence, the expansion of renewable energy capacities will represent on important cause of sustainability-related challenges. At the same time, there is an important existing literature on the social and environmental impacts of renewable energy generation that offers an important starting point for the discussion. The paper builds on this literature to first identify relevant sustainability risks in the realm of RE production and then extends the discussion to GH production via electrolysis.

The paper is structured as follows: in section Sustainability of green hydrogen production, the authors first present an analytical framework for the review of sustainability-related challenges in the area of GH. In section The sustainability of renewable energy: lessons for green hydrogen, this analytical framework is then applied for the review of known sustainability-related opportunities and challenges of renewable energy deployment in the electricity sector, focusing on solar and wind energy. Based on this, the analysis in section The sustainability of renewable energy: lessons for green hydrogen is extended to the foreseeable opportunities and risks of GH production with a particular focus on expected challenges in exporting countries. In section Conclusions, this article concludes with a discussion of key findings and an identification of important areas for future research.

Sustainability of green hydrogen production

In this section, the authors present an analytical framework for systematizing the existing findings on the sustainability-related benefits and risks of renewable energy deployment and GH production. The goal of the transition to climate neutrality, of which the development of GH is a part of, is to mitigate climate change by eliminating GHG emissions from economic activity while supporting sustainable development on a long-term basis. The concept of sustainable development was popularized in the United Nation's ‘Our Common Future’ Report [13]. The principles, processes, and concepts of sustainable development are widely used to guide and measure societal progress, to ensure that current generations meet their needs without compromising the ability of future ones, and while ensuring the well-being of the planet. According to Ref. [14]; the strength of the sustainable development approach lies in its different criteria including normative aspects, which “demands that analysts evaluate the actual contribution that different technical systems make as they diffuse or could diffuse” (p.725).

In energy development assessments, attention is placed on the feasibility and desirability of socio-technical changes, with the overall objective of protecting the livelihoods and well-being of current and future generations [15]. note that true sustainability requires that hydrogen is “produced in a clean reliable, affordable, and safe manner without harming neither the environment nor the societies” (p.18,059). True sustainability of GH production, therefore, requires the consideration of the three pillars of sustainability – social, economic, and environmental [16]. At the same time, it is widely acknowledged that these three dimensions are interdependent and cannot be fully separated from one another. In particular, social and economic issues are frequently strongly intertwined. Moreover, sustainable development is not predetermined exclusively by the socio-economic and environmental preconditions of a given locality. Finally, sustainability-related outcomes are enabled and constrained by governance-related elements. Taking these considerations into account, the suggested analytical framework distinguishes broadly between the environmental and socio-economic sustainability of GH. In addition, it considers questions of governance as an enabling factor for realizing sustainable GH production. In the following, these three analytical dimensions are further elaborated. A map of the conceptual framework is provided in Fig. 1.

Environmental dimension of sustainability

The Ecologic Footprint is a qualified index to monitor the environmental sustainability performance in relation to a wide range of categories (Rees, 2012; [17]. According to the [18]; the Ecological Footprint “measures the ecological assets that a given population or product requires to produce the natural resources it consumes […] and to absorb its waste, especially carbon emissions”. Following this approach, this article reviews the main ecologic challenges pertaining to RE resources, and GH. More specifically, it focuses its review on local impacts in the following areas: plants and animal life; land; freshwater usage and availability. In addition, it considers environmental implications that are global in nature. This includes potential implications of scaling-up renewable energy and GH for the use and extraction of mineral resources and related environmental considerations as well as climate-related impacts. While wind and solar energy are considered the most climate-friendly energy production technologies,

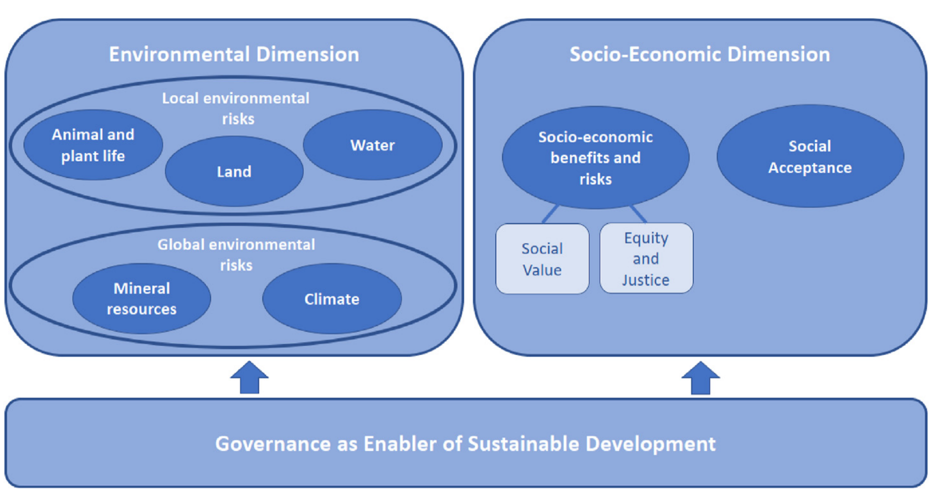

Fig. 1 – Conceptual framework of the sustainability assessment of GH production.

their use in GH implies competition with other potential uses, leading to differing outcomes in terms of GHG reduction.

It is worth noting that interferences between RE and natural ecosystems have been mainly studied in industrialized countries that host most of RE plants deployed to date. Such interferences may be exacerbated in countries with less advanced environmental management systems, such as unstable political landscapes or poor natural protection standards [19]. Moreover, most of the global biodiversity is currently located in such regions, requiring an even more cautious evaluation of potential risks linked to GH development [20]. Given the fact that many of the potential sites that have been identified for potential GH exports lie in countries with poor or insufficient environmental management systems, this article places particular emphasis on assessing risks against this background.

Socio-economic dimension of sustainability

Depending on the pre-existing socio-economic context and based on how GH activities are designed and implemented, potential positive and negative socio-economic impacts with direct and indirect influence on long-term sustainability may emerge. In this paper, the socio-economic dimension of sustainability refers to the potential for renewables and GH production to influence socio-economic development, especially at the level of the project host community. This may include positive and negative implications for the creation of social value, which is closely related to equity and justice [21]; Blasio, 2020; [11,22,23].

GH production activities have the potential to enhance or undermine sustainable development through value creation and impacts on general well-being of affected populations. According to Ref. [24]; obtaining social value in energy development processes involves three steps: “(1) Defining the social value of energy; (2) understanding how energy projects deliver social value via discrete energy services; and (3) designing the social-technical arrangements of energy systems such that they deliver enhanced social value” (p.67). In this vein, the paper identifies both opportunities and risks of renewable energy development and GH production for the generation of social value, composed of local value creation as well as access to affordable basic services, most importantly energy.

In addition, RE and GH development may mitigate or exacerbate inequalities and injustices in affected communities and regions. Normative criterion such as equity and justice are used in energy development processes to assess and ensure that energy development and transition processes adhere to justice principles [14]. In the context of this paper, the authors dedicate particular attention to equity and justice principles [25,26,27], with emphasis on the potential distribution of cost and benefits of RE and GH production projects.

Furthermore, this article considers the role of social acceptance as a criterion for assessing the sustainability of RE and GH production activities. According to Ref. [28]; socio acceptance refers to the broader societal acceptance of policies and innovations. Past energy and development endeavors have shown that success and the achievement of sustainability standards do not only depend on policy frameworks and technological advancements but are also influenced by social acceptance and support [29,30,31,28,32]. These two aspects are important because they can mitigate project development and operation delays, cancelations, supply insecurity and labour risks resulting from local conflicts and opposition [33]. The authors review and discuss case studies of energy projects where social controversies appeared, or where social acceptance was achieved.

Governance

Finally, questions of governance play a central role in enabling or constraining the sustainable development of RE and GH production activities. Governance is the processes of making and enforcing rules to organize society in all its complexities [34]. It is commonly agreed that good governance is an enabler for sustainable development with an influence on processes and distribution of outcomes [14]. For example, governance can play a critical role in reconciling sustainable development, climate and environmental protection needs [35]. Under the governance domain, the authors assess aspects of procedural justice with a focus on the inclusion and participation of relevant stakeholders at all levels of the decision-making process [27]. Questions of governance at the project level are especially important in low-income countries, where broader governance structures may not be sufficiently developed to prevent negative environmental and social impacts of GH production activities.

The sustainability of renewable energy: lessons for green hydrogen

RE development aims to substitute fossil fuels in power generation and has the potential to close the energy access gaps in developing countries. It also bears numerous global and local benefits in both the environmental and socio-economic fields, such as air pollution reduction [36], employment of local workers, geopolitical independence [37], local value creation, improved access to health care services in remote and marginalized communities [38,39], and infrastructure development [40,41]. It is therefore expected that the global expansion of RE could foster large volumes of GH production and will also entail and propagate such benefits. However, there are also negative externalities identified with RE development. With the increased production of RE for GH these challenges will not be an exception.

In the following, the authors discuss these opportunities and challenges for RE production. The results are presented according to the analytical framework outlined (Fig. 1). For each of the analytical categories, the authors summarize the observed benefits and risks of RE deployment, drawing on findings from the existing literature on RE in the electricity sector. Building on this, this paper then identifies additional benefits and risks that may arise from GH production in each of the analytical categories. The section closes with a consideration of governance-related factors and their role in enabling or constraining sustainable development, drawing on lessons from the deployment of RE.

Environmental dimensions of sustainability

Based on the analytical framework outlined in section Environmental dimension of sustainability, this sub-section presents the results regarding the environmental dimensions of sustainability as they pertain to RE and GH. In accordance with the framework, it first addresses environmental risks at the local level, i.e., potential impacts on plant and animal life, land and freshwater usage and availability, followed by potential impacts at the global scale, i.e., potential impacts on mineral resource extraction and climate change.

Potential local impacts on plant and animal life

Humans' and animals' health and habitats can be significantly influenced by RE development. Wind turbines can affect the life of birds and bats [42]: [43,44,45], create noise and visual pollution [46,47], impact local climate [48,49], and generate electromagnetic interference [50]. [51] have observed that the development of wind parks is positively correlated with birds' mortality, while [45] report that wind turbines affect between 3 and 14% of the areas suitable for soaring[1] in South Spain, with more extensive implications than mortality by collision. Specific impacts vary considerably and depends on the specific conditions of each locality. Noise can be caused by the aerodynamics of the wind flowing through the turbine blades or by machinery instruments such as the generator and cooling fans.

Poor planning of PV installations has also been shown to have negative repercussions on natural habitats, especially in regions in Southeast Asia and Africa with high biodiversity [52,19]. RE can also have undesirable implications for aquatic organisms: for example, offshore wind plants may interfere with benthic plants and sunlight exposure [53] and cause fish population overgrowth. At the same time, high-power submarine cables and the electromagnetic fields they generate can provoke negative effects on fish lives [44]. Vegetation is also impacted by the construction of PV plants in forests: plants and trees must be significantly shortened or completely removed for the installation of panels, with consequences on the ecological equilibria and release of soil organic carbon to the atmosphere.

Potential local impacts on land

RE generation, especially via windmills or solar PV, requires land [19]. Land competition between RE and agriculture is already a reality and is largely reported in the literature [54]. Activity such as deforestation, high-density infrastructure and contamination of soils all lead ultimately to enhanced erosion and ecologic imbalances, as [55] reported for wind farm during the construction phase. The same is true for PV constructions, where the land and habitat can be affected by heavy machinery and cable installations [56].

Large GH development requires additional free land for REE to fuel electrolysis. Recent research from Kakoulaki et al. (2021) shows that based on geographic availability for RE development in Europe, domestic REE could sufficiently cover both decarbonization of the electric grid and GH production, based on the current decarbonization goals. In other words, according to the authors, a competition between decarbonization of the power grid and the deployment of GH can be avoided. The ENSPRESO dataset presented by Ref. [57]; or the suitability analysis for the solar hydrogen project published by Ref. [58]; both investigate whether hydrogen production volumes expected by potential exporters are feasible with future projections despite limitations such as solar irradiance, high-resolution wind speed, setback distance, etc. Other investigations assessing RE and hydrogen potential at a large scale are underway [59]. Results can draw a more nuanced picture of the RE infrastructure needed to achieve climate targets and the challenges these would imply in terms of land utilization and the broad potential environmental risks. Of particular importance is to evaluate the capacity for these regions to satisfy internal demand as well as exports without compromising the land quality, as a necessary condition to ensure ethical trading and domestic sustainable development.

Potential local impacts on freshwater usage and availability

Desertic areas offer abundant solar energy resource, but water requirements for operating RE plants and for GH production can represent a significant pitfall [60]. found that the amount of water required for RE development is highly variable and insufficient in some environments with favorable levels of solar irradiation. The extent of water constraints can be quantified by the Water Scarcity Footprint (WSF) indicator, a suitable proxy that assesses the water stress of a region by putting in comparison water demand vs water availability [61,62]. In addition to the water use in the upstream segment of PV module production, cleaning and cooling of PV mirrors during operation involves significant water use. The total volume of water consumption has been estimated at 3.7–5.2 tons for each KW_p [63]. High WSF values can be a risk factor for local communities and the overall sustainability of local ecosystems [64,31]. Nevertheless, a full life cycle analysis presented by Ref. [65] shows that PV and wind are the least water-intensive energy technologies among all RE (330 and 43 L/MWh, respectively). In perspective, nuclear energy consumes between 1500 and 2700 L/MWh, while natural gas between 40 and 140 L/MWh [66,67].

In addition, GH production requires electrolysis and therefore electricity to split water into hydrogen and oxygen. Commercially available electrolyzers require purified water for this process. While innovative technologies based on salt water or wastewater (without depuration) might reduce the need for freshwater in the future, they remain at an early stage of development [68]. Currently, freshwater consumption for the production of 1 kg of hydrogen ranges between 9.1 kg of water for electrolysis using solid oxide electrolyzer cells (SOEC) [69,70]; pp. 875–884) and 18 to 25 Kg for polymer electrolyte membrane (PEM) electrolyzers [71,72,73,74]. As this indicates, the choice of electrolyzer technology thus has an implication for the environmental sustainability of GH in water-scarce environments. More broadly, it highlights that water availability represents a significant challenge for the sustainable production of large GH volumes in countries affected by scarce freshwater availability. The Middle East, Saharan and sub-Saharan regions for example, have outstanding solar irradiance but also suffer from water

[1] In this context, soaring refers to the action of some birds to maintain flight without wing flapping, using rising air currents.

scarcity – a relevant shortcoming for PV and CSP plants when it comes to the panel and mirrors maintenance and fresh-water needs for electrolysis [75,76,77]. Desalinization of seawater in these areas could offer a solution. However, sea water desalination comes with its own environmental risks. The most critical one is the treatment of brine – a hyper-saline solution that can also contain chemicals used during the purification processes–, but also the high energy consumption and the long-lasting adverse effects on other natural resources such as air and soils [78]. A recent study by Ref. [79] reviews a set of innovative desalinization components and suggests strategies to reduce the overall environmental impact.

Potential impacts on global mineral resource extraction and related environmental challenges

Additional risks are posed by the utilization of heavy and rare-earth metals necessary for the manufacturing of PV and wind technologies. Unlike other risk factors outlined above, these do not occur locally at the site of GH production but rather upstream along manufacturing supply chains. That said, a significant increase in mining activity of non-renewable raw material is expected to meet the demand of the RE sector, with potential repercussions on several sustainability aspects [80,81]. REE technologies are generally more metal-intensive than activities in the fossil fuel sector [82,83]. They require high volumes of steel and aluminum to build infrastructure and a large variety of other metals for various elements, such as PV glasses (e.g., silicium), generators (neodymium or dysprosium) or PV cells (indium und tellurium). Extraction, purification, and handling of these metals are challenging, and the risk of emissions or leaks is high [84]. argue that high amounts of lead (30 tons) and cadmium (2.9 tons) could be released to the environment due to the extensive growth of PV development by 2050. Unfortunately, the development of recycling cycles for minerals used in RE appliances lags and is currently still insufficient. For instance, only 1% of current lithium demand is recycled [85,86,87]. To respond to the escalation of raw material demand spurred by growing global GDP and RE expansion, intensive mining is foreseen in the next decades, posing deep concerns for environmental protection and biodiversity conservation [42,81,41].

The future expansion of GH will inevitably further increase the raw materials demand required to build RE systems as well as electrolyzers. Production of SOEC requires a high amount of rare minerals such as lanthanum and yttrium, a factor that could limit their future expansion. Nevertheless, further technological innovation is expected to reduce the requirement of these minerals by approximately 50% [88]. Raw materials' demand will also depend on hydrogen utilization appliances, like for example fuel cells, which require so-called platinum group metals. Table 1 provides an estimate of upstream mineral requirements of reaching the German target of approximately 100 TWh (or 15 TWh of REE) of GH produced by 2030 and assuming an equal distribution of RE (wind, solar and PV) and electrolyzer technologies. Based on the current and expected future mining rate, the mineral requirement as shown appears feasible (Tawalbeh et al., 2020; [87]. Nevertheless, the global demand for Indium in 2050 is expected to more than double, according to the Mineral World Bank

Table 1 – Estimated mineral requirement in 2030 for the global production of a) PV and wind turbines, and b) electrolyzers.

Mineral	PV [tons]	Wind [tons]	Total by 2030 [tons]
a)			
Aluminium	32,000	560	680,639.3
Copper	4000	3000	182,077.6
Silver	4	0	82.8
Gallium	2	0	41.4
indium	6	0	124.1
Selenium	10	0	206.9
Cadmium	15	0	310.4
Tellurium	25	0	517.3
Neodymium	0	100	3310.5

Mineral	Electrolyzers [kg]			Yearly by 2030 [in tons]
	PEM	Alkaline	SOEC	
b)				
Nickel	0	9.0000	1.0000	333.33
Zirconium	0	1.0000	0.3000	43.33
Lanthanum	0	0	0.2000	6.67
Yttrium	0	0	0.0300	1.00
Platinum	0.0020	0	0	0.07
Palladium	0.0020	0	0	0.07
Iridium	0.0008	0	0	0.03

Source: Data from Refs. [88,89,41]. Capacity factor (CF) wind: 40%; CF PV: 25%.

Report [90], raising concerns due to its need for appliances such as PV and PEM electrolyzers. The demand for nickel, widely used in alkaline and SOEC electrolyzers and batteries, has already grown by 20% in the last five years [88]. The global production in 2020 would only suffice to cover the estimated needs for RE in the power sector in 2050. The availability of nickel in the global market also poses a risk, as Indonesia, one of the world's largest producers, called for an export ban in 2020. Forecasting future trends and availability is particularly challenging, due to both uncertainty regarding future demand and geological reserves [91]. Large supplies of nickel and other minerals are present in ocean seabeds [41], sparking a debate on environmental protection frameworks for the marine ecosystem.

Climate-related impacts

Wind and solar power production do not generate any direct GHG emissions during the process of power generation. Thus, replacing fossil fuels in the power sector with wind and solar power generation is a critical element for building a climate-neutral electricity system. Currently, the process of producing the needed components and materials still leads to emissions upstream in the respective value chains. These can be reduced or even eliminated over time, however. Indeed, GH could play a key role in this context, for instance in the production of climate-friendly steel for the manufacturing of wind turbines.

Of course, for now, GH production also remains subject to upstream emissions, including those resulting from the production of wind turbines or solar PV installations as well as equipment related to the process of electrolysis. Taking these emissions into consideration, GH produced via wind energy shows the lowest GHG emissions, while more pronounced impacts are associated with solar PV, mainly due to GHG emissions produced during facility construction. An overview of the carbon footprint associated with different hydrogen production processes with potential causes for high discrepancies is shown in Table 2. That said, GH represents the process of producing hydrogen with the lowest GHG emissions and the potential to reach zero emissions in the future.

Nevertheless, hydrogen generates emissions during transport. Most of the emissions associated with hydrogen transportation depend on the amount of energy necessary to transform hydrogen into a form that is easy to be transported or stored, such as ammonia. Emissions generated by cargo ships and pipeline transport must also be considered. The emission reduction potential generated by switching from conventional fuel to hydrogen, therefore, also depends on the carbon footprint of these processes.

Noteworthy, the climate benefits of GH are also dependent on both the field of application (e.g., substituting conventional fuels in the automobile sector presents different benefits than during steel production) and potential alternative uses of renewable power. Most prominently, GH production may displace renewable power that would otherwise be available for the decarbonization of the national electricity systems. Indeed, given the existing carbon footprint of electricity production in Europe means that the direct utilization of renewable power in the power system would be more effective at reducing GHG emissions than via GH production, regardless of the end-use sector. Under current settings, the power gap generated by RE electricity diverted from the power grid to GH production would be covered by fossil fuel entering the system due to the rule of merit order (Bracker, 2017). Indeed, only a few countries, among those that have been identified as potential exporters of GH, present conditions that would make the export of GH beneficial to climate mitigation efforts. Table 3 offers a snapshot of that issue, comparing renewable shares in the power sector as well as shares of electricity imports. Most of these countries rely de facto exclusively on fossil fuels (Chile, Morocco, Saudi Arabia) or import a relevant share of the energy they consume (Namibia), underlining the climate pitfalls of diverting resources towards GH production and export. Again, these structural preconditions in the analysis of feasibility and benefit analysis of GH projects must be included at the earlier stages.

Nevertheless, efforts to meet climate-neutrality targets by mid-century require that GH technologies are deployed over time to enable cost reduction and to guarantee sufficient supply in the future. This means that the development of GH technologies over time needs to be balanced with the decarbonization of the power system in GH producer countries. For this reason, a political debate in the EU has developed on how to ensure that renewable energy capacities for the production of GH are additional to those needed for the decarbonization of power systems. A strict interpretation of power additionality would mean that GH should only utilize REE that is produced in addition to a baseline scenario defined without targets for GH production. Considering RE shares in the EU, no notable production of “additional” renewable power is likely in any European country any time before 2040. Afterwards, assuming a REE share increase beyond 60% in the European grid, climate benefits from grid-fuelled hydrogen or from surplus REE at risk of curtailment may emerge. Clearly, such a strict interpretation of additionality would pose a serious risk to a rapid scale-up of GH production to meet climate-neutrality targets.

To confront this challenge, a proposed amendment to the EU's [109] would impose a number of restrictions on the production of GH when intended to fulfil national targets for so-called renewable fuels of non-biological origin (RFNBOs). The current proposal of the amendment stipulates that the electricity utilized for GH production should fulfil one of three

Table 2 – Carbon footprint/global warming potential (GWP) of electrolysis via wind power, PV, and power from the grid. 1 Kg H_2 = 142 MJ.

	$gCO_2eq./KgH_2$	Notes	Source
Wind electrolysis	~1000	LCA, 78% of emissions generated during wind turbines construction	[92,93]
	430	Alkaline electrolysis, compression of produced H_2 is included	[94]
	710	LCA, alkaline or PEM electrolyzer at a scale of several $MW_{el.}$ Distribution and compression of the hydrogen are not included.	[95]
	1135	Including construction of equipment and production, transportation of materials, and emissions at the operating plant	[96]
PV electrolysis	From 2000 to a maximum of 7000	Collection of CF results from different studies. Most of emissions generated from PV manufacturing processes	[92]
	370	LCA, 800 MW wind plant	[97]
	2840	Including emissions during the construction of equipment and production, transportation of materials, and generated at the operating plant	[96]
	3550	LCA, alkaline or PEM electrolyzer at a scale of several $MW_{el.}$ Distribution and compression of the hydrogen are not included.	[95]
Power grid electrolysis	29,000	EU electricity mix	[98]
	14,200	German electricity mix	[99]

Table 3 – Share of REE and imported power in the electricity systems for countries candidate to become GH exporters [100,101].

Country	REE share national grid	Import share of electricity	Source
Chile	11.7% (data for 2016)	0	[102,103]
Namibia	29% (data for 2018/2019)	64%	[104]
Morocco	15% (data for 2017)	3%	[105]
Saudi Arabia	0.2% (data from 2018)	0%	[106,107]
Australia	29% (data from 2021)	n.a.	[108]

requirements: 1) direct use of power from the grid in a bidding zone that has an average share of at least 90% RE, 2) direct connection with a supplier of renewable power (without a grid connection), or 3) via a power purchase agreement (PPA) with a renewable power producer and transmission through the power grid. The first option is ruled out in most countries due to low RE shares in the power sector, making it impossible to demonstrate the needed reduction in GHG in the end-use application. The second option is technically viable, but it implies the on-site construction of RE facilities that are dedicated primarily to GH production. In the case of PPAs, the production of GH should also fulfil requirements of additionality as well as temporal and geographic correlation. Firstly, the power purchasing has to be certified as renewable and should not have been constructed more than 36 months before the installation of the electrolyzer (*additionality*). Secondly, it has to be certified that the time of power generation matches its use in the electrolyzer[2] (temporal correlation). Thirdly, the site of power generation has to be located in the same bidding zone or one that is interconnected with the bidding zone of the electrolyzer (geographical correlation).

No other jurisdiction has defined a similar approach to date. An alternative to the EU's regulatory model might be a political approach based on existing pledges for the deployment of RE within intended nationally determined contributions (INDCs) under the Paris Agreement. These could function as a reference baseline for planning additional capacities aimed at the production of GH. RE produced in excess of existing pledges might be considered as “additional” and therefore compliant with the additionality principle (see Fig. 2). This would still involve the challenge that current INDCs still remain largely insufficient to achieve the global target of limiting temperature increases to well below 2° Celsius.

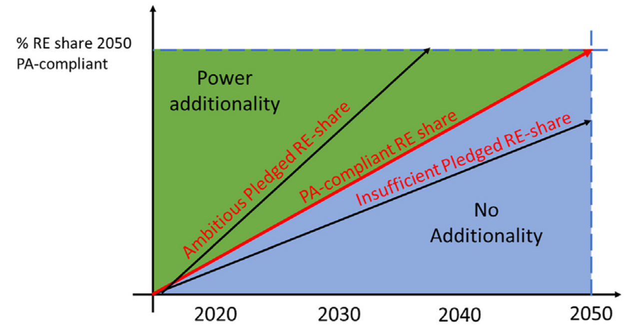

Fig. 2 – Additionality of RE power compared to baseline scenario in compliance with Paris Agreement. The Paris Agreement (PA)-compliant red line indicates the threshold for defining additional RE power. The blue areas define cases that offer no additionality, while the green regions depict situations where the additionality of RE power could be considered to be in place. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Socio-economic dimensions of sustainability

Having discussed challenges related to the environmental sustainability of RE and GH production, including climate-related issues, the following section discusses socio-economic dimensions of sustainability. This includes socio-economic benefits and risks, including questions of equity and justice, as well as challenges related to the social acceptance of GH.

Socio-economic benefits and risks

RE production activities have the potential to generate socio-economic benefits by enhancing local value creation through direct and indirect employment as well as other opportunities in operation, maintenance and manufacturing [110,111,112]. However, studies have also shown that such value creation does not necessarily accrue to local populations. For example, studies on the social impacts of RE development in Mexico, South Africa, and Morocco showed serious gaps and major obstacles to labor force participation and fair remuneration in the RE development sector. This has been attributed to the lack of capacity and skill development at the local level to match the often skill-specific requirements of RE projects. In the cases of the NOOR 1 solar thermal power plant in Morocco [31] and solar parks in Limpopo, South Africa [113], the potential to generate social value for local host communities through employment opportunities was limited to short-term unskilled and semi-skilled jobs.

Simultaneously, if not managed appropriately RE projects may have negative impacts on existing livelihoods and quality of life. For example, constraints on local water resources were identified as negative impacts by farmers in the case of the NOOR I solar thermal power plant in Ouarzazate, Morocco [31]. RE development has also been associated with locally unwanted land uses unfair land acquisition, relocations and compensations processes and interference with local landscapes, cultures, and social activities [114,115,31]. Moreover, land-use conflicts in Mexico were associated with unfair and unequal land leasing or sales, which [32] attribute to a possible local leader's patronage relationships networks and power imbalances between landowners and RE project developers. A similar trend was observed in South Africa and Mexico. This was especially problematic within vulnerable and marginalized communities, such as indigenous communities in Mexico [32] and areas in South Africa, where some communities experienced insecure land tenure due to the apartheid legacy [113].

[2] The correlation will be assessed on a quarterly basis for installations deployed before April 1, 2028 and on an hourly basis thereafter.

There are limited studies focusing on the socio-economic sustainability dimensions of GH. However, the previous review on the sustainability of RE and recent studies on the feasibility of the hydrogen economy [116,117,30] raise important questions in this regard. Scholars have pointed to opportunities for countries with abundant RE resources and for those looking to green their economy, such as jobs creation opportunities, tax revenues and generation of foreign exchange [7,30]. Like RE, they offer the critical potential to contribute to local value creation and socio-economic development [118]. However, as underscored by examples from the RE sector, related benefits may not necessarily accrue to local communities. Moreover, they have the potential to undermine existing livelihoods in host communities by placing pressure on local land and water resources. Compared to RE production, GH production in areas where freshwater resources are scarce may interfere with existing agricultural production and other local needs due to the additional water requirements for electrolysis [21,11,22,30,23]. While technologies for water desalination have been suggested to address this challenge, dependence on freshwater availability will remain a sensitive issue for the implementation of GH production, especially in arid areas such as the Middle East and North Africa [30] as well as areas in Sub-Saharan Africa already struggling with water scarcity for domestic and productive uses. To mitigate these impacts, the water-energy interdependences in these areas must be thoroughly assessed and addressed. Finally, scholars have also raised the issue of hydrogen safety: Hydrogen is a highly inflammable and explosive gas and any leaks, especially during production, distribution, and use, can result in major safety hazards [119,120].

In countries without universal access to stable electricity supply, additional REE dedicated to GH production may fuel further inequality in the energy sector. The production of hydrogen in developing countries could interfere with access to energy services for local economic development and productive uses, should the REE capacity only fuel GH production with disregard for local energy needs (the current share of REE in a selection of developing countries is reported in Table 3). Moreover, the distribution of risks and benefits in the planning, implementation, and operation of energy projects could have a direct or indirect influence on the sustainability of GH. The current narratives are such that most of GH produced in developing countries will be exported [116,30]. This dynamic has the potential to privilege importing countries over exporting countries, a situation that could provide fertile grounds for injustice and inequalities. Moreover, these imbalances have colonial undertones (Scholten et al., 2020), with the potential to re-kindle past and enduring injustices and inequalities.

Social acceptance

Numerous studies on social acceptance of RE development have been conducted in the last decade [121,122,123,124,113,125,126]. These studies paint a picture of broad national support and acceptance. For example, a study conducted by the IASS Potsdam on the social sustainability of the energy transition policy in Germany showed that 90% of the German population support RE development and transition to clean energy services [127]. However, despite the broader social support and acceptance of RE, support is often limited in project host communities [128,127].

Opposition to on-shore wind development has been strongest where land and landscapes are associated with special value, such as cultural, religious, or local aesthetics [129,128,130]. Sweden, known for its generally favorable attitude towards RE, skepticism was still reported in areas affected by wind development due to the local landscape interferences [123]. Similar sentiments have greeted wind-power developments in Germany, Denmark, Spain, and several parts of the United States [124,130].

In low-income countries, opposition to RE development has been mainly associated with locally unwanted land uses, unfair land compensation, forced relocations, noise and visual pollution and interference with cultures and exclusion of all relevant stakeholders [114,115,31]. In Mexico, for example, opposition to wind energy development was associated with interference with the makeup of indigenous landscapes, socio-cultural practices, lifestyles and ways of life [32]. The limited possibility for vulnerable and marginalized groups and disproportionally affected populations (such as indigenous populations, women, and other socially and economically disadvantaged groups) to participate in RE planning and implementation process was also identified as an underlying issue limiting social acceptance in Morocco, Mexico, and South Africa [128,113,31,32]. Moreover, social support and acceptance is frequently dependent on the perceived potential of RE to mitigate climate change and protect the environment (reduction of CO_2 and other GHG), generate health benefits (e.g., by reducing air pollution), potential employment opportunities, reduced energy costs, local development, energy security and independence.

As challenges with RE development have shown, social acceptance is of critical importance to the long-term sustainability of GH production activities in developing countries [33,131]. While little is known about the conditions for social acceptance and opportunities for mitigating social opposition to GH production activities, especially within project host communities in developing countries, lessons can be drawn from the RE development processes alluded to above [128,114,113]; Stanley Semelane et al., 2021; [31,32]. Overall, social acceptance and support of RE development processes were shown to be influenced by a multitude of issues related to the distribution of socio-economic risks and benefits, inclusion of diverse local stakeholders, threats to livelihood activities, trust in governance and management of projects.

Governance

The previous sections have pointed out that RE and GH development involve a series of potential impacts with implications for environmental and socio-economic dimensions of sustainability. Unlocking potential benefits while limiting possible risks, it is essential to implement appropriate governance mechanisms to ensure an equitable and inclusive development process. This, in turn, has significant repercussions for local acceptance. The development of RE offers important lessons in this regard.

This calls for the development of localized support mechanisms, especially at the project host community level. In this respect, important lessons can be drawn from the case of South Africa's independent power producers (IPPs), a government policy implemented through the Independent Power Producers Procurement Programme (IPPPP) that introduced renewable energy into the energy mix and supports socio-economic development of project host communities [132,113]. The IPPs model in South Africa mandates that 2.5% of the RE development project's profits are set aside to support the local host community's socio-economic development. Moreover, IPP policies such as "local content requirement, preferential procurement and local enterprise development" [113]: p.39 could be instrumental into developing and enabling local value creation through indirect job creation and local revenue generation. However [113], urges caution on how such policies are designed and implemented, especially in addressing continued injustices for the marginalized and vulnerable populations.

Transparent and inclusive community engagement with the development and implementation of energy projects has also shown enhanced community acceptance and support. A study on the challenges of community acceptance of solar parks in Limpopo, South Africa, concluded that: "the starting point towards realizing community acceptance is the inclusion of diverse stakeholders in the project planning, development, and management" [113]; p.39). At the very least, diverse audiences of stakeholders were shown to enrich the pool of ideas and allow for the comparison of several alternatives [115] reducing the frequency of conflicts [133].

Yet, as the case of RE development revealed, a mere community engagement might be insufficient, as the quality and the diversity of the stakeholders involved are also crucial to ensure sustainability criteria. This kind of engagement calls for intentional efforts and support mechanisms to motivate and encourage the participation of vulnerable and marginalized groups who may experience negative impacts of GH production activities. Moreover, to account for social acceptance and societal matters [32], propose the incorporation of an anthropological energy development approach in energy development processes that "seeks to understand the way local populations experience, conceptualize and evaluate energy social and political relations" [32]: p.3). More generally, it calls for the development of a culture of inclusion as proposed by Ref. [134].

More broadly, a lack of good governance has been shown to limit the possibility of vulnerable and marginalized affected groups (such as indigenous populations, women, and other socially and economically disadvantaged groups) to participate in RE planning and implementation processes [128,114,113]; Semelane et al., 2021 [31]; Walker et al., 2018; [28,32]. This has direct and indirect negative consequences for attaining social acceptance and the overall sustainability of RE production activities. The lack of international standards for good governance in energy-related projects has been identified as a major obstacle to sustainable development [8]; Buttner et al., 2017; [117].

Conclusions

In this article, the authors reviewed the potential challenges, risks, and impacts of GH production activities. Drawing on existing insights from the field of RE, this work has identified key risk areas as well as governance-related factors to ensure the environmental and social sustainability of GH production. While different environmental, socio-economic conditions and political dynamics in each country make it impossible to generate a uniform picture of the conditions and actions needed to ensure the sustainability of GH production, the GH sustainability criteria the authors propose can be used as a general guide for the identification and development of context-specific assessment approaches and measures. Unlocking benefits as well as managing risks and impacts related to GH production will depend on how activities are designed and implemented in the particular context of a given project. While some impacts cannot be avoided, such as increased pressures on land and water resources, the related environmental and socio-economic risks can be mitigated by ensuring good governance practices that promote social inclusion and community engagement. Developing international standards for good governance of hydrogen-related projects will therefore be a key to the sustainable development of the sector. This includes the question of "additionality" as discussed in section Climate-related impacts.

The integration of environmental and socio-economic aspects into the current GH decision-making processes can help reconcile sustainable development and climate goals from the onset. This is also relevant to mitigating disruptions of GH production activities and application processes in importing countries. From a sustainable development standpoint, GH production activities can support the achievement of multiple SDGs. The question of "additionality" of the related renewable energy capacities plays a critical role in this context. For now, this has been discussed mainly in climate-related terms. Additionality in this context refers to the need to ensure that RE capacities for GH production are "additional" those capacities required for maintaining the pace of decarbonization in the power sector, which is needed to meet international climate targets. Beyond this climate-focused perspective, it is critical that RE capacities deployed to produce GH generate additionality in terms of socio-economic benefits in countries and communities that host these projects. Otherwise, these activities run the risk of harming rather than enhancing socio-economic development in exporting localities and thereby exacerbating global inequalities. This not only raises fundamental ethical concerns but may also undermine social acceptance both in exporting and importing countries, thus slowing down the global deployment of GH.

Clearly, the review presented in this paper only represents a first step towards identifying potential risks of GH production. Moreover, it does not have the ambition to offer any quantitative assessment regarding the feasibility of scaling-up GH production to meet climate-neutrality goals. Rather, it seeks to point to risk areas, which should be addressed not only in the process of implementing GH projects but also in the area of technology development going forward. The further development of technologies for performing electrolysis with salt water or wastewater are a case in point. Similarly, impacts on the demand for certain mineral resources provide entry-points for future innovation and technology development.

It will be crucial to develop good practices for managing these risks that are adapted to regional conditions, i.e., local environmental conditions, national energy structures and socio-economic settings. In this context, researchers can play an important role in conducting systematic assessments of the sustainability-related impacts of GH production and export, as well as comparing and integrating results across different jurisdictions to generate and disseminate lessons learned. Such findings not only offer a basis for improving practices on the ground but also represent a vital basis for the ongoing development and improvement of international sustainability certification systems for GH. Moreover, they can add to an informed debate on critical issues related to questions of equity and justice within the transition to climate neutrality. Such discussions will be vital for advancing global cooperation in support of international climate targets in general, and for the promotion of global trade in GH specifically.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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