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Review

Sustainability regulations for PtX projects: Scope and impact analysis

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CONTEXT & SCALE Power-to-X (PtX) technologies represent a crucial tool for defossilizing hard-to-abate industries. However, by the end of 2024, the fast-growing green hydrogen and PtX sector faced upheaval: escalating costs, ongoing regulatory uncertainties, project cancellations, and postponed final investment decisions (FIDs). The gap between the necessary and actual progress toward a defossilized economy is widening. Key challenges include making PtX projects economically competitive and ensuring their impact on climate change mitigation.

Primarily, obstacles arise from strong competition wit fossil alternatives on one hand and the fact that the sustainability of PtX technologies is not inherently guaranteed on the other. This necessitates regulatory measures that enable a rapid and sustainable scale-up of electricity-based production processes. For this purpose, various legal frameworks, certification schemes, and incentive and support schemes have been developed in recent years; however, they differ significantly in terms of scope, instruments, and sustainability requirements. This review paper categorizes key sustainability regulations, focusing on criteria applied to PtX production, offering a comprehensive overview for scientific and industrial stakeholders in the PtX sector, and addressing pertinent challenges.

SUMMARY

The utilization of power-to-X (PtX) technologies as a substitute for fossil fuels is a key instrument in defossilizing the global economy, potentially making a significant contribution to sustainability efforts. This must be ensured or at least supported by legal measures to maximize the full sustainability potential. Thus, in recent years, regulations have been created to ensure sustainable PtX production on the one hand and to promote the use of PtX products on the other. The diversity and complexity of these regulations, differing in their scope of application, the applied instruments, and the respective sustainability requirements, among other things, create potential hurdles for PtX projects and complicate determining the respective influence on technical, economic, and environmental aspects. This review aims to summarize, classify, and assess current sustainability regulations and to evaluate the impact on potential PtX projects. The paper underscores the significance of the EU Renewable Energy Directive (REDIII) as the blueprint or reference for the legal regulations within the EU member states as well as the respective certification schemes and incentive and support schemes. The impact of sustainability criteria (power supply and GHG threshold) on PtX projects is analyzed and discussed, highlighting the importance of the electricity provision concept and sustainable carbon supply.

INTRODUCTION

Achieving climate neutrality requires defossilizing the overall economy. Power-to-X (PtX) projects, which convert renewable electricity (RE) into alternative fuels and chemicals, can significantly contribute to achieving the United Nations Sustainable Development Goals (SDGs). For instance, PtX can contribute to SDG 7 (by promoting sustainable energy solutions), SDG 13 (by reducing greenhouse gas [GHG] emissions), SDGs 8 and 9 (by creating economic opportunities, fostering innovation, job creation, and industrial growth), and SDG 12 (by enhancing resource efficiency and circular economy practices) (SDG7: Affordable and Clean Energy; SDG8: Decent Work and Economic Growth; SDG9: Industry, Innovation, and Infrastructure; SDG12: Responsible Consumption and Production; and SDG13: Climate Action).

Robust sustainability regulations are essential for achieving truly sustainable PtX production and ensuring a positive contribution to global sustainability agreements.[1] Many national and international sustainability regulations have been created and implemented to regulate and promote PtX utilization. In the context of the study, "sustainability regulation" is to be understood as an umbrella term for a wide range of regulations and schemes that define sustainability criteria/requirements for PtX products. While RE and biomass have been used and regulated for some time, PtX applications are relatively new, and the market ramp-up is still pending. Therefore, regulation and standardization in this area are dynamically developing, and their impact on PtX implementation and market uptake is not fully understood. Furthermore, various sustainability regulations differ in scope, application areas, instruments, and requirements, making it challenging for PtX stakeholders to identify their relevance and impacts.

Previous publications have already provided insights into sustainability criteria and their mechanisms. Multiple publications focus on singular schemes.[2,3] Other works provide comprehensive overviews of various schemes in table format[4–6] or in greater detail.[7–10] In further publications, the topic is touched on in a broader PtX context.[11,12] However, the regulatory environment is rapidly evolving, and there is a lack of comprehensive analyses examining the regulations and their impact on PtX projects. Thus, a thorough analysis of existing sustainability regulations (i.e., legal regulations, certification schemes, and incentive and support schemes) is needed.

Against this background, this review aims to summarize and assess current regulations regarding their application and impact area, sustainability requirements, and their effects on PtX projects. The characterization of regulations and the detailed comparison of sustainability requirements aim to facilitate a straightforward assessment of regulations and clearly summarize the respective requirements. By generically applying regulations to different PtX concepts, the significant impacts of the regulations are highlighted and discussed. In addition to existing literature, this study also covers the Climate Bonds Standard, the European Hydrogen Bank, the Japanese Hydrogen Society Promotion Act, and the revision of the Renewable Energy Directive (REDII)[13] from 2023 (REDIII).[14] To provide a valuable comparison of schemes, we did not focus on a specific geographic area but rather included a wide range of locations where relevant regulations are currently in place. Most of the voluntary certification schemes reviewed are applicable worldwide, with only a few exceptions. The analysis primarily focuses on the PtX producers rather than the demand side; thus, no market effects, such as production volumes or prices, are estimated. As regulations are continuously updated or added, this work considers and analyzes available data and information published up to March 2025.

First, the selected regulations are introduced and characterized, allowing for an assessment of their relevance in different contexts. In the following, the specific sustainability requirements are analyzed and compared. Regulatory impacts on PtX projects discusses the potential impacts of regulatory frameworks on PtX concepts, considering aspects such as energy and feedstock sourcing. Finally, the key findings and existing regulatory challenges are summarized, forming the basis for the conclusions drawn.

SUSTAINABILITY REGULATIONS

Due to the globally increasing significance of PtX, numerous regulations have been newly developed or adapted in recent years to regulate and incentivize PtX via different measures.

Table 1 lists and describes a selection of sustainability regulations, which are analyzed in the following. The selection is non-exhaustive, as further regulations exist and are continuously being developed. The selection was made considering their relevance in the PtX sector, the stage of elaboration, and their focus on sustainability.

Figure 1A shows the interaction between the sustainability regulations and (B) a characterization of the regulations according to their attributes. While legal frameworks define regulations at the state level, certification systems are primarily used by PtX producers to verify compliance with requirements and support the implementation of regulations. Certification schemes can also define or specify further sustainability requirements in more detail; however, some references refer only to parts of a regulation, e.g., GHG thresholds or specific definitions (see CertifHy non-governmental certification [NGC] and TÜV CMS70 and their references to REDIII). In addition to the certification systems presented in detail, International Sustainability and Carbon Certification (ISCC) EU, CertifHy EU Renewable Fuels of Non-Biological Origin (RFNBO), and REDcert-EU have been officially recognized by the European Commission to certify compliance with the REDIII requirements for PtX production. Their requirements correspond exactly to the REDIII, so they will not be analyzed further in this work.[15–17] Incentive and support schemes play a very important role in supporting the growth of PtX products in emerging markets. Generally, they include the requirements provided by legal frameworks, potentially adding further criteria. The European Hydrogen Bank and H2Global are examples of financing mechanisms for the developing markets for green hydrogen and PtX products. Both take the REDIII requirements as a reference and complement these requirements with additional environmental and social criteria. Projects that seek to receive the financial incentive must comply with these criteria. REDIII, here, refers to the latest revision of Directive (EU) 2018/2001 (short REDII), including supplementing delegated regulations (EU) 2023/1184 and (EU) 2023/1185. The US American 45V Clean Hydrogen Production Tax Credit only stipulates a 4-tiered GHG emissions threshold (for varying amounts of tax credit) and some environmental and wage requirements, resulting in overall very few sustainability requirements compared with H2Global and the European Hydrogen Bank. Other instruments incentivizing PtX products

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Table 1. Selection of important regulations affecting PtX

N/A	Regulation	Description
Legal frameworks[a]	Renewable Energy Directive 2023/2413/EU (REDIII)	EU framework obligating the use of renewable energy in various sectors
	EU Taxonomy Directive 2020/852/EU (EU Tax)	EU framework for implementing sustainability standards in investments; fulfillment is required if funds are to be obtained from sustainable investments
	Clean Hydrogen Production Standard (CHPS) (draft)	USA standard that aims to meet GHG thresholds of the BIL and IRA associated with clean H_2 production
	Low Carbon Fuel Standard (LCFS)	USA standard that aims to decrease the carbon intensity of California's transportation fuels
	Low Carbon Hydrogen Standard (LCHS)	UK standard that aims to support the UK Hydrogen Strategy with a definition for "low carbon H_2"
	Renewable Transport Fuel Obligation (RTFO)	UK framework that aims to encourage production and use of renewable transport fuels
	Japan Hydrogen Society Promotion Act (JHPA)	Japanese act to define Low-Carbon Hydrogen and derivatives for a smooth transition to a decarbonized, growth-oriented economic structure
Certification scheme[a]	CertifHy NGC (CertifHy)	EU-wide framework of GOs aims to develop a European framework of guarantees of origins (GOs) for green/low-carbon H_2
	CMS 70 TÜV Süd (TÜV)	international certification scheme aims to verify the quality of green H_2 and derivatives production
	Green Hydrogen Standard (GHS)	international standard that aims to establish a global definition of green H_2 and green H_2-derivatives
	China Hydrogen Alliance's Standard (CHAS)	China standard for clean and low-carbon hydrogen aims to promote the development of China's H_2 industry, realize carbon emissions targets, and achieve carbon neutrality
	Climate Bonds (CB)	international standard and certification scheme that sets criteria for clean H_2 production projects to be eligible for Climate Bond's investments
	South Korea Clean Hydrogen (SKCH)	South Korean certification scheme to promote clean hydrogen production and import
Incentive and support schemes[a]	H2Global	international support scheme that acts as a double auction platform, incentivizing H_2 production by closing the gap in H_2 price on producers' and off-takers' side
	European Hydrogen Bank (H2Bank)	EU public support measure that aims to kickstart the green H_2 economy by supporting the production of RFNBO H_2 within the EEA; this supportive scheme is partially funded through the EU ETS Innovation Fund
	Clean Hydrogen Production Tax Credit (45V)	US American tax credit established under the IRA to incentivize the production of clean hydrogen with up to 3$/$kg_{H2}$

RFNBO, renewable fuels of non-biological origin; NGC, non-governmental certification; EEA, European Economic Area; GO, guarantee of origin; EU ETS, European Emission Trading System; BIL, Bipartisan Infrastructure Law; IRA, Inflation Reduction Act.

[a]Legal frameworks, regulatory obligations setting the requirements to produce RFNBOs; Certification schemes, voluntary schemes that serve to prove compliance with own criteria or criteria from a legal framework; Incentive and Support Schemes, mechanisms supporting the PtX ramp-up through, e.g., public funding.

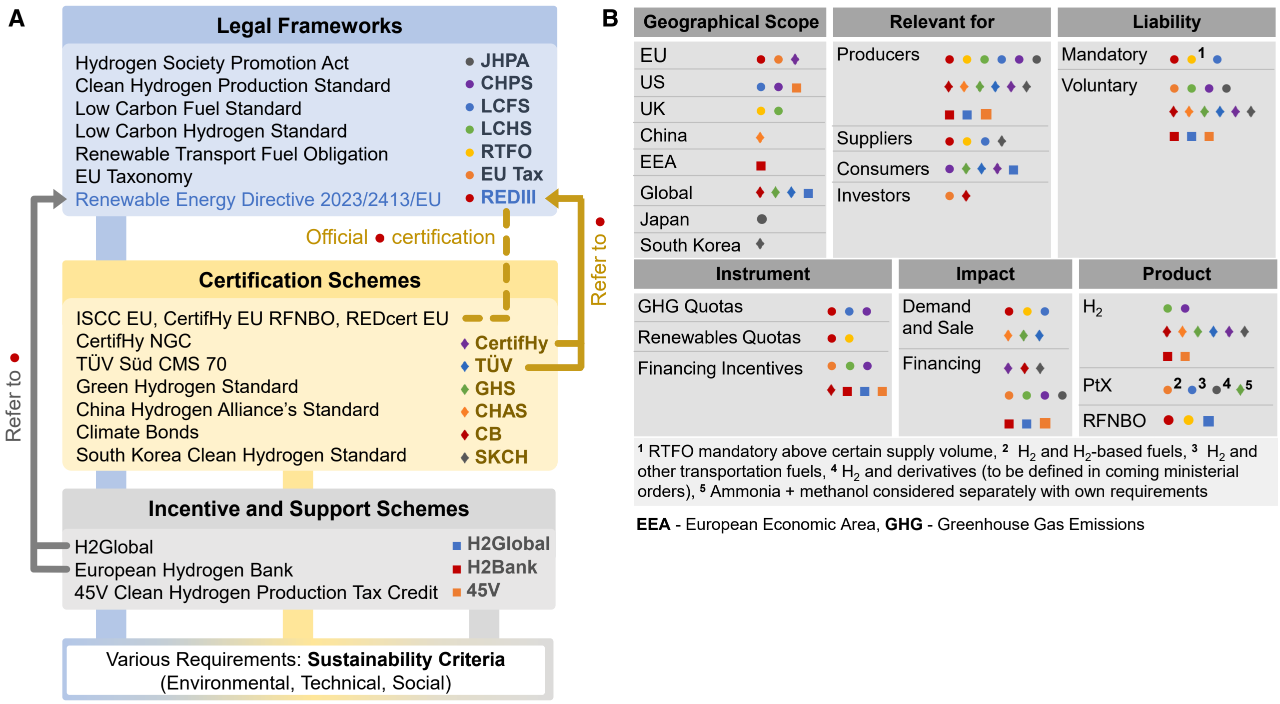

Figure 1. Interaction and characterization of selected regulations

(A) Selection of legal frameworks, certification schemes, and incentive and support schemes affecting PtX and their correlation.

(B) Info on where they apply, which stakeholders they are relevant for, their liability, which instruments they use to achieve which impact, and what product is defined.

include the EU Emissions Trading System[18] (EU ETS) and the EU Carbon Border Adjustment Mechanism[19] (CBAM). The EU ETS is a carbon market that seeks to reduce GHG emissions in sectors such as the energy industry and commercial aviation through a cap-and-trade system of emission certificates. The EU ETS establishes a carbon price, obliging companies to purchase certificates to offset their emissions. As this price increases, low-carbon alternatives, such as PtX fuels, become more attractive and competitive with fossil fuels. The CBAM, which imposes carbon tariffs on certain imports into the EU, encourages decarbonization in non-EU countries.[20] However, it is important to mention that the current CO_2 prices are mostly insufficient to establish PtX products' competitiveness solely via emission trading mechanisms. Both instruments encourage the substitution of fossil fuels to reduce GHG emissions, thus incentivizing the use of non-fossil alternatives. However, they do not specifically refer to PtX products and associated sustainability criteria.

In Figure 1B, the schemes are characterized on the basis of six distinct aspects. The geographical scope describes the area within which the regulation is applicable, where the scope of application could extend beyond the depicted area, particularly for importing PtX products. The mandatory regulations considered here directly obligate fuel suppliers (REDIII, Renewable Transport Fuel Obligation [RTFO], and Low Carbon Fuel Standard [LCFS]) and thus also directly affect fuel producers since this directly influences the demand and value of the products. In these mandatory cases, the obligations manifest as quotas on GHG emissions or share of renewables in energy demand. Non-obligatory regulations can also promote the sustainable use of PtX on a voluntary basis, often via financial incentives. Due to its obligatory property as a legal framework and the detailed sustainability criteria, the REDIII is assessed as a blueprint for other regulations, certification schemes, and incentive and support schemes. The REDIII directly impacts fuel suppliers within the EU and, thus, PtX producers worldwide by setting GHG reduction and RE quotas in Europe. Additionally, REDIII mandates RFNBO targets for the industrial and transport sectors. This creates a guaranteed demand and encourages production. Besides the mandatory regulations, certification schemes are also relevant for voluntary markets, in which environmentally conscious and transition-oriented players want to ensure the sustainability of their (consumed) products.

In the context of PtX, many regulations focus exclusively on the production of hydrogen. However, electricity-based products can also include a variety of hydrogen derivatives (e.g., ammonia, methanol, and methane). These products, including hydrogen, are addressed as RFNBOs in certain regulations, meaning that the energy bound in the product comes exclusively from renewable, non-biogenic sources. Since the designation as RFNBOs is often directly tied to specific regulatory frameworks, hydrogen and PtX products are distinguished in the following unless an explicit reference to the RFNBO-defining regulation is to be made. PtX products can include power-derived hydrogen and RFNBOs but may not fulfill all criteria defined for RFNBOs.

SUSTAINABILITY REQUIREMENTS

Sustainability in the context of defossilization is primarily associated with the reduction or avoidance of GHG emissions. However, further sustainability criteria are required to address other environmental, technical, and social aspects. Figure 2 provides a basic overview of requirements that are considered within the regulations characterized above. The requirements are clustered into power supply, environmental, and social criteria.

Power supply criteria

Electricity is the energy basis for any PtX product; thus, high electricity requirements are inherent. The type of energy source, as well as the logistics and circumstances of use, influences the sustainability of production, which is why many regulations define power supply requirements. Besides the definition of permissible energy sources, additional requirements can be defined to ensure the overall expansion of renewable energies and to avoid negative effects on infrastructure, such as grid congestion or jeopardizing of local energy transition, where exports of green PtX products compete with the local utilization of green electricity. The requirements of the regulations can be assigned to the criteria renewability, additionality, temporal correlation, and geographic correlation. "Renewability" requires that the electricity used to produce green hydrogen or green hydrogen derivatives must be derived from non-fossil sources. However, depending on the regulation considered, the specific definition of permissible (renewable) energy sources differs (see supplemental information). The criterion of "additionality" aims to ensure that the electricity utilized within the PtX plant is generated with newly added power generation plants, adding to previously existing power generation capacities. This prevents GHG emissions from being shifted between different applications or sectors. In other words, the expansion of PtX should not come at the cost of increasing the carbon footprint of the electricity grid by using its share of renewable energy, especially when the grid is not yet fully decarbonized. The criterion of "temporal correlation" requires that electricity production and power offtake occur to the same extent during a specified time interval, ensuring grid-compatible operation. "Geographical correlation" demands that electricity generation and PtX production take place in the same area to minimize transport effort and infrastructure needs (supplemental information).

Among the legal frameworks, the REDIII, LCFS, and RTFO address all power supply requirements, and the Low Carbon Hydrogen Standard (LCHS) also defines renewability and temporal correlation requirements. In contrast to the EU Tax, the Clean Hydrogen Production Standard (CHPS) (US) and the Japan Hydrogen Society Promotion Act (JHPA) (Japan), which do not specify such requirements, compliance is directly decisive for the specification (e.g., as RFNBO) and, thus, the value of the product (the product batch).

The RED has a leading role in the definition of power supply criteria, which are adopted and incorporated by several independent incentive and support schemes (H2Global and H2Bank) and certification schemes (CertifHy for the renewability criteria and CMS 70/TÜV for guarantees of origin [GOs] for renewable energy sources [RES] and the GHG threshold). Climate Bonds and the South Korea Clean Hydrogen (SKCH) are the only certification schemes defining independent power supply specifications, while Green Hydrogen Standard (GHS) and China Hydrogen Alliance's Standard (CHAS) do not cover these aspects.

The specific requirements for power supply are usually defined depending on the technical implementation of the power supply (electricity generation to PtX plant). A distinction is made in some regulations between "direct connection" and "grid connection" (see also supplemental information).

The specific definition of what additionality, temporal, and geographical correlation entails differs between regulations. The details are listed in Table 2. The time period for when the renewable energy plant started operating before the PtX plant differs vastly, spanning from up to 36 months (REDIII, 45V) time difference down to no allowed time difference at all (RTFO). The temporal correlation is defined as a time window of 15 min (TÜV) up to a whole year (45V). This will be adjusted to stricter requirements in the future for REDIII and 45V. For geographical correlation, either the relevant bidding or grid zone has to be followed, or a physical deliverability of the electricity needs to be ensured.

Obtaining electricity from the grid during curtailment periods is permitted in the REDIII, RTFO, and CB, each setting different requirements for this case. If no specific grid situation is given, all regulations require additionality, temporal and geographical correlation, and a renewable power purchase agreement (PPA). Due to the extensive and very specific criteria in individual cases, reference must be made to the regulations for further specifications and exceptions.

Environmental

Reducing GHG emissions is the primary motivation for subsidizing and applying PtX products. Therefore, GHG emissions reduction is a sustainability requirement defined by all regulations. In addition, regulations often include further environmental criteria, such as water supply and use, land use, biodiversity conservation, air quality, or resource management, to avoid sustainability issues in other areas. Therefore, the following section provides a more detailed analysis of the environmental requirements set out in the regulations, focusing on GHG emissions.

GHG emissions threshold

The definition of a GHG reduction threshold requires the definition of a methodology for determining the GHG emissions of the PtX product. Depending on the regulation, the maximum permissible GHG emissions, the GHG calculation methodology, and the system boundaries differ. With carbon-based PtX products, the origin of the carbon plays a major role, as it is released as CO_2 at the end of the product life cycle in most applications. Therefore, sustainable carbon/CO_2 sources can be defined directly or as part of the GHG calculation methodology (indirectly). Details on eligible carbon sources for PtX feedstocks with a strong focus on RED regulation can be found in Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH[21] and Alagu et al.[22]

Figure 3 provides an overview of the calculation methodology and the threshold values. A number of regulations employ a reference value for fossil comparison products, to which the PtX product must attain a defined reduction threshold. GHS and LCFS permit the lowest emissions; however, the GHS only

SUSTAINABILITY CRITERIA	Legal Frameworks							Certification Schemes						Incentive and Support Schemes		
	EU Tax	REDIII	CHPS	LCFS	LCHS	RTFO	JHPA	CertifHy	TÜV	GHS	CHAS	CB	SKCH	H2Global	H2Bank	45V
POWER SUPPLY																
Renewability	-	x	-	x	x	x	x	5	x	-	-	x	-	x	REDIII	-
Additionality	-	x	-	x	-	x	-	6	x	-	-	x	-	REDIII	REDIII	x
Temporal Correlation	-	x	-	x	x	x	-	6	x	-	-	x	x	REDIII	REDIII	x
Geographical Correlation	-	x	-	x	-	x	-	6	x	-	-	x	x	REDIII	REDIII	x
ENVIRONMENTAL																
GHG emissions	x	x	x	x	x	x	x	x	REDIII [1]	IPHE	x	x	x	x	REDIII	x
Land use	x	2	-	-	x	-	-	-	-	x	-	x [3]	-	x	-	-
Wastewater, Ambient water quality	x	2	-	-	x	x	-	-	-	x	-	x	-	x	-	-
Water conservation	x	2	-	-	x	x	-	-	x	x	-	x	-	x	-	-
Air Emissions, Ambient Air quality	x	-	-	-	x	x	-	-	-	x	-	x	-	-	-	-
Hazardous material management	-	-	-	-	x	-	-	-	-	-	-	-	-	-	-	-
Waste management	x	-	-	-	x	-	-	-	-	x	-	x	-	-	-	-
Noise and vibration	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-	-
Energy conservation, Resource use	x	-	-	-	x	-	-	-	-	x	-	-	-	-	-	-
Biodiversity conservation, quality	x	-	-	-	x	x	-	-	-	x	-	x	-	-	-	-
SOCIAL																
Land acquisition, Involuntary resettlement	-	-	-	4	-	-	-	-	-	x	-	-	-	x	-	-
Labor conditions	-	-	-	4	-	-	-	-	-	x	-	-	-	x	-	x
Affected communities	-	-	-	4	-	-	-	-	-	x	-	-	-	-	-	-
Indigenous people	-	-	-	4	-	-	-	-	-	x	-	-	-	-	-	-
Cultural heritage	-	-	-	4	-	-	-	-	-	x	-	-	-	-	-	-
Modern slavery, Child + forced labor	-	-	-	4	-	-	-	-	-	x	-	-	-	x	-	-
Stakeholder engagement	-	-	-	4	-	-	-	-	-	x	-	-	-	x	-	-
Anti-corruption, Transparency	-	-	-	4	-	-	-	-	-	x	-	-	-	-	-	-
No poverty	-	-	-	4	-	-	-	-	-	-	-	-	-	x	-	x
Gender equality, Fewer inequalities	-	-	-	4	-	-	-	-	-	-	-	-	-	x	-	-

- No specifications given
x Specifications given
(green) Specifications given with reference to other sources

1 Lower threshold for "Green H2+", **2** "Issues such as water and land use, other environmental impacts, and social impact are regulated by other legal sources in the EU and its Member States." (International PtX Hub, 2023), **3** Only applies for hydrogen produced from biomass (reduce risk of ILUC), **4** Refers to the World Justice Project's *Rule of Law Index,* **5** Proof of GO cancellation must be provided according to the consumed electricity, **6** Still on development

IPHE - International Partnership for Hydrogen and Fuel Cells in the Economy's *Methodology for Determining the Greenhouse Gas Emissions Associated With the Production of Hydrogen*, **ILUC** – Indirect Land Use Change, **GO** – Guarantee of Origin

Figure 2. Qualitative overview of sustainability criteria applied in the regulations

The figure provides an overview of the sustainability criteria specified in the respective legal frameworks, certification schemes, and incentive and support schemes.

covers some of the overall life cycle emissions. The LCFS uses a "well-to-wheel" approach but is unclear about covering emissions from raw material supply. Most regulations specify the threshold between 25 and 33 g_{CO2eq}/MJ, with the REDIII at 28 g_{CO2eq}/MJ in the middle of the ambition level. CMS70 (TÜV) defines different reference values depending on the product (H_2) utilization. The CHAS distinguishes between *clean H_2* (coal gasification with carbon capture and storage [CCS]) and *low carbon*

Table 2. Detailed overview of requirements for additionality, temporal, and geographical correlation

	Supply concept	Additionality	Temporal correlation	Geographical correlation
REDIII (+H2Global, H2Bank)	direct connection	36 months[a]	not applied	not applied
	grid connection		monthly starting 2030: hourly	same bidding zone; interconnected bidding zone[e]; offshore bidding zone
LCFS	not applied	not specified	9 months	within Californian grid or supplied to it following deliverability requirements
LCHS	not applied	not applied	30 min	not applied
RTFO	direct connection	not older than the PtX system in operation[b]	not applied	not applied
	grid connection		30 min	national grid or follow regionalization rules
TÜV	not applied	11 months	15 min[c]	same bidding zone adjacent bidding zone[e]
CB	direct connection	not specified	not applied	not applied
	grid connection		monthly	physical deliverability ensured
SKCH	not applied	not applied	monthly[d]	same grid
45V	not applied	36 months	yearly starting 2030: hourly	same grid region (or be physically deliverable)

[a]For grid connection, additionality applies only to plants that come into operation after 2027.
[b]New generation capacity came online at the same time or after the RFNBO production site started operating.
[c]Only for GreenHydrogen+ certification.
[d]Applies only to the facilities that come into operation by 2030. Beyond that, not yet specified.
[e]Under certain conditions.

H_2 (coal gasification) at the lowest ambition level. The Climate Bonds lowers the emission values over time and defines a threshold trajectory until 2050.

Besides differently defined system boundaries, some regulations also explicitly excluded emissions from GHG calculation (e.g., manufacturing of the production equipment). The tracking system describes the relationship between the physical product and its (green) characteristics. Mass balancing links the product and its traits, making them inseparable for trade. By contrast, Book and Claim allows for separate trading of the product and its properties in the form of GOs. However, this results in the loss of the product's green characteristic, and it can be sold as non-sustainable while the certificate is applied to another product.

In addition to the regulations analyzed, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) developed the "*Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen*,"[23] a calculation method that has been implemented into a technical specification (ISO/TS 19870) by the International Organization for Standardization (ISO).[24,25] The definition includes a well-to-gate boundary and excludes emissions from renewable energy sources (e.g., solar, wind, and hydropower). The IPHE standard is utilized (with some adjustments) by the GHS.

Other environmental requirements

Further environmental requirements are mainly set within the regulatory frameworks for financial incentives and in parts of general certification standards. One exception is the RTFO, which, as a mandatory regulation, defines additional environmental requirements and thus goes beyond the REDIII and LCFS requirements.

In general, sustainability requirements on land and water use are only applied in a few regulations (see Figure 2), even though these aspects could influence the sustainability of PtX projects.[26,27] Water is inherently needed as a feedstock for hydrogen production and for auxiliary purposes (e.g., heating/cooling and cleaning). However, from a techno-economic point of view, enabling sustainable water supply in most cases does not significantly impact the overall energy demands and cost of PtX production.[28,29] The effect of land use mainly depends on the location of RE generation, which accounts for the most significant proportion of the space required by PtX projects. However, unlike biomass cultivation, this land does not have to be fertile, and fewer biologically valuable areas can be used. Extending the sustainability requirements to include land and water use would, therefore, probably not present any significant hurdles for PtX projects.

Consideration of air quality and pollution can be part of the environmental impact assessment (EIA). Repeated references are made to the World Health Organization (WHO) Ambient Air Quality Guidelines, the World Bank, and SDG requirements, which involve, e.g., pollution thresholds, monitoring, and reduction targets. Waste management specifications are only covered by the GHS and H2Global, referring to the World Bank's requirements (GHS) and a mandatory EIA (H2Global). The GHS is the only regulation that mentions noise prevention and control, again referring to the World Bank's guidelines.

Social

Implementing PtX within the overall economy transformation toward sustainability might be associated with changes affecting communities, society, and people's livelihoods. Therefore, social sustainability criteria must be defined to counteract adverse consequences at a social level.[30]

Figure 2 indicates that social criteria are least represented within the three sustainability categories: they are only considered by the voluntary schemes LCFS, H2Global, 45V, and GHS.

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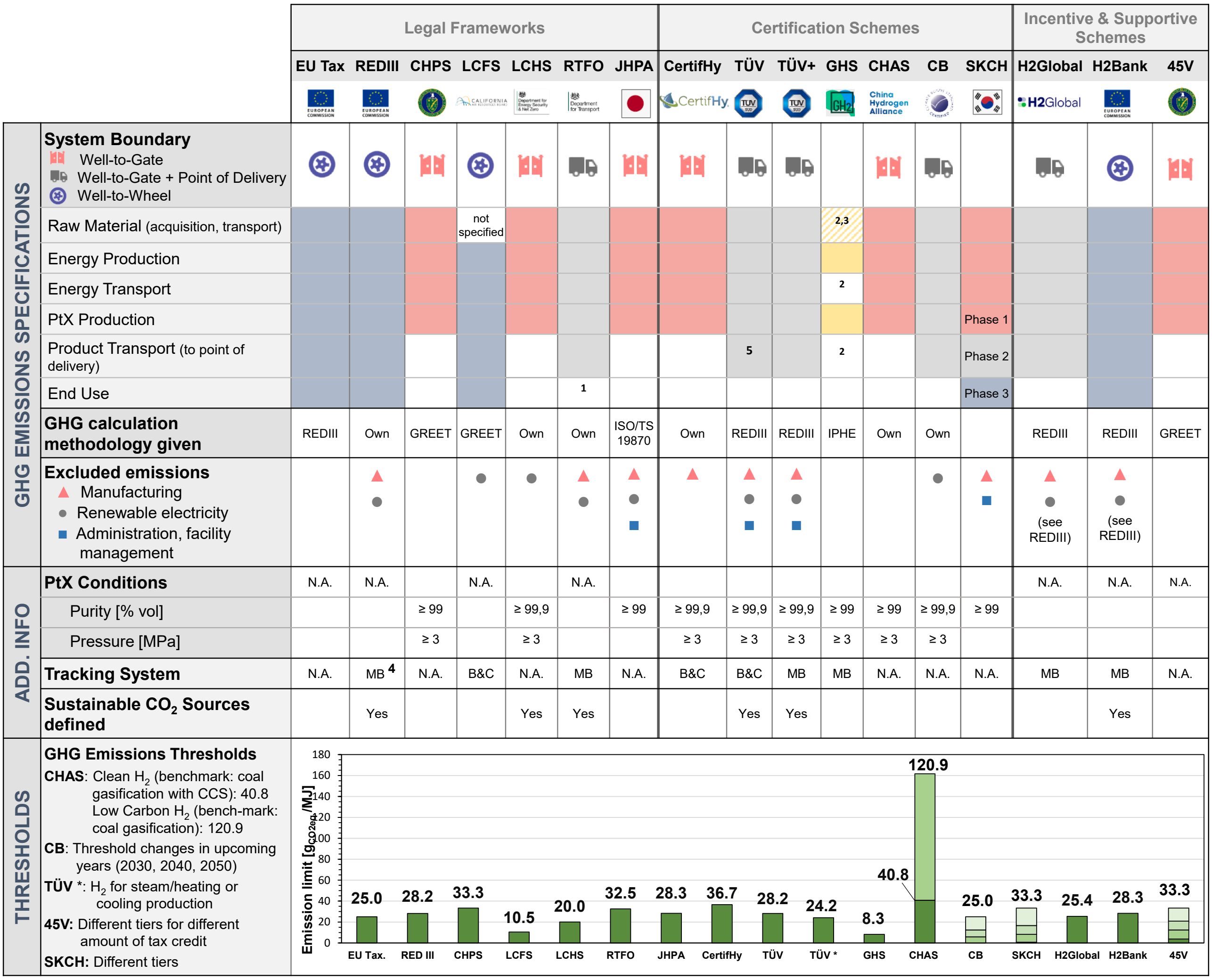

1 Emissions from the fuel in use shall be taken to be zero for RFNBOs (contrary to biofuels), **2** Emissions are encouraged to be measured, but they are not included in the GHG threshold, **3** Not counted: Water provision. Counted: Water treatment, **4** Only with MB, produced volume can be counted towards REDIII renewable energy targets (+sustainability criteria must be fulfilled). B&C is addressed in Article 19 but only benefits customer disclosure, **5** Optional, **6** Threshold for Ammonia: 16.0 g_{CO2eq}/MJ, Methanol: 15.1 g_{CO2eq}/MJ

N.A. – no information, **GREET -** Greenhouse gases, Regulated Emissions, and Energy use in Technologies model for life cycle analysis, **IPHE -** International Partnership for Hydrogen and Fuel Cells in the Economy's *Methodology for Determining the Greenhouse Gas Emissions Associated With the Production of Hydrogen*, **MB** – Mass Balance, **B&C** – Book&Claim

Figure 3. GHG emission criteria and methodology of the regulations

The figure provides an overview of GHG emission specifications/methodologies, related additional information, and GHG emission thresholds.

The LCFS requires an assessment of social risks based on the World Justice Project's (WJP) Rule of Law Index.[31] This index examines fundamental rights, civil justice, order, and security issues. For H2Global, compliance with several International Labour Organization (ILO) standards is required (e.g., CO14—weekly rest, C100—right to equal pay), as well as a social impact assessment (SIA), payment of a living wage, access to health services and insurance, gender equality, local stakeholder participation, and no forced resettlement. The GHS lists five social impact requirements (affected communities and livelihoods, resettlement, Indigenous peoples, labor and working conditions, modern slavery, and child and forced labor). It expects an SIA and evidence of due consideration and planning to maximize local development opportunities and include smaller businesses in the supply chain. Finally, the 45V requires compliance with prevailing wage and apprenticeship standards.

Technical requirements like the GHG threshold are designed as strict, quantifiable limits. Social parameters are not assessed in absolute terms but rather through a system of scoring, auditing, and due diligence to demonstrate compliance. The reduced emphasis on social aspects in many legal frameworks and certification schemes likely stems from the difficulty in quantifying and assessing these factors, making the verification process

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Table 3. Qualitative comparison of direct and grid connection concerning power supply criteria

	Impact	Direct connection	Grid connection
Technical	renewable energy diversity	• potentially limited usability of highly volatile power generation due to technical constraints of PtX technology (load change rate, min/max load of electrolyzer) • limited by local linkage to PtX site	• diversification through the use of multiple power generation locations • diversification through the use of different energy sources/power generation technologies
	flexibility/storage requirements	high demands to compensate/deal with direct transfer of volatile power supply	• reduced necessity due to less strict temporal correlation constraints[a] • lower demand due to diversified power supply (see “Renewable energy diversity”)
Economic	full load hours	lower due to higher volatility of power supply and/or related overcapacities	higher due to a more constant energy supply (see technical impacts)
	power costs	electricity procurement at generation costs without grid fees, etc., possible	charges anticipated for utilizing infrastructure and market platforms
Project realization	realization time	planning and approval of both power generation and PtX plant are required concurrently at the same site	a broader choice of electricity generation projects potentially with an advanced approval status
	available locations	location must be suitable for PtX production and power generation	broader choice of electricity generation projects unrestricted by location (within the grid region)
	compliance effort	no need to demonstrate a temporal or geographical correlation	• substantial documentation requirements for certification • significant requirements on grid operator and electricity trader
		advantageous	disadvantageous

Angle brackets indicate which connection is advantageous for PtX projects with regard to the criterion. Advantageous > disadvantageous.
[a]RTFO limited to 30 min, RED III limited to 1 month until 2030, then 1 h.

more complex and burdensome. However, this technical focus often results in a narrow view that neglects important social dimensions.

REGULATORY IMPACTS ON PtX PROJECTS

Ensuring compliance with sustainability criteria can significantly influence PtX projects regarding technical and economic aspects. This section shows how power supply criteria and GHG emission thresholds affect electricity-based production concepts, including technology and feedstock selection.

Impact of power supply criteria

Detailed power supply criteria (additionality, temporal correlation, and geographic correlation) are defined in the REDIII (also applied by H2Global and H2Bank), the RTFO, and the CB (see power supply criteria). In these frameworks, two main sourcing options are distinguished:

- Direct connection: a physical link between the power generation and PtX plant, excluding additional power supply from the grid. In this case, the physical connection ensures the direct temporal and geographical correlation between power generation and usage, eliminating the need for regulatory requirements. Since fluctuations in power generation are directly transmitted to the PtX plant (when no electricity storage is applied), fully simultaneous electricity production and consumption are required.
- Grid connection: power supply from the power generation plant to the PtX plant is provided via an electricity grid that connects multiple suppliers and consumers. To ensure that the respective generation facility indeed supplies the electricity used by the PtX plant, regulatory requirements regarding temporal and geographical correlation must be met. The specific requirements for temporal and geographical correlation vary between regulations but can never be stricter than those for direct (physical) connection.

Table 3 provides a qualitative comparison between a direct and a grid connection regarding the power supply criteria.

Technical impacts

Since a direct connection directly transfers the volatility of power generation to the PtX plant, technical limitations in electrolyzer operation can restrict the use of power generation technologies. For instance, a direct connection to a photovoltaic system would entail high volatilities and the shutdown of the electrolyzer at night unless internal storage is additionally used. Using highly volatile renewable energies increases the flexibility demands of the electrolyzer and potentially escalates downstream flexibility or storage demands (electricity or hydrogen storage). In addition, fluctuating power supplies can lead to faster degradation and/or defects in electrolyzer components, negatively impacting economics due to increased maintenance and operating costs.[32–34] By contrast, other power generation technologies are less volatile or already incorporate process-based storage options (concentrated solar power [CSP] plants), potentially making them more technically suitable for direct connection. Combinations of wind energy and photovoltaics can also lead to overall lower volatility.[35] However, utilizing multiple renewable energy sources via a direct connection imposes stringent requirements on the local availability of energy sources and the on-site space requirements.

By contrast, a grid connection enables technical and geographical (within the respective electricity grid or bidding zone) diversification of power generation. Consequently, a more constant supply of RE can be achieved, reducing flexibility and storage demands. Depending on the regulation, this can additionally be reinforced by the initially relatively mild requirements for temporal correlation compared with a direct connection. REDIII: until 2030, temporal correlation has to be balanced in a period of 1 month and then within 1 h, and RTFO requires balancing within 30 min.

Economic impacts

Generating and converting electricity from volatile renewable energy sources in PtX processes is typically associated with a significant oversizing of the process chain compared with average product demand.[36–39] Optimizing the sizing of individual process units concerning storage and production capacities for cost-minimal RFNBO production poses a challenge due to the limited predictability of electricity generation profiles. Here, grid connection seems advantageous since the achievable diversification of renewable power generation reduces overall volatility and increases full load hours. This reduces the need for oversizing and lowers investment costs. Furthermore, the lower requirements for temporal correlation, i.e., longer balancing intervals for production and consumption, counteract the need for overcapacities and thus reduce production costs. However, depending on grid electricity costs and the availability of RE production, this might be accompanied by increased GHG emissions, as the grid must be balanced by predominantly non-renewable capacities.[40]

A disadvantage of grid connection might result from additional charges such as grid fees and taxes, which may result in (significantly) higher electricity costs depending on local regulations.

Project realization impacts

The additionality criterion requires the build-up and associated approval procedures for additional power generation capacities. These additional approval timelines and associated uncertainties can hinder and prolong the implementation of RFNBO projects. This is particularly relevant for direct connection, as power generation permitting is tied and thus limited to the PtX plant location. Regarding REDIII, this is reinforced by a transition phase suspending additionality requirements for grid connection but not for direct connection. With grid connection, additionality applies only to plants that come into operation after 2027. The need for power generation to be directly and locally linked to the PtX plant within direct connection also represents a disadvantage regarding site selection. However, power supply criteria for grid connection are quite complex and require an extensive verification procedure to demonstrate compliance, which may not be available outside the EU. If the verification in the country of production fails to meet certification requirements, only direct connection can be applied.

Differences between regulations

As illustrated in Figure 2 and Table 2, the regulations exhibit significant differences in power supply criteria. Regulations with no or weaker additionality requirements allow for a broader range of power generation plants to be utilized, as they permit the use of existing facilities. Regarding the comparison between direct and grid connection, the REDIII temporarily reinforces the advantage of grid connection by suspending the additionality criterion until 2027—this exemption does not apply to direct connection. Regarding geographical correlation, the requirements across different regulations are similar, meaning that no major differences in power supply options beyond those already described are expected. However, substantial variations exist concerning temporal correlation requirements. The allowed balancing periods range from 15-min intervals to annual accounting. The longer the permitted balancing period, the greater the advantage of grid connection regarding the technical and economic aspects outlined above. Nonetheless, many regulations are set to become increasingly stringent in the future.

Impact of GHG emission threshold

All analyzed regulations consider the GHG emissions of PtX products to be a central element of sustainability assessment (see Figure 2). However, many regulations only consider hydrogen as a PtX product while not considering downstream derivatives like ammonia or methanol (Figure 1). Achieving the required GHG reduction for hydrogen production necessitates the use of electricity with very low GHG emissions (see Figure 4A). However, if regulations exclusively mandate the use of renewable energy under power supply criteria (e.g., REDIII), production emissions from electricity consumption may only result from using non-renewable energy for conditioning (compression or liquefaction).

A significantly greater impact of the GHG threshold is expected for the production of hydrogen derivatives, which is considered and sufficiently described within REDIII (also applied in H2Global and EU Tax) and RTFO. Figure 4B provides an evaluation approach for threshold compliance of hydrogen derivatives production using a decision tree. The lower part of the figure displays the emissions resulting from each decision pathway, along with an estimate of the range between the minimum and maximum cases. Further details on the calculation assumptions can be found in the supplemental information. The figure can be applied to evaluate compliance with both regulations since the GHG calculation methodologies are largely similar. Since RFNBO compliance under REDIII and RTFO allows only renewable energy for hydrogen production, no emissions from hydrogen production occur.

If only renewable feedstocks and renewable energies (in compliance with power supply criteria) are used throughout production, compliance with any GHG threshold is ensured (pathway 1). The minimal emissions resulting from product transportation indicate that conventional, predominantly fossil-based transport infrastructure can be utilized without a realistic risk of exceeding the permissible GHG emissions.

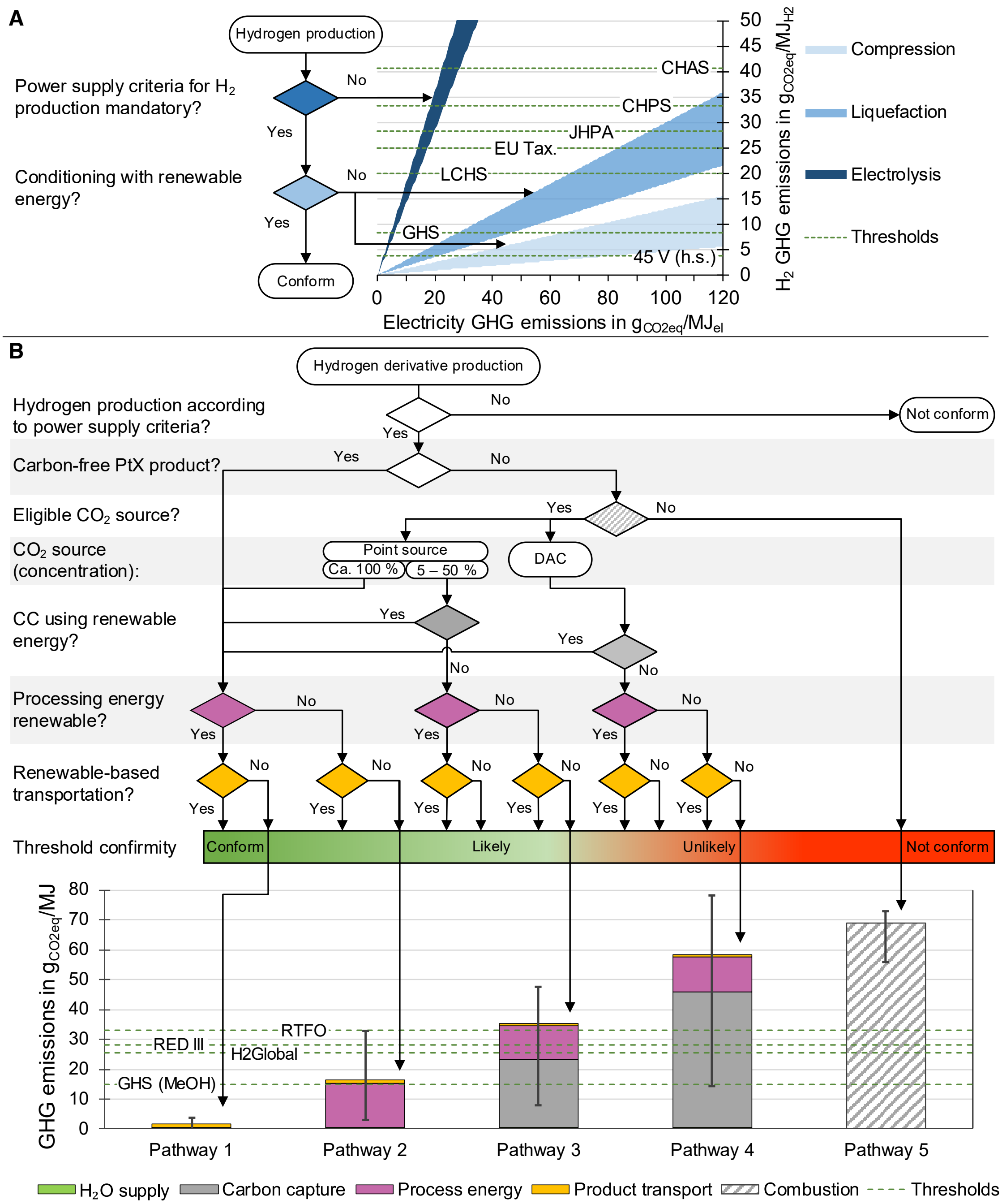

Figure 4. Tree diagram for GHG emission evaluation of hydrogen and derivatives

GHG emission evaluation for (A) hydrogen and (B) derivatives.

GHG emission calculation according to REDIII and RTFO methodology. The figure enables estimation of compliance with the GHG thresholds via a tree diagram. Arrows show the "probability" that the GHG reduction will be met and also give examples of emissions related to ammonia (carbon-free PtX product) and methanol (carbon-containing PtX product) production. Error bars visualize possible emission ranges, depending on the production concept (more information on the calculation of the bars and the upper and lower values of the error bar are given in the supplemental information). Horizontal lines indicate GHG thresholds of the respective regulations. DAC, direct air capture; h.s., highest support threshold; MeOH, threshold for methanol.

If non-renewable feedstocks are used in production, emissions may arise, potentially leading to non-compliance with the GHG threshold. A key factor in this regard is whether the PtX product contains carbon. For carbon-free products such as ammonia (NH_3), exceeding the thresholds is unlikely, even when fossil energy is used in downstream hydrogen processing (e.g., nitrogen separation, synthesis, and purification) (pathway 2). However, if energy sources with very high specific GHG emissions are used (e.g., at the level of the Polish or Cyprus power grid), strict GHG thresholds such as those set by H2Global and RED may be exceeded. Since the process energy required for ammonia production is higher due to the high synthesis pressure compared with most syntheses of carbon-based hydrogen derivatives, the potential emissions resulting from processing are also higher than in pathways 3 and 4.

For the production of carbon-containing PtX products, the CO_2 source plays a crucial role, along with the associated capture process and its energy demand. If a CO_2 source cannot be recognized as sustainable under regulatory frameworks (pathway 5), GHG emissions exceed the allowable threshold, regardless of whether methane (lower bound) or long-chain hydrocarbons (upper bound) are produced. Thus, the choice of CO_2 source is directly and fundamentally linked to the sustainability compliance of carbon-containing PtX products, even if only indirectly accounted for within the GHG threshold calculation.

If a permitted CO_2 source is used, the type and amount of energy required for capture and processing are decisive for the PtX product's GHG emissions. When exclusively renewable, non-biogenic energies are used in compliance with regulatory definitions, the utilization of CO_2 from "sustainable" sources does not increase GHG emissions (pathways 1 and 2). The same applies if pure CO_2 is already available and no additional energy is needed for capture.

Pathway 3 represents the use of eligible CO_2 from point sources with elevated CO_2 concentrations. Suppose the energy demand and related emissions for CO_2 capture cannot be allocated to the CO_2 source (as possible in biomethane production from biogas), significant emissions may occur from the CO_2 supply, potentially exceeding the GHG threshold.

Pathway 4 illustrates the case of PtX production using CO_2 from Direct Air Capture (DAC). Due to the considerably higher energy demand (electricity and heat) compared with point-source CO_2 capture, a very high share of renewable energy is required to ensure compliance with the GHG threshold. If fossil energy sources are used, adherence to the threshold is virtually impossible.

The supplemental information provides a detailed calculation of the GHG emissions of different PtX concepts as a case study.

Differences between regulations

Regarding GHG thresholds, the regulations differ significantly in several aspects, mainly threshold level and calculation methodology. As shown in Figure 4B, particularly for pathways 2 to 4, the specific emissions can vary significantly depending on the energy and feedstock supply. As a result, less ambitious schemes, such as the RTFO, may still be met, whereas highly stringent requirements, such as those under H2Global, might not be achievable. This underscores the importance for project developers to carefully assess and align their production strategies with the GHG emission thresholds of their target markets and the downstream certification requirements of their customers. REDIII and RTFO calculation methodologies are structurally similar, particularly regarding eligible CO_2 sources. Therefore, REDIII-based results can generally be transferred to the RTFO regulation with minor adjustments. Since the regulations may differ in specific details, Figure 4 should only be considered as an indication. A thorough compliance assessment with the target market (i.e., the applied regulation scheme) remains necessary, following the respective calculation methodology to ensure conformity.

KEY FINDINGS AND DISCUSSION

This section first summarizes the key findings of the analysis presented above. Other aspects of sustainability regulation are then discussed in a broader context.

Key findings

The presented review and analysis of sustainability regulation for PtX provides insights into the diverse scopes and requirements of existing regulatory frameworks. Through characterization, the various regulations are assigned to specific application areas and instruments, such as quota obligations or investment incentives. It turns out that mandatory regulations are primarily aimed at fuel suppliers to ensure consistency with the sectoral climate targets, providing detailed requirements for fuel production. Proof of compliance is provided by certification schemes, which in turn may require further sustainability criteria. Investment incentives, which can also be determined by legal frameworks and international support schemes, generally have more comprehensive, albeit less technical, requirements, which can also relate to social aspects.

The analysis of sustainability criteria reveals that most regulations share fundamental sustainability criteria but exhibit varying levels of ambition or stringency, causing problems in comparison of the schemes, compatibility of certification systems, as well as insufficient information for customers on the actual properties of their product.[41] The REDIII is of particular significance, as it not only defines detailed sustainability criteria and sets binding quotas for the entire EU but also serves as a reference or foundation for many other regulations. The key findings of the review can be summarized as follows:

- The requirements of sustainability regulations, i.e., legal frameworks, certification schemes, and market incentives, are very diverse. Depending on the intended product use and the goal of regulatory conformity (product value or investment promotion), a broad set of sustainability criteria can be applied to the PtX project.
- Mandatory regulations already make sustainable power supply and GHG emission reduction obligatory. All mandatory regulations aimed at fuel suppliers define requirements for power supply and GHG emissions from production.
- Social sustainability criteria are often not included. The clear focus of most regulations relates to climate mitigation. Social aspects, which can cover wide-ranging areas, are mainly considered in project-specific (investment) regulation rather than product-specific regulation.

The impact analysis in regulatory impacts on PtX projects shows the specific influences of regulation on PtX production concepts, especially regarding feedstock and energy supply. The key results are as follows:

- Power supply criteria indicate a more favorable power supply concept for PtX production via grid connection in terms of technical aspects. Compared with a direct connection, grid connection is associated with lower requirements for temporal correlation and higher flexibility in the choice of renewable power supply (see impact of power supply criteria). However, a direct connection can be financially more attractive if high grid fees occur or the grid is not sufficiently suitable for meeting the power supply criteria documentation requirements within the certification process.
- GHG emission criteria will most likely be reached for non-carbon products (H_2 and NH_3) if power supply criteria already ensure sustainable H_2 production in the respective regulation. An exceedance of the permissible threshold due to the energy consumption in hydrogen processing is only possible if energy sources with high GHG emissions are used.
- For carbon-based PtX products, utilization of CO_2 from eligible sources (defined by the respective regulations) is essential since the GHG threshold cannot be reached otherwise. Emissions from CO_2 supply can be crucial, as the associated energy requirements are, unlike H_2 production, not regulated by additional sustainability criteria.
- Production-related emissions can vary significantly depending on the production concept. For regulations with high ambition levels, it is crucial to accurately estimate production emissions at an early stage to ensure compliance.

Discussion of regulatory challenges and shortcomings

As with sustainable PtX products, aligning market and technology development with clear and consistent sustainability regulations—while balancing ambition and feasibility—remains a key issue. In the following, the remaining challenges and shortcomings are discussed further based on the existing regulatory framework and the points of criticism raised.

The challenge of timing

Regulatory ambiguities and complexities represent significant challenges for developing PtX projects, leading to increased uncertainty, higher costs, and potential delays. For example, before the REDIII came into place, many projects were on hold, and Final Investment Decisions (FIDs) were delayed due to the lack of a clear regulatory framework. Moreover, the pending approval of certification schemes and the national implementation of REDIII (Federal Emission Control Act: BImSchV) are critical to provide the necessary clarity for investment decisions. This ongoing implementation of the regulatory framework has created uncertainty for renewable energy and PtX project developers, hindering progress and increasing budgets.[42] This further delays the transition to sustainable energy solutions and increases the financial risk for investors.

The challenge of ambition

On the one hand, to facilitate profitable large-scale investments, it is essential to establish ambitious and mandatory installation and market share targets for a rapid market ramp-up. However, most PtX products are still not competitive with established fossil-based products. On the other hand, market incentives and regulations must ensure that PtX products significantly reduce GHG emissions without creating other negative environmental and social impacts. Too high standards may lead to insurmountable economic challenges for developing projects. Too-low standards at an early stage provide the risk of stranded assets, false incentives, and a too-slow transition toward GHG reduction levels that sufficiently support climate policy targets. In the complex world of PtX technologies, achieving a good balance between ''promote and challenge'' is difficult due to the diverse interests of many stakeholders. Moreover, it is crucial to recognize that the trade-off between maximizing project numbers and maximizing emission reductions per project is dynamic and may change over time. In the early phases of the market, funding projects with lower emission-reduction performance may be justified if they pave the way for more projects in the future. The focus should thereby, however, be on non-regret approaches, particularly with regard to long-term infrastructure requirements and targeted markets.

The challenge of regulatory diversity

With regard to the sustainability regulations analyzed in this study, a diverse and regionally differentiated regulatory landscape is currently emerging. Since, as shown in regulatory impacts on PtX projects, sustainability criteria directly impact process concepts and permitted resources, PtX project developers must make early design-phase decisions about which markets they intend to supply despite the variety of regulations and uncertainty around future developments. While designing production processes tailored to a specific market and its associated requirements may appear to be the most straightforward, minimal-cost approach, it limits options for potential off-takers and increases the risk that demand in the chosen market may not develop as anticipated. Conversely, aiming to meet all criteria, including those from the most stringent regulations, may increase product costs and compromise competitiveness in less ambitious markets.

Therefore, in a globalized economy, globally applicable and uniform regulations are advantageous to reduce complexity and create security for producers and consumers. However, the complexity of regulatory development and the need to find compromises between different national interests generally increase with the number of nations involved. A common understanding and agreement on the appropriate instruments and their conditions across jurisdictions with different resource conditions and industrial developments in various regions of the world shift the baseline in one direction or another. This situation generates risks with regard to the harmonization of regulations toward a lower level of ambition. In addition, a globally standardized definition would take a very long time and prevent a short-term ramp-up.

The challenge of competing interests in transition: Export of green products vs. defossilization of the grid

PtX projects implementing strict power criteria (such as REDIII) may contradict reasonable transformation pathways in regions highly attractive for investors due to low levelized cost of electricity but local grid constraints and increasing electricity demands. Particular challenges arise from economies with high renewable potential compared with long-term domestic demand but low renewable deployment. Here, an initial focus on the export of green hydrogen and derivatives has the potential to unlock the accelerated deployment of renewable energy capacities through international investments and offtake. This can positively impact the development of domestic supply chains and thereby reduce the cost of renewable energy installations, which will also benefit the domestic market ("spillover effect"). On the other hand, this gives rise to the risk that export-oriented new renewable energy capacities at the most economical sites slow down the ramp-up of the renewables share in the domestic energy system, where green electricity could be used more effectively to reduce GHG emissions. Maintaining a good balance between the export of PtX products and increasing the share of renewables for domestic use cannot be managed at the project level. Instead, this requires a long-term decarbonization strategy—typically an integrated national energy and climate plan such as in the context of the Nationally Determined Contributions. This enables managing the share of exported PtX capacity vs. increasing the RE share domestically over longer periods of time.

Regulatory shortcomings: Areas of application

The current sustainability regulations promote the use of PtX products, mainly in the mobility and transportation sector. However, the relevance of PtX products extends to critical "no-regret" and "hard-to-abate" applications where viable alternatives, such as direct electrification, are not feasible. These scenarios include essential industries like fertilizer production, chemical manufacturing, and steel production, where hydrogen or hydrogen derivates are indispensable. With the ambitious target within the REDIII that 42% of industrially used hydrogen should be green by 2030 (15 Article 22 a), it is crucial to ensure that regulatory frameworks support the transition in these hard-to-abate sectors. By prioritizing the adoption of green hydrogen in such applications, industrial carbon emissions can be significantly reduced and drive progress toward broader sustainability goals, ensuring that these critical industries align with future environmental standards.

Regulatory shortcomings: Social and environmental sustainability

Most mandatory sustainability regulations for PtX exclude crucial social and environmental aspects. Social considerations, such as community impact, job creation, and public acceptance, are frequently absent from regulatory discussions. Gale et al.[41] come to the conclusion "that the "social" dimension of sustainability (is) underrepresented, markedly so in some instances." While typically focused on GHG emissions and power sources, environmental criteria often fail to address other significant impacts, including land use, water sources, waste management, emissions, and potential relocations. These issues are particularly critical in large-scale projects like NEOM and HYPHEN, where the environmental footprint and social implications have generated considerable debate.[43,44]

To ensure a truly holistic sustainable development, it would be essential to incorporate social and environmental criteria into the regulatory frameworks of PtX production. This would help to mitigate adverse impacts, promote community engagement, and foster broader acceptance and support for these critical technologies. As such, projects would need to demonstrate a sizable contribution to creating good, fairly paid, and formal jobs; make a sizable contribution to creating regional and national economic value; and avoid negative impacts on the environment and society. The reliance on country-specific regulations entails the risk of further marginalizing social considerations by economic or political interests, reinforcing a system where technical criteria dominate, leaving the needs and well-being of communities underrepresented and overlooked.

On the other hand, the incorporation of social and environmental criteria would significantly increase the already high complexity of regulations and the certification process. In addition to potentially driving up the costs of PtX products, this could raise the project development effort to such an extent that projects are either not realized or not even initiated in the first place. Moreover, it is crucial to ensure that PtX is not disadvantaged compared with other fossil or renewable energy pathways due to stricter requirements. Given the rapidly advancing global warming, it can also be argued that climate considerations should be prioritized over other sustainability aspects. Therefore, such "non-PtX-specific" requirements could be ensured more fairly in overarching regulations (e.g., the EU Supply Chain Act).

Regulatory shortcomings: Full life cycle GHG emissions

Regulations often focus narrowly on direct emissions from PtX production and usage, neglecting the GHG emissions from the construction of renewable energy and PtX plants (see environmental) and hydrogen leakage. This focus might lead to a significant underestimation of GHG emissions since the production of renewable energy facilities can be highly energy-intensive and dependent on fossil fuels.[45] This simplification in GHG calculations has already been applied in the evaluation of biofuels, such as in REDII, where the expected error from omitting these emissions was considered negligible. However, this assumption should be reconsidered for PtX. Including life cycle emissions, with consideration of those from construction and operation, in analyses of sustainable hydrogen production has shown that they can contribute significantly to total emissions, making compliance with emission thresholds feasible only at favorable locations.[45] However, emission thresholds in PtX regulations are often compared with fossil fuel benchmarks, and the full life cycle emissions of these fossil references—including extraction, processing, and transportation—are frequently not considered. This oversight can lead to an unfair evaluation of the emissions associated with renewable technologies, especially when the ambition and compliance of PtX projects with environmental standards are monitored in detail, while fossil projects face limited scrutiny, particularly outside OECD countries.

While the current GHG thresholds represent a significant reduction compared with the predominantly used fossil references, they still result in relevant residual emissions. Thus, to achieve the necessary climate neutrality, these thresholds must be further lowered in the future or compensated through extensive and potentially limited offsetting measures.[46]

Consequently, to align with the Paris Agreement goals, adopting a more holistic and rigorous approach to life cycle GHG assessments is crucial, ensuring that indirect emissions and emissions from renewable energy source technologies are adequately accounted for in regulatory frameworks. While collecting emission data from material and construction presents challenges, the evolving understanding of material production and the anticipated reductions in carbon intensity, such as in steel manufacturing, suggest that regulatory frameworks should remain adaptable. Making the reporting of these emissions optional for project developers could provide valuable data while avoiding undue burdens on projects that may find it difficult to quantify these emissions accurately. Within a closed regulatory system, such emissions could potentially be more easily captured and regulated upstream, e.g., through an emissions trading system (such as the EU ETS). However, emissions outside the regulatory scope (in the case of the EU ETS, emissions outside the EU) would need to be addressed through additional mechanisms (such as the Carbon Border Adjustment Mechanism [CBAM[18]]).

CONCLUSION

The development of sustainability regulations for PtX projects is both necessary and complex. These regulations must be integrated with broader energy transformation efforts and aligned with global policy priorities, such as the SDGs, to address environmental, societal, and economic challenges. PtX regulations should contribute to a "just transition" by balancing and promoting environmental, social, and economic sustainability.

This review highlights the diversity of existing sustainability regulations and provides a structured and comprehensive overview of their characteristics and requirements. The analysis of regulatory impacts indicated that sustainability criteria directly impact process concepts and permissible energy and feedstock supply, underscoring the need for further quantitative analysis to better understand their effects on the technical, economic, and environmental attributes of PtX products.

The discussion of challenges and shortcomings highlights the complex tensions and trade-offs that must be considered in future regulations. While legal frameworks, certification schemes, and incentive and support schemes are essential for driving the market growth of green hydrogen-based products, their complexity and diversity pose significant challenges for project developers. The lack of harmonization across different regulations regarding the type and level of requirements hinders project development by creating uncertainty and constraining product markets. Greater alignment and standardization in regulations to ensure clarity for stakeholders and facilitate the creation of a cohesive global market would greatly counteract these problems. On the other hand, the limited time available to defossilize the economy and prevent the escalation of the climate crisis necessitates rapid implementation of regulations that provide certainty and clear frameworks for PtX projects. Alongside the legitimate pursuit of holistic sustainability, the urgency of time might necessitate a prioritization of directly climate-relevant sustainability requirements (like GHG thresholds) over broader social requirements (like gender equality or stakeholder engagement). Furthermore, it is crucial to ensure that renewable energy and PtX projects are not disadvantaged compared with alternative technologies. Considering the outlined sustainability requirements for PtX production results in a notable imbalance compared with fossil projects, where the monitoring of compliance with environmental and social standards is often less rigorous, particularly in non-OECD countries. This discrepancy raises concerns regarding the fairness of competition between renewable and fossil energy sources. Striking compromises will be essential to establish internationally and cross-sectorally aligned sustainability requirements that are both robust and comprehensive while still enabling focused and economically viable PtX projects for "no-regret" applications.

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AUTHOR CONTRIBUTIONS

S.B.: conceptualization, formal analysis, writing – original draft, writing – review & editing; K.L.: investigation, formal analysis, writing – original draft, writing – review & editing; D.G.R.: investigation, formal analysis, writing – original draft; S.S.: investigation, writing – review & editing; M.P.: writing – review & editing; M.K.: supervision, writing – review & editing; J.B.: writing – review & editing, validation; K.I.: conceptualization, methodology, writing – review & editing, supervision.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT to refine language and enhance readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

SUPPLEMENTAL INFORMATION

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