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Analysis of the levelized cost of green hydrogen: Time for complementary metrics?

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ABSTRACT

The Levelized Cost of Hydrogen (LCOH) is a widely used metric to evaluate and compare green hydrogen supply chains. This paper reveals two sets of challenges in its current use. First, we illustrate the substantial variation in system boundaries, components, end-user specifications, levels of detail in production operations, and spatio-temporal contexts in LCOH calculations. This results in inconsistent usage and interpretation of the metric and unreliable cross-study comparisons. Second, the LCOH only partially captures the complexity of variable renewable energy-based hydrogen production. The LCOH does not endogenously account for the profile, balancing and network requirements associated with additional renewables in the electricity system or services electrolytic hydrogen supply chains can provide to other parts of the energy system. The first set of challenges can be mitigated through transparent reporting of system boundaries and scales. Furthermore, we provide directions for methodological developments to overcome the second set of fundamental issues.

1. Introduction

The integration of climate-neutral hydrogen into energy systems is recognized as a critical step toward achieving net-zero emissions [1]. Climate-neutral hydrogen may play a pivotal role in decarbonizing hard-to-abate sectors such as heavy industry, long-distance transportation, and long-duration energy storage [2,3]. Green or renewable hydrogen will mainly be produced from renewable electricity, utilizing electrolyzer technologies [4]. Although green hydrogen is widely framed as a promising component of the energy transition, the scaling of supply chains and the competition for renewable electricity introduce uncertainty about the feasibility of green hydrogen implementation [5]. In addition, recent cost comparisons imply that replacing existing hydrogen supply chains with green hydrogen may remain not-cost-competitive for the next decade(s) [5]. For green hydrogen to be successfully implemented at scale, technical, economic, and regulatory challenges must be overcome. On the techno-economic side, this includes improving system efficiency, reducing equipment and material costs, and scaling production [2,6,7].

To identify cost-effective solutions for large-scale deployment, it is essential to assess and compare hydrogen supply chains [8,9] (Fig. 1). The Levelized Cost of Hydrogen (LCOH) is a widely used metric (see Fig. 2, illustrating the increasing number of publications between 2020 and 2025 reporting on the LCOH metric). It represents the average production cost per unit of hydrogen over the system's economic lifetime [10], enabling standardized comparisons of production technologies and configurations. The European Hydrogen Observatory ([11], p.11) defines it as:

> The LCOH is a method used to evaluate the total expenses involved in producing hydrogen throughout its entire lifecycle, including both capital (CAPEX) and operational costs (OPEX). The LCOH serves as a valuable tool for evaluating hydrogen against alternative energy options and determining its market competitiveness.

The LCOH equation traditionally accounts for capital expenditures (CAPEX), operating and maintenance costs (OPEX) for each component of the supply chain, discount rates, and inflation. It is mathematically defined as follows [12–14]:

$$\mathrm{LCOH} = \frac{\sum_{y=1}^{n} \frac{\mathrm{CAPEX}_y^{\mathrm{Total}} + \mathrm{OPEX}_y^{\mathrm{Total}}}{(1+r)^y}}{\sum_{y=1}^{n} \frac{\mathrm{H_2\ production}_y}{(1+r)^y}} \quad (1)$$

n represents the economic lifetime in years, $\mathrm{CAPEX}_y^{\mathrm{Total}}$ and $\mathrm{OPEX}_y^{\mathrm{Total}}$ are the total capital and operational expenditures for each year y, and r is the discount rate. The LCOH represents the average price required per unit of hydrogen produced to set the project's net present value to zero. The discounting of the physical hydrogen output in Eq. (1) arises from

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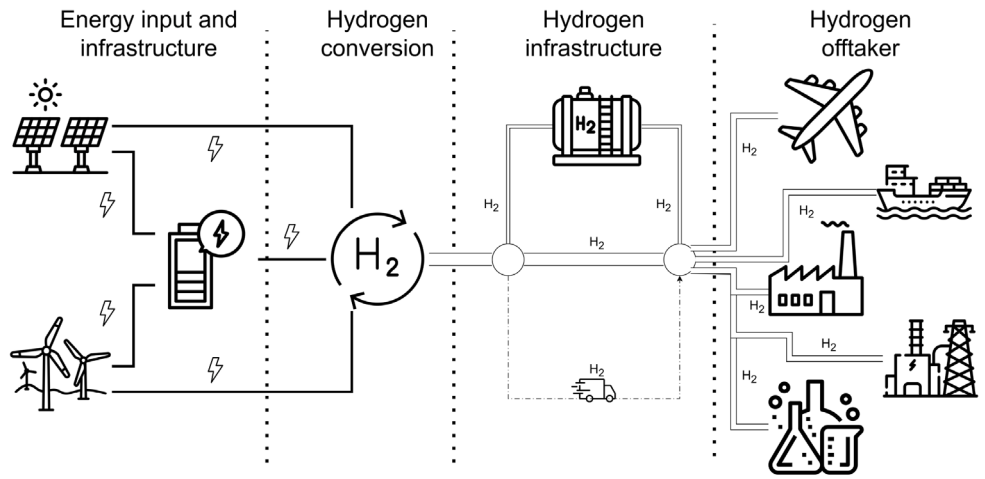

Fig. 1. Green hydrogen supply chains consist of four main components: energy input and infrastructure, hydrogen production or conversion, hydrogen infrastructure, and end-use. For electrolytic green hydrogen production, renewable electricity is supplied to electrolyzers (directly or via the grid), after which hydrogen is transported to end-users via pipelines or trucks, or as derivatives that require additional conversion steps.

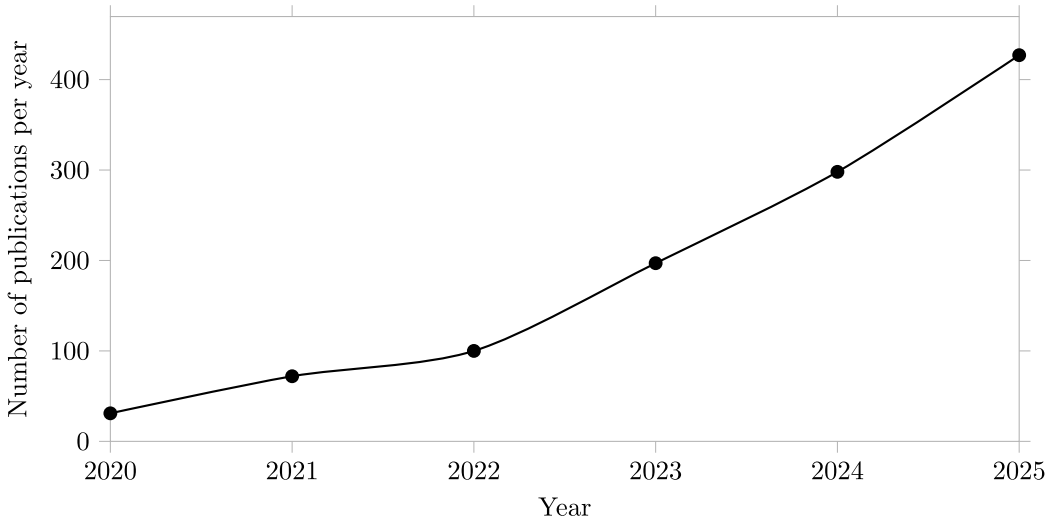

Fig. 2. Number of scientific publications per year in the Web of Science database with "LCOH", "Levelized Cost of Hydrogen", or "Levelised Cost of Hydrogen" in their title or abstract between 2020 and 2025 [16].

defining the LCOH as this break-even price that equates the present value of costs and revenues over the economic lifetime. It represents the reduced economic value of the anticipated revenues associated with the future output, not a decrease in the physical output itself [15].

Estimating the LCOH and comparing results across different hydrogen supply chains requires an understanding of the system boundaries, thereby defining the physical components [2,7] and the infrastructure needed to deliver hydrogen to end-users [8]. The hydrogen demand profile depends on the offtaker, as its wide range of applications [17] can result in variations in demand specifications and lead to different characteristics (temperature, pressure, purity) of the delivered hydrogen. These variations require additional system components and processes, which affect the system's cost and should therefore be reflected in the LCOH calculation.

In addition to technological and economic cost dimensions, other external costs and benefits are typically not incorporated into the cost assessments of hydrogen supply chains. Ruhnau et al. [18] and Kovaĉ et al. [6] show that, in addition to techno-economic costs, other relevant aspects affect the implementation potential of hydrogen supply chains, such as social and environmental aspects. Hydrogen may have an environmental impact, even when produced from renewable energy. Generally, this impact is presented through a Life Cycle Assessment (LCA) [19,20], but the corresponding environmental costs are generally excluded. Factors such as public acceptance (e.g. "Not In My Backyard") [6], esthetic quality of landscape, (local) conservation of nature, and (prevention of) environmental impact can be monetized as environmental, social, acceptance or disamenity costs when considering the implementation of energy technologies [18,21]. Moreover, the costs associated with a hydrogen supply chain depend not only on its individual factors or system components, but also on their interactions with the wider energy system. In particular, hydrogen production and delivery must be coordinated with the spatio-temporal availability of energy resources, infrastructure, and end-use.

This interaction is particularly important for green hydrogen, which is envisioned to be produced from time- and geographical-dependent variable renewable energy (VRE) sources [22]. This may require measures to balance demand and supply in the hydrogen and electricity system, such as storage capacity, network infrastructure, and demand flexibility [17]. However, the supplementary system measures and components – which all come at a cost – are not generally incorporated into LCOH calculations. In contrast, for renewable electricity generation, the exclusion of these cost aspects has been widely recognized in the scientific literature [23–26]. Joskow, a key figure in the inception

of the debate on system integration cost[1] [23], emphasizes that the Levelized Cost of Electricity (LCOE) is not capable of representing system integration costs and the time-dependent impact of integrating electricity into energy systems. For example, it does not account for integration costs such as balancing costs or profile cost [24].[2]

Although LCOE and LCOH have similarities, they differ because hydrogen and electricity supply chains and their roles as energy carriers differ, leading to distinct integration costs. For hydrogen, the integration cost is also impacted by conversion components and processes (e.g., electrolysis), infrastructure requirements (e.g., hydrogen compression, transport, and storage), and end-use requirements such as purity, pressure, and delivery profiles. While electrolyzers are subject to, e.g., minimum-load requirements and ramping constraints, they may also provide services to other energy systems, such as grid balancing, flexibility support, congestion relief, and curtailment reduction [28]. This may result in both positive and negative integration costs. In other words, the LCOH captures only a partial representation of overall system costs because it abstracts away from interactions within the energy system. However, as we will discuss in this article, when used within a clearly defined and consistently applied system boundary, it can still provide valuable insights into the techno-economic performance of a hydrogen supply chain.

Where the usefulness of the LCOE has been critically assessed in the last two decades [23,24,26] as we will argue in detail in Section 3.3, the LCOH metric itself has not typically been a topic of research. In addition to a few notable exceptions (Nicita et al. [29], Ishimoto et al. [30]), which are discussed below, several studies include an analysis of which techno-economic parameters affect the LCOH, including system configuration and components, conversion steps, technological efficiency, and infrastructure requirements [31,32]. Gea-Bermúdez et al. [33] emphasize furthermore that different kinds of techno-economic assessment are needed. They state that techno-economic feasibility studies – such as those that yield an LCOH metric – can be characterized as technology- or project-based analyses. These approaches enable incorporating detailed project-level data, but typically assess system cost relative to an external reference system rather than representing broader energy system interactions endogenously. For example, electricity prices are generally treated as exogenous inputs, whereas in assessments using energy system optimization models, they are determined endogenously [33]. As a result, the two approaches may lead to different outcomes because they reflect different analytical perspectives.

Nicita et al. [29] provide a review of life cycle costing approaches applied to a range of hydrogen technologies, covering dimensions such as definition of system boundaries, selection of functional units, cost categories, financial assessment methods, and adherence to life cycle cost guidelines. Their main finding is that uniformity in the literature is lacking due to inconsistencies in the inclusion of hydrogen technologies, partial coverage of the end-to-end life cycle, and cost categories that lack standardized methodologies. Ishimoto et al. [30] examine life-cycle cost approaches for fuel cell and hydrogen technologies, covering the components needed for harmonized cost assessments, including scope, calculation methods, discounting practices, data sources, and end-of-life treatment. They conclude that it is necessary to develop a uniform, clearly defined methodological procedure to generate comparable cross-study outcomes for LCOH and life cycle cost assessments.

Although both Nicita et al. [29] and Ishimoto et al. [30] identify methodological heterogeneity in LCOH calculations, they situate the metric within broader life-cycle costing literature rather than conceptually addressing the LCOH itself. Furthermore, the role of VRE-based inputs within green hydrogen supply chains is not explicitly considered. They also do not differentiate between limitations that can be overcome by a standardized methodology for LCOH calculations and those inherent to the metric, thereby representing knowledge gaps in the current LCOH metric literature.

To assess the limitations of the LCOH metric, we provide a structured analysis of the use of the LCOH metric as the basis of the aforementioned aspects that affect the cost of green hydrogen supply chains. We do so through an in-depth review of a sample of 30 studies selected from recent literature (Section 3.1). These aspects are not only evident in the reviewed studies themselves, but are also identified in the broader literature as relevant aspects for assessing hydrogen supply chains and their costs (system boundaries [2,7,8,22], spatio-temporal data [34–36], hydrogen end-point specifications [37], operational detail [35,38–40], and externalities [6,18]). By structuring this part of the analysis around these aspects, we make explicit where and how current LCOH calculations differ and evaluate the implications of these differences for the reliability and comparability of techno-economic assessments.

1.1. Contribution

Our analysis shows the diversity in how the LCOH is currently operationalized in the literature. We analyze its strengths and weaknesses and identify operational and fundamental challenges. Building on this assessment, a central contribution of this paper is to translate the identified operational challenges into practical methodological guidance for modelers, while also sketching directions for future methodological development to address the fundamental limitations of the LCOH. In doing so, we add to the limited existing literature on the LCOH metric in three ways.

First, we provide guidance for modelers (Section 4) to overcome operational issues for the LCOH metric. We propose a refined definition of the LCOH to harmonize the definition of system boundaries (Section 4.1). We identify the appropriate inclusion of the cost of the electricity input, depending on whether electrolysis is connected to a standalone VRE asset or is operated as a grid-connected asset. For grid-connected configurations, electricity costs depend on electricity market prices, PPA conditions, and dispatch strategies. In addition, we address VRE-related profile, balancing, and network requirements, as well as system services provided by electrolytic hydrogen production (Section 4.3). These recommendations translate identified literature inconsistencies and limitations into practical guidance for more transparent, comparable LCOH assessments and emphasize where complementary methods are needed to address the metric's fundamental limitations.

Second, we provide a critical review of the LCOH's strengths and weaknesses as a metric for green hydrogen supply chains (Section 3.3). We separate operational and fundamental limitations relevant to the use of LCOH metrics (Table 8). We provide evidence that fundamental limitations cannot be resolved by refining LCOH alone, as its project-level formulation does not capture system integration costs, network effects, or the challenges it presents or value it offers to the wider energy system, requiring complementary system-level analyses, approaches, or metrics.

Last, we provide a basis for future formalization of potential complementary metrics to overcome the fundamental limitations of the LCOH. We demonstrate that while the LCOH and LCOE metrics share several similarities and limitations, important distinctions arise from the inherent differences between the energy carriers. Hydrogen can be supplied with varying properties (e.g., pressure and purity) and the carriers face distinct challenges related to deployment and integration into the energy system.

The remainder of this paper is structured as follows. We subsequently describe the methodology (Section 2), the results and discussion of the in-depth analysis of the selected studies (Section 3.1) and

[1] There is a complementary perspective to integration costs related to the economic or "market value" of renewable electricity production (see Hirth et al. [27]). For the sake of simplicity, we focus on "integration costs" in this paper to avoid confusion.

[2] Profile costs are defined as the combination of overproduction, full-load hour reduction and backup costs [24].

use of the LCOH outside of academia (Section 3.2), the overview and reflection on the key strengths and weaknesses of the LCOH metric (Section 3.3), guidance for modelers (Section 4), possible alternative metrics and approaches (Section 4.4), and finally the conclusion (Section 5).

2. Methodology

First, we conduct a systematic literature search using the PRISMA approach [41] to identify the studies that make use of the LCOH in recent scientific research (summarized in Fig. 3).

The review focuses on recent peer-reviewed studies that include "LCOH", "Levelized Cost of Hydrogen" or "Levelised Cost of Hydrogen" in their title or abstract. The Web of Science collection is searched with the following query:

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(TI=(LCOH OR ''levelized cost of hydrogen'' OR ''levelised cost of hydrogen'')
  OR
AB=(LCOH OR ''levelized cost of hydrogen'' OR ''levelised cost of hydrogen''))
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Here, TI denotes the Title field and AB the Abstract field. Using these search terms, a total of 1253 records were identified. Restricting the publication period to 2020—2025 excluded 128 records, leaving 1125 studies for eligibility assessment [16].

Studies are excluded when they do not assess hydrogen production, do not include renewable energy as an input to hydrogen production, or constitute review studies rather than original analyses. Studies that compare hydrogen supply chains based on renewable energy with non-renewable alternatives are included. For all included studies, the unit of analysis is the renewable-hydrogen supply chain(s); where a study also considers non-renewable pathways, these are excluded from the data extraction and analysis. To balance temporal coverage with the depth required for detailed qualitative assessment, we subsequently select the five most cited eligible articles from each publication year (2020–2025), yielding 30 studies. Citation counts are used as a proxy for citation impact and academic visibility, while stratification by publication year ensures coverage across the full study period rather than allowing individual years to dominate the sample. The resulting sample is intended to allow detailed, critical analysis of different applications of the LCOH, rather than to provide a statistically representative characterization of the complete literature. This selection strategy may introduce citation-related and publication-age bias, including a preference for more established authors, technologies, regions, or methodological approaches, and for papers that have had more time to accumulate citations.

Second, an analytical framework is developed to structure the evaluation of how LCOH is applied in the literature, based on the five aspects identified as critical for the development and integration of green-hydrogen supply chains (see Section 1). These five aspects are presented in Table 1.

Third, in-depth analysis of the selected sources is performed. If a paper mentions or documents an element (see Table 1), the corresponding cell of the analytical framework is marked, and, when possible, a specific (numerical) value or statement is included. All coding decisions and extracted numbers are traceable via the selected papers, ensuring transparency. We provide a full description matrix in Appendix A and summarize the main patterns in Section 3.1.

This structured review is used to synthesize the selected literature and identify trends, patterns, and inconsistencies in the calculation of the LCOH metric. In addition, the use of the LCOH metric is analyzed in non-academic research and documentation on hydrogen perspectives such as McKinsey [42], DNV [43], the IEA [44], and IRENA [45].

In what follows, we separate the descriptive analysis of how the 30 selected studies operationalize the LCOH (Section 3.1) from a broader interpretation of the conceptual applicability and suitability of the metric (Section 3.3). The interpretations derived from the literature review are not reported as frequency-based findings or as statistically representative results of all scientific literature reporting on the LCOH. However, informed by the observed use of the LCOH in the selected literature, we are able to highlight strengths and weaknesses of the metric.

Table 1
Aspects for the green hydrogen supply chain and how they are assessed in our analysis.

Aspects	Elements
System boundaries	Energy source, system components, scale, and what elements of the LCOH equation are included.
Spatio-temporal data	Geographical location, temporal resolution
Hydrogen end-point specifications	Hydrogen state of matter, pressure, temperature, hydrogen purity, and hydrogen demand profile.
Operational detail	Level of technical detail in the representation of the variable and time-dependent operational characteristics of hydrogen supply chain components – including efficiency, and degradation – as well as the assumed heating value used for hydrogen conversion.
Externalities	Social costs, Environmental costs, Disamenity costs.

3. Results

The following sections include the findings and insights on the usage of the LCOH in academia (Section 3.1), outside of academia (Section 3.2), and the reflection on the LCOH (Section 3.3).

3.1. Use of the LCOH in the academic literature

We find that across the analyzed papers, the LCOH is used as a project or technology-focused metric that enables first-order benchmarking across production routes. However, its interpretation and application are inconsistent, and even the LCOH formulation varies across the studies (Section 3.1.1). When analyzing the components and boundaries of the system, we find that 9 out of the 30 include only electricity generation and electrolyzer, while 19 studies add balancing components (e.g., storage) in the supply chains, and only 4 studies actively mention the inclusion of transmission infrastructure (electricity and/or hydrogen).

Generally, as described in Section 3.1.1, system integration and sector coupling are partially represented and in a simplified way. Most studies capture this through boundary extensions of physical components (e.g., adding storage, limited transmission, or grid-connection cases) and static assumptions (e.g., fixed cost, take-as-produced), rather than modeling endogenous, time-resolved interactions between energy carriers, demand, generation, and conversion. Almost all studies specify the selection of time-dependent data and geographic area (Section 3.1.2), but many different resolutions are considered (from per-minute time steps to annual averages (Table 3)). Demand-specific data are generally excluded, and end-product conditions remain sparsely reported. As presented in Section 3.1.3, hydrogen end-point specifications are partially presented: 18 studies report some characteristics (e.g., pressure/temperature/state), yet only 6 mention purity and just three quantify it. Externalities are mostly excluded.

Based on these findings, it can be concluded that the LCOH is used in widely different ways. The findings are detailed in Appendix A and elaborated on in the following sections.

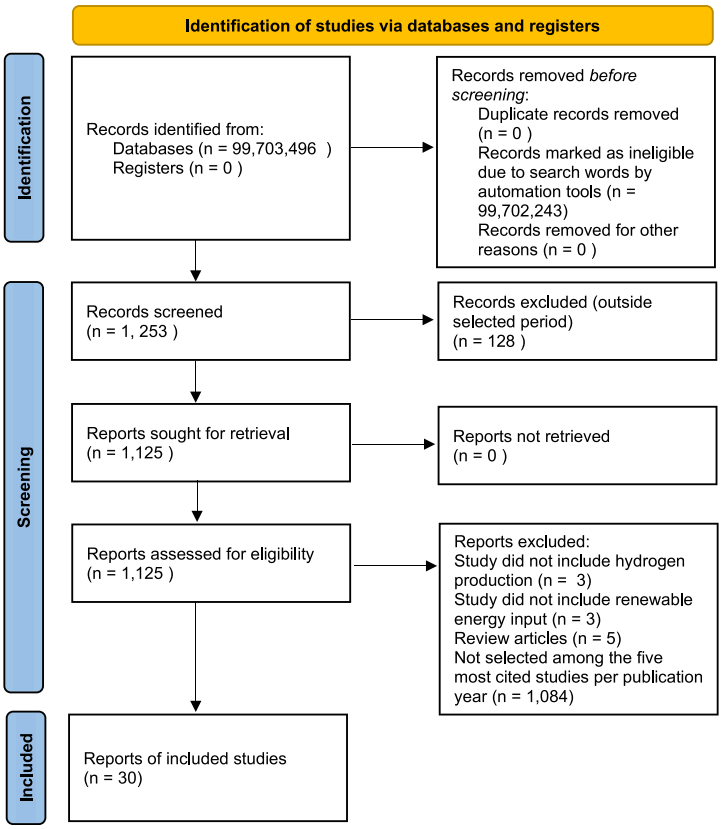

Fig. 3. PRISMA approach [41] for the systematic literature search and subsequent selection of the 30 papers considered for in-depth analysis.

3.1.1. System boundaries

In general, it is not explicitly defined what should be included within the system boundaries for the LCOH calculation, which undermines transparency and comparability. Most studies employ Eq. (1), which incorporates CAPEX and OPEX of the components of the hydrogen supply chain, fuel/energy input cost/electricity cost, hydrogen produced and corrected for by discount rate. However, they include different elements. For example, most studies neither mention nor include soft costs. When they are included, they are included in different ways; as labor cost [46–51], installation cost [47,50,52–55], land (lease) cost [55–57] and sometimes as decommissioning, tax, insurance or administration costs [46,48,57]. In addition, some specifically introduce replacement cost [22,58] or salvage value as a cost reduction [59]. In general, the studies analyzed consider only the production of hydrogen. However, Pan et al. [60] and Tera et al. [55] assess the coupling of energy sources and carriers. There, not only is hydrogen produced, but also electricity or heat. Minutillo et al. [61] also include the revenue from excess solar energy based on fixed electricity prices. Lastly, both Li et al. [62] and Saif et al. [57] include the sale of oxygen, produced as a byproduct, to revenues, lowering LCOH.

There are also many differences in the system components that are believed to be required for green hydrogen supply chains cost assessments. In some of the studies analyzed, only the energy source and the production method are part of the system configuration, while others also include infrastructure or storage components for the electricity and/or the hydrogen. Although almost all studies consider VRE-based hydrogen production, the inclusion of storage components differs. Table 2 provides an overview of the storage included per study.

In addition to differences in the system components included, there are no predefined standards for the scale or size for the LCOH calculation. As a result, some studies consider smaller scales (1 kg/h [71] or 3 kW [52]), while others have higher volumes (500 tons per day [46] or 100,000 tons of hydrogen per year [56]). The difference in scale is not identified when looking at the LCOH outcomes, which presents the findings as monetary unit per unit of hydrogen. Because scaling can reduce costs through economies of scale and other potential advantages, explicitly incorporating scale into cross-system comparisons provides insight into how certain outcomes are realized.

Table 2
Storage components in the analyzed studies. Categories are not mutually exclusive: references may appear in more than one storage category and therefore category totals should not be summed.

Balancing/Storage components	Studies
No storage included	[47–50,53,55,56,63–66]
Electricity storage included	[51,52,57,60,62,67–71]
Hydrogen storage included	[46,51,52,54,58–62,68,71–75]

3.1.2. Spatio-temporal data

All analyzed studies define geographic regions for hydrogen production, except for two that do not provide these specifications. Kim et al. [50] consider experimental data at laboratory scale and Tera et al. [55] use biomass as energy input. For the latter, biomass transport is included as a cost but further geographical specifications are excluded. For studies that specify the geographical region, the way in which corresponding geographical factors are incorporated into the cost estimation differs. This also corresponds to the temporal resolution, which varies from minute-level time steps to total annual hydrogen production (Table 3).

The combination of temporal resolution and geographical conditions determines the amount of energy that can be supplied from VRE sources, as well as its cost, given their inherent intermittency.

There are different sources of energy input for hydrogen supply chains, with some standalone hydrogen supply chains. Others have a combination of grid-connected and off-grid system scenarios. Table 4

Table 3
Temporal resolution of the analyzed studies.

Temporal resolution	Studies
Per minute	[70]
30 min	[69]
Hourly	[48,49,51,52,54,55,57–63,66–68,71,73–75]
Daily	[46,47,50]
Annual	[53,56,65,72]
Not specified	[64]

Table 4
Grid connection considered in the analyzed studies.

Grid connection	Studies
Off-grid standalone supply chain	[47–49,51–53,55,57–59,63,65,68–70,72,75]
Mixed cases (grid-included and off-grid scenarios)	[46,54,60–62,66,67,71,73,74]
Full grid-included	[50,56,64]

Table 5
Hydrogen offtaker representation in the analyzed studies.

Demand profile	Studies
Take-as-produced	[47–50,52–59,61,63,64,66,67,69–72,74,75]
Defined fixed demand profile	[60,62,65,68,73]
Enables inclusion of fluctuations in hydrogen demand profile	[46,51]

summarizes the extent to which grid connections are considered in the studies.

3.1.3. Hydrogen end-point specifications

All studies indicate –directly or indirectly– whether liquid or gaseous hydrogen is produced, and the pressure levels at the electrolyzer or storage location, thereby providing some hydrogen characteristics within the supply chain. 18 studies share –at least partial– information on hydrogen characteristics such as pressure levels, temperature, and purity of the produced hydrogen. In some cases, more specifics are shared, mainly for pressure levels. For example, Giampieri et al. [51], Vives et al. [66], Nasser and Hassan [54], Minutillo et al. [61], Nasser et al. [58], and Fan et al. [71] specified the pressure levels due to compression processes.

Only in six studies were purity levels actively mentioned and only three included them as a percentage: 99.9% [64], 99.5%–99.9% [67] and 99.9% [71]. The three others referred to "high purity" [48,51] and "high level of gas purity" [50]. Hydrogen purity is also included indirectly in four studies: Fan et al. [56] and Nasser and Hassan [54] include purification cost. Tera et al. [55] and Nasser et al. [58] implicitly assume a sufficiently high hydrogen purity, as evidenced by their consideration of fuel cell operation in their analyses.

For all studies, the focus is on the production side of the supply chain, with none paying direct attention to offtaker demand. Generally, most estimate production costs as "take-as-produced", ignoring offtaker interactions, preferences, or time- or location-dependent variations in hydrogen demand profiles, although this can affect the production cost. Of the 30 studies, 23 provide a take-as-produced approach. However, in the studies by Ishimoto et al. [46] and Giampieri et al. [51] the green hydrogen produced is stored in large-scale storage facilities, which enables interaction with potentially fluctuating hydrogen demand profiles. The interaction with hydrogen offtakers is represented in Table 5.

3.1.4. Operational detail

All analyzed studies, except one [55], consider electrolytic hydrogen supply chains powered by VRE. Electrolyzer operation can be affected by intermittent energy input [38–40]. The effect is included in different ways in the literature. Some studies have excluded it, others assume a fixed impact (e.g., fixed degradation rate) without specifying the effect of the intermittency, and only very few consider the impact on an operational level. The detail level required to accurately reflect the behavior of the electrolyzer powered by VRE is excluded in all studies, with the study by Xu et al. [70] as a notable exception.

Table 6
Classification of analyzed studies by operational detail for assessing hydrogen supply chains.

Operational detail	Studies
Low	[46,47,50,53,56,57,64–66,72,75]
Medium	[52,58,60–63,68,69,74]
High	[48,49,51,54,55,59,67,70,71,73]

Table 7
Heating values considered in the analyzed literature.

Heating value	Studies
LHV	[46,51,53–55,57,60,69–71,73]
HHV	[48,49,52,56,58,59,64,66,72,75]
Both	[50]
Exact value	[62,63,74]
Not specified	[47,61,65,67,68]

We have divided the studies into Low, Medium, or High levels of detail to assess hydrogen supply chain operations and consider the effects of VRE-based intermittency (see "Operational detail" in Table 1). Studies that include a "low" level ignore the effects of intermittent power input and consider fixed capacity factors and load hours, and ignore stack degradation due to variations in loading. The "medium" level consists of studies that address the intermittent nature of VRE and often include batteries or other storage systems to enable stable hydrogen production. The impact of stack degradation is excluded or simplified. Lastly, the "high" level of detail for hydrogen supply chain operations consists of studies that include the most detailed analysis for electrolyzer operations, affected by variable power input and the corresponding stack degradation, thus affecting the production rate. This classification offers a structured overview of the diversity in operational detail in the analyzed literature. While this classification is interpretative, it offers an overview of the diversity in operational detail in the analyzed literature

The classification results are presented in Table 6 and in more detail in Appendix A. This heterogeneity in representing operational detail directly undermines the comparability between studies, especially for VRE-based systems because utilization, efficiency, and stack lifetime, and the corresponding replacement costs, depend on operational cycling [38–40]. Consequently, the results of studies conducted at different operational levels can predominantly capture the implications of modeling choices regarding the temporal resolution and representation of operational behavior and degradation, rather than the underlying differences in costs or technologies.

For the estimation of the LCOH, the selected heating value affects the amount of produced hydrogen. However, there is also no consensus on the hydrogen heating value. Both the Lower Heating Value (LHV) and Higher Heating Value (HHV), as well as some exact conversion values are considered, see Table 7.

3.1.5. Externalities

For the calculation of the LCOH, the focus is on the cost of technology in the analyzed studies. Disamenity costs are acknowledged as a relevant cost component by Ruhnau et al. [18], but they are excluded by the analyzed papers. The same holds for social costs, except for the study by Al-Qahtani et al. [64]. They include the impact on human health in the cost per kg. However, they did not include it in the LCOH but in a separate metric that estimates the total cost of hydrogen per kg.

Table 8
Strengths and weaknesses of the application of the LCOH metric for the assessment of green hydrogen supply chains. For the weaknesses, the sections are shown where we provide guidance for modelers related to each weakness.

Strengths	Weaknesses
• Enables technology and system configuration comparisons using a uniform output-based approach. • Allows for a transparent cost breakdown of specific components, such as the share of CAPEX of components in LCOH. • Focuses on technology costs and production.	**Operational issues** • No requirements for (physical) system boundaries, non-technology cost, and financial parameters for cost estimation. (Section 4.1) • No requirements for consistent representation of VRE-based electricity input and system configuration in cost estimation. (Section 4.2) **Fundamental limitations** • Incapable of representing profile, balancing, and network requirements related to VRE-based hydrogen supply chains. (Section 4.3) • Incapable of representing system services hydrogen supply chains may provide. (Section 4.3)

In this metric, they also include the cost of resource depletion and the ecological impact. Neither component is considered part of the LCOH by the studies in this analysis. Thus, there is uniformity among the analyzed studies on the inclusion of social and disamenity costs.

However, in Rezaei et al. [72], environmental costs are monetized and included in the LCOH estimation. They include environmental costs as follows: "Environmental cost refers to the expenditure that would be incurred if an amount of CO_2 emission entered to the atmosphere." (p.1056) [72]. Li and Taghizadeh-Hesary [65] include a specific environmental cost related to CO_2 emissions. Nasser and Hassan [54], Nasser et al. [58], and Rehman et al. [75] include these as a cost reduction resulting from carbon credit gained by CO_2-emission reduction. Lastly, Tera et al. [55], Tebibel et al. [59], Al-Buraiki and Al-Sharafi [52], Fan et al. [71], and Saif et al. [57] quantify the environmental impact but exclude cost estimates. This highlights that the importance of environmental elements is recognized but only sporadically monetized in the LCOH.

3.2. Use of the LCOH outside academia

In the scientific community, LCOH is generally (part of) the outcome of techno-economic performance assessments of hydrogen supply chains or to compare various system configurations. However, outside academia, LCOH is often used as a benchmarking tool to establish target costs for green hydrogen supply chains to be achieved by a specific year. In those reports, a specific LCOH has become a goal in itself.

In the *Global Energy Perspective 2023: Hydrogen outlook* by McKinsey & Company [42], it is brought forward that blue hydrogen supply chains and regions with low-cost renewable energy have the potential to reach low LCOHs for export. Additionally, they emphasize that 80% of the clean hydrogen produced in 2050 will be less than 1.80 $/kg, and 30% less than 1.50 $/kg. It is not specified what the system boundaries are nor what components are included for these cost estimations. The US DOE presents an ambition for the LCOH [76]. In their national hydrogen strategy, a target of 2.0, or at best 1.0 $/kg is mentioned, which is expected to be obtained through an electricity cost of 20 $/MWh, a capital cost for conversion of 150 $/kW, and a capacity factor of 90%. They state "[..] requiring the use of clean firm electricity, such as nuclear or geothermal energy, or for variable renewables to be complemented by storage." (p.41) [76]. Hence, the need for system integration for power generation is acknowledged.

DNV presented their *Hydrogen Forecast to 2050* in 2022 [43]. Here, LCOH is directly mentioned to compare different production methods. They also discuss electrolyzers, both focusing on the CAPEX per kW_e and an estimation of the LCOH of renewable energy-based green hydrogen supply chains, stating that "Globally, green hydrogen will reach cost parity with blue within the next decade." (p.5) [43]. For the LCOH estimation, they include the traditional LCOH formula, including CAPEX, OPEX, and fuel cost, but also carbon cost for non-renewable hydrogen production and financial support to reduce CAPEX and OPEX. The considered hydrogen supply chain is not detailed.

In 2024, the IEA [44] and IRENA [77] published their outlook and strategy for green hydrogen. Both reports acknowledge that in Europe blue and gray hydrogen will remain cheaper than green hydrogen, as evidenced by initial bids from the European Hydrogen Bank ranging from 6.2 $/kg in Greece to 14.2 $/kg elsewhere. However, both reports lack a detailed breakdown of their methodologies for determining LCOH. In its outlook, the IEA [44] projects that 22 Mt of low-emission hydrogen will be produced by 2030, with some locations expected to achieve production costs below 2.0 $/kg in a net-zero scenario. This analysis focuses primarily on geographical diversity in renewable resources. For the LCOH, only hydrogen production costs are considered. In the IRENA report *Green Hydrogen – Strategy: A Guide to Design* [77] more focus is placed on the total supply chain, stating that conversion costs, including compression and liquefaction, add additional expenses, with compression adding 1.0–1.5 $/kg and liquefaction 2–3 $/kg. Transporting hydrogen incurs additional costs. If these costs are too high, long-distance transport becomes economically unfeasible, resulting in hydrogen production at demand sites.

3.3. Critical reflection on the LCOH metric

Several strengths and weaknesses of the LCOH are identified and summarized in Table 8. The LCOH has the ability to present a detailed cost breakdown, offering insights into the contributions of individual components or assets, such as energy sources, electrolyzers, storage, and transmission, to the overall cost structure. By isolating the contribution of each component or asset, the metric enables a more focused and targeted approach to technological developments, highlighting where there is potential for cost reduction. This granular transparency provides a valuable tool for identifying cost-reduction opportunities and optimizing system designs. This is well represented in Grimm et al. [47], Minutillo et al. [61], and Shin et al. [48], where the contributions of each component for the energy input and hydrogen supply chain are presented. The LCOH holds the potential for a standardized approach that enables generalized outcomes across various hydrogen supply chains, technologies, and projects, providing a uniform metric. For example, Nasser and Hassan [54] assess hydrogen production in Egypt based on different energy sources and equipment (PV panels, wind turbines, or electricity grid) and conversion technologies (PEM or SOEC). Similarly, Ishimoto et al. [46] conduct a comparative analysis of complete hydrogen supply chains delivering to Rotterdam and Tokyo, using liquid hydrogen and ammonia, and present both configurations using a common metric of euros per kilogram of hydrogen delivered.

There are two main issues related to how the LCOH is currently operationalized (Operational issues in Table 8). The first relates to the lack of specificity requirements with respect to the boundaries of the system, which may lead to inconsistencies when comparing studies. Without explicitly defining the scope of the systems under evaluation, the metric can result in misleading conclusions and cross-study comparisons. There is no transparent set of requirements of what elements should be included in the cost estimate when using the LCOH.

This relates to the definition of the LCOH, such as the one of the European Hydrogen Observatory [11] (Section 1), which allows for many different interpretations of the system boundaries of a hydrogen supply chain.

The metric also does not require the inclusion of hydrogen demand specifications, such as hydrogen purity and pressure. These attributes influence the suitability of hydrogen for various applications, yet LCOH provides no mechanism to differentiate costs based on such specifications. Including these end-product characteristics may be done in one study, but excluded in another. In the study by Al-Qahtani et al. [64], for instance, the purification stage and its associated components are explicitly incorporated into the LCOH calculation, whereas in Rezaei et al. [49], which focuses on scaling renewable hydrogen projects in Australia, these elements are omitted. Although both studies apply the same cost metric and assume uniform output, the underlying systems comprise markedly different components and processes. Cost for non-technology aspects, such as environmental, social, and disamenity costs, are generally ignored in the analyzed studies. The latter is consistent, but this may lead to incomplete cost assessments.

In addition, in many of the reviewed papers, financial parameters are not (fully) included. Emblemsvåg [26] points out that the financial parameters should be included to obtain a complete cost overview. The lifetime of the systems and the discount factors must be considered jointly for investment decisions. The weighted average cost of capital (WACC) is important and context-specific (e.g., level of risk exposure, and country) and must be specified for each hydrogen system or set of technologies.

The second operational issue in the use of LCOH for green hydrogen supply chains is the lack of requirements for VRE-based energy input, leading to inconsistent and often incomplete representation of the impact of VRE-based electricity input. Although many studies incorporate location-specific wind and solar profiles, the implications of temporal variability and fluctuating utilization of electrolyzers are not consistently reflected in cost assessments, partly due to the differences in temporal resolution considered in the analyzed studies (see Section 3.1.2). In addition, there is often no clear distinction between different electricity supply configurations. Standalone systems versus grid-connected system configurations yield fundamentally different electricity costs, but this is not reflected in most of the LCOH literature. Nevertheless, this distinction is recognized by some authors; Fan et al. [56] represent electricity input through electricity purchase for grid-connected electrolysis, whereas Rehman et al. [75] incorporate electricity costs based on the full cost of generation within an off-grid VRE-based hydrogen supply chain.

The second set of challenges relates to more fundamental limitations in the misrepresentation of the time-dependent aspects of green hydrogen supply chains and the balancing and network implications of the produced electricity or hydrogen (Fundamental limitations in Table 8). First, the LCOH for VRE-based supply chains is, in its current form, unable to capture the complexities associated with sector coupling and system integration. As Joskow [23] argues for VRE-based electricity, the levelized cost metrics compare technologies as if their output were a homogeneous commodity, while the value of the output varies strongly between hours and system conditions. Related to this, Emblemsvåg states that for VRE-based electricity systems, reliability, availability, and maintainability must be explicitly ensured by incorporating balancing or back-up components to meet required performance levels [26]. Similarly, the IEA acknowledges for the LCOE that the levelized cost metric "[..] lacks representation of the value provided to the system [..] that are critical to the adequacy, reliability and quality of electricity supply" (p.75, [10]).

Electricity and hydrogen are different commodities, but given the similarities of LCOE and LCOH as cost metrics, the limitations of VRE-based electricity production provide insight for green hydrogen supply chain assessments, particularly as they become increasingly integrated and interconnected. LCOH comparisons for VRE-based hydrogen supply chains ignore the difference in value of hydrogen in periods of scarcity and surplus, the associated balancing requirements and network constraints under different system conditions. As a result, "take-as-produced" assumptions, which are made for most of the analyzed studies, favor pathways with high annual output ignoring additional flexibility, storage, or backup required to meet time-varying demand and capture high-value periods. Potential network-related requirements are typically not considered. Hence, LCOH cannot fully account for the balancing and network implications of VRE-based hydrogen production.

Second, hydrogen can provide time-shifting and balancing services to the power system via flexible electrolysis, storage, and reconversion, so integration can in some cases lower costs in the electricity system, yet such cross-vector benefits are not captured by the LCOH. Anticipated green hydrogen supply chains are characterized by potential interactions with other sectors and systems and therefore cannot be assessed as stand-alone systems. Rather, they should be assessed within a wider, integrated system context, as they can provide services that entail both integration costs and benefits for the hydrogen system itself and the electricity system. As a result, evaluating green hydrogen supply chains requires complementary approaches to the LCOH that capture total system costs and system-level interactions.

4. Guidance for modelers

The following recommendations serve as guidance for modelers to enhance the consistency, transparency, and comparability of future LCOH assessments and to provide directions for future methodological development.

4.1. Harmonization of system boundaries

LCOH inconsistencies arise from a lack of standardized description of system boundaries and divergent definitional interpretations. Transparent definitions are needed across the entire lifecycle — from VRE to the hydrogen end-use. To realize this, specific guidelines can be set to harmonize the analyses. LCOH can draw inspiration from LCA, which uses explicit system boundaries (e.g., 'cradle-to-grave'), ISO standards, and functional units to ensure consistent, comparable environmental impact analyses [20]. For the LCOH, this could entail a unit of delivered hydrogen at a specific time and location with predefined purity and pressure levels. Clearly defining and transparently reporting the system boundaries can be an initial step to enabling meaningful interpretations and comparison of LCOH results. These developments could help to address the first operational issue emphasized in Table 8, while maintaining LCOH's usefulness for component-level cost breakdowns and project- and technology-focused analyses. We propose an refined LCOH definition capturing the guidance we offer above:

> A project- or technology-focused metric that quantifies net hydrogen production costs by subtracting all relevant revenues from by-products and services, expressed in monetary units per unit produced. Costs include all annualized expenditures for energy supply, conversion, and end-use delivery over the project's lifetime. The cost estimate must transparently incorporate the boundary of the system, scale of the system, spatio-temporal resolution, potential externalities, and financial costs to meet predefined delivery criteria, including time, location, quantity, and specific end-point characteristics.

Table 9
Per-time step electricity cost accounting for electricity market-driven grid-connected hydrogen supply chains using the day-ahead prices as reference electricity prices, distinguishing between not producing hydrogen and reselling PPA-sourced electricity (left column), or using this electricity for hydrogen production (right column). λ^{PPA} represents the power purchase agreement electricity cost and λ^{DA} the day-ahead electricity price. Costs are defined as positive numbers, while negative numbers indicate a profit, assuming electricity can be sold. Consequently, when $H_2 = 0$, resale revenues are deducted from the PPA cost as $\lambda^{PPA} - \lambda^{DA}$.

Market prices versus PPA	$H_2 = 0$	$H_2 > 0$
$\lambda^{DA} < \lambda^{PPA}$	$\lambda^{PPA} - \lambda^{DA}$, resulting in a loss on reselling the electricity	λ^{PPA}
$\lambda^{DA} > \lambda^{PPA}$	$\lambda^{PPA} - \lambda^{DA}$, resulting in a profit due to reselling the electricity	$\lambda^{PPA} + (\lambda^{DA} - \lambda^{PPA}) = \lambda^{DA}$, representing the opportunity cost

4.2. Representation of VRE-based electricity input

Researchers must account for time- and location-specific factors and should not neglect or oversimplify the effects of VRE input on hydrogen supply chain operations (second operational issue in Table 8). In this context, a distinction must be made between two system configurations (Fig. 4) with regard to the way electricity is supplied to the electrolyzer: (i) systems in which the electrolyzer is directly coupled to VRE assets, and (ii) systems in which the electrolyzer is grid-connected. Both imply fundamentally different cost representations.

In configuration (i), the relevant cost of electricity is the cost of the generation and delivery to the electrolyzer. Here, the LCOE can provide an approximation of the electricity supply cost, provided that VRE impact is adequately accounted for, and may serve as a representation of the energy input cost component in the LCOH estimation.

In configuration (ii), the electricity cost is determined by electricity market conditions rather than by standalone electricity generation costs, even when electricity is procured through a power purchase agreement (PPA). For grid-connected electrolyzers, the electricity cost component in the LCOH calculation is determined by the PPA price, the day-ahead (DA) electricity market price, and the assumed operational strategy (dispatch) of the electrolyzer. If the electrolyzer is dispatched to satisfy a predefined hydrogen demand profile, this demand profile fully determines the operational schedule of the electrolyzer. If no such hydrogen demand profile is imposed, the electrolyzer operation is driven by electricity market and hydrogen market conditions. In this case, or when the PPA is oversized with respect to the electrolyzer capacity, PPA-sourced electricity can be used for hydrogen production or resold on the electricity market, and the associated costs and revenues in the LCOH calculation.

Regardless of what drives the dispatch, the cost of the consumed electricity can be defined per time step, as presented in Table 9. When producing hydrogen and the DA price is below the PPA price, the relevant electricity cost for hydrogen production is the PPA price. However, if the price exceeds the PPA price, using electricity for hydrogen production implies an opportunity cost; that is, assuming the electricity could be sold, it corresponds to the profit that would have been obtained by reselling the electricity rather than using it to produce hydrogen. Therefore, electricity should effectively be valued at the DA price.

This demonstrates that the effective electricity cost considered in the LCOH calculation is influenced by the contracted PPA price, the dispatch of the electrolyzer, and the allocation of electricity between resale to the market and its utilization for hydrogen production. Additional costs, such as grid fees, tariffs, and guarantees of origin, may further affect the total cost associated with the electricity input. Therefore, the energy input component of the LCOH must be calculated differently for standalone VRE systems and grid-connected configurations.

4.3. Energy system integration and system services

Table 8 highlights two fundamental limitations of LCOH: its inability to account for VRE-related profile, balancing, and network implications, and to accurately represent time- and location-dependent system services. To address these challenges, VRE-based hydrogen should not be treated as a homogeneous commodity, since its characteristics depend on both temporal and spatial factors. It should be explicitly defined when, where, and under which system conditions hydrogen is produced and supplied. It should also include accounting for additional system requirements such as flexibility, network requirements, balancing, backup, and integration, which may affect the cost of hydrogen supply chains.

At the same time, electrolytic hydrogen supply chains may provide services to the electricity system, e.g., through balancing using flexible electrolysis or reduction in curtailment by using surplus renewable electricity for green hydrogen production. Where relevant, such services should be reflected explicitly in cost assessments, for example, as avoided integration costs or as additional revenue.

However, the extent to which such effects can be incorporated within an LCOH framework is limited and requires a representation of temporal and spatial dynamics. This limitation arises because LCOH aggregates lifetime costs and hydrogen production into a single output, obscuring when and where costs and benefits occur and whether they lie within the specified supply chain boundary. As a result, capturing both the additional system requirements and the potential system benefits requires specific alternative metrics, to which we will return in Section 4.4. Future studies should therefore clearly state whether and how such system interactions are considered, and explicitly acknowledge the limitations of LCOH when these effects are not captured.

4.4. Alternative metrics and approaches

A widely discussed metric is the System LCOE introduced by Ueckerdt et al. [24]. The development of the System LCOE was motivated by the challenges posed by the economic evaluation of VRE-based electricity generation and specifically the incorporation of system integration costs. The System LCOE is described as follows: "[..] System LCOE of a technology are defined as the sum of generation costs and integration costs per generation unit from that technology." ([24], p. 62). The formulation for the System LCOE is:

$$System\ LCOE_{VRE} = LCOE_{VRE} + \Delta_{VRE}$$

The Δ_{VRE} represents the integration cost (profile cost, balancing cost, grid cost) for adding one unit of VRE-based electricity to the background energy system. In the context of green hydrogen production, this means one needs to think about the cost of adding one unit of green hydrogen production, which entails an additional upstream cost related to the integration of additional VRE in the system.

However, a system LCOH metric has not yet been developed. Using the principles of the System LCOE could support the introduction of a "System LCOH". It would need to account for the intermittency introduced by VRE, which electrolyzer flexibility can only partially absorb or mitigate. Both hydrogen and electricity production need to account for these dynamics to reflect the system costs involved in integrating hydrogen into energy systems. Still, effectively applying a "System" LCOH requires further research since the profile, network, balancing, or other integration costs are not well understood in a nascent hydrogen system.

Next to the System LCOH, a value-adjusted LCOH (VALCOH) can be considered as an alternative metric to the LCOH, representing the market value rather than the system integration costs. The VALCOH can be

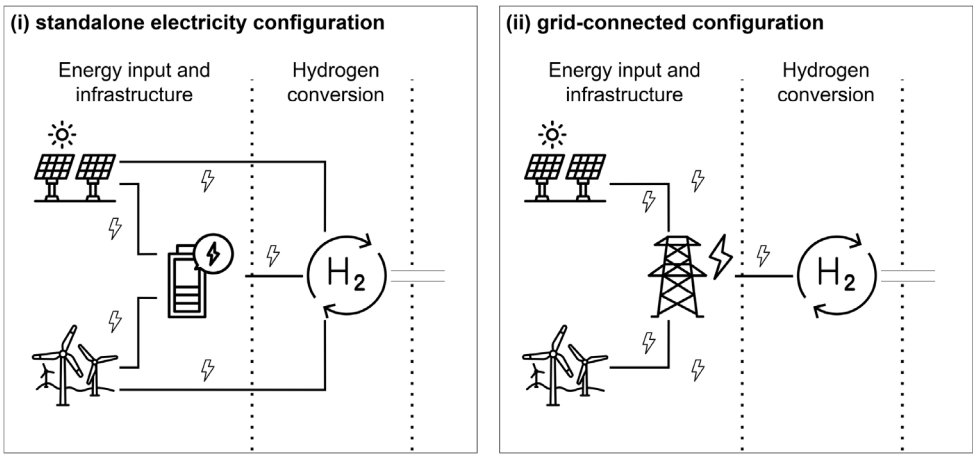

Fig. 4. Conceptual representation of two electricity supply configurations for electrolytic hydrogen production, highlighting the distinction between cost-based electricity input in standalone VRE systems and price-based electricity input in grid-connected systems.

defined by analogy with the IEA's value-adjusted LCOE (VALCOE) [10]. The VALCOE provides a quantified approach to system services that a specific technology provides in the context of the (regional) energy system at that time. For the VALCOE, three value streams are distinguished: energy, capacity, and flexibility, which could each be analyzed in isolation. The energy value streams would be analyzed in relation to production scheduling to reduce the marginal cost of electricity input relative to the market average, the capacity credit stream would measure a plant's ability to guarantee hydrogen flow at system-peak demand and is valued at the shadow price of adding peak performance assets (e.g., stand-by electrolyzer, additional compressors), and the flexibility value stream could reflect rapid pressure and flow balance over minutes to hours. It would be monetized as the avoided cost of ancillary equipment that would otherwise be needed to stabilize the energy system. Combining the deviation of these three streams compared to the average of the system and subtracting them from the LCOH would yield the VALCOH; a negative adjustment would indicate the above-average system value, while a positive adjustment indicates the below-average value.

However, there may be limits to how far these potential alternative cost metrics can be adapted to hydrogen supply chains to accurately reflect the deployment and integration of green hydrogen systems. The System LCOH and VALCOH concepts discussed in this study should therefore be regarded as preliminary directions for future methodological development rather than formalized, tested, or validated metrics. These limitations are likely to become more pressing with an increasing level of system integration and sector coupling. In such contexts, alternative approaches, such as energy system models, may be better suited to capture system-level interactions and value streams.

5. Conclusion

The LCOH is one of the most common metrics for comparing the techno-economic performance of green hydrogen supply chains. The metric holds the potential for comparative assessments of technologies and system configurations by employing a standardized, output-based evaluation. It enables a transparent cost breakdown that isolates the contribution of individual components of the configuration, technology, or project, while attributing specific CAPEX shares to the LCOH.

Delivering on these promises is, however, contingent on the requirements for the operationalization of the LCOH identified in our analysis. A transparent specification of system boundaries is required, as promoted by our refined definition of the LCOH. A consistent treatment of electricity inputs in electrolytic hydrogen production requires an explicit distinction between standalone electricity configurations and grid-connected configurations. Where possible, modelers should explicitly consider the value of the system services and integration effects. Our analysis of the scientific literature revealed several inconsistencies in the use of the LCOH metric relative to the requirements outlined above, resulting in unreliable comparisons across supply chains. Although all analyzed studies consider renewable energy sources, mainly wind and solar, coupled with electrolysis, the scale and scope vary significantly. Some studies only include production costs, while others incorporate storage, transmission, and different revenues (e.g. hydrogen sales, oxygen sales, and carbon credits). System boundaries are inconsistent between studies or not mentioned at all. Most of the studies analyzed assume production rates without accounting for variability of renewable energy sources. Although some include storage options to stabilize hydrogen output, most do not capture the impact of fluctuating power input on electrolyzer degradation and operational efficiency. Additionally, excluding monetized social and environmental externalities and disamenity costs limits the comprehensiveness of LCOH.

We also identify and emphasize fundamental limitations of the LCOH in assessing VRE-based hydrogen supply chains. The metric is not fully capable of capturing system integration costs and system services. Especially for VRE-based electrolysis, the electricity input and hydrogen production depend on time and system conditions. The metric is unable to capture the complexities of interaction and integration with the energy system. It does not adequately represent the costs and benefits arising from coupling with other energy sectors, and the services that hydrogen supply chains may provide to other parts of the energy system. These fundamental limitations cannot be fully resolved through an alternative operationalization of the LCOH. Future LCOH analyses should therefore explicitly acknowledge these limitations, ensuring that the scope, underlying assumptions, and interpretation of the reported results are communicated transparently and unambiguously.

When the limitations of the LCOH metric are acknowledged, the metric can remain useful in estimating production costs, enabling a meaningful first-order comparison between different green hydrogen supply chains. However, alternative metrics or analyses should be considered when the metric is unable to reflect the complexity of the hydrogen supply chain as part of the energy system.

The consequences of relying on the LCOH for VRE-based hydrogen production extend beyond academia. For companies, it increases the risk of underestimating costs or overlooking critical project components. For policymakers, it may lead to poorly-targeted incentives or unrealistic production cost benchmarks. Stakeholders must move toward more transparent, comprehensive cost frameworks by refining the LCOH, using the LCOH correctly, or embracing alternative approaches that better reflect the full system cost and complexity of VRE-based green hydrogen supply chains in integrated energy systems.

We therefore conclude that it is "time for complementary metrics" to describe the techno-economic performance of green hydrogen supply

chains. This should be understood as a call to investigate and develop complementary metrics alongside the conventional metric, rather than to replace the existing metric in full.

CRediT authorship contribution statement

L.S.F. Frowijn: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Z. Lukszo:** Writing – review & editing, Project administration, Funding acquisition. **K. Bruninx:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2026.158266.

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