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Review

Towards an Understanding of Hydrogen Supply Chains: A Structured Literature Review Regarding Sustainability Evaluation

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Citation: Fredershausen, S.; Lechte, H.; Willnat, M.; Witt, T.; Harnischmacher, C.; Lembcke, T.-B.; Klumpp, M.; Kolbe, L. Towards an Understanding of Hydrogen Supply Chains: A Structured Literature Review Regarding Sustainability Evaluation. *Sustainability* **2021**, *13*, 11652. https://doi.org/10.3390/su132111652

Academic Editors: Seung-Jin Lee, Xiaobo Xue Romeiko, Debalina Sengupta, Shweta Singh and Junbeum Kim

Received: 2 September 2021
Accepted: 12 October 2021
Published: 21 October 2021

Abstract: Hydrogen technologies have received increased attention in research and development to foster the shift towards carbon-neutral energy systems. Depending on the specific production techniques, transportation concepts, and application areas, hydrogen supply chains (HSCs) can be anything from part of the energy transition problem to part of the solution: Even more than battery-driven electric mobility, hydrogen is a polyvalent technology and can be used in very different contexts with specific positive or negative sustainability impacts. Thus, a detailed sustainability evaluation is crucial for decision making in the context of hydrogen technology and its diverse application fields. This article provides a comprehensive, structured literature review in the context of HSCs along the triple bottom line dimensions of environmental, economic, and social sustainability, analyzing a total of 288 research papers. As a result, we identify research gaps mostly regarding social sustainability and the supply chain stages of hydrogen distribution and usage. We suggest further research to concentrate on these gaps, thus strengthening our understanding of comprehensive sustainability evaluations for HSCs, especially in social sustainability evaluation. In addition, we provide an additional approach for discussion by adding literature review results from neighboring fields, highlighting the joint challenges and insights regarding sustainability evaluation.

Keywords: hydrogen supply chain; sustainability evaluation; review

1. Introduction

Hydrogen has been identified as an attractive alternative to fossil fuels when building green and circular energy systems and economies [1–5]. Versatile applications such as fuel cell vehicles, hydrogen heating [6], and its use as seasonal energy storage allow for a hydrogen economy where "a network of primary energy sources (are) linked to multiple end uses through hydrogen as an energy carrier" [7] (p. 40). Because of the increased availability of renewable energy, technological progress, and ambitious climate goals [8], hydrogen is currently at the forefront of research and is being utilized in a rising number of pilot projects [9]. Usually, hydrogen supply chains (HSC) capture the entire supply chain from production to consumption [10–12]. HSCs are characterized by high heterogeneity. Production in HSCs can either occur using renewable or non-renewable energy [13]. Hydrogen production knows a great variety of different methods and technologies (e.g., electrolysis, thermochemical methods reforming, gasification, photocatalysis partial oxidation, fermentation, pyrolysis, photoelectrochemical methods, biophotolysis, photofermentation) and a huge variety of materials (e.g., water, coal, methane, sludge, algae) [3,13,14]. Various forms of hydrogen distribution (pipelines, ships, etc.) and storage take place within this supply chain, contingent on both production and end-use (e.g., in public transport, energy, industry, etc.) [15,16]. The societal narrative of hydrogen as an energy carrier includes its promise to reduce emissions and achieve more sustainable energy systems [17,18]. In considering these aspects, the question arises whether these promises can be fulfilled and how to evaluate an HSC in terms of its sustainability. This is especially important considering the critical acclaims of a large-scale hydrogen economy. For instance, due to high energy losses when synthesizing and utilizing hydrogen, it is argued that a hydrogen economy may never be relevant except for niche applications [19].

In general, sustainability evaluations have been a long-standing research issue in management science because the core requirement towards corporate management can be interpreted as a strategy perspective, ensuring the long-term existence of a firm [20,21]. This implies that most corporate operations (from supply towards manufacturing and sales) and strategic planning activities in the financial or organizational domain must be aligned with sustainability objectives to achieve a competitive sustainability position [22]. Several methods and concepts have been introduced to support managerial decision making throughout the management circle of strategy definition and planning, implementation, and control [23]. For example, a life cycle assessment (LCA) offers the opportunity to shape how people view and deal with products. This is accomplished by improving sustainability knowledge and deriving implications for research and practice [24,25]. Sustainability evaluations have been applied in many industries, firms, and organizations of all sizes, from touristic beach management to handicrafts [26–28].

The question of how to assess the sustainability of hydrogen supply chains is a well-discussed topic, with many researchers aiming to create and introduce sustainability evaluation methodologies for HSCs [29]. For example, Ren et al. [30] suggest a sustainability evaluation method for HSCs by collecting a vast number of sustainability indicators from existing literature. Xu et al. [31] introduce a multi-criteria assessment framework for sustainable hydrogen production by systematically examining past literature on the topic analyzing the used sustainability dimensions. Similarly, Gnanapragasam et al. [32] propose a comprehensive indicator system for assessing hydrogen production from solid fuels based on existing literature. Maggio et al. [33] conduct a literature analysis concerning hydrogen production from renewable energies to foster their integration into the energy grid; however, they focus on the possible effects of hydrogen production on the energy and fuel markets. In a literature review regarding distributed energy systems using hydrogen as an energy vector, Fonseca et al. [34] found that a vast majority of papers consider technological and economic performance characteristics, outnumbering any environmental and social assessments. However, they were not specifically looking for sustainability assessments but were rather focused on hydrogen energy systems. Wulf et al. [35] discuss common thresholds to define indifferences and preferences in PROMETHEE (Preference ranking organization method for enrichment evaluation) for LCSA (Life Cycle Sustainability Assessment) of the European hydrogen production and present a new approach to identify and quantify such thresholds. Bhandari et al. [36] reviewed LCA studies regarding hydrogen production, mainly focusing on electrolysis and the technologies' environmental performance. Focusing their analysis only on the HSC stage of production, they find that the environmental dimension of sustainability is often (only) assessed in terms of global warming potential. More recent publications by Melideo et al. [37], Mehmeti et al. [38], and in particular Xu et al. [31] show that a growing number of scientific publications also taking into account other criteria (e.g., energy efficiency, acidification potential, resource consumption), however, they also show that global warming potential still remains the most applied impact category [39]. El-Emam and Özcan [8] provide a similar review focusing only on hydrogen production technologies and comparing them primarily regarding economic aspects. Iribarren et al. [29] review LCA studies for hydrogen energy systems and develop a sustainability assessment framework for HSCs based on Life Cycle Sustainability Assessment (LCSA).

However, to the best of our knowledge, no comprehensive review has been conducted that summarizes the present results on assessing all sustainability dimensions across all stages of hydrogen supply chains. This article aims to fill this pertinent research gap in the HSC research domain. Thus, within this paper, an interdisciplinary approach is applied to answer the research question regarding the current state-of-the-art of research literature regarding a sustainability evaluation of hydrogen supply chains. To this end, the following research question is therefore pursued in this study: *How can the scientific literature regarding sustainability assessments of hydrogen supply chains be structured and which research gaps can be identified?* To approach this research question, we (i) introduce three dimensions of sustainability, (ii) examine the degree to which the supply chain is currently assessed (e.g., are specific stages or entire supply chains captured), and (iii) combine these triple bottom line and supply chain segmentation perspectives.

The contribution of this paper is threefold: First, we present a comprehensive multi-disciplinary literature review regarding the sustainability assessment of HSCs. Second, we develop an analysis structure to identify the building blocks of sustainable supply chains. With this structure, we address the question of sustainability evaluations regarding HSCs. Third, we identify and discuss specific research gaps. In addition, we introduce a comparative analysis regarding literature review results in neighboring fields for an enlarged view regarding sustainability evaluation. The remainder of this paper is structured as follows: Section 2 outlines the conceptual background with the details of individual sustainability indicators. Section 3 presents the methodological approach for the literature review. Within Section 4, we describe the findings from the literature review and discuss these in Section 5, pursuing a cross-field comparative view of results and identifying research gaps. Finally, Section 6 provides a conclusion and outlook regarding further research directions.

2. Conceptual Background

The literature on supply chains is often subdivided into differing numbers of stages. Thomas and Griffin [40] name three stages of supply chains as the traditional stages: procurement (sourcing), production, and distribution. In more recent publications on the sustainability assessment of HSCs, however, we found that—even though the definitions were not homogeneous—the majority of publications defined the stages of the supply chain slightly different from the traditional three components, e.g., [37,41–43]. For our manuscript, we followed the dominant definition in the literature and defined the relevant stages for our analysis as production, distribution, and use.

One of the most notable differences to the traditional definition of stages is the integration of the procurement/sourcing stage into the production stage, as these two processes are very strongly connected in HSCs [37] because for the majority of (green) HSC production technologies, energy (in the form of electricity or heat) is the main input for the production process (apart from water) [44]. The most prominent of such technologies is electrolysis [38]. Energy as an input factor causes strong interdependencies between the analysis of both sourcing and production. Therefore, it is very difficult to establish a meaningful distinction between the sustainability assessment of both stages—especially since (as described above) the vast majority of scientific literature does not distinguish between both stages in their analysis. This integration of sourcing and production stages is also in line with the FC-HyGuide, the methodological guide for performing LCAs for hydrogen and fuel cell supply chains developed for the European Commission [37]. The fact that we decided to distinguish between the stage of distribution and use is based on the special role of hydrogen as energy storage in multiple different application contexts (e.g., renewable energy peak compensation, FCEVs). This extraordinary role is also mirrored in the literature on HSCs, with numerous papers targeting this particular stage (storage/distribution) of the supply chain. Once again, this definition follows the abovementioned FC-HyGuide [37] and its defined HSC stages. However, for the purpose of our research, we decided to merge the purification and the use stage into one stage.

Concerning the sustainability evaluation, we identified several potential indicators and elements in the existing literature. In a broader view of sustainable development, the 17 sustainable development goals formulated by the UN can be evaluated [45]. In the research field of cleaner production, where technical production systems are evaluated, the sustainability objective is usually operationalized with technical, environmental, and social criteria [46]. This literature stems from multiple research domains and targets different application fields, e.g., from biobased chemicals [47] and sustainable cities [48] to wastewater treatment [49]. From a methodological perspective, for example, Bappy et al. [50] apply an extensive method set regarding sustainability evaluation—they use the Analytical Hierarchy Process and Hierarchical Evidential Reasoning based on the Dempster–Shafer (D-S) theory, with results compared to Yager's recursive rule of combination. Within the context of energy and SCM, several research contributions have outlined the value of the triple bottom line (TBL) approach as an evaluation criteria structure [21,51–57]. Therefore, a segmentation in a social, economic, and environmental perspective is applied. Specific criteria within the three perspectives are largely contested and hard to unify.

Some examples may outline this further: Seuring and Müller [58] published one of the most cited papers regarding sustainability evaluations in supply chain management. However, this research does not contain specific operational evaluation criteria. Brandenburg et al. [59] apply a six-dimensional structure to a sustainability literature review with a comprehensive category for papers including all three dimensions and the intersection categories as social–environmental, social–economic, and economic–environmental. Gmelin and Seuring [60] (p. 3) connect the standard TBL approach to life cycle management: "Life-cycle management (LCM) reflects the sustainability factors of the TBL from a product life-cycle point of view [. . .] and consists of life-cycle assessment, social lifecycle assessment, and life-cycle costing." Therefore, life cycle assessments (LCA) and their specific keywords can be set synonymous with the TBL approaches in sustainability evaluation. Sauer and Seuring [61,62] apply the sustainable supply chain management (SSCM) evaluation scheme to a specific supply chain, analyzing mineral industries. They propose a specific evaluation and management approach with 17 different key areas for governmental intervention questions. Neutzling et al. [63] further connect the SSCM debate to the role and strengthening of sustainable product innovations, including innovation management research streams into the SSCM discourse. Rebs et al. [64] extend the existing SSCM evaluation approaches with the concept of system dynamics (SD).

2.1. Environmental Sustainability

The environmental dimension of sustainability is connected to protecting the planet from negative human influences. This addresses the key areas of climate protection (reduction of greenhouse gas emissions, see Arunrat et al. [65]), natural resource protection (reducing consumption and pollution of air, water, and soil, see [66,67]), protection of flora and fauna (see [68,69]), and reduction in waste volumes and toxicities [70,71]). For our research, we chose to use one category for greenhouse gas (GHG)-related impacts on the climate and another category for all other negative effects on the environment, specifically other emissions and habitat destruction. Furthermore, we consider energy and exergy analyses to be part of environmental sustainability [72]. Therefore, the criteria of environmental sustainability considered in this thesis include:

- *Emissions harmful to the climate* considers all GHG emissions (climate change effects mitigation).
- *Other emissions and processes harmful to the environment* addresses all other impacts on the environment, such as non-GHG emissions, resource depletion, and destruction of habitats.
- *Energy and exergy* considers all aspects regarding the cumulative energy or exergy demand and the energy efficiency.

2.2. Economic Sustainability

Following Brandenburg et al. [59], economic sustainability can be interpreted either macro-economically or micro-economically, depending on the context and objectives. The indicators for labor productivity, market concentration, and import dependency [73] are seen among the former, while the revenue and capacity utilization indicators as used in Lovrić et al. [74] are referred to as examples of the latter. The long-term development of economies and societies should not be hampered but supported by HSCs [8]. On the corporate level, HSCs must be efficient and profitable to guarantee company survival [75]. Beyond this distinction, the innovative capacity associated with hydrogen technology adoption may be understood economically in a twofold manner, too: On the one hand, as a long-term market advantage of the respective company for the commitment to a new technology portfolio, such as technology opportunities of hydrogen utilization [76]. On the other hand, as the innovation capability itself, which, if high, enables the company to pursue continuous technological evolution and thus facilitates sustainable operational development [77]. On a macro scale, cross-fertilization effects are considered, considering the at best positive effects of HSCs on other technical developments, e.g., in digitalization, renewable energies in general, or competitive factors such as education [78,79]. Accordingly, we consider the following criteria of economic sustainability in this work:

- *Macroeconomic development* considers all economic aspects on a global and societal level. Macro-development is, for example, assessing the question of long-term efficiency and economic self-reliance of HSCs.
- *Microeconomic development* considers all aspects of detailed economic assessment based on single-use cases either on an individual level (e.g., specific case studies) or in general (e.g., LCC).
- *Long-term competitiveness* addresses the long-term feasibility of technologies in comparison to others.
- *Innovation capability* considers the evaluation of the corporate-level impact on innovation systems and competitiveness. This dimension also addresses aspects that form the basis for potential innovations and improvements in HSCs and related fields.

2.3. Social Sustainability

Social sustainability can be defined as the maintenance of "the cohesion of a society and its ability to help its members work together to archive common goals, while at the same time meeting individual needs for health and well-being, adequate nutrition and shelter, cultural expression, and political involvement" [80] (p. 12). Cuthill [81] notes that social sustainability tends to be neglected compared to the other domains and that an adequate framework to address this is lacking. In a literature analysis, he identifies four key dimensions: social capital, engaged governance, social infrastructure, and social justice and equity. However, the focus of his work is urban growth and not technology or process assessment. Boström [82] lists a set of 15 sub-aspects that are attributed to social sustainability in the interdisciplinary literature, including basic and extended human needs, social justice, social infrastructure and services, learning and self-development, health, culture, and quality of life. Magee et al. [83] argue that economics and ecology themselves are elements of social sustainability, on par with the categories of politics and culture, each with seven subcategories. Although we do not follow the hierarchical view of the sustainability domains in this paper, dimensions such as ethics and accountability, dialogue and reconciliation (both politics), engagement and identity, or performance and creativity show that the understanding of social sustainability goes far beyond the preservation of socially tolerable conditions. Other frameworks were developed with the explicit purpose of corporate sustainability reporting, such as the GRI standards (Global Reporting Initiative). In addition to aspects of employee treatment (e.g., training, non-discrimination, and safety), customer concerns (e.g., customer privacy, marketing, and labeling), and socioeconomic compliance are also considered. The Guidelines for Social Life Cycle Assessment of Products and Organizations released by UNEP/SETAC [84] consider 40 subcategories of social sustainability, discussed specifically along a stakeholder framework. From this diversity of themes, we aggregated criteria that collectively capture the essential facets of what is conceptualized as social sustainability in the academic literature. To this end, the themes were clustered by thematic proximity and subsumed into the following concepts serving as a categorization framework for the subsequent review:

- *Health and safety* considers all aspects of human physical integrity. Emissions are only considered in this category if their impact on human health is apparent from the indicator (e.g., human toxicity potential) and a focus of the respective paper.
- *Social security* addresses all aspects of individual economic security and prosperity.
- *Culture and community* considers all aspects of culture and social interaction.
- *Prospects, well-being, and individual development* address aspects such as discrimination, exploitation, transparency and recognition, education, training, and personal advancement.

3. Review Methodology

A systematic literature review is conducted to provide a comprehensive and structured overview of the state of the art of sustainability evaluation of HSCs. Rousseau et al. [85] define systematic reviews as "comprehensive accumulation, transparent analysis, and reflective interpretation of all empirical studies pertinent to a specific question." To ensure the inclusion of all relevant publications and avoid bias, systematic reviews follow clearly defined steps [86,87]. This paper utilizes the approach by Denyer and Tranfield [87], who provide specific guidelines for systematic reviews in organization and management studies. The review process by Denyer and Tranfield [87] consists of a five-step procedure. This procedure and its application for this research will be described in the following section, including all minor methodologic adjustments made for this paper's purpose.

The first step of the procedure is the *question formulation*. An unambiguously defined research question is essential for systematic reviews, and it allows to define the exclusion and inclusion criteria and enhances the use of findings. The goal is to define a suitable unbiased, precise, encompassing, and meaningful research question—including explicit consideration of hydrogen supply chains focusing on the sustainability evaluation aspect. This resulting research question is as follows: *How can the scientific literature regarding the sustainability assessment of hydrogen supply chains be structured, and which research gaps can be identified?*

The second step of the review procedure is the *locating of studies*. The initial literature scoping regarding the research questions, keywords, and search strings was conducted to identify relevant studies. Electronic databases and literature search engines ScienceDirect, EbscoHost, and Google Scholar were searched for papers and publications in late 2020 using the keywords and Boolean connectors (OR, AND) listed in Figure 1.

The titles and abstracts of identified publications (using the keywords/search strings) were scanned to ensure consistency with the research questions. In this first stage of the review, publications were only included if their title, keywords, or abstracts clearly indicated that the publication deals with the topic of the research questions. Afterward, a forward/backward search was conducted. In sum, a total of 616 publications remained after the *location of studies*. In this literature review stage, all relevant publications were collected (academic papers, conference, and discussion papers, non-peer-reviewed papers, books, and grey literature). This procedure follows the guidelines by Denyer and Tranfield [87], who highlight the importance of including all potentially relevant literature in this first step to ensure an all-encompassing overview.

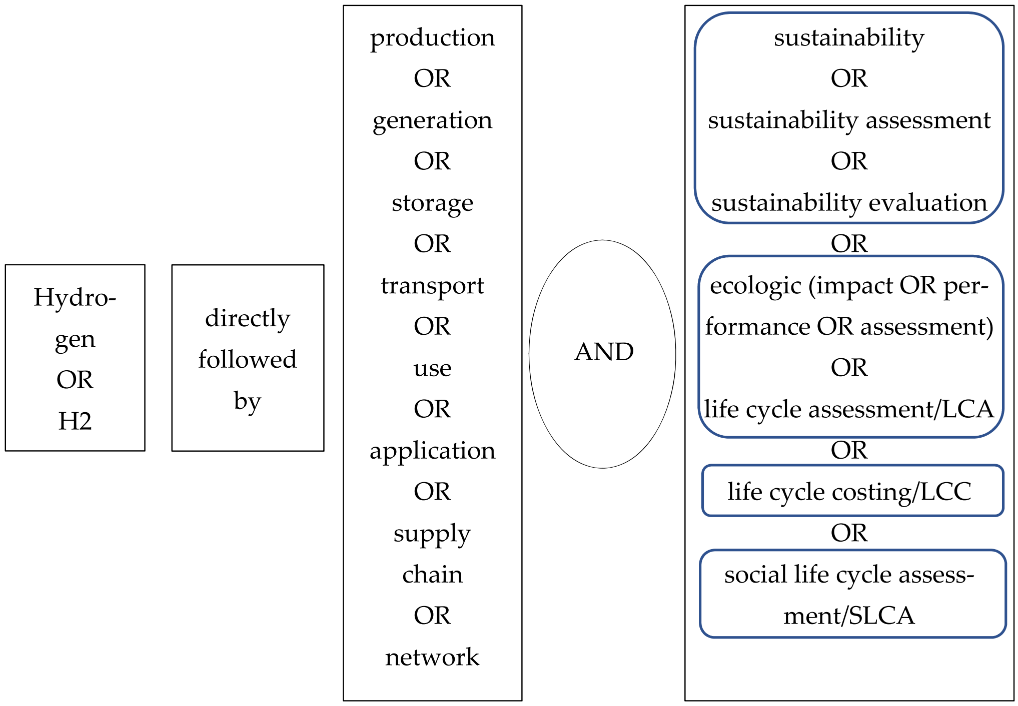

Figure 1. Search strings.

Based on the publications obtained, the *study selection and evaluation* focuses on the relevance assessment of the considered studies. The selection based on publication contents follows predefined exclusion and inclusion criteria [87]. The applied criteria for inclusion or exclusion for this review are described in Table 1.

Table 1. Inclusion and exclusion criteria.

Category	Inclusion Criteria	Exclusion Criteria
Hydrogen	Thematic focus on hydrogen supply chain (including hydrogen production, distribution, and consumption).	No inclusion of papers with sole focus on technical engineering.
Sustainability	Assessment of (at least) one sustainability dimension (environmental, economic, social). Explicit mentioning of sustainability is not required.	No inclusion of papers without consideration of both hydrogen and at least one sustainability dimension.
Publication type	Publications in journals and conference proceedings	No inclusion of non-journal or non-conference publications

In this step, the full texts of the publications are checked to determine whether a publication needs to be excluded or included. Of the 616 potentially relevant publications found previously, 328 had to be excluded as they did not meet the criteria defined above or, in some cases, because the full text of the original document was not accessible. At the end of the *study selection and evaluation*, a final sample of 288 publications built the basis for the literature analysis and synthesis in the further steps of the review.

The last two steps of the procedure are *analysis and synthesis* and *reporting and using the results*. They are combined for this paper while distinguishing between descriptive and thematic analysis and synthesis. Analysis and synthesis in systematic reviews are two different but strongly connected processes. While the goal of the analysis is to break the publications into their constituent parts and to describe their relation, the synthesis aims to "make associations between the parts identified in individual studies" [87] (p. 685). The descriptive part of analysis and synthesis aims at giving a general overview of different quantitative aspects, while the thematic part focuses on an analysis and synthesis of the content of the found publications.

4. Results

4.1. Descriptive Analysis and Synthesis

The distribution of the year of publication, as shown in Figure 2, reveals a steep upward trend in relevant publications starting in 2016. Furthermore, the interest in hydrogen appears to fluctuate with a decrease in the number of publications (starting) in 2009, 2013, and 2018.

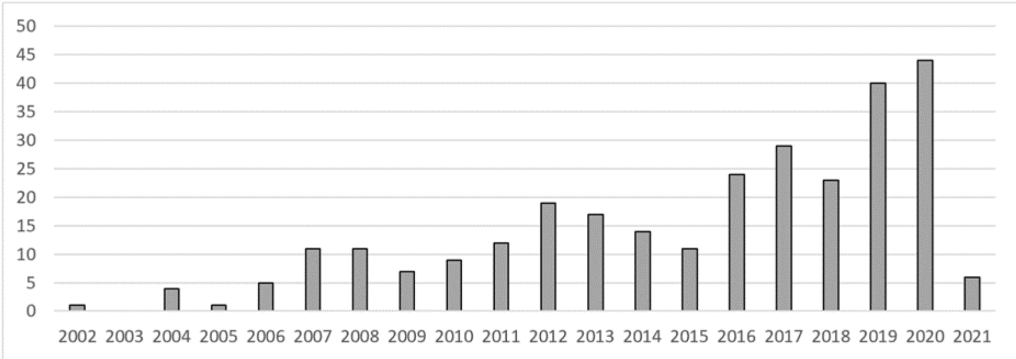

Figure 2. Number of publications per year.

Similar trends can be observed in other literature review papers in the research area of hydrogen and sustainability assessments. El-Emam and Özcan [8] observed that the number of publications of studies considering hydrogen economics increased starting in 2002. The authors cited technological maturity and environmental concerns as the reason for the growing interest in hydrogen. Fonseca et al. [34] found a rising interest in distributed energy systems using hydrogen from 2009/2010. However, their bibliometric summary showed dips in 2015 and 2017. The latter decrease could not be found in our literature analysis. The bibliometric summary in less recent work by Bhandari et al. [36] on the LCA of water electrolysis for hydrogen production shows a decreased number of publications between 2009 and 2011. The increase in the number of publications on the topic as depicted in Figure 2 may also be partly explained by the general grown interest in Life Cycle Sustainability Assessments as, for example, shown by Fauzi et al. [88].

As depicted in Table 2, the journal with the highest number of pertinent publications is the *International Journal of Hydrogen Energy*, which is focused exclusively on hydrogen-related research. In addition, the *Journal of Cleaner Production* is strongly represented as the only clearly interdisciplinary journal, followed by outlets in the domain of energy markets and systems research. A bulk of 81 publications falls into outlets with only a few other identified publications in the literature review ("Others").

Table 2. Number of publications per outlet.

Journal	Number of Publications
International Journal of Hydrogen Energy	107
Journal of Cleaner Production	27
Energy	15
Applied Energy	13
Renewable and Sustainable Energy Reviews	11
Energies	10
Energy Procedia	8
Sustainability	6
Bioresource Technology	5
Energy Policy	5
Others	81

4.2. Thematic Analysis and Synthesis

The publications were categorized into the dimensions defined in Section 2. A publication is only assigned to a dimension if it constitutes a main thematic focus within the study. A mere mention does not substantiate such an assignment. The assignment to sustainability dimensions is not mutually exclusive, and a paper can be assigned to multiple categories simultaneously if all of them are considered sufficiently. Additionally, the identified sustainability dimensions are assigned based on the stage of the supply chain, which is being assessed. We distinguish between production, distribution (including both: transport and storage) and use. If a publication assesses the full supply chain or full energy systems, a separate category is applied—regardless of the definition of hydrogen supply chain used in the publication. It should also be emphasized that the supply chain stages are assigned on a per sustainability dimension basis and not on a per paper basis. This means that our category scheme allows us to accurately represent single papers that assess different supply chain stages using different sustainability dimensions.

The assignment to the three dimensions of sustainability depicted in Figure 3 shows an underrepresentation of social sustainability. In contrast, the economic and environmental dimensions are well populated with the environmental assessment being the most common. The median year of publication is most recent for economic sustainability, followed by the social and environmental dimensions (see Table 3). This can also be observed in Figure 3, showing that economic considerations increased more than the social and environmental dimensions of sustainability evaluations.

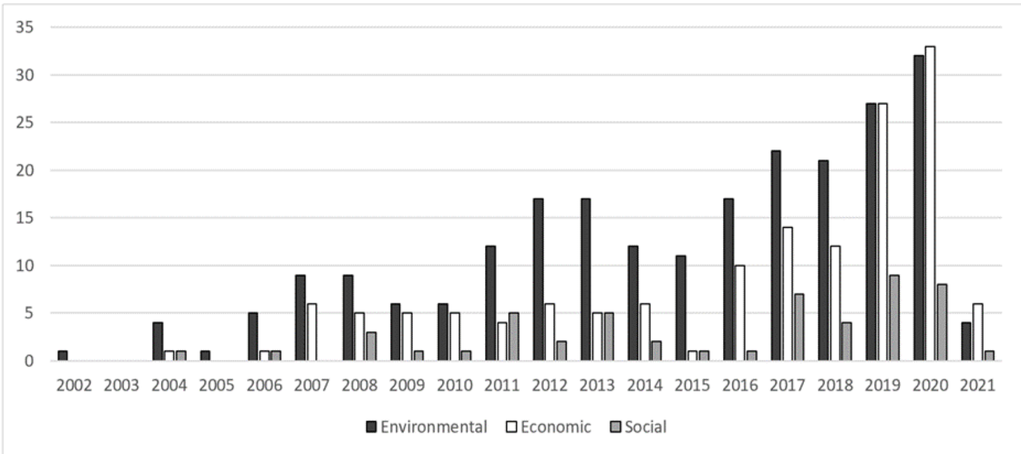

Figure 3. Year of publication depending on sustainability dimension.

Table 3. Number of publications and median year of publication per sustainability dimension.

Sustainability Dimension	Number of Publications	Median Year of Publication	Average Year of Publication
Environmental	233	2016	2014.8
Economic	147	2018	2016.2
Social	52	2017	2015.4

The detailed results presented in Table 4 show that some categories are only sparsely populated—especially regarding the HSC stages of *distribution* and *use*. Furthermore, the most common subcategories are the *emissions harmful to the climate* for the environmental dimension, the microeconomic perspective for economic considerations, and *health and safety* for the social assessment. On the contrary, only seldom represented subcategories in the three triple bottom line dimensions are *energy/exergy* (environmental), *innovation capability* (economic), and *culture and community* (social).

Table 4. Detailed categorization of publications (multiple affiliations possible).

		Stages of Hydrogen Supply Chains			
		Production	**Distribution**	**Use**	**Full**
Environmental	Emissions harmful to the climate	125	13	10	77
	Processes harmful to the environment (not climate-related)	103	9	5	40
	Energy, exergy	73	3	5	32
Economic	Macroeconomics	7	0	3	18
	Microeconomics	74	15	4	37
	Long-term competitiveness	28	5	1	26
	Innovation capability	4	0	2	4
Social	Health and safety	23	5	1	20
	Social security	9	2	1	5
	Prospects, well-being, and individual development	7	0	0	3
	Culture and community	1	0	0	2

5. Discussion

5.1. Supply Chain Stages

When considering the entirety of the supply chain, the distribution and utilization stages are underrepresented in the identified research literature on HSC sustainability assessment. This is in line with the typical 'upstream' perspective of sustainability evaluations and the traditional perspective within energy supply chains, with most sustainability evaluations focusing on the first primary energy use sequences [89–93]. From a methodological perspective, the question can be raised whether the underrepresentation of publications in the *distribution* and *use* category may be due to our literature search process's systematic bias or because few papers fit these categories. We believe that our search strings are broad enough to account for all categories but are also aware that a larger number of papers might exist undetected with particular application use cases, especially in the use category. The forward and backward search further mitigates any possible systematic search bias. While the use of individual search strings for specific practical manifestations of hydrogen supply chain stages, e.g., hydrogen applications such as fuel cell electric vehicles or production methods such as steam reforming, would have likely yielded more results, we consider this aspect equally limiting for all stages of the supply chain.

We believe that the main reason for this observation is that hydrogen consumers and the distribution of hydrogen are mostly discussed in combination with hydrogen production. This is because the hydrogen supply chain is usually only considered up to the specific use case that is the thematic focus of the publication. For example, if the sustainability of a fuel cell electric vehicle is assessed, this likely goes hand-in-hand with considering hydrogen production and distribution. Notable examples for this approach are the publications by Ahmadi and Kjeang [94], and Khzouz et al. [95], following the traditional Well-to-Wheel-analysis. Therefore, those papers are not categorized into use but rather into a *full supply chain*. In contrast, papers frequently only consider hydrogen production methods. As there are no prior stages to hydrogen production—at least in our categorization scheme—the category is well populated. Furthermore, the definition of the hydrogen supply chain is often vague and ambiguous and depends on the use case. Thereby, the full supply chain category serves as a bucket category for all papers that explicitly or implicitly claim to assess the full supply chain although, for example, only production and distribution may be considered.

Finally, the state-of-the-art research in a new technology field such as hydrogen is mainly dominated by the production area because this is naturally the first application area of new technology with much testing and piloting research reported upon [96–100]. In the case of hydrogen, this production-oriented research dates back to the first half of the last century [101]. Therefore, it is obvious that the sustainability evaluation of such processes might have a head start over the 'downstream' supply chain stages.

5.2. Sustainability Dimensions

We first want to address the underrepresentation of the social dimension where health and safety are relatively frequently assessed, but the other initially defined subdimensions, culture and community, individual well-being, and social security, are rarely considered. It should be noted that a large majority of papers that are categorized into the health and safety subdimension do not explicitly assess this dimension under the umbrella of social sustainability but rather by considering the impact on health in the form of toxic emissions. Papers that only briefly mention human toxicity potential as part of an emission assessment but do not further discuss the impact on health were not associated with this dimension. The overall lack of publications with an explicit focus on social assessments is largely expected since this has also long been acknowledged in other research areas, for example, Eizenberg and Jabareen [102] or Missimer et al. [103]. These reasons for the underrepresentation of the social dimension can also be applied to the research area of HSCs, resulting in the following aspects accounting for the low quantity of publications in this area.

First, social sustainability may not be considered a pressing issue for establishing hydrogen supply chains. The goal of environmentally friendly hydrogen pathways and the required cost determining whether a project can be practically realized are more relevant in the research domain. Second, social sustainability is mostly relevant when considering specific projects at a specific location. However, most papers only regard a specific technology without assessing the social implications that depend on the practical, large-scale implementation at a specific location. Third, more than the other areas of the triple bottom line approach, social criteria require a long-standing experience with HSC implementation. For example, work conditions and other social impacts can only be evaluated and measured during and after a long period after setting up an HSC. Therefore, it is convincing that this dimension is underrepresented in relation to the state of general development and implementation. Finally, it can be argued that social sustainability criteria themselves are often less objectively measurable, requiring human-centered research designs and difficult isolation of effects on multi-causal constructs such as health, well-being, culture, or social security perceptions. Further research might follow up on this area with proceeding implementation and increasing timeline experiences in HSCs.

In contrast to the social sustainability dimensions, the economic and environmental impacts can be assessed much easier, for example, by considering resource and energy efficiency as well as emissions. Our results table also reflects this, showing that environmental and economic aspects are indeed considered much more frequently. Of those, the category of the emissions harmful to the climate is by far the most common. This is in line with expectations as hydrogen is generally discussed as a means to reduce greenhouse gas emissions to mitigate global warming. For the economic dimension, the most important subcategory is microcosmic considerations, only barely lacking behind the environmental assessments. Here, publications typically consider the levelized cost of hydrogen often calculated based on the operational and capital expenditure, all important measures to judge the real-world feasibility of hydrogen technologies.

5.3. Combined Discussion

When applying a combined perspective on the stages of the HSC and the sustainability dimensions, the used dimensions do not appear to differ between the supply chain stages. This means that our research could identify no vastly different sustainability assessment scheme for the individual stages of the HSC. However, one exception is the category of micro- and macroeconomics, where the macroeconomic view appears to be applied to the full supply chain more frequently than the individual stages of the HSC. This is mainly because the relevant publications discuss the implications of full-scale hydrogen economies where macroeconomic implications are more relevant.

It should also be stressed that the research objectives of the hydrogen papers considered differ widely. For example, some papers only provide a high-level perspective on the advantages and sustainability implications of hydrogen, whereas other papers consider hydrogen technologies from a very technical point-of-view, e.g., Caliskan et al. [104] and Byun et al. [105]. Furthermore, stages of the HSC may be assessed regarding their sustainability from different perspectives. Here, a good example is the production of hydrogen. While many papers consider hydrogen production concerning possible technical methods, e.g., steam reforming or electrolysis, others assess the sustainability implications of the location or production scale.

Regarding the recent development of research in the triple bottom line dimensions of the HSC, we note a significant increase in the economic and environmental dimensions since 2016. The increase in research considering the environmental aspects of the HSC in recent years can be attributed to the generally increased interest in sustainable technologies and the societal awareness for the possibilities that hydrogen technology offers. The increased research interest with a focus on the economic aspects of the HSC also started in 2016 but became very notable in 2019, thus showing a slight time-lag to the increase in environmental research. This seems sensible, since the motivation to research HSCs stems from environmental considerations, and thus, economic feasibility and cost considerations play a downstream role.

5.4. Comparative Analysis

To provide an extension of the discussion perspective, we conducted a blind spot analysis. We assume that any literature review based on a given set of keywords exerts, per definition, a focus on the implemented research, which is distorted in terms of missing connections to neighboring fields. This was mitigated herein by integrating two additional procedures: First, an expert study was implemented to identify the relevant neighboring fields in a topical mapping. For this study, we conducted an expert group interview study in April 2021 with five experts from research and industry sectors, such as logistics service providers and retail companies. Experts' characteristics can be revealed as follows: Two experts from the field of retail logistics with more than 15 years of operational and leadership experience in distribution logistics and an academic management degree. One expert from a leading German logistics service provider with a Ph.D. degree and more than 20 years of experience in general cargo shipment networks in Germany and Europe, specializing in sustainability issues. Two experts from regional logistics service providers with more than ten years of operational experience each and an academic degree. From this discussion, three further adjunct fields interacting with the question of sustainability evaluation of hydrogen supply chains were identified:

- Sustainability evaluation of electric vehicles (I);
- Sustainability evaluation in the energy sector (II);
- Sustainability evaluation regarding circular and sharing economy concepts (III).

Second, relevant and representative selected literature reviews were screened from these adjunct topical fields to connect the presented findings and compare results across topical areas. We provide a selected literature review comparison for these fields and connect them to our literature review results.

(I) For electric vehicles and their comprehensive sustainability evaluation, Kumar and Alok [106] outline the importance of intermediaries, infrastructure questions, and total cost of ownership (see also [107]) regarding electric vehicles and incentive policies within the five analyzed categories antecedents, mediators, moderators, consequences, and sociodemographics based on 239 publications from the research literature. This corresponds with the findings regarding economic sustainability addressed in our paper. In addition, Austmann and Vigne [108] provide an interesting complementary analysis using a Twitter keyword analysis to explain the missing link of the environmental attitude of consumers towards electric vehicle sales in European markets. Again, we can also ascertain that the social sustainability dimension is underrepresented in literature reviews from the neighboring field of electric vehicle topics. We can link these findings for the field of electric vehicles, for example, to the following HSC-related results of Bekel and Paulik [109], Logan et al. [110], and Yang et al. [111].

(II) Regarding sustainability evaluations in the energy sector, Kumar et al. [112] review multi-criteria decision making towards sustainable development regarding energy systems planning. They categorize the criteria considered in the literature into five groups: social/ethical, organizational/institutional, environmental, economic, and technical. Martín-Gamboa et al. [113] provide a review of life cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainable assessment of energy systems. They also find five groups of criteria: technical, economic, environmental, social, and mixed. Wang et al. [114] and Antunes and Henriques [56] provide reviews on multi-criteria decision analysis in sustainable energy decision making, where they categorize the criteria into technical, economic, environmental, and social categories. All the mentioned reviews find an increasing trend in the usage of multi-criteria decision-making methods for supporting decision-making in the energy sector since these methods allow to consider decision-makers' preferences to balance the trade-offs of incommensurable criteria in sustainability evaluations. From our literature and publication insights regarding HSCs, we can link the specific publications of Apostolou and Enevoldsen [115], Bareiß et al. [116], Fang [117], Parra et al. [118], Xu et al. [119], Fonseca et al. [34], and Bahrami Ziabari and Ghandehariun [120] to these issues regarding sustainability evaluations in the energy sector.

(III) In the context of circular, green, and sharing economy concepts, Sarja et al. [121], for example, describe in their literature review the central role of the economic sustainability perspective in addition to a catalyst role of legal frameworks. This corresponds with the increased research work and output found in this paper for the economic sustainability evaluation dimension for HSCs. Furthermore, Cimen [122] reports challenges in transitioning towards a circular economy (CE) in the construction and building industries. As a central finding, it is reported that the multi-perspective angle of different stakeholders in this sector is crucial for successful CE concepts. This is in line with the results presented in this paper about the importance of a multi-perspective approach, such as that represented in the triple bottom line concept enacted herein. Third, Bressanelli et al. [123] outline the central role of social and economic improvements in a transition of the electronic industry towards CE, along with the importance and support of digitalization developments in this context. The social and economic evaluation items do connect to the research results presented in this paper, too. Fourth, Baleta et al. [124] describe the importance of a holistic view within the environmental dimension, including energy and water systems in addition to the climate change GHG discourse—corresponding with the identified and applied subfactors for the environmental sustainability perspective within this paper. As examples, we are listing at least the following three papers detailing this perspective in connection to the HSC: Sharma et al. [125], Chandrasekhar et al. [126], and Alanne and Cao [127].

6. Conclusions

Our research shows no general lack of research on the sustainability of hydrogen supply chains as a central part of the future green and circular energy systems and economies. In contrast, plenty of publications analyze various sustainability dimensions—even if this is not explicitly mentioned. Nevertheless, the underrepresentation of social sustainability assessments also shows in the research area of hydrogen. Especially non-health-related social impacts are often neglected. While economic and environmental criteria are often applied, the economic dimension appears to focus on economic competitiveness and microeconomics, neglecting the macroeconomic view and the ability to foster innovation.

Research implications include the fact that further method development, testing, and empirical evaluation for the areas of social sustainability evaluation are warranted. In addition, the supply chain stages of distribution and usage require a special focus in the HSC research for the coming years. This is important to preclude any misdirection of political support, funding, and wrong management decisions due to incomplete information. Since HSCs are implemented mainly due to their expected sustainability contributions, this is even more important. Reviews in the fields of electric vehicles, energy sector, and circular and sharing economy concepts show that similar concepts, e.g., regarding social sustainability, are found in these neighboring fields.

The limitations of our approach include the fact that both stages of the supply chain and the sustainability dimensions leave room for ambiguity and are not necessarily exhaustive. For example, technical indicators and social acceptability are not represented in our categorization scheme. Other indicators such as non-renewable energy use and emissions, e.g., particulate matter, could result in climate and non-climate related impacts. In these cases, the best effort assignment was performed where the intention of the publication and the framing of the indicator was considered. In addition, all-encompassing coverage of the diverse use stage of HSCs is difficult to achieve and is unlikely to cover all potential application contexts. Our paper also only assesses the status quo of HSC sustainability literature but does not provide a conclusive explanation for the identified results. While we discussed some hypotheses in the prior sections, we consider this to be subject to future research. Furthermore, we do not analyze the sustainability assessment methodologies, i.e., the approach of calculating and combining sustainability indicators.

Management implications hint at the situation that in investment decisions for HSCs, today, special attention and care would have to be directed at the social sustainability angle because there are no established instruments and no large benchmarking basis in existence for this evaluation area. Therefore, management would have to avoid the misdirection of funding due to a 'social sustainability blind spot' for hydrogen supply chains. At the same time, the increased importance of the economic sustainability perspective is vital for management decisions and is starting to be reflected in research work and publications. Still, management decisions and concepts would have to insist on deeper analyses regarding this angle. It cannot be forgotten that the basic framework and motivation for the shift towards hydrogen supply chains and energy systems is motivated by the expected benefits for the ecological dimension of sustainability, notably GHG emission reductions. Therefore, this angle also has to be evaluated further, and no reduction in research endeavors in this area is warranted. Management will have to prove these GHG reduction contributions for hydrogen for each and every project investment and implementation.

Policy implications include the fact that public support and funding are warranted for engineering and technology research in a shift towards hydrogen energy systems fostering sustainability and the eminent sustainability evaluation in the three dimensions of ecological, economic, and social sustainability.

In general, hydrogen is on the path towards a central cornerstone of future sustainable energy systems. Analyses such as this literature review specifically regarding sustainability evaluation will play a crucial role as "navigation charts" for future research and management decision making with an exceptional amount of investment volumes expected in the area of hydrogen supply chains for future green and circular economy systems.

Author Contributions: Conceptualization and methodology: All authors; validation: H.L., S.F. and T.W.; formal analysis and investigation: H.L., S.F., T.W., C.H., M.W. and T.-B.L.; data curation: H.L., S.F., T.W., C.H. and M.W.; writing—original draft preparation: H.L., S.F., T.W., C.H., M.W.; T.-B.L. and M.K.; writing—review and editing: All authors; visualization: H.L., S.F., T.W. and C.H.; supervision: T.-B.L., L.K. and M.K.; project administration: All authors. All authors have read and agreed to the published version of the manuscript.

Funding: The project on which this manuscript is partially based was funded by the Federal Ministry of Education and Research under the grant number 03WIR5201C.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: A list of the reviewed categorized publications in this study is openly available on FigShare at https://doi.org/10.6084/m9.figshare.16732612 (accessed on 11 October 2021).

Acknowledgments: We acknowledge support by the Open Access Publication Funds of the Göttingen University.

Conflicts of Interest: The authors declare no conflict of interest.

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