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A multi-perspective framework to address manufacturing and transportation challenges in green hydrogen supply chains

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Abstract

The strategic changeover towards green hydrogen supply chains entails a large number of challenges in determining strategic manufacturing, transportation, and supply chain decisions such as the locations for the generation and storage or the transport mode for the transfer of green hydrogen. Such decisions face three dedicated obstacles interesting for research analysis. First, such decisions in a greenfield setting have in many cases never been made before, reducing the access to historical information about manufacturing and transportation volumes, aggravated by new levels of uncertainty in many global manufacturing and transportation contexts. Second, at the same time, new data sources and computation capabilities become available in a digital Industry 4.0 setting, creating big data and data lake settings where traditional decision support methodologies have limited access and use in this regard. Third, an integrated evaluation of economic, environmental, and social sustainability aspects together with a resilience perspective is required as trade-offs between these different performance dimensions have to be incorporated. This paper outlines and addresses the three specific challenges by deriving a concept of how to integrate the three standard sustainability perspectives with the added resilience perspective and how to tailor this towards decision-making in a strategic, data-driven and digital setting of emerging green hydrogen supply chains.

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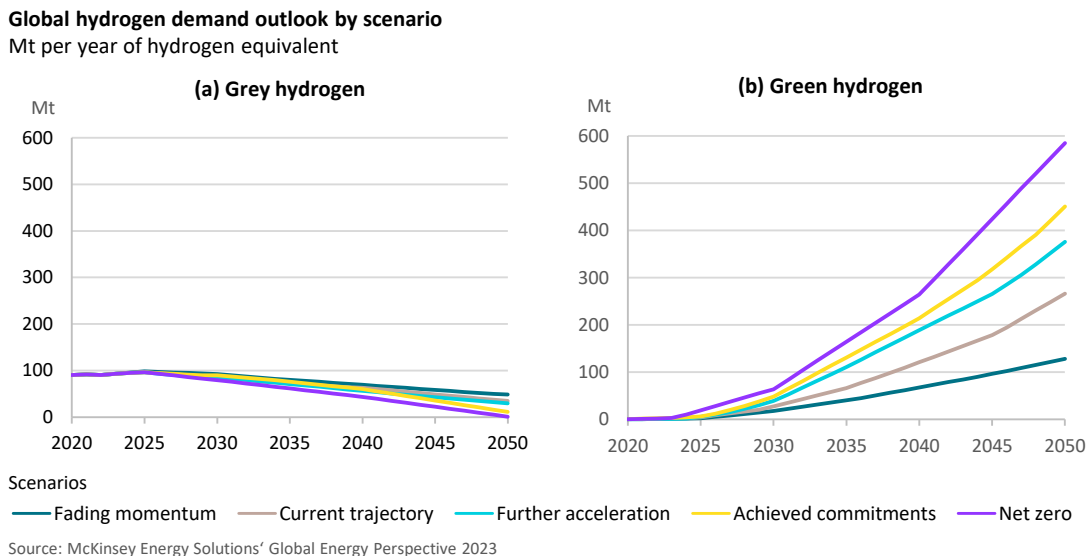
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1. Introduction

Hydrogen is a versatile energy carrier and base chemical with many applications. It is considered to play a vital role in the decarbonization of economies, industries, and energy systems and therefore faces considerable changes in dedicated supply chain and transportation settings and designs. In this context, so-called green hydrogen, which is derived from renewable energy sources, is considered the environmentally friendly energy carrier of the future, whereas grey hydrogen (derived from non-renewable fossil fuels) may serve as a bridge to supply industries and the mobility sector while they are transitioning to the hydrogen age. Global demand for hydrogen is expected to increase from 90 Mt in 2020 (grey hydrogen) to between 125 and 585 Mt in 2050 (green hydrogen) [1], see Figure 1. These quantitative volumes obviously translate into corresponding manufacturing and green hydrogen production volumes in this regard. Such a dynamic growth and, at the same time, the shift from non-renewable to renewable energy sources poses several challenges to the development and changeover of the corresponding supply chains. Numerous hydrogen supply chain projects are currently under development to support global sustainable economy objectives and climate protection plans. While these supply chains are intended to foster sustainability, a systematic analysis from a triple-bottom-line perspective is largely missing [2], [3], [4]. In this regard, comprehensive multi-criteria decision support and management methods that combine, for example, economic cost analysis and simulation, social sustainability evaluation, and environmental sustainability are strongly needed as this would be the basic prerequisite to fulfill the sustainability expectations directed towards green hydrogen supply chains. In addition, recent developments also call for a comprehensive resilience evaluation and design perspective for future supply chains that are emerging for new hydrogen applications. This is connected to the ongoing digital transformation, enabling new data gathering and analytical methods, but at the same time advancing traditional methods from past applications in operations, logistics, and supply chain management (OLSCM), especially in real-world empirical settings. Therefore, this paper proposes a multi-perspective framework that integrates the segments of economic, environmental, and social sustainability as well as resilience evaluation. The new framework facilitates method development and application for hydrogen supply chains and serves as a testbed for new design and decision principles in digital supply chain environments of the future.

The remainder of this paper is organized as follows: Section 2 presents a comprehensive planning framework to overcome the challenges in production and logistics for green hydrogen supply chains. With “Empirically Grounding Analytics” (EGA), which combines analytical and empirically supported methods, a promising approach to overcoming these challenges is available. Still, it must be embedded in a carefully designed multi-perspective approach. Section 3 begins with a brief discussion of multi-criteria decision-making and presents the four selected perspectives of the proposed approach in more detail. The article ends with dedicated conclusions in Section 4.

Fig. 1. Scenario forecast for global (a) grey and (b) green hydrogen demand development, see [1].



2. Comprehensive Planning Framework for Hydrogen Supply Chains

2.1. Production and Transportation Challenges in Hydrogen Supply Chains

A hydrogen supply chain is a complex inter-organizational network that ranges from feedstock to production, storage, distribution, marketing, and application processes [5]. The effective fulfillment of the tasks depends a) on the system delimitation, b) on the planning horizon, and c) on the degree of centralization. Moreover, this is combined with a multitude of evaluation criteria and objective areas like, for example, the triple bottom line approach in sustainability management, including economic, social, and environmental sustainability criteria, as well as a resilience perspective to ensure a reliable supply of hydrogen.

Regarding the system delimitation, the imminent question is how such a supply chain is configured [6]. This can be answered as part of the network design. The entire supply chain or just one or more of its stages can be considered together. Here, it is necessary to determine the number of organizational units per supply chain stage and their interaction across stages as well as within stages, whereby the network decision also depends on the technology selection if there is a choice between different alternatives [7].

A further distinction can be made according to the chosen planning horizon. If a more long-term perspective is chosen, the focus is on constitutive decisions that are made, for example, as part of the network design and concerning location decisions – even including legal and public finance frameworks [8]. Other tasks such as demand forecasting, production allocation planning, inventory decisions, and pricing decisions, on the contrary, are part of a more operationally orientated planning [9]. Both, the system delimitation (here in the sense of the scope of the supply chain stages included) and the planning horizon can be used to create a matrix in which many managerial planning tasks are systematized that arise in the context of hydrogen supply chain management (see Figure 2).

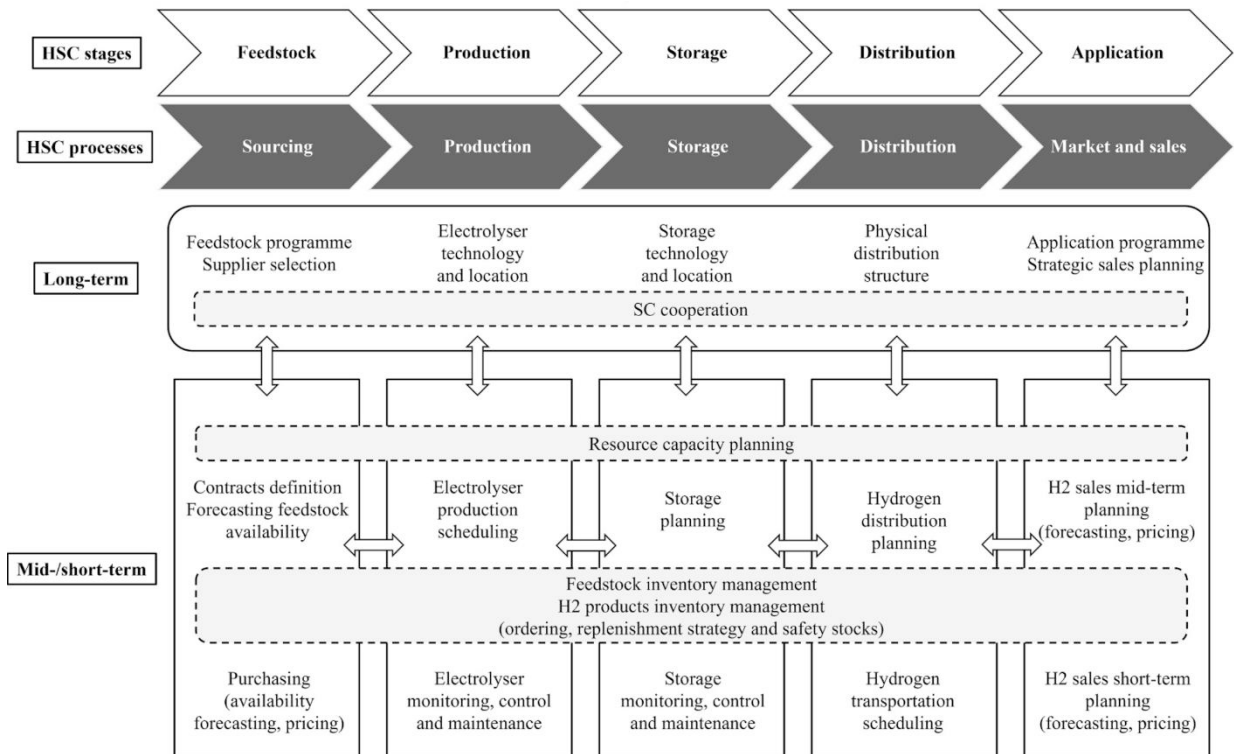


Fig. 2. Planning matrix for renewable Hydrogen Supply Chains (HSC), see [5].

2.2. Necessity of Empirically Grounding Analytics

The context of decision-making and decision analysis has significantly changed due to big data availability and artificial intelligence applications for use in supply chain decision-making. Therefore, the design and build-up of new hydrogen supply chains can be seen as a role model or pilot case for future situations, where novel supply chains might be designed and built up based on uncertain data and the use of artificial intelligence applications. To optimize hydrogen supply chains, a wide range of data is crucial. This includes, for example:

- *Demand forecasts*: This could be for specific industries, market segments, or entire regions, predicting how much hydrogen will be needed.
- *Production capacity*: Data is needed on the feedstock availability and the capacity to convert the feedstock into hydrogen.
- *Infrastructure data*: Information on the characteristics of hydrogen production plants, storage facilities, and transportation options are important.
- *Technology specifications*: Understanding the efficiency and capabilities of different hydrogen production technologies and transportation methods is essential.
- *Cost and emissions data*: Knowing the costs associated with each stage (production, storage, transport) and the related emissions is crucial for economic and environmental analysis.
- *Social factors*: Qualitative data on social acceptance, risk tolerance, and stakeholder relationships within the supply chain is valuable for successful implementation.

As most of this data is not known with certainty, a holistic methodological approach is required for the design and evaluation of future hydrogen supply chain systems. Such an approach must combine quantitative methods from operations management (e.g., optimization methods from the field of Operations Research) and meta-analyses of dynamics in complex networks (e.g., simulation and System Dynamics) with business analytics (e.g., Machine Learning on available data pools) and field research in terms of empirical work. Empirical work is required in particular to identify, describe, and explain phenomena observed in practice, to gather field data for quantitative models, and to include aspects such as the behavioral attitudes of stakeholders [10]. This informs a current trend in operations management and business analytics research, the “coupling” of analytics approaches and empirical data, labeled the “Empirically Grounding Analytics” (EGA) approach, see [11] and Figure 3.

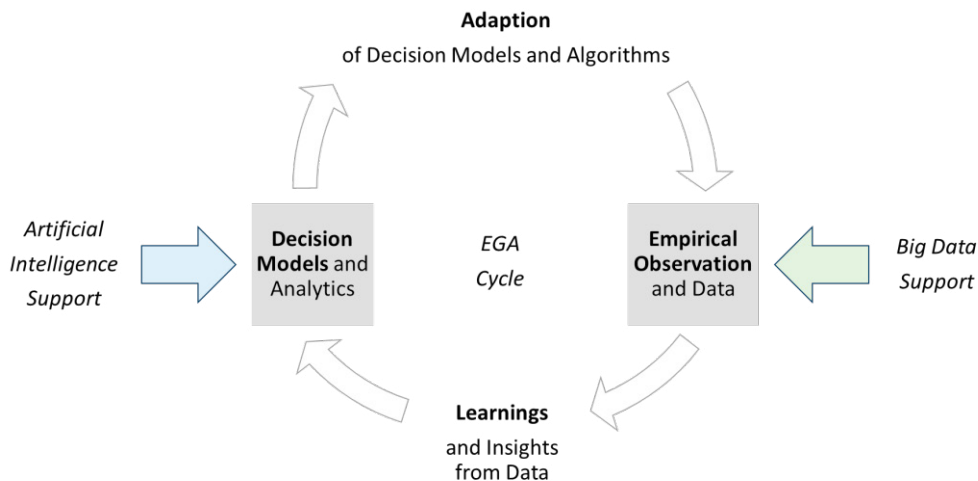


Fig. 3. Empirically Grounding Analytics (EGA) approach, see [11].

2.3. Proposed Multi-Perspective Approach

While the planning matrix from Figure 2 allows for a basic categorization of the planning tasks, it does not provide any information about the (organizational) degree of centralization on which the solution to the involved tasks is based or on the criteria that are to be applied for evaluating the involved decisions. Many quantitative network design approaches adopt a centralized decision-making perspective and attempt to optimally harmonize the individual stages of hydrogen supply chains such that the selected (economic) goals are achieved in the best possible way. However, this completely neglects that legally independent actors with their particular interests collaborate within such supply chains. These individual interests do not necessarily have to be in harmony with the design or operation of the network from a holistic perspective and call for systematic game theoretical analyses.

Furthermore, this is connected to an increasing availability of data types and volumes (“big data”), which severely affect decision-making processes. Hydrogen supply chains are exemplary for many globally developing supply chains and can therefore be a role model or prototype for the design of supply chains under modern conditions. The insights gained here can also be valuable and helpful for the development of future supply chains.

Besides such brand-new supply chains, also existing supply chain structures like in the food, appliances, or apparel supply chain sectors could strongly benefit from the method development and adaption derived from the proposed hydrogen supply chain development case. Also, in existing supply chains, the main strategic management challenges stem from the increased availability of data across all supply chain stages and actors as well as the requirement to implement multi-dimensionally sustainable operations. These interdependencies are outlined in Figure 4.

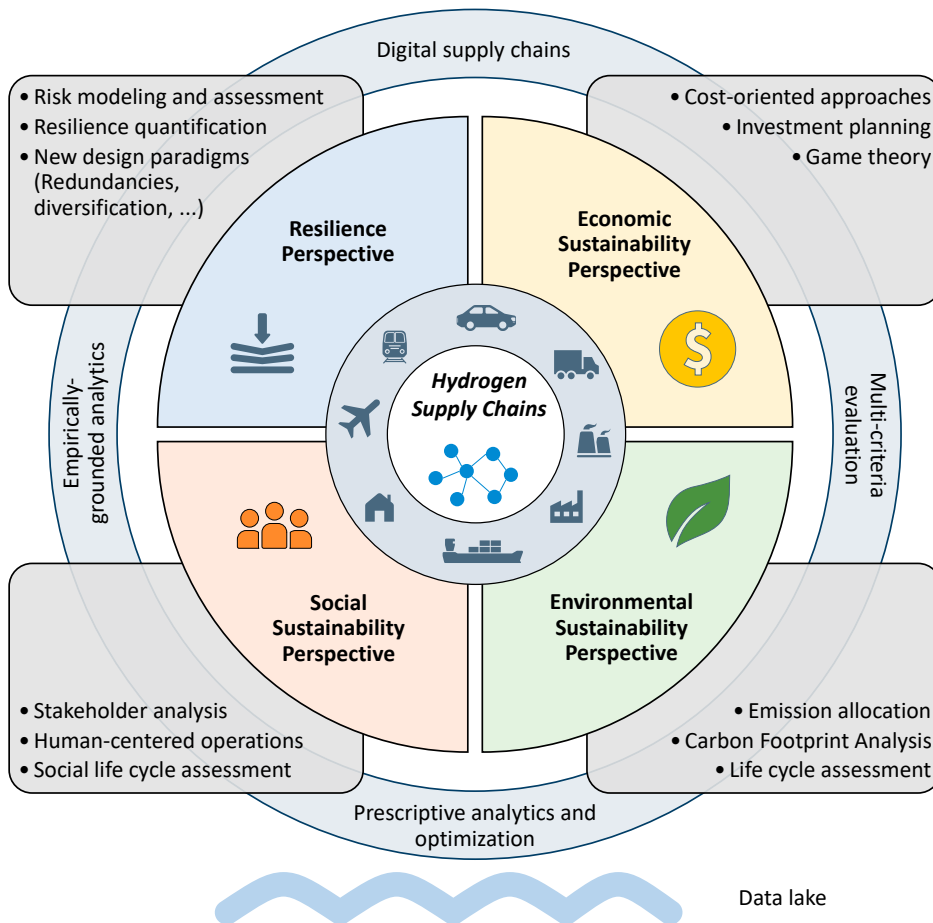


Fig. 4. A holistic framework for hydrogen supply chain design and evaluation (own figure).

3. Four Evaluation Perspectives

Since multiple decision-makers and stakeholders (i.e., governments, investors, producers, distributors) with diverging objectives that may even change over time are involved in the development of hydrogen supply chains a multi-criteria perspective is required. Multi-criteria decision-making (MCDM) distinguishes between two primary paradigms: Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM). Each tackles decision-making under multiple criteria but adopts distinct approaches. MADM is characterized by a finite set of pre-defined alternatives and aims to identify the most preferred option based on their attribute values. This involves evaluating alternatives against a set of attributes (e.g., cost, performance, risk) and assigning weights reflecting their relative importance. In contrast, MODM deals with situations where an infinite number of feasible solutions exist within a defined search space and addresses therefore design decisions.

The objective is to identify the solution that optimizes multiple, potentially conflicting objectives (e.g., minimizing cost and ensuring sustainability). Besides mathematical programming algorithms, heuristic approaches, such as Non-dominated Sorting Genetic Algorithm (NSGA II) and Multi-Objective Particle Swarm Optimization (MOPSO), are employed to navigate the solution space and achieve Pareto optimality, where no further improvement in one objective can occur without sacrificing another. Consequently, MODM approaches are more suitable for the design of hydrogen supply chains, even if MADM can be used at certain points in the design of hydrogen supply chains. MADM and MODM usually assume a single decision-maker. If, on the other hand, different decision-makers with individual and potentially conflicting objectives must be considered, this situation can be modeled with the help of cooperative or non-cooperative game theory to coordinate the actors.

3.1. Economic Sustainability Perspective

The production of hydrogen from renewable sources is an important step to make the economy carbon-free. Such a transition process is associated with considerable changes and investments, which means that the efficient use of resources is essential. When looking at hydrogen supply chains from an economic perspective, two approaches can be distinguished [12]. The first approach involves holistic modeling and design of supply chains, considering various stages and technical restrictions [13]. Typically, the aim is to plan the production, storage, and transportation infrastructure in such a way that a given demand is satisfied. Methodologically, linear programming and mixed-integer linear programming are often used here. The second approach captures the objectives and potential conflicts between the actors. In these actor-centric approaches, production capacity is often assumed to be given, and demand results endogenously. Game theory, discrete choice models, or systems dynamics approaches are methods of choice here.

Regarding economic measures, cost-oriented approaches dominate. In particular, life cycle costing (LCC) plays an increasingly important role in the design of hydrogen supply chains because it takes account of the strategic and dynamic planning nature. The LCC uses the concept of levelized cost, which represents a cost expression per output unit. In the specific case of the levelized cost of hydrogen (LCOH), the total costs over the lifetime are divided by the total amount of hydrogen produced during this period [14]. Instead of using the discounted cash flow, which is complex to calculate, the fixed charge rate method is mainly used, which calculates the period-based revenues required to cover the investments.

While the holistic modeling approaches focus primarily on cost-oriented objective functions, profit-oriented objectives often dominate the actor-centric approaches. The latter calls for price and greening level decisions in hydrogen supply chains, see for example [15]. Other economic objectives include the risk aspect, such as value-at-risk. Advanced approaches should not focus exclusively on individual economic objectives, but combine these in multi-criteria approaches with other, e.g., environmental or social, criteria.

3.2. Environmental Sustainability Perspective

As hydrogen is to be used in the economy to reduce carbon dioxide emissions, hydrogen supply chains and their operations have to be assessed in terms of how successful they are in achieving decarbonization. Such an environmental sustainability evaluation involves various aspects like the eco-assessment of transport operations which is known to be a challenge in all kinds of industries, see [16]. Foremost, the extent to which a hydrogen supply chain

contributes to decarbonization depends on the type of feedstock that is used to produce the hydrogen at the early supply chain stages, see [17]. For example, if hydrogen is produced from natural gas, this grey hydrogen comes with a substantial carbon footprint and hardly contributes to decarbonization. In contrast, using renewable energies like wind power, photovoltaics, or biomass leads to green hydrogen with a much smaller carbon footprint. However, the availability of land and water for scaling up these energy sources may become a limiting factor in some regions of the world, see [18]. There are further potential feedstocks, such as nuclear power, which are (almost) carbon-free but highly controversial from a societal perspective due to their external cost and effects. This illustrates that the environmental perspective is also linked to a social sustainability perspective and a regulatory perspective (is hydrogen generated from nuclear power considered ‘green hydrogen’?), where resolutions to the inherent conflicts are still missing.

Next to the feedstock issue, further environmental sustainability challenges occur at the downstream supply chain stages. In particular, transportation, storage, and transformation processes cause loss of hydrogen (e.g. due to boil-off) or are in turn energy consuming (e.g., if hydrogen is transformed into ammonia for more efficient transportation by ship). The resulting transformation losses along an entire hydrogen supply chains have, thus, to be included in the environmental sustainability perspective next to the economic analysis. Furthermore, the environmental sustainability of a supply chain also depends on resilience requirements for the design and operations of hydrogen supply chains. For example, if feedstock is to be sourced from a diverse set of suppliers rather than just from a single supply source to reduce unilateral dependencies, the environmental performance of the supply chain may suffer due to less efficient transportation over longer distances. Such tradeoffs also need to be considered in a holistic sustainability evaluation.

3.3. *Social Sustainability Perspective*

In connection to the environmental perspective of sustainability, also the social perspective regarding working conditions and social impact on societies is important for a hydrogen supply chain evaluation. Especially, a social sustainability evaluation is of interest from an ex-ante perspective due to investment decisions and lock-in effects. For example, with battery electric vehicles (BEV) it was learned that ex-post evaluations have the potential downside that operating global supply chains with large-scale raw material volumes can hardly be changed after initial basic investment and location decisions. Regarding the BEV case, this was recognized for example for lithium production in the battery production value chain and specific detrimental human working conditions in such contexts [19].

As future green hydrogen supply chains are seen as one of the major hopes in a transition towards climate-friendly economies such a social sustainability evaluation should be conducted ex ante. From this, similar lock-in effects of large-scale investments for production locations and conditions in hydrogen supply chain contexts could possibly be avoided. With this insight, future supply chain design regarding hydrogen production, transport, and use might be informed and inspired by specific design decisions like location, actors, and networks used. Within this research stream, the Social Life Cycle Assessment (SLCA) should be aligned and developed further to the specific requirements of digital and hydrogen supply chains [20].

A specific contribution from such research could be the application of SLCA to dedicated hydrogen supply chain cases as a proof of concept, extending existing generalized propositions and international guidelines towards a specific application case [21]. The method development research in this area would have to address the issue of dealing with data availability or missing data. Usually, missing data would lead to the exclusion of certain criteria and performance indicators from a decision-making process. In the future, online data search and artificial intelligence applications might be used to complement or even delineate or simulate missing data to “complete the picture” in a specific decision situation, for example, investments and decisions within existing transport infrastructure to facilitate the implementation of new hydrogen supply chain settings [22]. This is depicted as a complex concept captured in the following Figure 5.

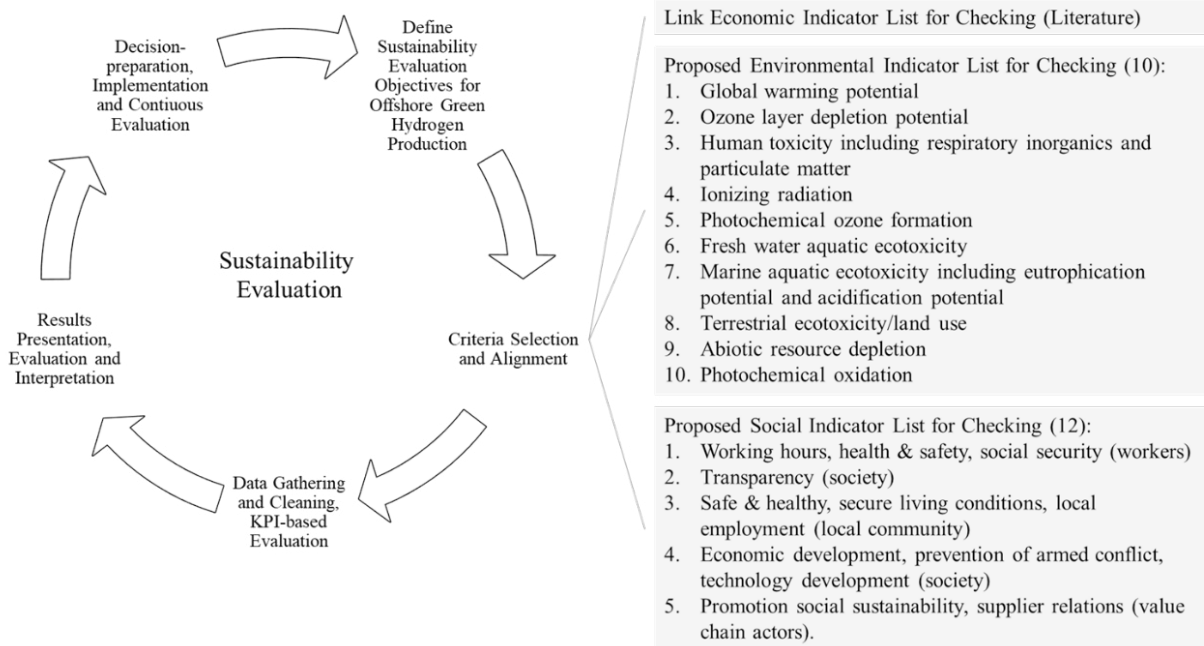


Fig. 5. Example conceptual detail regarding the establishment of a social life cycle analysis, see [19].

3.4. Resilience Perspective

The reliability of hydrogen supply is an important factor for many hydrogen applications [23]. The potential propagation of disruptions in the supply chain (such as supply shortages, accidents, or blocked transport routes) may lead to severe disturbances in service at the demand points and cause high financial losses. Therefore, the key idea of resilience in supply chain management is to enhance the ability of such chains “to prepare, respond and recover from disturbances and afterward maintain a positive steady state operation in an acceptable cost and time” [24].

This requires new design paradigms (such as redundancies, diversification, safety capacities, etc.) that usually contradict traditional design approaches focusing on (economic) efficiency as well as environmental and social sustainability of the supply chain. Moreover, as noted by [25], appropriate optimization models need to be developed to improve the supply chain’s capability to withstand disruptive events and to support recovery from disruptions.

From a methodological perspective, suitable metrics to operationalize supply chain resilience need to be developed and used to evaluate alternative supply chain configurations [26]. Several metrics have been compiled by [27] with a focus on infrastructure resilience and by [28] with a focus on manufacturing plants. Exemplary metrics focusing on the absorptive resilience capacity of a supply chain comprise failure rate, depth of impact, residual performance, and resistive duration. Metrics focusing on the adaptive and restorative resilience capacities include, for example, recovery duration, recovery rate, and restored performance [26]. These metrics need to be adapted to the specific characteristics of hydrogen supply chains and integrated into the related planning models.

4. Conclusion

In this paper, the potential that hydrogen can have for the decarbonization of the economy is first elaborated. However, the conditions necessary to realize this potential are currently largely lacking. A corresponding hydrogen infrastructure needs to be established, and from a production and logistics perspective, a planning matrix can be identified that differentiates tasks depending on the system boundaries and the planning horizon. In this paper, it is

proposed that the degree of organizational centralization of the hydrogen supply chain should also be included in order to actively take into account the individual interests of the players. The tasks systematized in this way can be tackled using modern methods of operations research, management, engineering, and computer science. However, this article emphasizes the possibilities opened up by increasing digitalization and data availability. The concept of “Empirically Grounding Analytics” paves the way for interlinking empirical findings with the above-mentioned methods and thus achieving even better-substantiated decision support. This paper also advocates adopting a multi-dimensional perspective. To this end, we suggest supplementing the three well-known economic, ecological, and social dimensions of sustainability with a resilience perspective. It is important not to ignore recent experiences with regard to supply chain disruptions but to explicitly include the aforementioned risks in the planning in order to make it more robust. Thus, researchers in diverse areas like operations research, management, engineering, or computer science are therefore required to bring together their expertise and collaborate to support industry, politics, and society during the transition path toward more sustainable economies based on the large-scale use of green hydrogen.

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