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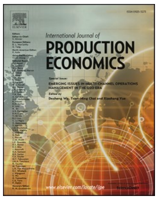

Renewable hydrogen supply chains: A planning matrix and an agenda for future research

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ABSTRACT

Worldwide, energy systems are experiencing a transition to more sustainable systems. According to the Hydrogen Roadmap Europe (FCH EU, 2019), hydrogen will play an important role in future energy systems due to its ability to support sustainability goals and will account for approximately 13% of the total energy mix in the coming future. Correct hydrogen supply chain (HSC) planning is therefore vital to enable a sustainable transition, in particular when hydrogen is produced by water electrolysis using electricity from renewable sources (renewable hydrogen). However, due to the operational characteristics of the renewable HSC, its planning is complicated. Renewable hydrogen supply can be diverse: Hydrogen can be produced de-centrally with renewables, such as wind and solar energy, or centrally by using electricity generated from a hydro power plant with a large volume. Similarly, demand for hydrogen can also be diverse, with many new applications, such as fuels for fuel cell electrical vehicles and electricity generation, feedstocks in industrial processes, and heating for buildings. The HSC consists of various stages (production, storage, distribution, and applications) in different forms, with strong interdependencies, which further increase HSC complexity. Finally, planning of an HSC depends on the status of hydrogen adoption and market development, and on how mature technologies are, and both factors are characterised by high uncertainties. Directly adapting the traditional approaches of supply chain (SC) planning for HSCs is insufficient. Therefore, in this study we develop a planning matrix with related planning tasks, leveraging a systematic literature review to cope with the characteristics of HSCs. We focus only on renewable hydrogen due to its relevance to the future low-carbon economy. Furthermore, we outline an agenda for future research, from the supply chain management perspective, in order to support renewable HSC development, considering the different phases of renewable HSCs adoption and market development.

1. Introduction

Many countries have defined strategic tasks for reducing fossil-based energy sources to achieve emission goals. In this context, hydrogen presents an exciting opportunity to pursue ambitious climate and environmental policies for seeking clean fuels or, generally, low-carbon technologies for society. Hydrogen strategies and roadmaps have been proposed and updated to facilitate the adoption of hydrogen supply chains (HSCs) in, among others, Japan, Korea, the USA, the UK, Canada, Norway, and the EU (Canadian Government, 2020; DOE, 2020; FCH EU, 2019; Intralink, 2021; Japanese Government, 2017; Norwegian Government, 2020; UK Government, 2021). Countries are in different positions in terms of developing their hydrogen economies; while some see a strong need to import hydrogen, others see a high potential for exporting hydrogen. Accordingly, hydrogen is expected to constitute about 13% of the energy mix in the EU by 2050 (FCH EU, 2019), and by 2050 the hydrogen economy is estimated to represent US$750 billion in the USA and US$2.5 trillion in the global market (DOE, 2020).

Among these developments to reduce the dependence on fossil-based processes, particular attention is paid to the so-called renewable HSCs, where hydrogen is produced by water electrolysis, using electricity from renewable sources such as solar, wind, hydro and geothermal ones (in the text we refer to them as renewable feedstock Li et al., 2019)). However, the development of renewable HSCs is still immature, and the planning of renewable HSCs is challenging due to the following operational characteristics.

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In addition to the wide spectrum of applications, such as the transport industry, the steel and iron industry, the chemical and refinery industry, and buildings, there are various forms of renewable feedstocks for producing hydrogen which are characterised by high uncertainty in terms of their availability and performance. Moreover, hydrogen can be produced in large volumes in a centralised production facility or in small volumes in local systems. Depending on the geographic location and types of applications, hydrogen can be stored in different forms, and thus transported via different logistics means, such as trucks, pipelines, compressed tanks, liquified tanks, etc. Storage is paramount in operating renewable HSCs. In fact, hydrogen can be seen both as a final product and as an energy carrier, for example, to store electricity, both in terms of time and space. On the one hand, hydrogen storage can be used strategically to shift demand and supply across seasons, while on the other hand, storage is also used as a buffer for smoothing short-term supply and demand mismatches due to operational uncertainty. Furthermore, to achieve energy and economic efficiency, hydrogen needs to be integrated with energy systems, both in terms of feedstocks and applications, and an international perspective is needed to consider where supply and demand are generated.

Therefore, renewable HSCs are complicated, due to their potential diversity (types of stages, such as feedstock, production, storage, distribution, and application) and extensions (scaling of the supply chains and integration with other supply chains). There is a need to investigate the planning of HSCs, as a set of tasks which support decision-makers identifying alternatives within the supply chain processes (sourcing, production, storage, distribution, and market and sales), and selecting the most appropriate ones to satisfy a set of goals or objectives (Stadtler et al., 2015), such as cost, efficiency and safety. Moreover, the design and operations of renewable HSCs and therefore their performance are also affected by market development and technology selection, and vice versa. In this context, making renewable HSCs more complicated, technologies used for feedstock, production, storage, and distribution still have different maturity levels or technology readiness levels (TRLs), which impact the adoption and market development of renewable HSCs. Existing renewable HSCs are often used for pilot and demonstration purposes, whereas scale-up renewable HSCs are rare but imminent. To increase TRLs and facilitate the adoption of large-scale renewable HSCs, policy-making bodies are currently (beginning of the 2020s) funding research and development activities (Griffiths et al., 2021), with the aim of achieving stable growth for market activation, and eventually maturity, with a time horizon between 2020 and 2050.

Boosted by the availability of research funding, studies on hydrogen have mainly developed from a technological perspective, as methods, technologies, materials, among others for hydrogen production, storage and distribution. Largely pushed by the recent technological advances and the widespread adoption of renewable energy, this perspective is one of the main research topics for hydrogen production and use systems (Griffiths et al., 2021; Hong et al., 2021). These studies have resulted in knowledge contribution to the development approaches, methods, models, and technical design aiming at achieving the most suitable and efficient technological solutions to address HSC challenges (El-Emam and Özcan, 2019). The analysis of technology conditions has mainly focused on technical practices and performance of specific methods for hydrogen production, storage and distribution. For example, Bolat and Thiel (2014) and Muresan et al. (2013) have focused their research on hydrogen production systems, while Gallardo et al. (2021) have investigated renewable hydrogen production based on solar technologies. Hurskainen and Ihonen (2020), Lahnaoui et al. (2021) and Mingolla and Zu (2021) have proposed a technological assessment of hydrogen distribution and transport for both hydrogen and its derivatives.

However, some review studies scoping the HSC have been published, focusing mainly on two research streams: (i) the approaches and the models to achieve the optimal configuration of HSCs or of their single stages, and (ii) environmental impact assessments in terms of ecological performance and CO2 emission factors.

Concerning the first stream, Dagdougui (2012) investigated different approaches to HSC planning focusing on methods and models for the stages' designs, such as production, storage, and distribution. Agnolucci and Mcdowall (2013) focused on the analysis of hydrogen infrastructures within the HSC on a spatial scale from national to regional and local scales for transport sector application. Li et al. (2019) presented a comprehensive review of HSCs considered as a whole and of single stages, proposing system analysis, solution approaches, and optimization-based models for planning HSCs within the transport sector.

Concerning the second research stream, Bhandari et al. (2014) analysed the environmental impact of different hydrogen production technologies through a life cycle assessment (LCA) analysis, while Maryam (2017) also focused on performance measures, such as cost minimization and environmental impact reduction. Balcombe et al. (2018) reported the decarbonisation potential associated with the stages of HSCs' encompassing feedstocks and hydrogen production, and El-Emam and Özcan (2019) reviewed large-scale clean hydrogen production by providing an economic and environmental assessment of the existing and most promising technologies. Recently, Griffiths et al. (2021) proposed a comprehensive review of hydrogen production and utilization for different applications by considering a sociotechnical perspective to assess the industrial decarbonisation process.

Even though these reviews have summarised hydrogen studies, they lack a comprehensive overview of the planning problems and tasks which are essential for decision-makers for managing the forthcoming dynamic development of renewable HSCs from a supply chain (SC) management perspective. Given the specific renewable HSC operational characteristics and uncertainty, directly applying the traditional approaches to supply chain planning to renewable HSCs seems insufficient. Moreover, the design and operation of an renewable HSC depend on the current phase of renewable HSC adoption and market development and how mature the technologies are, but both are still characterised by high uncertainty due to renewable HSCs' potential diversity and extensions. Thus, when designing an renewable HSC, long-term and short-term perspectives on uncertainty need to be included, and studies of renewable HSCs should adopt a dynamic view.

The contribution of this study is twofold. First, we introduce a planning matrix with related planning tasks for renewable HSCs. The planning matrix is developed by adapting the well-established matrix introduced by Stadtler et al. (2015), through a synthesis of the content analysis-based literature review of renewable HSCs. Second, we present an agenda for future research to support the selection of proper solutions to planning tasks, outlining the promising topics and areas in emerging renewable HSC studies. This agenda considers the main goals defined by hydrogen strategies and roadmaps, and describes changes based on the different phases of the adoption and market development of renewable HSCs. We present a comprehensive overview of potential problems and methodologies that operations and supply chain managers and researchers need to address in the future.

The remainder of this paper is structured as follows (see Fig. 1). Section 2 defines the stages of renewable HSC superstructures (feedstock, production, storage, distribution, and application) and the main existing pathways. Section 3 describes the methodology used for the data collection, adopting a systematic and structured approach (a systematic literature review). Section 4 presents an analysis of the state of the art of renewable HSCs, covering various articles distributed over time, journals and processes in renewable HSC. Section 5 synthesizes the content analysis of the literature identifying the various planning tasks for renewable HSC with respect to time horizons and processes in renewable HSC and highlighting the current challenges. Then, in Section 6, we present the impact of the renewable HSC adoption and market development on the definition of objectives and goals that decision-makers set for the identified planning tasks. In Section 7, we present future research approaches and methods needed to support the decision-making process in finding the most appropriate solutions. Finally,

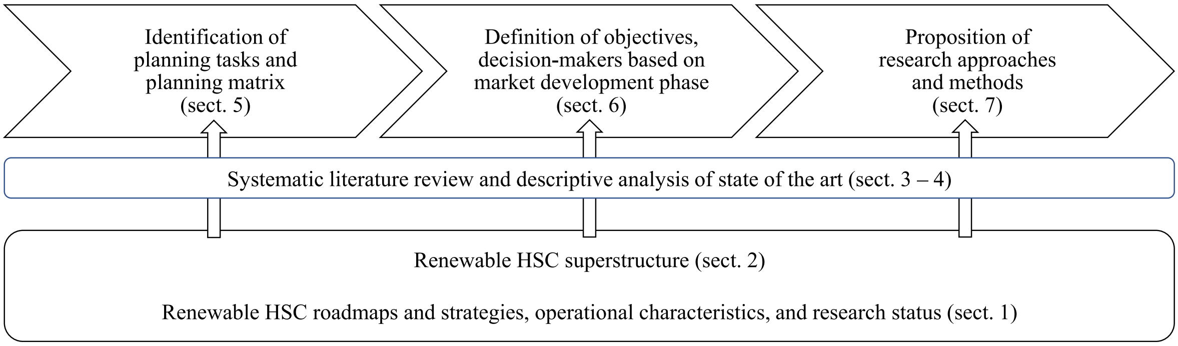

Fig. 1. Planning of renewable HSCs: structure of the research.

Section 8 concludes the study.

2. Superstructure of renewable HSC

Currently, most hydrogen production uses fossil-based processes, which account for approximately 94% of total production (Nordic Energy Research, 2022). As clean hydrogen will achieve the sustainability goals, we focus on the new development of renewable-based production methods and thus exclude HSCs emphasizing fossil-based production. We note that one renewable alternative of hydrogen is biomass gasification with carbon capture and storage; however, this technology needs further development and its industrial production will not begin until the 2030s or later (UK Government, 2021). Thus, in this study, we focus on the potentially cleanest technology pathways of renewable hydrogen, where hydrogen is produced by water electrolysis, using electricity from renewable sources such as solar, wind, hydro and geothermal ones (renewable feedstock). However, we have to be aware of the ongoing debates about the taxonomy of green, blue and grey hydrogen (Climate Weekly, 2022; S&P Global, 2022). In the reviewed literature, there is no consistent definition of renewable hydrogen; for instance, green hydrogen is interchangeably referred to as renewable hydrogen (Griffiths et al., 2021).

There are plenty of potential applications for hydrogen, such as fuel for fuel cell electric vehicles (FCEVs) and electricity generation, feedstocks in industrial processes (steel, chemical and glass production), and heating for buildings. All these applications need structured and diffused renewable HSCs, which cover operations from different feedstocks through several stages, such as production, storage, and distribution, to supplying hydrogen for final applications (see Fig. 2). This superstructure represents the foundations of renewable HSCs.

As illustrated in Fig. 2, in a renewable HSC, various renewable sources as solar, wind, hydro and geothermal ones, are converted into electricity used for water electrolysis. Hydrogen can be produced with or without an electricity grid. In the former case, hydrogen production may need to compete for supply, as electricity is often used for other purposes. In the latter case, supply disruption is common. Thus, hydrogen

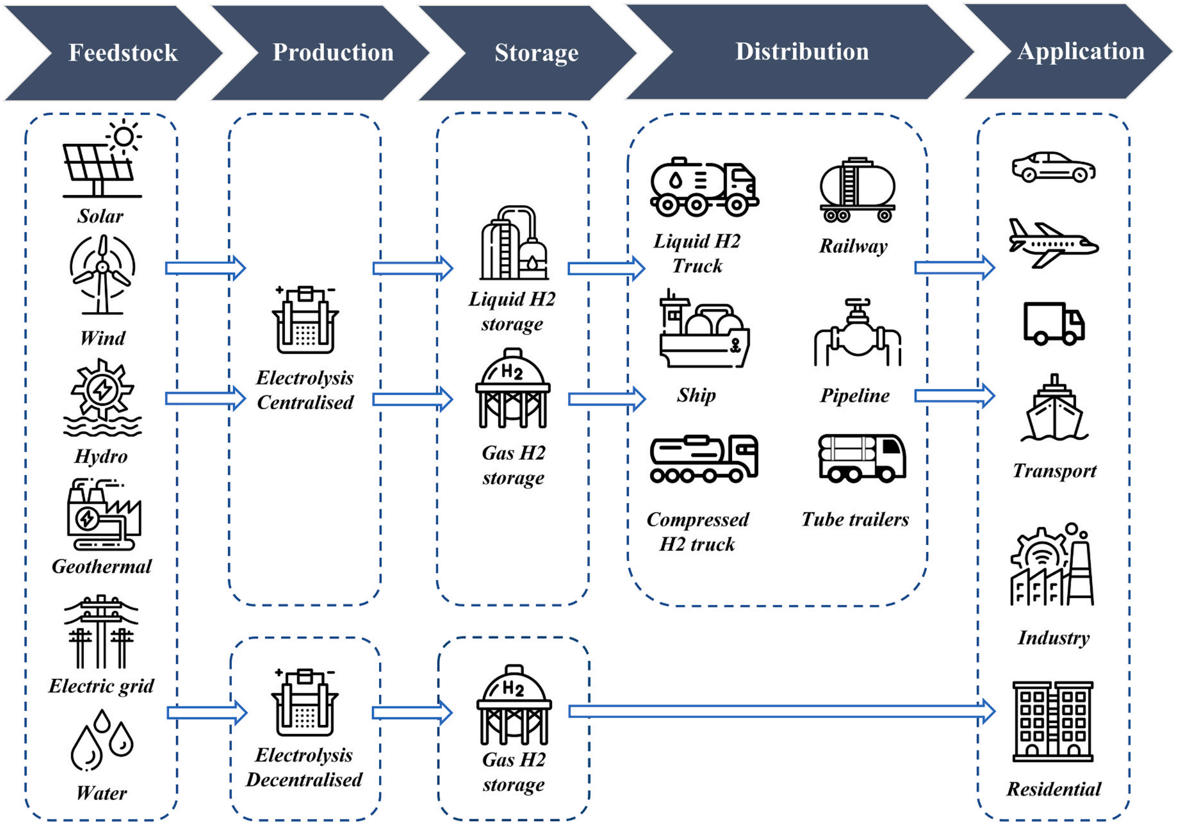

Fig. 2. Superstructure of renewable HSCs.

production without an electricity grid needs to manage the uncertainty of feedstock availability, but its advantage lies in the assurance of clean sources.

To satisfy the demand for hydrogen, the renewable HSC needs to be configured with a proper distribution network to transport hydrogen from the production sites to the points of use.

A decentralised electrolyser involves both onsite production for stand-alone and self-sustaining end-users/customers and distributed production consisting of facilities placed close to the point of use (Griffiths et al., 2021). Generally, production is often attached to wind power or solar photovoltaic (PV) systems, which implies small-scale production and thus potentially more expensive production and investment costs per unit of hydrogen produced (Tang et al., 2022). However, this setting is characterised by cheaper distribution costs due to short distances; preferably, it should be combined with storage solutions where compressed hydrogen is temporarily kept.

On the other hand, a centralised electrolyser, which is realised in combination with a large-scale power plant (such as a hydropower plant or other alternatives), implies an abundant and cheap electricity supply (Tang et al., 2021). However, due to the distance between the production and application sites, the distribution cost can be expensive. A preferable form of distribution comprises gaseous hydrogen via pipelines or liquid hydrogen via trucks and ships.

The application aspect can also influence the settings of hydrogen distribution. In the transport sector, for example, refuelling stations for FCEVs or bunkering stations for hydrogen-fuelled vessels are required to cover broad areas of interest. In the industrial and residential sectors, points of use are sparser and more concentrated within industrial clusters and residential areas. The selection of the distribution mode needs to be synthetized with the volume of transported hydrogen and the spatial-scale area covered by the supply chain, namely regional transport (from production sites and terminals placed in different regions), local transport (same regional area) and local distribution (between refuelling stations and terminals in the same region).

Due to the intermittent availability of renewable feedstocks and random demand along the distribution network, hydrogen storage systems have to maintain supply during peak demands and to provide a resource reservoir when demand is low while production continues. Hydrogen can be stored and transported in different ways, depending on its state (gas or liquid). Hydrogen in gas form is kept at a high pressure at about 350–700 bars, whereas liquid hydrogen needs a cryogenic temperature, meaning additional energy consumption in the liquidation process. Also, hydrogen can be stored in the forms of adsorption (on the surfaces) and absorption (within) on other solids, such as metals or chemical compounds. While liquid hydrogen can be transported via railways, ships and road by trucks, compressed hydrogen is often transported via pipelines, tube trailers, and compressed gas trucks. Also, hydrogen storage often occurs in several stages to fulfil the various purposes of renewable HSCs.

From the above description, it is clear that these stages are characterised by planning problems that operations and supply chain managers have to face (e.g., which feedstock to select, where to locate production, how to operate storage facilities, etc.). A commonly used framework in supply chain management to describe the main planning problems and corresponding tasks is the supply chain planning matrix (Stadtler et al., 2015). This matrix categorises the planning problems and tasks in accordance with two dimensions: (i) the supply chain processes of procurement, production, distribution, and sales, and (ii) the planning horizons, namely long-term and mid-/short-term. More specifically, the unique supply chain processes are matched with the supply chain stages: the feedstock, production, storage, distribution, and application stages correspond to sourcing, production, storage, distribution, and market and sales processes, respectively.

However, due to the unique operational characteristics of renewable HSCs and their adoption and market development, the planning matrix for traditional supply chains is inadequate to represent and summarise the different renewable HSC-related planning problems and tasks. Therefore, a new planning matrix needs to be developed specifically for renewable HSCs, and this represents one goal of the current study, in addition to the definition of an agenda for future research.

3. Research methodology

To develop an renewable HSC planning matrix, we conducted a systematic literature review (SLR) as the content analysis, since it ensures the replicability of the study, improves the traceability of the arguments and ensures the validity and reliability of the results (Sudusinghe and Seuring, 2022). Specifically, in carrying out the SLR, we followed the three-step guidelines provided by Tranfield et al. (2003).

Step 1. – Planning the review

In this step, we identify the need, prepare the proposal and develop the protocol for the SLR. Specifically, the need and proposal for the SLR were described in the previous sections, while for the SLR protocol, we adopted the PRISMA protocol (Moher et al., 2009).

Step 2. – Conducting the review

The review was conducted according to the PRISMA protocol (see Fig. 3). In this step, we first collected relevant articles using the Scopus database in two separate searches. Scopus was selected mainly because of its broad coverage of journals in management, engineering and environmental sciences (Ahi and Searcy, 2015).

The first search adopted a two-group keyword structure with the purpose of collecting multiple large-scale keywords to consistently cover the published works related to HSCs. The first group (group A) consists of the keyword that defines the search context of this analysis, namely ‘hydrogen’, while the second group (group B) consists of the keywords that characterise the search scope, namely ‘supply chain*’, ‘logistic*’, ‘production management’, ‘operations management’, and ‘supply network*’. The logical operators ‘AND’ and ‘OR’ were used to generate the search strings within ‘Title, Abstract and Keywords’ (e.g. ‘[keyword of Group A] AND [keyword of Group B OR another keyword of Group B]’). We limited the search to articles in English and within the following subject areas: ‘energy’, ‘engineering’, ‘chemical engineering’, ‘environmental science’, ‘computer science’, ‘material science’, ‘business, management and accounting’, ‘mathematics’, ‘social science’, ‘multidisciplinary’, ‘decision science’, and ‘economics, econometrics, and finance’. This first search resulted in 1154 articles (see Fig. 3).

The second search was then conducted to overcome the potential limitation of the first search: The choice of the specific keywords can be overly limiting in providing good coverage of the investigated area of interest, thus resulting in an incomplete set of articles. In the second search, only ‘hydrogen’ was used as a keyword, and the search was limited to articles published in the 70 most relevant journals dealing with supply chain management and operations management in the following subject categories: business, management and accounting (all); computer science (all); computer science applications; decision sciences (all); economics and econometrics; engineering (all); industrial and manufacturing engineering; information systems and management; management science and operations research, strategy and management; and transport. The selection of the journals was based on authors’ experience, the selection is presented in Appendix A. The second search resulted in a total of 996 articles, which, combined with the results of the first search, led to a total of 2133 articles (after removing duplicates).

We then screened these articles according to the following inclusion criteria:

i. Journal articles: Only journal articles (original research articles or reviews) were considered, while conference papers, book chapters, technical reports, etc. Were excluded.

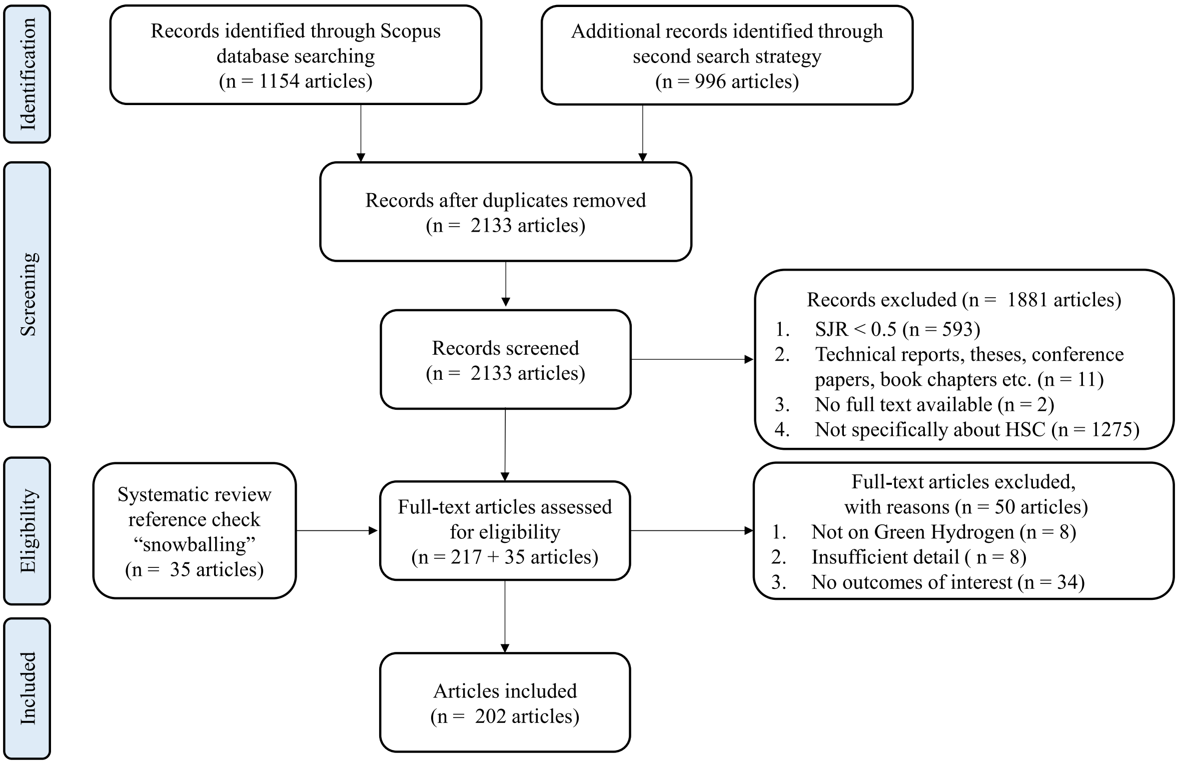

Fig. 3. PRISMA protocol diagram.

ii. Scimago Journal Rank (SJR) index: Only articles published in journals with an SJR index greater than or equal to 0.5 were considered.
iii. Full text availability: Only articles with full text availability were considered.
iv. Renewable HSC: Only articles focusing on renewable HSCs were considered; this was determined by screening titles and abstracts.

It is worth mentioning that to ensure the reliability and objectivity of the results, point iv was executed independently by two authors of this study. This approach is not new in the field of SLRs (Duriau et al., 2016; Seuring and Gold, 2012). Also, Seuring and Müller (2008) stated that *‘this is the minimum requirement, but given the time-consuming process, it is somehow unrealistic to include more than this’*. When the two authors had different judgments, the related articles were assessed in a discussion involving all the authors until a final consensus was reached. At the end, the article set was reduced to 217 articles.

The full texts of the articles were then read by all the authors to confirm suitability for the topic (renewable HSCs) and discarded if irrelevant. This step resulted in 167 articles.

Lastly, a snowballing procedure was conducted, whereby additional relevant articles were extracted from the references of the eligible articles. These new articles were then evaluated, limiting the selection to those in English and screening their contents considering Criteria i–iv. In the end, 35 additional articles were considered eligible, and this led to a total of 202 articles to be included in the SLR (see Appendix B).

Step 3. – Reporting and dissemination

In this step, we first presented the results of the descriptive analysis (Section 4), where we indicated how the selected articles were distributed over time and over journals. Moreover, we distributed the articles according to the categories used in the content analysis (Section 5). The content analysis represents the second part of this step, in which we analysed the content of the articles based on categories deductively derived from the SC planning matrix (Stadtler et al., 2015). These correspond to the SC processes of the SC planning matrix (i.e., sourcing, production, storage, distribution, and market and sales), with each divided into the two levels of planning horizons (i.e., long-term and mid-/short-term). Specifically, since the aim of the content analysis is to support the development of an renewable HSC planning matrix, this was considered a logical choice. Such a deductive categorisation represents common practice in literature reviews for situations in which the literature on the topic already exists (Seuring et al., 2021; Seuring and Müller, 2008). As stated by Beske et al. (2014), this approach contributes to the *‘external validity as the research design is set up in a rigorous manner and transparently described’*. Moreover, to ensure reliability and objectivity in the categorisation, the same approach was adopted in conducting the review (see Step 2 – Conducting the review) that was applied for the categorisation. As described above, the results of the content analysis were then used to build the planning matrix presented in Section 6.

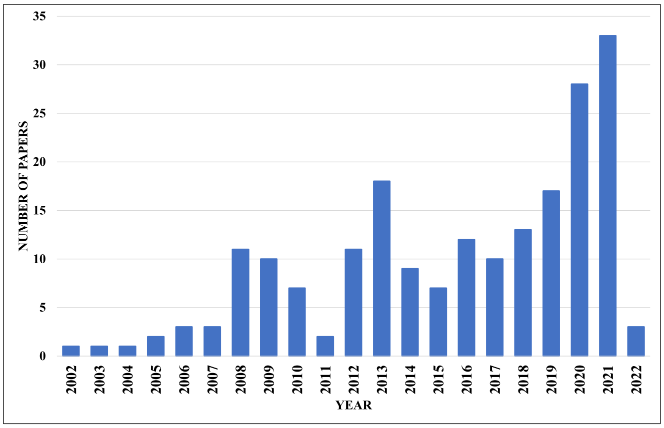

Fig. 4. Distribution of articles over time.

4. Descriptive analysis of the state-of-the-art on renewable HSCs

As illustrated in Fig. 4, interest in research on renewable HSCs has increased over the years, especially after 2015 with the signing of the Paris Agreement, which aims to substantially reduce global greenhouse gas emissions to limit global warming (European Commission, 2016). Relevant to this perspective is the statement by Daryl Wilson, the executive director of the Hydrogen Council: 'Hydrogen is absolutely critical to the realisation of our decarbonisation goals as set out in the Paris Agreement […] We need hydrogen from the standpoint of moving our energy around in the new energy economy.'

However, despite the increased interest in renewable HSCs, a very limited number of articles have been published in journals with domain topics in supply chain management and operations management (e.g., the *International Journal of Production Economics*). In fact, most of the articles are published in energy- and environment-related journals (the *International Journal of Hydrogen Energy*, the *Journal of Cleaner Production*, *Energy*, etc.). Fig. 5 presents the journals with the number of articles published in descending order. The category 'Others' groups all remaining articles.

Of the 202 articles, 16 were identified in journals within the supply chain management domain. Four articles were found in the *European Journal of Operational Research* (André et al., 2013; Bapna et al., 2002; Lim and Kuby, 2010; Schulte Beerbühl et al., 2015), three in *Transportation Science* (Daziano and Achtnicht, 2014; Kang and Recker, 2014; MirHassani and Ebrazi, 2013), two each in the *International Journal of Production Economics* (Finnah and Gönsch, 2021; Kostin et al., 2015), *Transportation Research Part C: Emerging Technologies* (Brey et al., 2016; Crönert and Minner, 2021) and *Transportation Research Part E: Logistics and Transportation Review* (Li et al., 2021; Parker et al., 2010), and finally one article each in *Computers and Industrial Engineering* (Woo and Kim, 2019), *Expert Systems with Applications* (Torreglosa et al., 2016) and *Production and Operations Management* (Glenk and Reichelstein, 2020).

The lack of a supply chain management perspective in hydrogen studies was also confirmed by the topics of the articles. Only 24% of the articles (48 out of 202) considered all five processes of the HSC (i.e., sourcing, production, storage, distribution, and market and sales) (see Fig. 6). Moreover, considering the same figure, it is also interesting to note that the majority of articles deal with long-term supply chain planning tasks, confirming that we are still in the early investigation phase, when strategic decisions mainly focus on renewable HSC adoption and market development.

5. Planning tasks in renewable HSCs

As mentioned before, the selected articles were classified according to the different SC processes (i.e., sourcing, production, storage, distribution, and market and sales) and the two planning horizons (i.e., long-term and mid-/short-term) of the SC planning matrix. Below we summarise the current state of the art for each of these categories, and we analyse these from an SC management perspective. Our aim is to identify the different planning tasks, and the associated challenges, and subsequently we define the planning matrix for renewable HSCs.

In the following, Section 5.1 deals with long-term planning tasks, while Section 5.2 deals with mid-/short-term planning tasks.

5.1. Long-term planning tasks

This section reports the current research dealing with long-term planning tasks. Specifically, we discuss each process in renewable HSC. As discussed before, each process is often linked to other processes, and hence the last subsection deals with the whole renewable HSC.

Sourcing. Generally, hydrogen can be produced via water electrolysis using different renewable energy sources, such as solar, wind, hydro and geothermal. As illustrated in Fig. 6, sourcing has never been studied alone but always in combination with other renewable HSC processes, particularly the production process. Choices in the sourcing process, in fact, strongly impact planning tasks in the production process, such as the type, location and size of facilities (Almansoori and Shah, 2012; Cantú et al., 2021). A typical planning task in the sourcing process is the selection of the best feedstock from an economic perspective (Tseng et al., 2005), often integrated with planning tasks in the production process. Almansoori and Betancourt-Torcat (2016), for example, determined the most economic production technologies based on different available sources. In the existing literature, authors have mainly adopted the MILP modelling approach, which includes the analysis of the geographical location, availability and quantity issues in problem settings (Almansoori and Shah, 2009; De-León Almaraz et al., 2015).

Researchers have recently started considering sourcing from existing energy systems and infrastructures. For example, Almansoori and Shah (2012) considered the alternatives of importing feedstocks from neighbouring grids or external sources (e.g., another country) instead of building new production facilities. A similar study was conducted by Mohseni and Brent (2020). Multiple sourcing, together with the safety stock of energy sources, represents a potential solution to deal with feedstock uncertainty (as a consequence of intermittent renewables, such as solar and wind sources) (Almansoori and Shah, 2012).

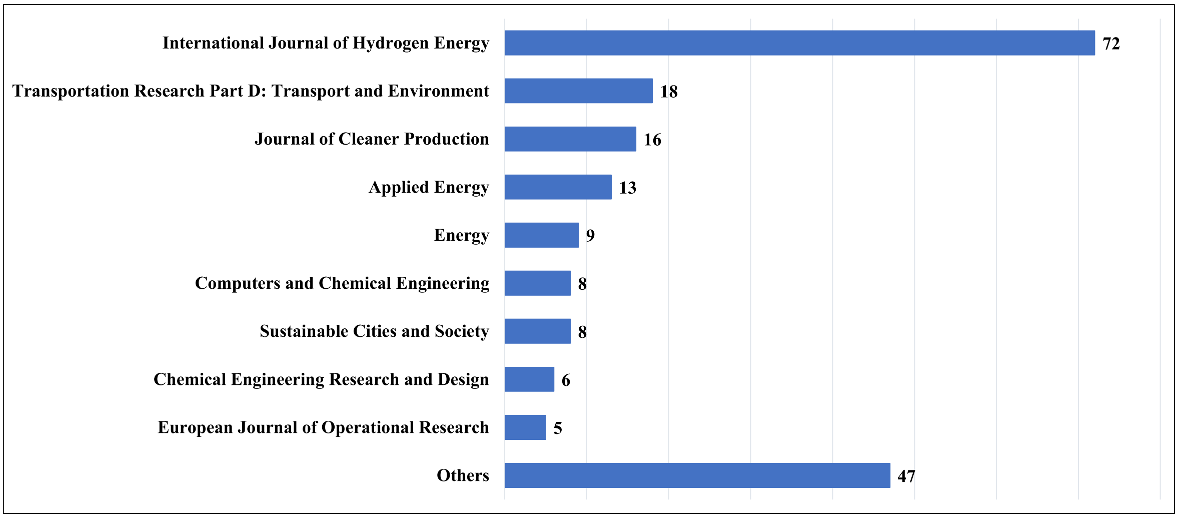

Fig. 5. Distribution of articles over journals.

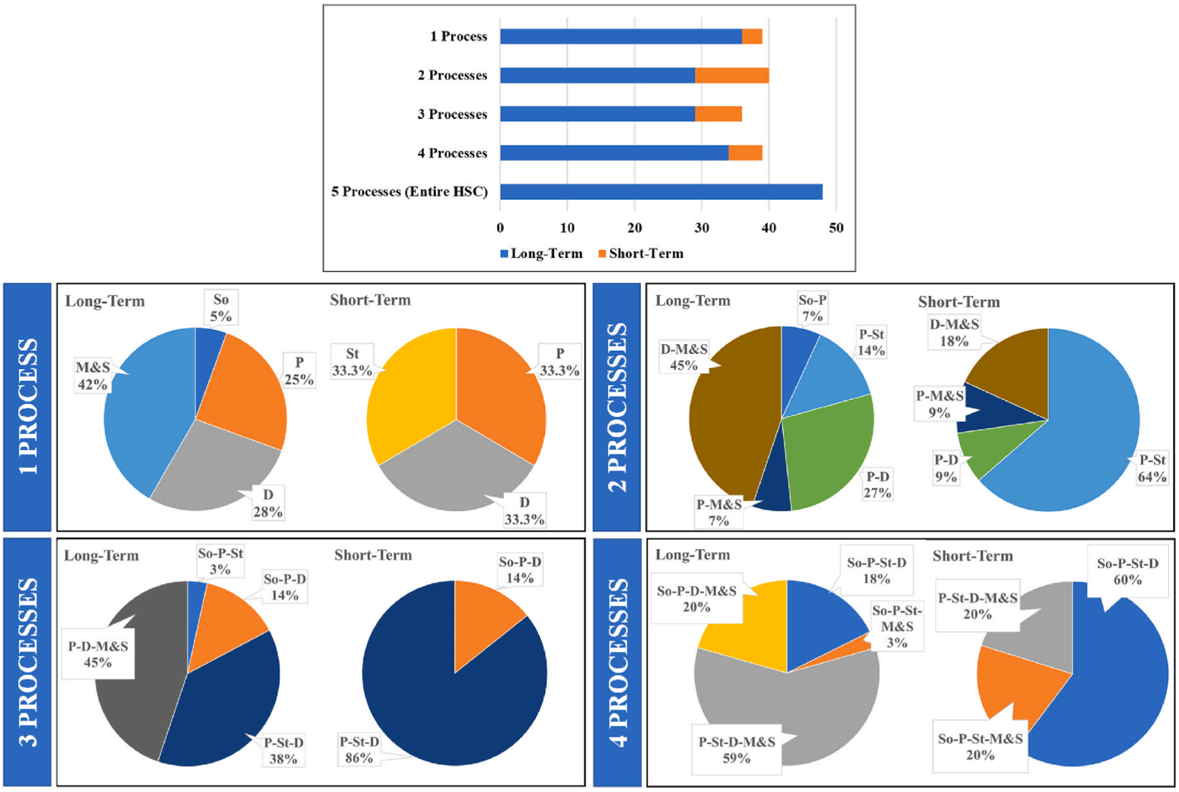

Fig. 6. Topics considered by the articles. So = sourcing; P = production; St = storage; D = distribution; M&S = market and sales.

Finally, another emerging research topic is the inclusion of environmental impacts on feedstock choices, for example, adding environmental constraints in MILP (Almansoori and Betancourt-Torcat, 2016), adopting multi-objective MILP techniques (Carrera and Azzaro-Pantel, 2021a), and including environmental protection policies (e.g. CO2 taxations) into the model (Han and Kim, 2019).

In conclusion, planning tasks related to sourcing have to consider two main challenges. The first is the availability and quality over time of different sources, their location and accessibility, and their price in relation to the energy market and long-term agreements with suppliers (Almansoori and Shah, 2012). The second is the uncertain features of these sources, in the light of which it could be interesting to establish sources' portfolios and resource pooling principles to reduce supply risk.

Production. As discussed before, the production process is often evaluated together with the sourcing process, since these are closely interconnected. Moreover, as indicated in Fig. 6, the production process is often also coupled with the storage and/or distribution processes. As reported by various authors (Agnolucci et al., 2013; Almansoori and Betancourt-Torcat, 2016; Cantú et al., 2021), typical planning tasks in the production process relate to the number, locations, technologies, and scales of hydrogen production facilities. These decisions are usually made through MILP models that consider, among others, trade-offs between establishing facilities and transport links (Almansoori and Shah, 2012), or through GIS modules embedded within the MARKAL model (Balta-Ozkan and Baldwin, 2013). Also, some studies have considered different hydrogen demands to reflect the different phases of hydrogen adoption (Ball et al., 2007; Dayhim et al., 2014; Talebian et al., 2019), because different demands 'lead to significant changes in the structure and cost of the optimal supply chain network' (Almansoori and Shah, 2012). These studies confirmed the high impact of the hydrogen adoption level on the production process, and more generally on the whole renewable HSC: In the initial phase, when the adoption level is low, small onsite decentralised production is convenient, since it is more expensive to transport small amounts of hydrogen than to produce it in small-scale units; however, in later phases, when the adoption level increases, centralised larger-scale production capacities are more economical, leveraging economies of scale. Situations can, however, change if existing electricity grids are usedBalta-Ozkan and Baldwin (2013). When distribution and transmission costs are avoided, centralised production becomes convenient, also in the initial phase. Nevertheless, in this case one concern is whether hydrogen can be defined as renewable, as this depends on the source of electricity in the grid.

Another factor affecting the number and locations of production facilities is technology maturity, but its impact on production decisions has barely been studied. Two related studies (but still not essentially targeted) are those of Chen et al. (2021) and Wu et al. (2021). The authors investigated the impact of different electrolysers' lifetime on the choice of production method and location. Demirhan et al. (2021) further investigated the effect of reducing electrolysers' costs related to technology maturity.

Finally, another current topic includes not only economic considerations but also environmental and safety considerations in the models for the production stage (Al-Breiki and Bicer, 2021; Almansoori and Betancourt-Torcat, 2016; De-León Almaraz et al., 2015).

In conclusion, the above-mentioned planning tasks are complex, as they are affected by certain significant factors. The selection of electrolyser technology and its production capacity is not straightforward. On the one hand, there is the desire to exploit as much as possible the sources' availability, selecting an electrolyser whose capacity matches the peak availability of sources (Almansoori and Betancourt-Torcat, 2016). On the other hand, this would result in redundant electrolyser capacity and a long return of investment (Balta-Ozkan and Baldwin, 2013). Therefore, it is critical to investigate the trade-off of investment cost in electrolyser capacity to balance the availability of feedstocks and the idle time of the electrolyser.

Similarly, the other main planning tasks are complex, for example, the location of the production facilities, which cannot be considered alone since it impacts the form of the distribution. As mentioned by

Almansoori and Shah (2012), electrolysers can be located close to the feedstocks, and the produced hydrogen can be distributed via a complex network (for example, in transport sector application, a centralised production with distribution to refuelling stations). Alternatively, electrolysers can be installed close to the point of use with a more straightforward distribution mode (for example, in industrial sector application, the hydrogen production could be a local installation within the steel production facility).

Finally, these planning tasks are further influenced by the hydrogen adoption level and by the technology maturity, which have however been overlooked in the literature and represent one of the main challenges that renewable HSC managers have to face.

Storage. The main role of storage is to withstand any demand/supply fluctuation. In fact, as stated by Tlili et al. (2020), the role of hydrogen storage is twofold: 'on the one hand, it allows ensuring a seasonal storage in order to cope with the variability of renewable energy resources. On the other hand, hydrogen storage is a key component of the hydrogen supply chain allowing to bridge between discontinuous production and demand, exhibiting non-matching profiles'. Typical planning tasks related to hydrogen storage involve the type and number of facilities, facilities' capacities, and facilities' locations (Almansoori and Betancourt-Torcat, 2016), and these problems are usually solved with MILP models (De-León Almaraz et al., 2015; Güler et al., 2021).

Another planning task is related to the type of storage form. Hydrogen, in fact, can be commonly stored in two ways, as compressed hydrogen in high-pressure tanks and as liquid hydrogen in liquid tanks. The former is characterised by a lower energy volumetric density than the latter, but despite the special requirements for the vessel material, it involves relatively lower capital and operational costs (Agnolucci et al., 2013; Yang et al., 2021).

The planning tasks related to this process (i.e. storage type, facilities' locations, etc.) depend on the hydrogen adoption (hydrogen demand volume, location, etc.), and the tasks are interconnected with the decisions in the production and distribution processes (De-León Almaraz et al., 2015). For example, Yang et al. (2021) found that storing (and distributing) gaseous hydrogen is convenient when the demand is low and the distance to the point of use is short, while storing (and distributing) liquid hydrogen is more efficient and suitable for large-scale and long-distance transport. Similar results have been reported by Talebian et al. (2019) and Tlili et al. (2020). However, to make liquefied hydrogen solution operationally feasible and economically viable, technological advancements are still needed for a reduction in the capital and operational costs of liquefying hydrogen (Reuβ et al., 2017), or in the maturity of new technologies to store hydrogen, such as liquid organic hydrogen carriers (LOHC), hydrides, etc. (Reuβ et al., 2017; Tlili et al., 2020).

It is worth mentioning that the major studies regarding storage often deal with economic analysis, while environmental analysis has only recently raised concerns (Cantú et al., 2021; Kazi et al., 2021; Kim et al., 2021). However, what has completely been overlooked is safety analysis, which is particularly important in the case of liquid hydrogen, as a consequence of the boil-off problem (Al-Breiki and Bicer, 2021). Furthermore, as stated by Agnolucci and Mcdowall (2013), it would be interesting to include an analysis of the real lifetimes of facilities.

In conclusion, planning tasks related to this process depend on several factors. First of all, the location of storage facilities depends on the scope of storage (Woo et al., 2016): If the storage function aims to handle overproduction during the availability peak of feedstocks, it should be installed close to the production facility; while if the storage function is to buffer the fluctuation in demand, it should be installed close to the point of use. Also, storage can be seen along the distribution to balance the flows. Moreover, due to the seasonality of feedstocks, a renewable HSC may also need to consider strategic storage (Tlili et al., 2020).

Furthermore, the different planning tasks related to the storage process are interconnected, both in relation to the tasks and with the decisions taken in the production and distribution processes: As an example, the location of storage facilities depends also on their capacities, as well as on the type of hydrogen stored (liquified or compressed gas), and the decision is also affected by the distribution network (Yang et al., 2021; Xu et al., 2022).

Finally, we need to be aware of the impact that technological advancements and market development aspects have on these planning tasks. Technological advancements, for example, will lead to a reduction in capital and operational costs for liquefied hydrogen, hence rendering it more convenient, affecting not only the planning tasks related to the storage process, but also to the other processes.

Distribution. From a long-term perspective, the distribution process plays a vital role in effectively designing renewable HSCs. Typical planning tasks in the distribution process concern the identification of the most efficient and effective hydrogen transmission mode, and the choices are closely related to other renewable HSC processes (Johnson and Ogden, 2012). This was evident in Fig. 6, which illustrated that the distribution process is often discussed together with other processes in renewable HSC. The main factors affecting the choice of transmission and distribution modes are the physical states and the spatial and temporal hydrogen demands, in other words, the travel distance from the production site to the end-users and the hydrogen demand profile.

Similar to the storage process, hydrogen can be transported as a liquid or compressed gas. With the former, the major transmission methods are tankers via railways, roads or ships, while with the latter, hydrogen is moved via high-pressure pipelines, tube trailers or railway tube cars. Some articles have investigated the most cost-effective means of transporting hydrogen at scale. In this regard, based on distance and demand, compressed gas is preferred for short distances and at a small scale of hydrogen, while, as the values of these two factors increase, first liquid hydrogen is preferred, then giving way to gas hydrogen via pipelines, which is the most prominent option at large scale and for massive quantities (Reuβ et al., 2019; Griffiths et al., 2021; Lahnaoui et al., 2021). Exploiting existing infrastructures, such as natural gas grids, is an emerging and economically viable opportunity to boost hydrogen-based transition and reduce the costs of the distribution. In this case, its practical application faces some limitations related to pipeline material degradation and structural integrity (Cerniauskas et al., 2020; Quarton and Samsatli, 2020). Regarding related studies, current challenges focus on environmental and safety perspectives. The environmental impact assessment in terms of ecological performance and CO2 emission factors is discussed in an LCA analysis (Wulf et al., 2018) or carbon emission measurement (Reuβ et al., 2019). Several articles have discussed risk-related technical issues by considering hydrogen infrastructure safety performance, especially in terms of material properties (structures containing hydrogen whether in liquid or gas state), since several damage mechanisms, such as embrittlement and fatigue crack propagation, could occur for existing infrastructures (Ratnakar et al., 2021).

Finally, a recent research stream has focused on the potential conversion of hydrogen to other chemicals, such as ammonia or LOHC, since they can be stored under ambient conditions without the need for high pressure, resulting in a cost reduction (Bano et al., 2018; Hurskainen and Ihonen, 2020).

Moreover, to include the final application stage in the distribution stage, another related decision concerns the refuelling station. The major challenge is on the location and size of hydrogen refuelling stations, since the goal is to select appropriate geographic locations where a certain number of facilities can be arranged to meet determined end-users' demand, taking into consideration economic, environmental, technological, social, and energy constraints. To achieve this, several approaches are discussed, such as the MARKAL model (Gül et al., 2009), the flow-refuelling location model (FRLM) (Zhao et al., 2019), and the flow-capture location model (FCLM) (Crönert and Minner, 2021).

To summarise, one of the main planning tasks related to the distribution process is the selection of the hydrogen transmission mode. This decision depends on several factors, namely the available technologies, the volume of hydrogen in the supply chain, the distances to cover, and whether the hydrogen is liquified or compressed (Johnson and Ogden, 2012). Moreover, this planning task is interconnected with decisions on storage capacity and locations (De-León Almaraz et al., 2015). As with the storage process, it is important to consider the yield factor related to the process duration and potential leakages.

Finally, this planning task, together with the decisions regarding the location of refuelling stations or other points of use, are affected by the market development aspects (Zhao et al., 2019; Li et al., 2019).

Market and sales. Today hydrogen has become a particularly attractive option in a variety of new applications, such as the transport, residential, and industrial sectors for heat and power generation. In particular, the most prominent use lies in the transport industry, employed as FCEVs (public and personal transport) and internal combustion engines (limited to shipping and aviation) (Janic, 2008; Logan et al., 2020; Hensher et al., 2022). However, although its current practical use is rather limited in scope, very promising scenarios are on the horizon, leading to a rapid transition to a hydrogen economy. To boost this transition, more efforts are required to reduce the uncertainty in the estimation of hydrogen demand, which is a key aspect impacting the renewable HSC structure and thus other renewable HSC processes. For instance, the choice of centralised or decentralised production, as well as distribution modes, is strongly affected by the demand profile, since, when growth in hydrogen demand is expected, centralised production with a pipeline network is preferred. According to Li et al. (2019), three different approaches are adopted to forecast hydrogen demand: (i) the adoption of a logistic substitution curve, that is, an S-shaped diffusion curve to describe hydrogen market development as a function of time and number of adopters (Almansoori and Shah, 2009; Agnolucci and Mcdowall, 2013); (ii) the adoption of socio-economic factors estimated at spatial and temporal scale (Dayhim et al., 2014; Moreno-Benito et al., 2017); and (iii) a method based on a MARKAL/TIMES model, where the energy system model and a SC model is integrated, aimed at evaluating both infrastructure deployment, cost, and techno-economic specification (Agnolucci et al., 2013).

Specifically, long-term demand forecasts are crucial for market and sales, and these correspond to forecasting the market development. In addition to business, economic, political, and competitive factors (Li et al., 2019), which are included in traditional SCs, the level of adoption of hydrogen technology also significantly affects market and sales. Therefore, substantial investigation is needed when it comes to demand forecasts and their long-term projections.

The whole renewable HSC. As discussed in each process in renewable HSC, the planning tasks at each process both influence and are influenced by those at other processes in renewable HSC. For example, the distribution mode selected (truck, railway, pipeline, etc.) depends on the location of the production facilities with respect to the location of the point of use. On the other hand, the distribution mode determines whether liquid or gaseous hydrogen should be stored. Hence, it is critical that the renewable HSC design takes place with a holistic view, considering all the processes in renewable HSC, instead of being solely based on a single process. This is the only approach to ensure that the renewable HSC is optimised, and over the years, researchers have begun to understand this. Since the first study of Almansoori and Shah (2006) on HSC design, where only three processes were considered (i.e., production, storage, and distribution), an increasing number of studies have included all five processes (Cantú et al., 2021; Carrera and Azzaro-Pantel, 2021a; Moreno-Benito et al., 2017).

Moreover, researchers are suggesting multi-period analysis in designing renewable HSCs (De-León Almaraz et al., 2015; Han and Kim, 2019): renewable HSCs are optimised not just for a specific period but for an extended period, in other words, renewable HSCs are designed considering increasing hydrogen adoption. In fact, from the literature it emerges that the main factor influencing renewable HSC design is the level of hydrogen adoption. High investment costs for certain infrastructures (e.g. pipelines) are sustainable only if hydrogen adoption is high (Griffiths et al., 2021). Similarly, economies of scale are achievable only when the hydrogen demand is high (hence, when hydrogen adoption is high) (Agnolucci and Mcdowall, 2013). At the time point when hydrogen adoption is low, renewable HSC design is different to achieve cost efficiency (e.g., solutions with low investment costs have to be preferred), and therefore the profitability of renewable HSCs is questioned. In fact, Tlili et al. (2020) reported that at the beginning of hydrogen deployment, government incentives are crucial to help industries overcome the ‘death-valley’. They reported that an increase in hydrogen adoption from 1% to 5% led to a reduction in the cost of hydrogen of around 25%. Common incentives reported in the literature are CO_2 taxes (Cho et al., 2016; Contaldi et al., 2008). Another alternative to reducing the initial costs of renewabel HSC development is integrating the renewable HSC with existing infrastructure. Cerniauskas et al. (2020) reported that reassigning a gas pipeline to deliver hydrogen would lead to a 30% cost reduction in distribution (transmission) in comparison to a newly built hydrogen pipeline. Furthermore, to reduce hydrogen costs, it is important also to consider the possibility of integrating the renewable HSC with other energy systems; in this way, it is possible to reduce the initial investment by avoiding the establishment of new feedstock facilities (Almansoori and Shah, 2012) and by improving the utilization of production, since renewables’ intermittent feature will be mitigated (Won et al., 2017).

In the light of the above, we can summarise that a key aspect for an efficient renewable HSC is its cooperation. It is critical that the processes of a renewable HSC are integrated and correlated (Cantú et al., 2021). As there are different stakeholders and decision-makers who may influence or own various facilities of a renewable HSC, it is important to investigate the cooperation mechanisms and thereby strengthen the SC links, for instance, to achieve the proper configuration (vertical integration). Moreover, a renewable HSC needs to be integrated with other energy systems using electricity or providing energy carriers with other supply chains, where the by-products (for instance, oxygen) of a renewable HSC can be used. Thus, it is also important to find the right cooperation among supply chains (horizontal integration). Finally, the renewable HSC cooperation mechanisms are dynamic, that is, they depend on increasing hydrogen adoption.

Table 1 presents a summary of the planning tasks and the open challenges for each process in renewable HSC.

5.2. Mid-/short-term planning

This section discusses current research dealing with mid-/short-term planning tasks. Despite the limited number of studies on mid-/short-term planning tasks (see Fig. 6), there are still studies to be reported, as in the previous section, that have focused on the identification of the main mid-/short-term planning tasks and the associated challenges. Similar to long-term planning, the last subsection deals with the whole renewable HSC.

Sourcing. With the mid-/short-term planning horizon, the typical sourcing planning tasks deal with the selection of the feedstock, that is, the procurement strategy (Dagdougui et al., 2012). Due to the intermittent features of renewables, such as wind and solar power, the supply availability and consequently the cost of generating electricity both vary considerably (Tang and Rehme, 2017). Therefore, a procurement strategy can have economic benefits. Won et al. (2017) demonstrated that integrating multiple intermittent energy sources and dynamically selecting sources led to a substantial cost reduction, of between 30% and 63%, compared to systems with a single and dedicated energy source. Similar results were reported by other authors (Demirhan et al., 2021; Khojasteh, 2020; Yuansheng et al., 2021).

Another important planning task is defining contracts with suppliers. In the electricity market environment, the price can be decided beforehand, based on forecasted electricity prices, or it can follow market trends (MansourLakouraj et al., 2021), where it is possible to leverage

Table 1
Summary of the long-term planning tasks and open challenges of each process in renewable HSC.

HSC process	Planning tasks	Challenges
Sourcing	Selection of the best feedstock from an economic perspective	Sources' availability and quality over time Sources' location and accessibility Sources' costs Sources' uncertainty
Production	Selection of number, locations, technologies, and scales of production facilities	Trade-off investment costs Interconnected to other processes Renewable HSC adoption and market development Technology maturity
Storage	Selection of number, locations, type, and capacity of storage facilities	Interconnected to other processes
	Selection of hydrogen form	Potential leakages Renewable HSC adoption and market development Technology maturity
Distribution	Selection of distribution structure	Interconnected to other processes
	Selection of hydrogen form	Potential leakages Renewable HSC adoption and market development Technology maturity
Market and sales	Selection of most suitable market applications	Uncertainty in the estimation of hydrogen demand
	Long-term demand forecasts (sales planning)	Renewable HSC adoption and market development
Whole renewable HSC	Evaluation of the cooperation mechanisms for vertical and horizontal integration	Renewable HSC adoption and market development

demand-side management, as suggested by Mansour-Saatloo et al. (2020) and Seyyedeh-Barhagh et al. (2019). However, it should be noted that such decisions should present a holistic view of the whole renewable HSC, since the strategic adoption of hydrogen storage systems to deal with intermittent feedstocks cannot be neglected (Seyyedeh-Barhagh et al., 2019).

To summarise, the main planning tasks in mid-/short-term sourcing are twofold, namely defining the procurement strategy and defining contracts with suppliers. The former deals with the short-term selection of sources from a supplier portfolio, with the aim to compensate for daily fluctuations in availability and price (Won et al., 2017). The latter deals with setting the price (flat vs. variable, based on the electricity market), the total amount and the general conditions of supply (MansourLakouraj et al., 2021). This is often challenging because it is affected by two main aspects, which are the forecasting of feedstock availability and the price of energy sources. Specifically, the electricity price represents a crucial aspect to be investigated. In fact, renewable HSCs will be increasingly integrated with other energy SCs in the future, and interdependencies between supply chains will affect each other, with consequences for the coordination and allocation of resources.

Production. The main planning tasks include planning and scheduling production. In particular, according to Van Den Heever and Grossmann (2003), typical planning decisions are whether each plant operates in each planning period and the hydrogen production levels for each plant in each planning period. Typical scheduling decisions concern the exact production rate in each scheduling period and which customer to produce for (which refuelling station to serve). Similar mid-/short-term planning tasks were reported by other authors (Demirhan et al., 2021; Li et al., 2008; Yang et al., 2021). These decisions are closely linked to the forecasted availability, source prices, and demand. We also need to be aware that hydrogen production often needs to passively follow sources' availability. Due to the difficulties of forecasting, Van Den Heever and Grossmann (2003) have suggested that production planning and scheduling should be integrated. Also, to overcome the limitation that planning and scheduling have different time scales, they have suggested a rolling horizon approach.

As with the sourcing process, decisions here should also consider storage configurations (Yang et al., 2021). Moreover, it is important to include maintenance activities in production planning, but this has only been discussed to a limited extent (Woo et al., 2016; Yang et al., 2020).

In conclusion, the main tasks in the planning process are the planning and scheduling of production: Given the plan to use production resources (i.e., whether each plant operates in each planning period and the hydrogen production levels for each plant in each planning period), the weekly and daily (up to hourly) scheduling of production based on the actual performance of the electrolyser are decided. As in traditional SCs, these decisions are often challenging because of the difficulties in forecasting. Contrary to traditional SCs, as described above, forecasting availability and the prices of sources are very complicated (Van Den Heever and Grossmann, 2003). Furthermore, the planning tasks are closely connected to tasks in other planning processes, for example storage. Finally, these planning tasks should be integrated with monitoring, control, and maintenance of production plants.

Storage. Due to the spatial and temporal gap between production and demand, hydrogen storage is crucial (Reuβ et al., 2021). As described under the long-term planning tasks, storage is pivotal for coping with fluctuations and uncertainties in demand and supply (Woo et al., 2016). Typical mid-/short-term planning tasks are capacity planning and inventory management, which aim to determine which storage system(s) to use, their hourly inventory level, as well as their hydrogen consumption and filling rates (Yang et al., 2020). Moreover, another important aspect to be considered is the leakage and/or absorption of hydrogen from hydrogen storage systems (Xu et al., 2022). Gaseous hydrogen can leak from containers and can be absorbed by the container itself. Liquid hydrogen can leak as a consequence of the boil-off problem (Al-Breiki and Bicer, 2021). The leakage increases as the hydrogen, whether gaseous or liquid, is stored longer. Besides being a potential safety and environmental hazard, this also represents a yield or quantity loss issue, which needs special attention as an inventory management aspect (O'Dwyer et al., 2022; U.S. Department of Energy). Furthermore, storage-related decisions should also consider the operational costs of feeding in and releasing out hydrogen from the storage (Al-Breiki and Bicer, 2021; Liu et al., 2010). Finally, although the maintenance requirements for storage systems are high, their impact on capacity planning has not been discussed in the literature (Garcia et al., 2016; U.S. Department of Energy).

In conclusion, knowing the size and capacity of storage systems from long-term planning tasks, the mid-/short-term planning tasks are quite related to resource capacity planning and inventory management in terms of how much to fill different tanks and for how long. The main challenge of these tasks is that they should consider the yield factor related to potential leakages (O'Dwyer et al., 2022). Moreover, there is a clear link between the performance of the storage system and its monitoring, control, and maintenance.

Distribution. The mid-/short-term planning tasks here are related to the scheduling and routing of hydrogen distribution from the production site or storage system to the final point of use (He et al., 2021a, 2021b). In particular, since the selected articles mostly deal with the transport sector, refuelling stations are considered as the final point of use. For instance, Reuβ et al. (2021) proposed an optimization model to connect the production site and the fuelling stations by including the factors of distance, time, and cost. In addition, their model also considered the refuelling stations' demand and production sites' capacity.

Sometimes, these mid-/short-term planning tasks are integrated with the long-term ones (e.g., decisions about the siting of the refuelling stations). In this case, researchers have focused on traditional location routing problems. This is the case with Kang and Recker (2014), who '*developed a facility location problem with full-day scheduling and routing* *considerations*'. Their study indicated the importance of integrating long-and mid-/short-term planning tasks, since decoupling the two levels by adopting only a location model *'significantly overestimate[s] the number of stations required'*. Moreover, the planning tasks of this process are interconnected with the planning tasks of other processes, especially production and storage (Yang et al., 2021).

To summarise, in this process, decision-makers should plan the transport between stages, in particular from electrolysers to storage and from storage to point of use, based on the distribution modes and their capacity selected in long-term planning. Daily and weekly, decision-makers should schedule deliveries according to routing policies (Kang and Recker, 2014). The complexity of these tasks is that they are linked and interconnected to both the long-term distribution planning tasks and the mid-/short-term planning tasks of other processes (especially other production and storage tasks) (He et al., 2021a; Yang et al., 2021).

Market and sales. As we have seen, hydrogen demand, both in terms of quantity and variability, has a high impact on the mid-/short-term planning tasks (Li et al., 2018). However, despite this important factor, no study has discussed related issues, such as forecasting methods. Similarly, there is no study on mid-/short-term sales planning.

The whole renewable HSC. As discussed before, processes in renewable HSCs are interconnected with each other, and this is also valid for mid-/short-term planning. Therefore, typical mid-/short-term planning tasks (e.g., resource capacity planning) require a holistic perspective, where the interdependencies of the different planning processes are considered. Production planning, for example, is affected not only by internal aspects (e.g., maintenance planning), but also by aspects related to the sourcing process, such as sources' availability and variable prices, since these can limit the production rate. Storage capacities should consider internal aspects (e.g. problems of leakage and boil-off gas (O'Dwyer et al., 2022)). Sometimes distribution modes (trucks, pipelines, etc.) not only serve as a distribution but also as a storage function. In fact, He et al. (2021a) proposed a flexible scheduling and routing model in which hydrogen trucks serve as both distribution and mobile storage in order to '*make intermittent electrolytic H_2 production more competitive by providing extra spatiotemporal flexibility*'. They reported a decrease of the hydrogen cost by 9%, thanks to a reduction of the required trucks and stationary storage capacities of 83% and 165%, respectively. Van Den Heever and Grossmann (2003) suggested a similar idea of viewing pipelines as storage. However, studies that adopt a holistic perspective are still lagging.

In conclusion, the different mid-/short-term planning tasks need to be integrated, and a holistic view is essential for the success of renewable HSCs. This, however, complicates the decision-making process. Moreover, renewable HSC managers have to be aware that, contrary to traditional SCs, in renewable HSCs the different planning tasks are mainly supply-driven, since sourcing availability is an important influential factor (Reuβ et al., 2021). In the light of this, inventory management is crucial, both at the sourcing level (feedstock inventory management) and at the production level (H_2 products' inventory management), to smooth the material flow and the energy flow along the entire renewable HSC.

Table 2 presents a summary of the planning tasks and the open challenges for each process in renewable HSC.

Table 2
Summary of the mid-/short-term planning tasks and the open challenges at each process in renewable HSC.

HSC process	Planning tasks	Challenges
Sourcing	Selection of the procurement strategy Definition of contracts with suppliers	Sources' condition (price of energy sources, forecasting of feedstock availability, etc.)
Production	Planning and scheduling production	Forecast sources' availability, prices, and demand Interconnected to other processes Integration with maintenance
Storage	Resource capacity planning Inventory management	Potential leakages Interconnected to other processes Integration with maintenance
Distribution	Scheduling and routing of distribution	Interconnected to long-term distribution planning tasks Interconnected to other processes
Market and sales	Sales planning	No study on mid-/short-term sales planning
Whole HSC	Resource capacity planning Inventory management	Planning tasks are supply-driven

6. Planning matrix for renewable HSCs

The synthesis of content analysis has allowed us to determine the planning tasks for the different time horizons and processes in renewable HSC involved, which are summarised in the renewable HSC planning matrix presented in Fig. 7.

Due to the uncertainty of technology and unclear renewable HSC adoption and market development, even though there is an expectation of a high demand for hydrogen in the future, the growing path of renewable HSCs is undecided. As mentioned above, previous literature focused on these aspects investigating the impact of technology uncertainties and demand development on the structure and cost of renewable HSCs. While in this section, we discuss how the adoption of renewable HSCs and, consequently, the phases of their market development will imply different objectives and stakeholders involved in the decision-making process for each planning task.

As renewable HSC scale-up is essential for reducing the cost and thereby the market price, there is a chicken-and-egg issue, that is, how to create incentives for stimulating the expansion on both sides of hydrogen supply and demand. For instance, for fuel cell (FC)-enabled vehicles, the market development of vehicles should cope with the design of renewable HSCs, so that the size of the hydrogen infrastructure fits its demand growth. On the one hand, a renewable HSC needs a significant investment in infrastructure and a critical mass for its development, for instance production, storage, and distribution facilities to support refuelling stations, for its application. Hydrogen distribution costs will remain significant if key infrastructures are lacking. Therefore, renewable HSC investors would like to see a strong demand for FC-enabled vehicles and thereby hydrogen. On the other hand, FC-enabled vehicle producers would like to expand the market and production only if there is sufficient support for operating the vehicles, in other words, a network of refuelling stations. But, without a scale-up demand, there is a lack of incentives for renewable HSC infrastructure investment. In addition, there is technology uncertainty with regard to the development of renewable HSC infrastructure and stages. Even though some technologies are ready, some need to be proven at scale while others still need to be tested and proved.

Fig. 7 presents renewable HSCs as a sociotechnical system (Griffiths et al., 2021), highlighting how the SC planning tasks identified in previous section, and the adoption of renewable HSCs are affected by external drivers, both institutional drivers and end-users. As discussed in the introduction, many countries are developing roadmaps and strategies (institutional drivers, for example cap and trade or carbon tax programmes) to enhance the adoption of renewable HSCs. Also, end users are driving the adoption of renewable HSCs with an increasing awareness of the need for a sustainable future, also stimulated by new incentive schemes from governments.

These drivers have a relevant impact on defining the objectives of planning tasks introduced in the previous section and consequently affect the supply chain configuration and operations (Griffiths et al., 2021). First, external drivers impact factors that characterise the adoption level, such as the hydrogen demand volume and renewable HSC scale (regional to national/international). Second, as different

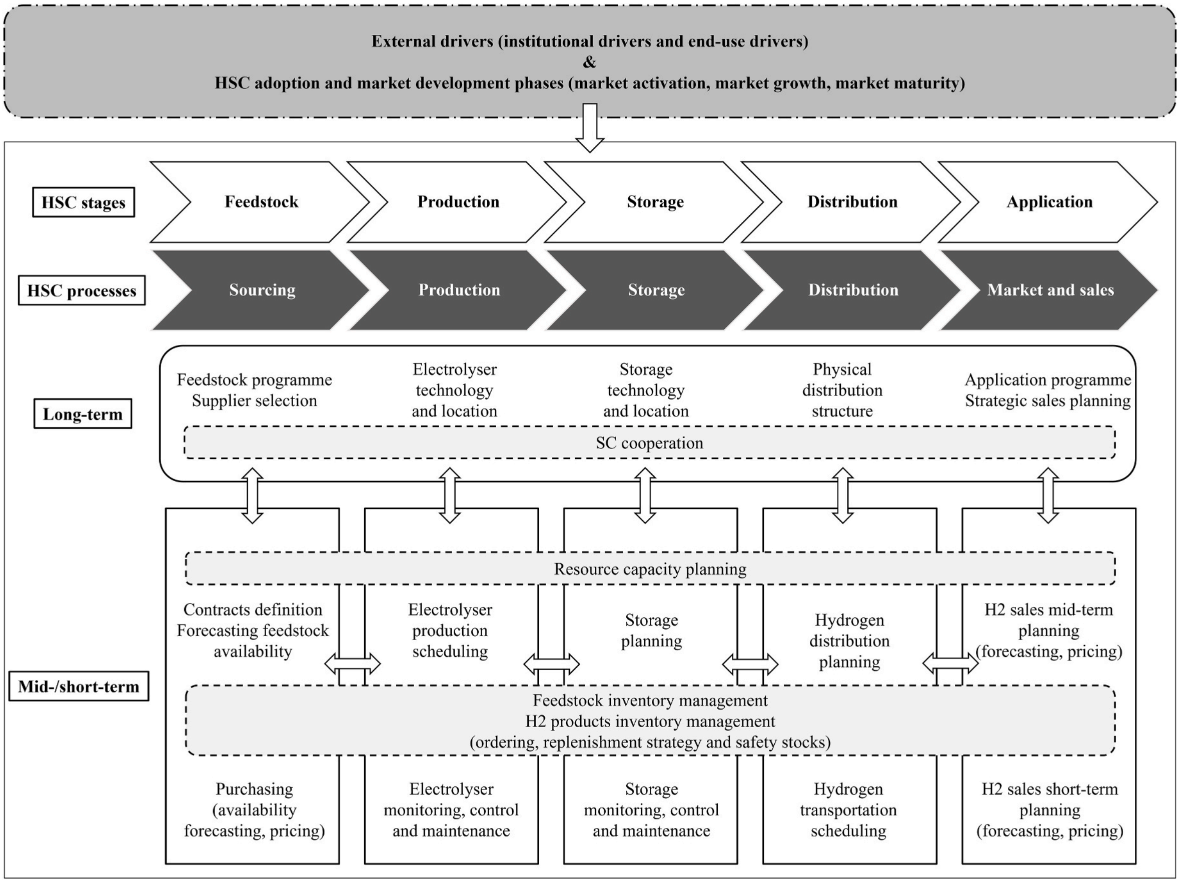

Fig. 7. Planning matrix for renewable HSCs.

decision-makers and stakeholders are involved, the external drivers impact specific objectives that support the selection of solutions to the planning tasks previously defined.

Understanding the stakeholders' objectives is essential for the successful market development of renewable HSCs. Below we summarise the different phases of market development and how renewable HSC planning tasks are affected (see also Table 3):

- *Market activation:* Currently (2020–2030), we are in the early phases of adoption of renewable HSCs, where actors are innovating and activating the market, creating new opportunities and new challenges. Here, the main stakeholders involved are governments, R&D institutions, and major players in the energy and transport sectors. Their goal is to develop and demonstrate the feasibility and applicability of renewable HSCs through the implementation of mature technology. In these phases, there are strong incentives and investments to support the main objective of first adoptions with first

Table 3
Summary of the impact of different phases of market development on HSC planning tasks.

	Market activation 2020–2030	Market growth 2030–2040	Market maturity 2040–2050
Main stakeholders	Governments R&D institutions Major players in the energy and transport sectors	Producers Distributors Investors	Producers Distributors
Secondary stakeholders	Producers Distributors Investors	Governments R&D institutions	Governments R&D institutions Investors
Objectives	Development of first adoptions with first network infrastructures	Positioning in the market, extending the network infrastructure and services	Keeping operations up and running efficiency
External drivers	Strong incentives and investments from governments for first adoptions Limited impact of market demands/requirements – mainly from early adopters	Strong market policies and demands/requirements Dedicated incentives from governments for boosting impact on emissions Market policies and user demands/requirements	Strong market policies and demands/requirements Dedicated energy policies from governments for increasing resilience
Primary KPI	Feasibility and applicability of renewable HSCs	Market share	Cost Efficiency Service level
Secondary KPI	Cost Efficiency Impact on emissions	Cost Efficiency Service level Impact on emissions	Impact on emissions

network infrastructures, led by early adopters. Knowledge should be obtained to stimulate and understand how renewable HSCs penetrate markets. Efficiency, cost, and impact on emissions are secondary indicators that are monitored to indicate future directions.

- *Market growth:* According to the roadmaps and strategies, in the next decade (2030–2040), when the market has been activated and the first renewable HSCs are in operation, there should be a phase of constant market growth, where the role and presence of government institutions will diminish to support the extension of initial networks, while R&D institutions will focus on developing more mature technologies (more efficient and reliable), while the adoption of renewable HSCs is driven by market policies, where different actors (producers, distributors, and investors) compete with the main goal of positioning themselves in the market, extending the network infrastructure and services, following traditional market policies and demands/requirements. Here, the main indicators used by these stakeholders are market share, cost, efficiency, and service level, while governments can support the adoption with some policies to incentivize the use of green hydrogen and so pursue the continuous reduction of emissions.
- *Market maturity:* Finally, from 2040 to 2050, there should be a phase of mature market development, where the competition between renewable HSCs will be based on cost, efficiency, and service level, since the environmental purpose has mainly been reached. The main objective will be to keep the renewable HSCs operations up and running. The economic growth here is based on technological leadership, but the operations of renewable HSCs will still be affected by external factors related to the market policies in particular in energy sector (such as electricity price, feedstock availability, etc.). Governments will probably act as observers, and in the case of disruptions or extraordinary events in the energy sector, they will intervene considering the different energy supply chains involved.

7. Agenda for future research

After defining the decision problems as planning tasks (Section 5) and how their solutions depend on the different objectives influenced by stakeholders involved along the different phases of renewable HSC adoption and market development (Section 6), we discuss the potential approaches and propose an agenda for future research on renewable HSC planning.

- *Extended renewable HSC design modelling.* Modelling approaches (both material flow-based and energy-based) need to consider the whole renewable HSC (vertical integration) and its relationship with existing energy supply chains (horizontal integration). In addition to the material flow, financial/economic flow and information in conventional supply chains, it would be interesting to investigate how to combine energy flow and possibly emissions along entire renewable HSCs. This gives a new direction from the supply chain management perspective. Here, storage has a paramount importance and role to keep energy stored compensating for the high level of uncertainty, so it is mandatory to include the inventory management problem as central in the design and operations of renewable HSCs to find an optimal trade-off.
- *Multi-objectives and multi-decision makers' approaches.* There are many stakeholders in the development of renewable HSCs with various concerns regarding the performance of renewable HSCs, especial in the initial phase of renewable HSC adoption (see Table 3). Current studies seldom clearly distinguish these differences, often with conflicting concerns, such as the ownership of the hydrogen costs (see chicken-and-egg puzzle). The environmental performance concern, from a government perspective, adds even more complexity (Carrera and Azzaro-Pantel, 2021b). Risk and safety in renewable HSCs are other important aspects to be considered in some operations along renewable HCSs, such as storage, transport, and bunkering (Fazli-Khalaf et al., 2020). Multiple objective approaches are mandatory to comprehend the different objectives that the different stakeholders have. The approaches also support multiple decision-makers in finding the most appropriate solutions, thereby providing guidelines for designing policy support schemes to stimulate renewable HSC adoption.
- *Robust renewable HSC design.* Future research should focus on the development of decision support systems that can guide stakeholders in selecting the most appropriate configurations based on the evolution of the adoption level, in other words, decisions which not only provide a sound outcome at the decision timepoint, but also prepare favourable options when the future event (such as the selection of technology) has been revealed (Güler et al., 2021). Alternatively, we should consider the possible dynamic expansion of capacity (electrolyser and other facilities) by using diffusion models. As the TRL and market development are changing over time, the decision of capacity and location should open options for future increases. Option and real option models could be used for such investigations. Also, the impact of government incentive schemes (for example, cap and trade, carbon tax, and R&D funding), development of technologies and their maturity, integration with existing infrastructure (i.e. existing pipelines), and the different levels of competition/cooperation among the actors in the supply chain need to be considered in a multi-scenario analysis where uncertainties about their evolution are included to find the most robust configuration (Cho et al., 2016; Contaldi et al., 2008). In short, along with the TRL and market development, we need develop a vision for renewable HSC adoption pathways.
- *Feedstock-driven supply chain.* The production of green hydrogen is strongly related to the availability and quality of feedstocks. The feedstock supply of hydrogen, such as solar and wind power for electricity, is often uncertain. This may not be the case in a traditional SC, as the supply can usually be stably maintained, for instance, in a typical manufacturing SC. Hydrogen production is more supply-driven than demand-driven according to current supply chain studies. The selection of the feedstock portfolio has still not been thoroughly investigated, and uncertainties in quantity, quality, and cost need to be included in the renewable HSC configuration and operations (Han and Kim, 2019). In the long term, climate changes can also impact feedstock availability, so studies should consider external factors in a dynamic way. As supply fluctuation is an important feature of a renewable HSC, it is also interesting to investigate the reverse bullwhip effect, that is, how information disruption affects the supply chain operation but with the source of impact from the upstream of a supply chain.
- *Case studies and data accessibility.* Current studies mostly highlight long-term planning instead of short-term planning, for instance, network designs of hydrogen production and distribution. Facing the pressure of developing cleaner energy systems, scholars are investigating various settings of renewable HSCs. However, data on hydrogen applications is often missing in these studies (Agnolucci et al., 2013), or in some better situations there are limited examples of hydrogen applications. Lacking benchmark operations systems and data makes the analysis at the detail (short-term) level less thorough. Also, the validation of models is often missing in current studies, including the validation of assumptions concerning the links between long- and mid-/short-term planning. Typical cases at different stages of the renewable HSC should be presented. Due to the current low level of adoption, most of the data still come from experimental or small-scale applications, and they need to be adapted to predict the potential evolution of technology in terms of performance and cost.
- *Transition to other industrial applications.* The transport sector still dominates the main focus of renewable HSC studies. The common structure of a renewable HSC includes wind, solar and hydro sources (small scale) as the feedstock, electrolyser, compressed tube storage,

and distribution (refuelling stations). These studies present new knowledge about renewable HSCs. On the other hand, there are fewer studies on hydrogen applications in the steel industry or buildings, which have different features of demand, requirements of distribution, etc., and are worth investigating in the future. Identifying the similarities and differences between HSCs in different sectors is important. There should be a general HSC framework with emphasis on vertical and horizontal integration, in order to cohere renewable HSC adoption.

- *Integrated resource capacity planning.* Weekly and daily plans need to consider the variability in supply and demand, as well as integration with other energy supply chains and applications (Won et al., 2017). Specifically, integration with the electricity market and the price of electricity should be a relevant factor in planning, since these factors impact all the phases of the supply chain. Overall resource capacity planning is preferable instead of a local optimal solution at each stage (feedstock, production, storage, and distribution). This requires advanced and more complex models that need to be validated using data from applications. Hydrogen production is more likely a continuous process (such as the refinery and chemical process), but hydrogen distribution could still be either a discrete or continuous process. Control theory should play a role in short-term planning and scheduling to cope with the processes. When the level of the hydrogen pathway adoption is relevant, data-driven approaches can be applied to find quick, effective, and robust solutions to planning problems.
- *Extended inventory management models.* As storage and distribution are major activities in HSCs, future research should extend the traditional inventory management models to include features of renewable HSCs, such as the integration of material flow and energy flow, volume versus mass of stocked hydrogen, lifetime and duration of stocked hydrogen, storage performance (i.e. % leakage), and risk and safety issues in storage and operations (O'Dwyer et al., 2022). A renewable HSC can also be viewed as a feedstock-driven supply chain, therefore the intermittent and uncertain supply should be highlighted by extending the insights of existing inventory management models (Weitzel and Glock, 2018). In addition, in planning and controlling storage in HSC, we should pay extra attention to the time interval of modelling, as operations and market trading practice provide information updating and decisions on an hourly basis (Finnah and Gönsch, 2021). However, existing studies often assume a large time interval (daily and weekly), because stochastic modelling such as the Markov decision process is more challenging (Fokkema et al., 2022; Schrotenboer et al., 2022).
- *Combined forecasting modelling.* Supply and demand forecasts are affected by several factors, thus advanced modelling based on data-driven approaches should be developed to overcome the limitations of traditional time-series forecasting. For example, environmental conditions impact feedstock availability and local incentives for hydrogen adoption and pricing policies for the electricity sector impact the final demand for hydrogen. Weather forecasts and the evolution of the electricity market are among the other external factors to be included in forecasting models for feedstock and hydrogen demand. Scenario analysis is an alternative for providing settings for long-term forecasting and planning, whereas data analytics and data mining could provide some insight into supply and demand patterns, thereby supporting short-term forecasting.

8. Conclusion

To achieve a fossil-free energy system in the future and reduce emissions, countries are initiating and investing in hydrogen research and development as well as their infrastructures. Because of these strategies for more sustainable solutions, we are at a time point welcoming the potential scale-up of renewable HSC operations. Along with these opportunities, we also encounter challenges, which include the operational characteristics of renewable HSCs, uncertainty of technology, the impact of national roadmaps and strategies, and market development, among others.

Against this background, we have introduced for the first time a renewable HSC planning matrix, where the different planning tasks are identified. Specifically, the planning tasks are determined based on the content analysis of the literature review, and they are reported with respect to two planning horizons, namely long-term and mid-/short-term, and with regard to the different planning processes in renewable HSC (sourcing, production, storage, distribution, and market and sales). From the analysis of planning tasks, it emerges that: (i) it is important to consider jointly the planning tasks related to the different processes, since these are interconnected, and (ii) the adoption of renewable HSCs and market development are important factors which impact the definition of planning tasks. Based on the content analysis, we were able to derive a research agenda.

Our content analysis indicates that the function and planning tasks of sourcing, production, storage, distribution, and market and sales should be considered jointly. However, designing and operating a renewable HSC is not easy, as there are many influential factors and choice alternatives at each stage of the HSC to determine the final choices. The renewable HSC adoption and market development are important factors that impact the definition of planning tasks and decision-makers' objectives in the planning process. Specifically, we need to understand the various concerns of stakeholders along with the development pathways, and therefore introduce accordingly appropriate objective functions and assumptions in modelling the supply chain management.

The derived research agenda is encouraging, as the development of renewable HSCs opens new areas for research and investigation. We may need to incorporate incentive schemes in renewable HSCs (Nordic Energy Research, 2022) so as to improve the coordination of the system in initiating a renewable HSC operation. Also, along with the dynamic development of renewable HSCs, we may apply real-option models and diffusion models to examine investment alternatives, so that infrastructure expansion can cope with market development and technology readiness. Subsequently, renewable HSC development becomes business-driven. Also, some mid-/short-term planning problems have not been tackled, for instance, the yield and quantity losses in hydrogen storage and distribution, which provide opportunities to extend inventory management studies. The addition of energy flow provides another lens to view a supply chain. It should facilitate the performance measure of the system but could also complicate the analysis. Our research agenda should provide guidelines for those scholars interested in improving renewable HSCs. Moreover, it should provide insights and overview of the challenges of the renewable HSCs planning tasks useful for both managers directly involved in the design and management of renewable HSCs and managers whose companies are strongly energy-dependent.

This study also has some limitations. We have focused mainly on electrolyser-based production, but we have not considered carbon capture and storage systems. Furthermore, we have indicated the importance of integrating other energy systems, but these energy systems (for instance, electricity) are often viewed as external inputs to renewable HSCs. Nevertheless, we have not stressed that a scale-up renewable HSC may affect the electricity production and market, largely due to the relatively small scale of renewable hydrogen in the current situation. These concerns will affect hydrogen operations and therefore renewable HSCs. Some future discussions of these aspects should be welcomed to support the transition to a low-carbon future energy system and society.

Data availability

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Appendix A

Table A1
List of the 70 most relevant journals used in the SLR

List of Journals	
Advances in Production Engineering and Management	Journal of Manufacturing Systems
Annals of Operations Research	Journal of Manufacturing Technology Management
CIRP Annals - Manufacturing Technology	Journal of Operations Management
Computers and Industrial Engineering	Journal of Purchasing and Supply Management
Computers and Operations Research	Journal of Rail Transport Planning and Management
Computers in Industry	Journal of the Operational Research Society
Decision Sciences	Management Science
EURO Journal on Transportation and Logistics	Manufacturing and Service Operations Management
European Journal of Operational Research	Manufacturing Review
Expert Systems with Applications	Mathematical Methods of Operations Research
Flexible Services and Manufacturing Journal	Mathematics of Operations Research
IEEE Transactions on Systems, Man, and Cybernetics: Systems	Naval Research Logistics
Industrial Management and Data Systems	Omega
International Journal of Advanced Manufacturing Technology	Operations Management Research
International Journal of Logistics Management	Operations Research
International Journal of Logistics Research and Applications	Operations Research Letters
International Journal of Management Science and Engineering Management	Operations Research Perspectives
International Journal of Operations and Production Management	OR Spectrum
International Journal of Physical Distribution and Logistics Management	Production and Operations Management
International Journal of Production Economics	Production Planning and Control
International Journal of Production Research	Public Transport
International Journal of Shipping and Transport Logistics	Research in Transportation Business and Management
International Journal of Sustainable Transportation	Robotics and Computer-Integrated Manufacturing
International Journal of Systems Science	Supply Chain Forum
International Journal of Systems Science: Operations and Logistics	Supply Chain Management
International Journal of Transportation Science and Technology	Sustainable Cities and Society
International Transactions in Operational Research	Transport Reviews
Journal of Advanced Transportation	Transportation
Journal of Air Transport Management	Transportation Research Part C: Emerging Technologies
Journal of Business Logistics	Transportation Research, Part A: Policy and Practice
Journal of Cleaner Production	Transportation Research, Part D: Transport and Environment
Journal of Engineering and Technology Management - JET-M	Transportation Research, Part E: Logistics and Transportation Review
Journal of Environmental Economics and Management	Transportation Research, Series B: Methodological
Journal of Management	Transportation Science
Journal of Manufacturing Processes	Transportmetrica A: Transport Science

Appendix B. LIST OF 202 SELECTED ARTICLES

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