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Coalition analysis for low-carbon hydrogen supply chains using cooperative game theory

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ABSTRACT

Low-carbon hydrogen is a promising option for energy security and decarbonization. Cooperation is needed to ensure the widespread use of low-carbon energy. Cooperation among hydrogen supply chain (HSC) agents is essential to overcome the high costs, the lack of infrastructure that needs heavy financial support, and the environmental failure risk. But how can cooperation be operationalized, and its potential benefits be measured to evaluate the impact of different allocation schemes in low-carbon HSCs? This research works around this question and aims to analyze the potential of cooperation in a generalized low-carbon HSC with limited and critical resources using systems and cooperative game theory. This work is original in several aspects. It evaluates cooperation effects under different benefit allocation schemes while considering infrastructure agents' dependencies (production, transportation, and storage) and specific traits. Additionally, it provides a transparent, replicable methodology adaptable to various case studies. It is highlighted that HSC coalitions form hierarchies with veto power, pursuing common goals like maximizing decarbonization and demand fulfillment. A cooperative game theory toolbox is developed to evaluate, display, and compare the results of six allocation solutions. The toolbox does not aim to determine the best allocation scheme but rather to support smart decision-making in the bargaining process, facilitating debate and agreement on a trade-off solution that ensures the viability and achievement of long-term coalition goals. It is built on three naïve and three game-theoretical allocation rules (Gately, Nucleolus, and Shapley value) applicable to peer group games with transferable utility. Results are presented for an 8-agent low-carbon HSC along with the total environmental benefit, the allocated individual shares, and numerical indicators (stability, satisfaction, propensity to disrupt), reflecting the acceptability of allocations. Numerical results show that the Nucleolus achieves the highest satisfaction among stable allocations, while the Gately allocation minimizes disruption propensity. Naïve rules yield different outcomes: "equal distribution for producers" carries the highest risk, whereas "equal shares for all agents" and "proportional to individual benefits" rules are stable but perform poorly on other criteria.

1. Introduction

Energy transition must be accelerated to provide inexpensive and clean energy, as energy consumption is expected to rise [1]. Renewables intermittency has been a limitation to the penetration of renewable energy sources (RES) in the energy mix. To meet this challenge, hydrogen (H_2) represents a promising alternative to recover the overproduction of electricity (e.g., from solar and wind parks), creating greater flexibility in energy systems [2]. A hydrogen supply chain (HSC) can be defined as a system connecting different stakeholders or agents who are represented by nodes (Fig. 1). Main supply chain nodes include energy sources, hydrogen production, transportation, storage, and distribution to the end customer. The introduction of large-scale low-carbon[1] HSCs is envisioned to play an important role in reaching net-zero greenhouse gas emissions due to its high decarbonization potential [3,4].

There are several low-carbon options in HSCs and these are, in some cases, labeled by colors to differentiate their environmental impact

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[1] In this work, the term low-carbon hydrogen is used instead of green hydrogen to create a generic scenario that can be applicable to several countries or regions.

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depending on the energy sources and production technologies used [5]. Today, the status quo corresponds to the so-called gray hydrogen produced using steam methane reforming (SMR), and blue hydrogen is produced when carbon capture and storage (CCS) is added to SMR technologies [6]. The definition of green hydrogen is more complex since it has been used in different ways in the last two decades, sometimes referring to the use of renewable energy sources and some other low-carbon hydrogen options [7]. The debate over hydrogen labeling has led to the introduction of new definitions, such as those proposed by the Renewable Energy Directives of the European Commission: Renewable Fuels of Non-Biological Origin (RED II (EU) 2018/2001) [6]. Other HSC nodes are hydrogen conditioning form (gas and liquid), transportation (tube trailers and pipeline for gaseous H_2; tanker trucks for liquid H_2; solid-state hydrides for solid H_2), storage (cylindrical tanks for gaseous H_2, spherical tanks for liquid H_2), and distribution to the focal agent, e.g., industry or other markets like refueling stations [8–11]. The arrows from Fig. 1 represent the sequential dependency of the different technologies while the transportation of hydrogen (in long distances) is explicitly mapped by the transportation node. At a global level, it is anticipated that hydrogen fuel and feedstock will be categorized based on their carbon footprint rather than using color labels, with differentiated pricing for low- and high-carbon hydrogen, as one aspect of the value of hydrogen for business customers [11]. Thus, each kilogram of hydrogen is expected to have an associated environmental impact based on its life cycle assessment [12], depending on the HSC used.

Low-carbon options align with the Green Deal Industrial Plan expressing that the achievement of climate neutrality by 2050 will require full mobilization and deeper cooperation among all stakeholders or agents operating across the different chains of Europe's net-zero industry [13]. The topic of cooperation has been addressed in various fields, including biology, sociology, economics, and supply chain management. There are several theories related to cooperation, e.g., evolution theory [14,15], social exchange theory [16], network analysis [17], behavioral theory [18,19], cooperation for innovation [20], tragedy of the commons [21,22], Rawls' theory of justice (fairness) [23], complexity theory (agent-based modeling) [24], systems analysis, stakeholders and resource dependence theory [25,26], game theory [27,28], etc. Different theories can be interconnected, and multidisciplinary approaches are often needed. As an example, Axelrod and Hamilton [29] developed multidisciplinary research by linking mathematics, economics, and political sciences through game theory by analyzing cooperation in the prisoner's dilemma [30]. Cooperation is an evolving topic in hydrogen research. Some works address cooperation from a policy perspective, highlighting the importance of hydrogen storage and transportation or hydrogen energy industrial cluster dynamics [31]. Others consider technological agents [32], use collaborative innovation theory based on patent data [33,34], have concrete applications, e.g., hydrogen fuel cell vehicles in Qatar and the Gulf Cooperation Council [35], or focus on participatory theory, public engagement, and trust [36]. Policy and technological cooperation are important topics [31]. Other research gaps relate to private involvement and government collaboration [37], but academia, industry, research, regions, and clusters are also identified as key participants [31,34].

Moreover, several authors have pointed out that it is not enough to analyze separately the problems of hydrogen production, storage, or transport to develop the hydrogen economy [38,39], since stakeholders in hydrogen initiatives often have conflicting visions, interests, and objectives, creating challenges in collaboration, coordination, and acceptability [40]. The discussion on the viability of the low-carbon HSCs is dominated by economic analysis focusing on cost efficiency and the effectiveness of investments [41,42], and only a few studies focus on how to maximize decarbonization benefits [39,43–45], although the two should be achieved parallelly. Even less papers discuss potential trade-offs between these aspects [7,46,47]. If the stakeholders with different visions towards hydrogen can be articulated and put together, a win-win approach could occur [48–50]. According to Ricci et al. [36], trust is lacking in political authorities, businesses, industries, and across various social groups. Analyzing agent dynamics could help unify varied interests around shared goals [51]. A systems perspective is needed to make the green transition a reality [38,39]. In a systems approach, the environmental impact of the HSC is an additive process,

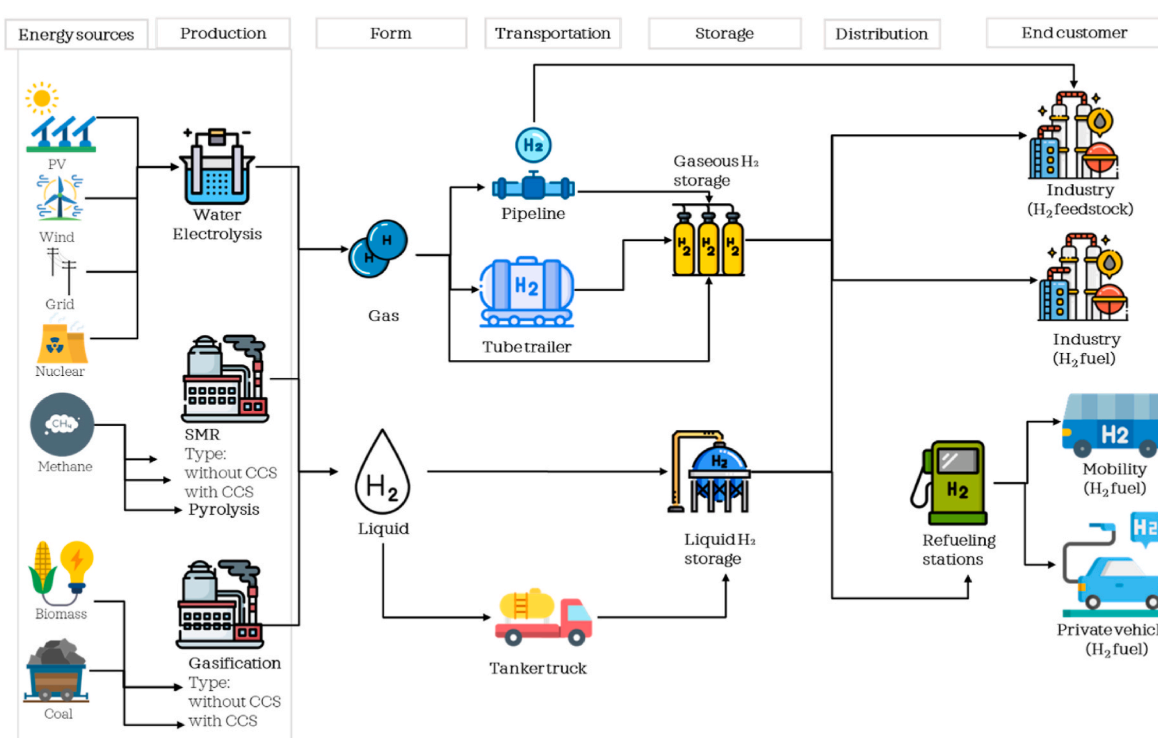


Fig. 1. A generic hydrogen supply chain (for H_2 fuel and feedstock). *Icons*: flaticon.com.

where the different HSC agents together make up the overall environmental impact. The vast, interrelated ecosystem reveals the complexity and tension between macro-level ambitions for hydrogen and the micro-level realities of its integration across sectors and stakeholder groups [52]. In addition, risks and benefits are acceptance factors for stakeholders [53].

Investments facilitating HSC scenarios without the capacity to achieve maximum decarbonization benefits would lead to environmental failures [39]. This paper argues that to avoid the risk of such failures, the quantification of the emissions (environmental benefit) must be done by following a systems approach [43–45]. In addition, this risk must be considered when developing effective financial policies [54,55] and appropriate incentive schemes facilitating cooperation among HSC agents. De-risking, risk-sharing, and customized financing solutions are needed [56]. In this sense, it is expected that groups of agents of HSCs will cooperate and form coalitions to be eligible for financial support capable of mitigating risk [50]. One definition of a coalition refers to "companies in physical proximity (region, cluster, industrial park/site) sharing energy-related assets (e.g. renewable energy generation, energy networks, energy storage), or energy services, implementing energy exchanges (e.g. recovery and use of waste heat from industrial and manufacturing processes) or being involved in energy communities" [13]. Based on contract and game theory, agents in a typical coalition follow some allocation rules on how the benefits achieved through cooperation should be shared among members [57].

Cooperative game theory has been identified as one of the most used theoretical frameworks, as detailed in Section 2.2; and together with a system approach, it provides a useful quantitative option to analyze the effects of cooperation in HSCs. Based on the literature review on hydrogen and collaboration with a specific focus on cooperative game theory, five research gaps are identified in relationship to the analysis of (1) HSC structure, (2) HSC hierarchy, (3) agents' dependency, (4) allocation rules used, and (5) results' comparison and visualization tools. The main objective of this research is to use a system approach and cooperative game theory for calculating the maximum decarbonization potential of a generalized low-carbon HSC scenario that captures multiple agents' particularities (type, decarbonization potential, hierarchical position, and capacity), and to analyze the effects of cooperation under different benefit allocation schemes. Another objective is to provide a detailed and transparent methodology that can be easily replicated and extended to different case studies. As a general hypothesis, it is assumed that if the different stakeholders have clarity in terms of the potential risks and benefits, they might be willing to collaborate if a positive outcome is ensured. In this sense, the identification of a common goal, decarbonization in this case, allows the calculation of the total benefit and its allocation to the different agents of the coalition. The motivation is to offer a toolbox for informing agents about potential allocation schemes, their associated benefits, and risks to facilitate decision-making and prevent possible conflicts.

The whole methodology consists of a model-building process with two phases (conceptual and methodological) and six steps. The conceptual phase includes the identification of the collaboration problem, the selection of the applicable theoretical framework, and the identification of stakeholders. In the game theory methodological phase, the process starts with the identification of hydrogen coalition opportunities and then the identification of an important structural feature of the HSC. In the treated case, there is dependency among the agents forming a hierarchy which results in a graph-theoretic model, referred to as the peer group situation. To the best of our knowledge, no previous paper has addressed the problem of cooperation in HSCs considering the structural positions of HSC agents. Then, for the cooperation analysis, three naïve allocation rules are identified, which correspond to intuitive distribution strategies used in practice. Another novelty of this paper is the identification of an adequate transferable-utility game model, called peer group game, which quantifies the cooperation potentials of the various groups of agents in the peer group situation and allows for the use of game theoretical solution concepts, namely the Nucleolus, the Shapley value, and the Gately value. To the best of our knowledge, no previous work has included the use of Gately value in hydrogen cooperative games. This paper is also unique in the sense that a variety of allocation rules is considered and normatively[23] analyzed along appealing properties. These six allocation rules allow the quantification of the total benefit, the individual allocation, and some criteria related to acceptability and form a toolbox for the visual coalitional analysis to support and facilitate decision-making. Both the hierarchical dependency relations and the individual characteristics of the agents are accounted for in the computation of the realizable total benefit for each alliance of agents.

The remainder of this paper is organized as follows: Section 2 presents a literature review to identify, on the one hand, the key stakeholders of the HSC and, on the other one, the existing research on energy systems and cooperative game theory. Section 3 defines the problem and presents the case or coalition opportunity, along with a list of the naïve rules. Section 4 introduces the methodology for cooperative game rules by detailing peer group games. In Section 5, the comparison of results and their discussion are provided through the numerical results and the toolbox explanation. Finally, conclusions and future perspectives are presented.

2. Literature review

To explore potential cooperation strategies for deploying HSCs and underpinning the identified gaps, this section presents a literature review of both hydrogen stakeholders and cooperative game theory in energy systems.

2.1. Stakeholders and agents in HSCs

Hydrogen supply chains are complex systems with multiple stakeholders' groups interacting at multiple levels. The interrelated system reveals the complexity and tension between macro-level ambitions for hydrogen and the micro-level realities of its integration across sectors and stakeholder groups [52]. A non-extensive map of stakeholders or agents is presented in Fig. 2. The active participation of a broad array of stakeholders adds complexity, shaping market dynamics, public perception, and policy frameworks [52]. In this work, stakeholders are categorized as institutional agents or infrastructure ones based on [52,58,59], and their roles and interests are listed in Table 1. From Tables 1, it can be found that institutional agents are numerous (e.g., government, policy makers, industry, academia, suppliers, etc.). The need for collaboration among companies, institutions and neighboring countries has been highlighted in Ref. [60]. Infrastructure agents can be represented by all the technologies from the HSC, as presented in (Figs. 1 and 2b) and described in Table 1. The two groups of agents connect through the end-users. One of the key gaps identified in a previous work [50] was the need for formal analysis tools to study the effects of cooperation in the HSC deployment. In Section 2.2, the literature on the study of agents' cooperation, from the game theoretical perspective is analyzed.

2.2. Cooperative game theory and energy research

By using keywords like "cooperation", "hydrogen", "energy", "game theory", and "cooperative game" several works were found, and 103 were selected for further analysis and categorization (the search took place in November 2024 in Scopus and Web of Science). Some works use

[2] Normative refers to using a rule-based framework grounded in commonly predefined game-theoretical principles for evaluating and comparing allocation rules. The proposed methodology does not specify which coalition should be selected.

[3] In this work the end-user is not modeled.

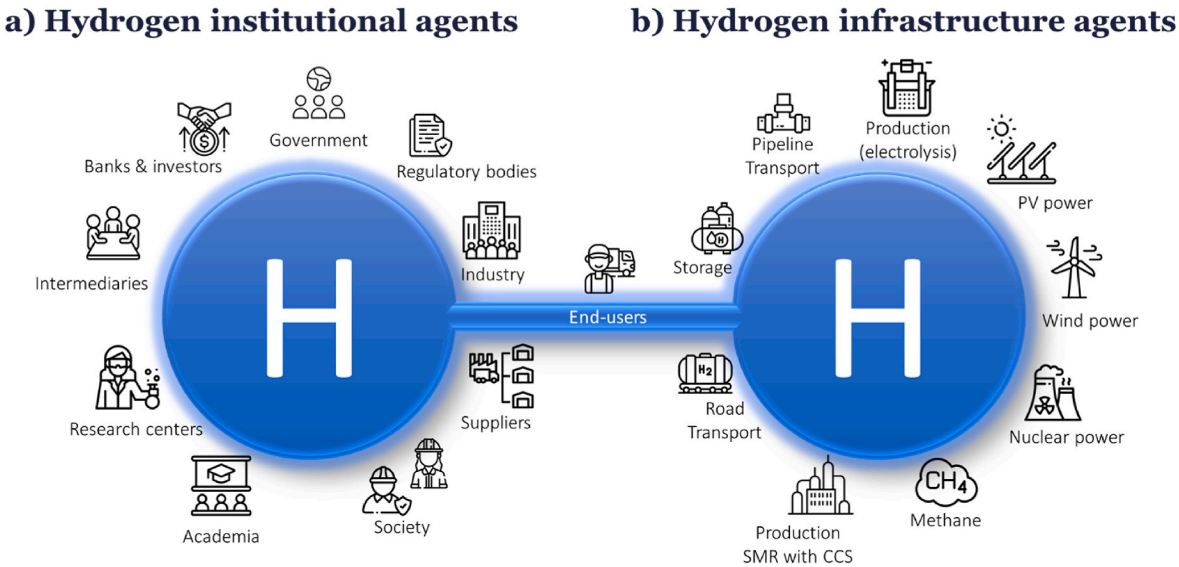


Fig. 2. Map of agents in hydrogen supply chains. Note: The list of agents is for illustrative purposes only. *Icons*: flaticon.com.

non-cooperative game theoretic approaches [where the main solution concept is Nash-equilibrium, e.g., Refs. [62,63], Stackelberg games [64, 65], and evolutionary games (where the main solution concept is evolutionary stable strategies), e.g., a public-private partnership cooperation scheme based on evolutionary game theory for hydrogen production, renewable sources and refueling stations in China has been explored in Ref. [66]. The same methodology was used in relation to stakeholder interests on the new subsidy policy of hydrogen fuel cell vehicles in China [67]. In green and blue hydrogen development [68], a synergistic operation strategy of electric-hydrogen charging station alliance is proposed based on differentiated characteristics [69], and sharing hydrogen storage capacity planning for multi-microgrid investors [70].

In this work, the focus is on cooperation. Cooperative game theory can be used to operationalize the benefit allocation, making potential conflicts among actors clearly articulated and suggesting potential schemes. Cooperative game theory has been applied in some contexts of hydrogen systems. One group of papers uses the Nash bargaining solution [28,71] to find a Pareto-efficient point of the feasible set of utility vectors the players can achieve by mutually agreed coordinated actions (which are typically derived from system-level optimization). In the underlying Nash bargaining model, only the two extreme forms of collaboration appear: the no-cooperation mode when each player acts independently to maximize his/her utility, or the full-cooperation mode when all players act in a coordinated way to achieve a Pareto-efficient system outcome. For example, a Nash-bargaining solution for cooperation in wind-hydrogen systems has been proposed in Ref. [72], and a weighted Nash-Harsanyi bargaining solution for a similar system in Ref. [73]. A model on the cooperative operation of an industrial, commercial, and residential integrated energy system with hydrogen energy based on Nash bargaining theory is presented in Ref. [74]; and a coordinated planning model for multi-regional ammonia industries leveraging hydrogen supply chain and power grid integration was developed in Ref. [75].

Only a few papers use the classical transferable-utility (TU) cooperative game model [27], where the players' utilities are assumed to be quasi-linear, thus the Pareto-frontier of the feasible set of utility vectors is a hyperplane perpendicular to the summation vector (1,1, …,1). Differing from the Nash bargaining model, in TU cooperative models, all forms of partial cooperation are also considered; a TU-game specifies the achievable maximum total utility values for all possible coalitions of players. The papers on hydrogen systems that apply TU-game theory typically use a TU-game model as part of a multi-layer framework designed to integrate various types of actors based on optimally coordinated actions. The role of the TU-game model is to quantitatively capture the benefits of cooperation and propose an allocation (almost exclusively the Shapley value) that is perceived as "fair" and hence provides incentives for the various actors to work together and maintain the alliance. In Ref. [76], the power-to-gas technology is introduced to construct a multi-energy integrated system for isolated island microgrids, and four possible planning models are proposed by using various game theory analysis methods. In that paper, the agents are regions. It is found that using hydrogen and methane has synergistic effects, improving the total income of the system. The Shapley allocation is proposed for feasible alliances, and core membership is checked to validate the stability of the alliance. In Ref. [77], a two-stage market clearing model is proposed to determine the optimal trading amount and allot profits based on the Shapley value in a proposed local integrated electricity-hydrogen market. In Ref. [78], an integrated energy system with electricity, gas, heat, and hydrogen loads is investigated. The economic returns of each subject are analyzed under different operation modes. The authors apply the Shapley value to quantify the contribution value of the subject to the alliance. It is found that, compared with the independent (no-cooperation) mode, the overall benefits of the integrated energy system, as well as the benefits of all subjects, increase in the cooperative mode. In Ref. [65], a two-level model for optimizing the operation of an integrated energy system with hydrogen storage is constructed. The lower level of the system is a benefit allocation mechanism based on the Shapley value of a suitable TU-game.

Moreover, it has been noticed that cooperative and non-cooperative games are sometimes coupled, and in other cases, one of these options is used in bilevel models. The article [65] presents a bilevel model to integrate energy systems with hydrogen energy storage systems. First, a non-cooperative model at the upper level is used. Then, a 3-player TU-game in the lower level is applied by using the Shapley allocation. Similar examples are given in Refs. [64,79]. Some bilevel models would benefit from having a clear explanation of cooperative games (purpose and development) or treating cases with more agents. It is highlighted that a limited number of game theoretical methods have been applied and that the treated problems are diverse, e.g., eco-industrial parks [80, 81], and regional cooperation [75]. Several papers search for inter-plant cooperation where the stakeholders are infrastructure agents. Most of the cooperation games papers use cost or profit allocation [81,82], or GHG reduction as the benefit function [65,83] with potential repercussions in the related allocations.

2.3. Research gaps and objectives

Five research gaps have been identified: (1) The interrelated system reveals the complexity and tension between macro-level ambitions for hydrogen and the micro-level realities of its integration across sectors and stakeholder groups [52]. In this sense, the HSC structure analysis is of utmost importance when benefits are allocated. A deep analysis is needed to identify the type of agents, their relationships and position in the HSC. (2) In most of the above-discussed cooperative game papers, all players are alike in the sense that no player could prevent another player from benefitting from participating in an alliance. In cooperative game terminology, no player has veto power on another player obtaining a positive payoff. In supply-chain situations, however, such crucial dependency of upstream agents from downstream agents is inevitable, making the HSC hierarchy and structure highly important. The hierarchy can be presented horizontally or vertically, the latter being more explicit in terms of dependencies among hierarchical levels. This structural feature of HSC represents a special type of collaboration situation known as a peer group game situation [84]. Moreover, the quantification of the shares of different agents is not a trivial task because the HSC hierarchy might also include agents that do not offer carbon reductions but possess veto power that can be used to block the realization of cooperative, system-level objectives. Thus, this paper identifies a research gap regarding the hierarchical nature of HSCs and proposes game-theoretical methodologies to evaluate the effects of cooperation in achieving the decarbonization goals. (3) Current research does not analyze the effects of dependency [85] in low-carbon HSCs in detail. The use of TU games allows a set of solutions that could provide decision-makers the possibility to identify collaboration strategies and their impacts by considering the dependency aspect. (4) It is also important to understand the consequences of naïve rules, often applied intuitively in real cases. These can be compared to game-theoretical rules. For solving TU games, not only the Shapley or Nucleolus rules are available. To the best of our knowledge, the Gately value, which is important due to its proportional nature, has not been applied yet. This paper will be the first to apply it. (5) Finally, there is a need to improve the visualization of results to facilitate decision-making through a transparent analysis of HSC cooperation options.

In this context, the main objective of the paper is to use a systems approach and TU games for analyzing the maximum decarbonization potential of a generalized low-carbon HSC scenario that captures all agents' particularities (type, decarbonization potential, hierarchical position, and capacity), to map their contributions to this maximum, and to find appropriate benefit sharing scheme for their allocation to align

Table 1
Categorization of stakeholder groups and agents.

Stakeholder group	Agents	Interest	Reference
a) Hydrogen institutional agents			
Government	Countries, politicians, and agencies financing or regulating policies	Contributing to the economy and adhering to legal requirements	[59–61]
Banks and investors	Banks, investors, shareholders	Providing financial support for hydrogen projects through loans, investments, or company stakes	[52]
Regulatory bodies	Policymakers and regulators	Shaping the hydrogen industry via policies, regulations, and incentives; ensuring compliance and providing feedback	[52,61]
Industry	Public/private companies with actual or potential role as producers (equipment, or hydrogen), consumers, or intermediaries	Achieving acceptable profit, return on investment, innovation, and minimizing failure risks	[59,61]
Intermediaries	Industry associations	Representing interests of groups within the hydrogen industry	[52]
	Social impact and advocacy, NGOs	Advocating, educating, recommending policies, and conducting research	
	Partnership initiatives	Collaborating with stakeholders to achieve shared hydrogen goals	
	Lobby groups	Aligning organizational activities with group objectives	[61]
Suppliers	Primary producers and suppliers	Receiving early requirements, long-term orders, fair pricing, and on-time payments	[52]
	Equipment and component manufacturers	Manufacturing hydrogen-specific equipment, components, and systems	
	Technology and service providers	Developing electrolyzers, fuel cells, tanks, compressors, and other hydrogen production and distribution technologies. Offering services	
	Infrastructure providers for storage and distribution (DSOs, TSOs)	Receiving early notice of requirements and consistent volume demands	[52,58]
Research and development	Research centers	Advancing hydrogen technology and training skilled professionals	[52]
Society	Society	Minimizing noise, pollution, and maximizing job creation and safety improvements	[61]
	Staff and skilled workforce	Promoting skills development, good wages, and favorable working conditions	
Academia	Universities, laboratories, and research groups	Supporting training and skills development programs	[52,59]
End-users	Petroleum refining, ammonia and chemical industries Steel, cement, glass, industrial gas Mobility sector (heavy-light duty vehicles buses, shipping, aviation)	Ensuring acceptable prices, good service, and quality	[52,61]
b) Hydrogen infrastructure agents			
Energy source	Renewable energy sources (PV, wind, hydro, etc.) Fossil sources: Methane Other: Nuclear	Ensuring competitiveness, reduced GHG emissions, safe, reliable, and sustainable operations, and acceptable profit	[5]
Production	Hydrogen producers (electrolysis, SMR, SMR with CCS, pyrolysis, gasification)		
Transportation	Infrastructure providers for distribution (tube trailers, pipelines, trucks)	Receiving early notice of requirements, consistent volume, and acceptable profit with low risk of failure	[52,58]
Storage	Infrastructure providers for storage (gas, liquid, solid-state hydrides)		[10,52,58]
Distribution	Hydrogen retailers (e.g. refueling station)	Selling hydrogen to end users with acceptable profit and low risk of failure	[52,61]
End-users	Petroleum refining, ammonia and chemical industries. Steel, cement, glass, industrial gas Mobility sector (heavy-light duty vehicles buses, shipping, aviation)	Ensuring acceptable prices, good service, and quality	

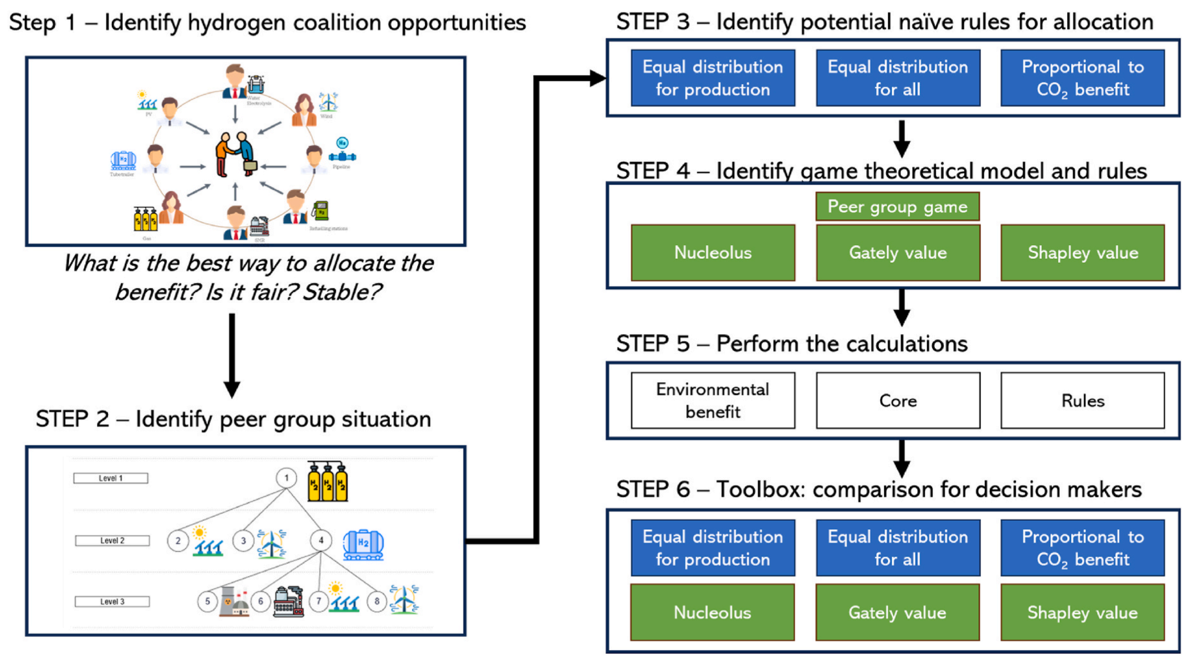


Fig. 3. Methodological framework. *Icons*: flaticon.com.

potential conflicts in interest and overcome the negative consequences of unacceptable distribution in coalitions. To achieve this, the paper will propose a game theoretic toolbox for decision-makers. The primary focus is on GHG emission and its distribution among HSC agents; however, to avoid environmental failure risk, this distribution should be closely linked to how the financial means available to develop the low-carbon HSC are shared among agents. In an intuitive way, one could argue that an actor's proposed share from the total available financial means should be determined by its share of contribution to the system-level environmental benefits. However, this is not as simple because the supply chain hierarchy might include actors that do not offer carbon reductions but possess critical resources so they can block the realization of cooperative, system-level objectives. This is because HSCs, like any supply chain, have a sequential dependency path [85], additively accumulating benefits for groups of agents but potentially also agents with veto power for the cooperation. In peer group game problems, the quantification and allocation of benefits can be done by using different rules. Naïve allocation rules are often used because they are considered intuitively as fair. However, they can sometimes be arbitrary and ignore individual characteristics of the agents (e.g., their contribution potential and power position). Thus, it is by no means certain that they are perceived as acceptable by all. Hence, it is proposed to apply more formal allocation rules too, compare them with each other and with the naïve rules in respect of the following game-theoretical evaluation criteria: (1) stability level, (2) satisfaction level, and (3) propensity to disrupt level, reflecting the important perception of agents in respect to the acceptability of an allocation scheme. More specifically, allocation rules based on the Shapley value, Nucleolus, and Gately value are used because their sound conceptual basis provides efficiently computable allocations with appealing properties in peer-group games and Shapley and Nucleolus rules have already been applied in supply chain management literature [86–88].

Based on the previous elements, the proposed methodology consists of six steps as presented in Fig. 3 and discussed in the following sections.

3. Problem statement and case specification

This section describes how a low-carbon hydrogen coalition is formed. The HSC cooperation is supposed to be motivated by the scaling-up efforts to reduce global GHG emissions. There might be different reasons that bring different agents to cooperate and many situations where system configuration influences the potential benefits of the coalitions; in this case, the reasons are to achieve pre-defined decarbonization targets while fulfilling a given demand. Low-emission hydrogen at scale requires well-chosen configurations with substantial emission reductions along the supply chain [3]. The article [89] highlight that different low-carbon hydrogen scenarios might have different decarbonization potential. For this, individual decarbonization benefit needs to be known in advance. This work addresses the research question: How can cooperation be operationalized, and its potential benefits measured to evaluate the impact of different allocation schemes in low-carbon HSCs?

3.1. Identification of hydrogen coalition opportunities

Step 1 of Fig. 3 consists of the identification of the coalition opportunity. This work proposes the use of a hypothetical case to give a pedagogical illustration of the application of the methodology. In agreement with most of the cooperative game theory works from the literature review, hydrogen infrastructure agents are considered (i.e., energy source, production, storage, and transport). The case builds on several assumptions listed below and illustrated in Fig. 4:

3.2. Identification of the peer group situation

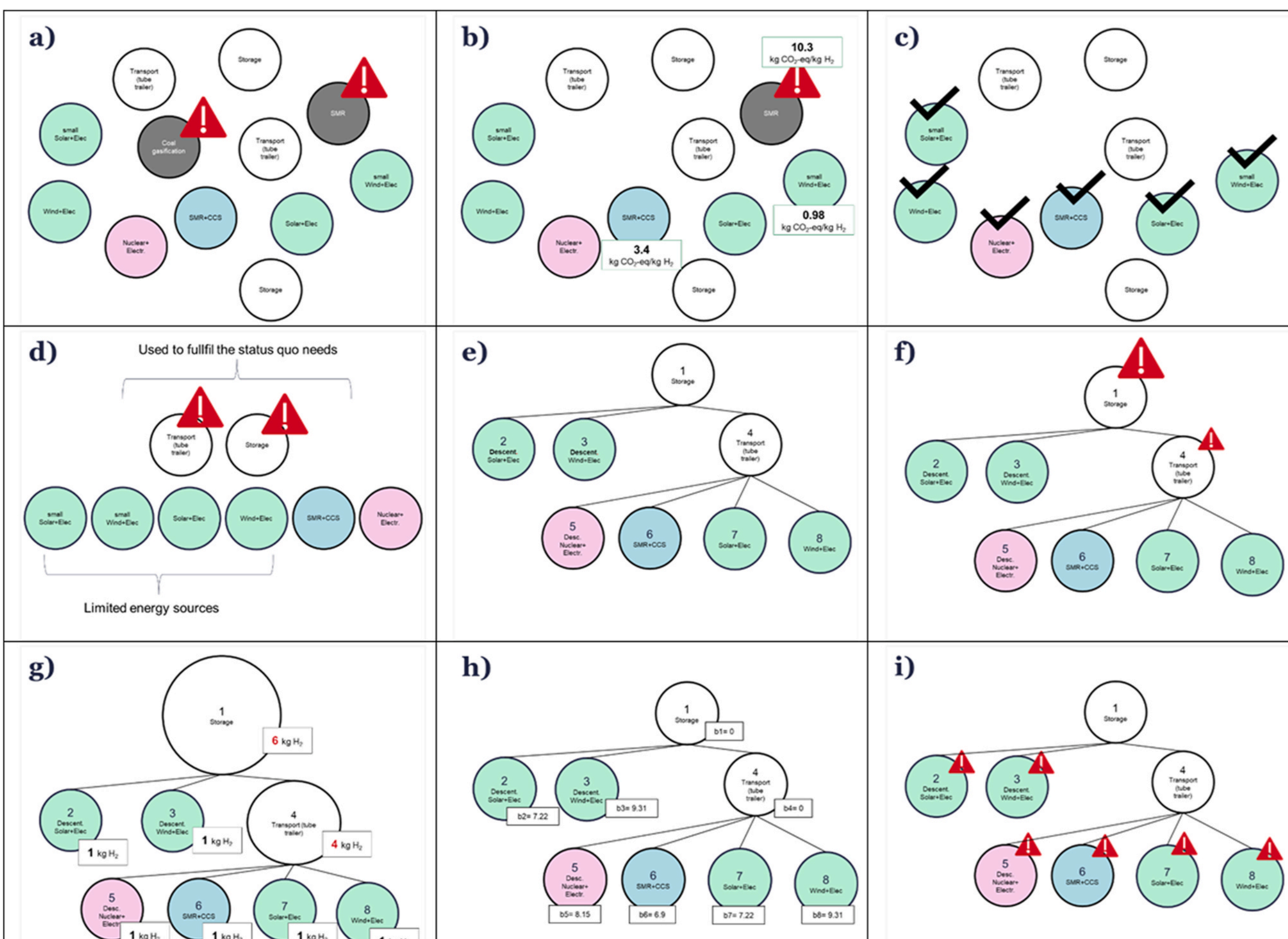
Step 2 of Fig. 3 involves case identification, with a particular focus on the HSC structure. The HSC coalition opportunity resulted in a structural map of an HSC with three levels of agents. Using graph theoretical terminology, the structural map is a rooted tree graph (Fig. 5). On the top level (Level 1) of Fig. 5, there is agent 1, which corresponds to the hydrogen gaseous storage. In Level 2, the centralization degree is given. Agents 2 and 3 represent electrolysis production by using directly renewable sources, solar or wind in place without transportation needs (decentralized options). Agent 4 represents the centralized alternative with an agent in charge of the transportation of gaseous hydrogen in tube trailers. Supply chain agents have a sequential dependency [85], meaning that the output of a lower-level agent is the input for the higher-level agent in a vertical setup. Agent 4 is connected to agents in Level 3, which are those for which the facilities are transported far away from the user point (storage) and, hence, depend on a more complex logistics system. Agents 5, 7, and 8 use electrolysis production with different electricity types (nuclear, solar, and wind, respectively). Agent 6 is an agent producing H_2 by using SMR coupled with CCS. The coalition aims at (1) reducing carbon emissions, (2) scaling up low-carbon technologies, and (3) ensuring the equitable distribution of available means (e.g., environmental benefits or financial benefits).

This input-output dependency makes the chain hierarchical and results in a unique sequence of superiority; higher-level agents have a critical role since they can facilitate or hinder efficient cooperation and the realization of system-level objectives. When studying agents' dynamics, the hierarchical structure from Fig. 5 calls for the peer group game model [84], where agents with potential individual capabilities are tied in a hierarchy that influences the agents' collaboration possibilities. Only through collaboration within this group can the agents fully realize their potential environmental benefit [84]. In a peer group situation, each agent except one has a single direct superior in the hierarchy; thus it can be represented by a rooted tree graph (Fig. 5).

3.3. Naïve allocation rules

Step 3 of Fig. 3 refers to the identification of naïve allocation rules. In daily practice, agents might propose and use different types of naïve rules to define the benefit allocation among the different contractual parts. Fairness is an important concept when discussing allocation schemes. It is defined as "the quality of treating people equally or in a way that is reasonable" (Oxford Dictionary). However, fair or equitable distribution of proceeds of a joint endeavor is not straightforward to find; different rules lead to different results, and a mutual acceptance of using them is key to a contractual cooperation of the parties. Agents' willingness to participate depends on the perceived fairness of the system [95]. Using an allocation rule, be that naïve or sophisticated, fairness is what the agents find it to be and what is mutually acceptable for them.

Three frequently used naïve allocation rules are discussed for the proposed case (Fig. 6). First, the "equal distribution, but only for producers" (PE: producers equally) rule allocates an equal share of the total benefit but only to the production agents. This rule might be supported by the argument that the performance of an alliance is measured in terms of emission savings during hydrogen production, but the infrastructure nodes do not contribute to that. Second, the "equal distribution for all agents" (AE: all equally) rule allocates an equal share to all members of the HSC. This rule recognizes the crucial role of storage and transportation in the functioning of the low-carbon HSC and treats all components of the system equally. Third, the "proportional to CO_2 benefit for all agents" (BP: benefit proportional) rule allocates the total carbon benefit of the coalition in proportion to the agents' potential benefit. In contrast to the PE and AE rules, the BP rule emphasizes the individual differences in the agents' contributions to the performance of the alliance. Since the infrastructure agents do not add to the total



(caption on next page)

Fig. 4. Case definition considerations.

a) Any cooperating group of agents is expected to achieve at least 70% GHG savings [90] with regard to the status quo. In Fig. 4a it is displayed that technologies using fossil fuels without CCS, although mature, are not retained.

b) Since carbon reduction is the main reason supply chain agents cooperate here, the value function is expressed in global warming potential, i.e., kg $CO_{2\text{-eq}}$. In this way, the individual benefit of each agent is assumed to be known. In Fig. 4b, the emissions of SMR and SMR + CCS [91], and wind electrolysis [92] are compared to indicate how the agents can be pre-selected.

c) According to recent auctions, only production agents can apply for financial support based on the decarbonization potential [90], see Fig. 4c. In some programs, a strict requirement on only renewable sources may exist, but here, additional sources, like nuclear, are displayed to provide a wider vision.

d) Diversification is considered by assuming capacity limitations, i.e., each production agent is assumed to have limited capacity, and the different production agents have the same maximum capacity (Fig. 4d). In real scenarios, there might also be a limited capacity for some energy sources. However, it is important to highlight that if such constraint is not present, a single technology offering high CO_2 benefit (e.g., solar, wind, or nuclear + electrolysis can offer CO_2 reductions higher than 70%) could decide to work independently instead of cooperating with the coalition, since it can individually ensure the demand fulfillment. Notice that solar and wind facilities' nodes can vary in location, which might result in centralized (transportation is needed) or decentralized systems. The production agents in Fig. 4d are assumed to be placed in a different location based on the individual agent's capacity, while storage and transportation agents represent the cumulative potential to store or transport hydrogen in a given coalition. e) A hierarchical structure exists in HSCs because of the sequential dependency among the infrastructure agents [85]. In Fig. 4e, the hierarchy is displayed vertically while in Fig. 1 (HSC), it is shown in a vertical manner. However, these figures differ in the HSC representation because Fig. 1 categorizes the agents per type (e.g., all energy sources are placed at the same level, i.e., left side), while in Fig. 4e, the distance to achieve the leading agent is relevant. From a bottom-up analysis, in Fig. 4e, four centralized production agents exist (agents 5, 6, 7, and 8); three of them use electrolysis with different energy sources, and one uses SMR + CCS. These are connected to transport (agent 4) because they need logistics support from an external agent to move H_2 over a long distance to the storage agent (agent 1), assuming this is the closest point to the end customer. On the other hand, decentralized options (electrolysis using solar and wind power – agents 2 and 3) are displayed at a higher level in Fig. 4e, due to their proximity to the coalition leader.

f) Storage is placed in the leading position because of the sequential dependency but also due to the energy storage capability of hydrogen [32,93,94], considered as one of its main advantages when compared to other energy carries such as electricity. If hydrogen is produced but cannot be stored, the flexibility associated with hydrogen is lost. In a hierarchy, every agent maintains a relationship with the leader, either directly or indirectly through one or more intermediaries. Agent's economic opportunities are constrained by their position within the hierarchy. In Fig. 3g, the production capacity utilization depends on storage and transportation. Gaseous storage tanks and tube trailers are well-established technologies currently used for gray hydrogen storage and transportation from the status quo option (SMR). Since auctions are not related to storage and transportation agents, additional capacity for these agents is not considered in this work. Instead, they should decide if they store and transport gray or low-carbon hydrogen, so they can be considered as limited resources from which decisions may affect the actual implementation of a given project. Storage and transportation infrastructure, and scalability of these technologies are highlighted as critical challenges to scaling-up HSCs [31,52].

g) The functional unit for production is defined as 1 kg H_2 to facilitate any conversion and comparison. Then, each production agent in a coalition is compared in terms of kg CO_2-eq/kg H_2 and the total benefit will be given in kg CO_2-eq. Fig. 4g, illustrates the total capacity per agent in relation to the agent's size. Agent 1 manages 6 kg H_2, agent 4 handles 4 kg H_2, and the production agents 1 kg H_2 each. However, the results can also be reported in a consistent 1 kg H_2 for all agents.

h) There is transparency in the coalition in terms of the visibility of the agents' actual contributions, positions, and connections. In Fig. 4f the individual benefits (b_i) are listed for all agents.

i) The production agents have a particular interest in distributing H_2 to end-users, they are seeking collaborative technologies for the distribution and storage of H_2, and not the other way around because they try to increase the facilities' utilization by assuming that a stable market exists.

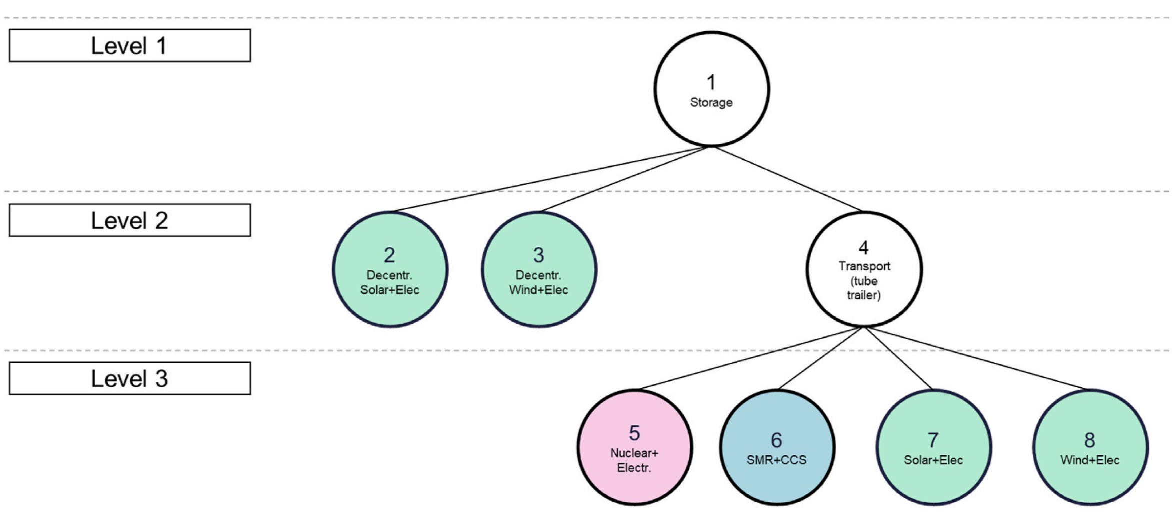


Fig. 5. A generic structural representation of a low-carbon hydrogen supply chain

emission savings, hence, similarly to the PE rule, storage and transportation are also not rewarded under the BP allocation rule.

The article [95] distinguish three types of distributive fairness principles: equality, meritocracy, and max-min fairness. From the above three allocation rules, the AE rule clearly embodies the equality principle because it provides the same share to all participants. On the other hand, the BP rule is meritocratic because it distributes the proceeds of cooperation in proportion to the contribution of the participants. The PE rule mixes these two principles inasmuch as it first groups the nodes as productive vs. non-productive based on their contribution potential, then splits the proceeds of cooperation in proportion to the contribution of the groups. Finally, the shares allotted to the groups are distributed equally among the group members. The list of presented naïve allocation rules is not exhaustive, and many additional naïve rules can be defined and considered by the agents. These can then be evaluated against and compared to more sophisticated rules based on cooperative game

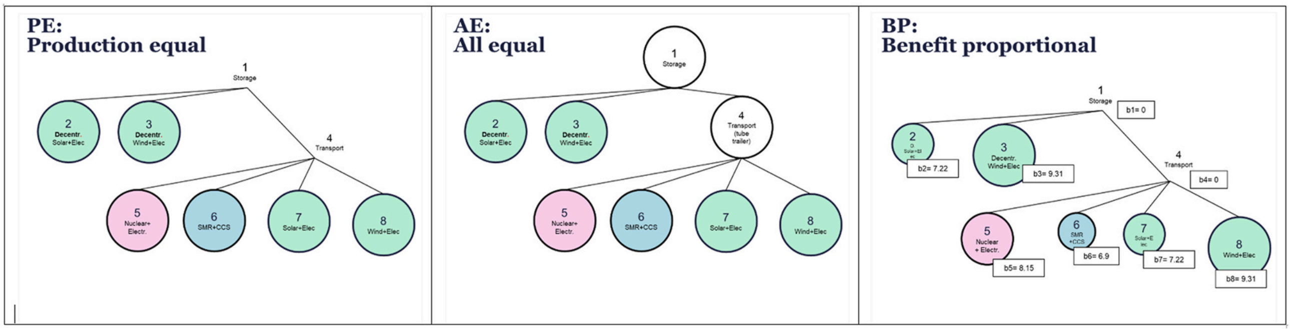


Fig. 6. Graphical representation of naïve rules (the size of the nodes reflects whether, and how much the input of the agents is considered)

theory. A mathematical description for highlighting the differences among these rules is given in the Appendix: AE allocation rule (Table A1), BP allocation rule (Table A2), and PE allocation rule (Table A3).

4. Cooperative game theoretical methodology

As previously introduced, cooperative game theory provides appropriate concepts for modeling the generic configuration of low-carbon HSC as a game and analyzing potential collaborative coalitions. The hypothetical case calls for a peer group game that is associated with a specific type of multi-agent situation (see, Fig. 5). In this Section, Step 4 of Fig. 3 is developed.

A *peer group situation* is formally given by a triplet $(N, T, (b_i)_{i\in N})$ where $N = \{1, \ldots, n\}$ is the set of agents, T is a tree graph on node set N with $1 \in N$ as a distinguished node, called the root, and a system of nonnegative numbers associated with the nodes. The root node gives an orientation for the $n-1$ undirected edges which connect the n nodes, and a level structure to the tree graph. The root is the only level 1 node. The nodes directly connected to the root are the level 2 nodes, the nodes directly connected to a level 2 node are the level 3 nodes, etc. For each level k ($k \geq 2$) node $i \in N\backslash\{1\}$ denoted by $t(i) \in N$ the *direct superior* of i, that is the unique level $k-1$ node to which i is connected to by an edge. Notice that only root node 1 has no direct superior. For each node $i \in N$ denoted by $P(i) \subseteq N$ the set of nodes on the unique *path* from i to 1, that is, for level k node i the set $P(i) = \{i, t(i), t^2(i) = t(t(i)), \ldots, t^{k-1}(i) = 1\}$. For example, in Fig. 5, $P(1) = \{1\}$, $P(4) = \{4, 1\}$, and $P(8) = \{8, 4, 1\}$. Notice that the agents are numbered such that the superiors have lower numbers, that is, $t(i) < i$ for all $i \in N\backslash\{1\}$. For each node $i \in N$, it is denoted by $Q(i) \subseteq N$ the set of *dependents* of i, that is, $Q(i) = \{j \in N : i \in P(j)\}$. Since $Q(i)$ consists of i and all nodes j for which i is a superior, $Q(i)$ is the i-rooted subtree of the 1-rooted tree T. Finally, for each node $i \in N$, it is denoted by $R(i) = N\backslash Q(i)$ the set of agents who are not a dependent of agent i. For example, in Fig. 5, $Q(1) = N$, $Q(4) = \{4, 5, 6, 7, 8\}$, and $Q(8) = \{8\}$, thus, $R(1) = \emptyset$, $R(4) = \{1, 2, 3\}$, and $R(8) = \{1, 2, 3, 4, 5, 6, 7\}$. Node $j \in N\backslash\{1\}$ is called a *leaf* of tree T if it is not the superior of any node, that is, if $Q(j) = \{j\}$. Finally, the numbers $b_i \geq 0$ associated with the nodes $i \in N$ indicate some capability of the agents. In the peer group situation depicted in Fig. 5, the production agents are the leaves of the tree hierarchy, and the individual potential benefit numbers will be the carbon emission savings the agents can provide.

In order to capture the influence of agents' positions in the hierarchy on the efficiency of their individual capabilities in various group combinations in peer group situation $(N, T, (b_i)_{i\in N})$, Brânzei et al. [84] associated a *peer group game* (N, v) with coalition value $v(S) = \sum_{i:P(i)\subseteq S} b_i$ for each coalition $S \subseteq N$. Thus, the potential individual benefit b_i of agent i can only be realized and added to the total benefit of the coalition if all superiors of i are also members of the coalition. In Fig. 5 example, $v(\{1\}) = b_1$, $v(\{j\}) = 0$ for all $j \geq 2$ (because 1 is not in coalition $\{j\}$), $v(\{1, 2\}) = b_1 + b_2$, but also $v(\{1, 2, 5\}) = b_1 + b_2$ (because $t(5) = 4$ is not present in the coalition). Notice that $v(N) = \sum_{i\in N} b_i$ in any peer group game because all agents are connected to root agent 1 in the *grand coalition N*. Since a coalition value can be positive only if root agent 1 is a member of the coalition, agent 1 has veto *power*, that is, $v(S) = 0$ for all coalitions $S \subseteq N\backslash\{1\}$. In this work, it will be assumed, without loss of generality, that also $v(\{1\}) = b_1 = 0$.

Peer group games are a very special type of cooperative games because the values of the coalitions are obtained in a particular way from a highly structured situation. The general cooperative game model, introduced by von Neumann & Morgenstern [27], has been proven useful in modelling and analyzing complex multi-agent situations where each agent can partially influence the possible outcomes and the influence of various groups of agents can be measured on the same interval scale.[4] The aim is to untangle the intricate interconnections of these influences and quantify the relative importance of each agent based on some desirable principles. To perform this analysis for generic peer group games, it is needed to formally introduce the necessary concepts and results from cooperative game theory,[5] but for illustration, the peer group game associated with the peer group situation depicted in Fig. 5 is used.

Brânzei et al. [84] show that any peer group game (N, v) is a *convex game*, that is, the inequality $v(S) + v(T) \leq v(S\cup T) + v(S\cap T)$ holds for any two coalitions $S, T \subseteq N$, or equivalently, the *marginal contribution* $v(S\cup i) - v(S)$ of player $i \in N$ to coalition $S \subseteq N\backslash\{i\}$ is monoton non-decreasing with respect to inclusion of the coalitions player i joins. In fact, peer group game (N, v) induced by peer group situation $(N, T, (b_i)_{i\in N})$ can be written as the linear combination $v(S) = \sum_{i\in N} b_i\, u_{P(i)}(S)$ for all $S \subseteq N$, where $u_{P(i)}$ is the *unanimity game* related to path coalition $P(i)$, defined as $u_{P(i)}(S) = 1$, if $P(i) \subseteq S$; and $u_{P(i)}(S) = 0$, otherwise. For example, $v(\{1\}) = b_1\, u_{\{1\}}(\{1\}) = b_1$, because coalition $S = \{1\}$ contains path $P(i)$ only for $i = 1$. On the other hand, $v(N) = \sum_{i\in N} b_i$, because the grand coalition N contains path $P(i)$ for all $i \in N$.

An *outcome* of the cooperative game (N, v) is a vector of numbers $(x_1, x_2, \ldots, x_n)$ specifying the *payoffs* to the players with the general understanding that higher payoffs mean preferred outcomes for the players. Payoff vector $(x_1, x_2, \ldots, x_n)$ is *Pareto-efficient* if equation $x_1 + x_2 + \ldots + x_n = v(N)$ holds. This property embodies stability against unanimously advantageous feasible deviations from the given payoff vector for all players. Among the Pareto-efficient outcomes are the *imputations* which are also stable against advantageous feasible deviations by single players, that is, which satisfy the *individual acceptability* inequalities $x_i \geq v(i)$ for all $i \in N$. Notice that Pareto-efficient outcomes exist in any game, but the set of imputations is not empty if and only if $v(N) \geq \sum_{i\in N} v(i)$ holds.

[4] For a few examples from the vast literature on profit/cost allocation applications of cooperative game theory closely related to the topic of this paper, see [77,86,102,116–119].

[5] More on the basic concepts and results summarized here can be found, for example, in the fine texts by Refs. [120–122].

Table 2
Core system in peer group game related to Fig. 5.

$x_1,$	$x_2,$	$x_3,$	$x_4,$	$x_5,$	$x_6,$	$x_7,$	x_8	$\geq$	0
$x_1 +$	.	$x_3 +$	$x_4 +$	$x_5 +$	$x_6 +$	$x_7 +$	x_8	$\geq$	$B - b_2$
$x_1 +$	$x_2 +$	.	$x_4 +$	$x_5 +$	$x_6 +$	$x_7 +$	x_8	$\geq$	$B - b_3$
$x_1 +$	$x_2 +$	x_3	.	.	.	.	.	$\geq$	$B - b(Q(4))$
$x_1 +$	$x_2 +$	$x_3 +$	$x_4 +$	.	$x_6 +$	$x_7 +$	x_8	$\geq$	$B - b_5$
$x_1 +$	$x_2 +$	$x_3 +$	$x_4 +$	$x_5 +$	.	$x_7 +$	x_8	$\geq$	$B - b_6$
$x_1 +$	$x_2 +$	$x_3 +$	$x_4 +$	$x_5 +$	$x_6 +$	.	x_8	$\geq$	$B - b_7$
$x_1 +$	$x_2 +$	$x_3 +$	$x_4 +$	$x_5 +$	$x_6 +$	$x_7 +$	.	$\geq$	$B - b_8$
$x_1 +$	$x_2 +$	$x_3 +$	$x_4 +$	$x_5 +$	$x_6 +$	$x_7 +$	x_8	$=$	$B = \Sigma_{i\in N} b_i$

Further strengthening of the stability of outcomes by requiring resistance against advantageous feasible deviations for coalitions of all sizes leads to the prime set-valued solution of cooperative games, the core.

Step 4 of Fig. 3 consists of the identification and definition of game theoretic allocation rules, from which three are proposed (Shapley value, Nucleolus, and Gately value) for comparative purposes. Subsections 4.1-4 present the special features of the core (as a key component of cooperative games) and the three applicable game theoretic rules in peer group games.

4.1. Core

The *core* of a cooperative game (N, v) is the set of Pareto-efficient payoff vectors which satisfy the *coalitional acceptability* inequalities $\sum_{i\in S} x_i \geq v(S)$ for all coalitions $S \subseteq N$, $S \neq \varnothing, N$. This system of linear constraints may admit no solution, but in convex games the core is always not empty [96]. The difference $f(S,x) = \sum_{i\in S} x_i - v(S)$ of the total payoff allocated to coalition S and what it can achieve on its own is called the *satisfaction* of S with allocation x. The core can thus be given as the set of Pareto-efficient payoff vectors no coalition is dissatisfied with. Formally,

$$Core(N,v) = \{x \in \mathbf{R}^N : f(N,x) = 0 \text{ and } f(S,x) \geq 0 \text{ for all coalitions } S \neq \varnothing, N\}. \quad (1)$$

The core has a nonempty *relative interior*, if exists a Pareto-efficient payoff vector x such that $\sum_{i\in S} x_i > v(S)$ for all coalitions $S \neq \varnothing, N$. Notice that core outcomes must satisfy exponential many linear constraints, but some of them might be redundant. Clearly, the more constraints can be dropped from the core system (1) without enlarging the set of solutions, the easier to find stable allocations or to decide whether a given payoff vector belongs to the core.

Peer group games are in the intersection of two well-known classes of games having a nonempty core, namely convex games and games with a veto player (for which the allocation $(x_1 = v(N), x_2 = 0, \ldots, x_n = 0)$ is in the core if player 1 has veto power), thus the core in peer group games is always not empty. It was shown by Brânzei et al. [97] that *in peer group games, only linearly many coalitions are needed to determine the core*, namely, the grand coalition N, the single-player coalitions $\{i\}$ for all $i \in N$ and the coalitions $R(i)$ for all $i \in N \backslash \{1\}$. Formally, the core of peer group game (N, v) with $v(\{1\}) = b_1 = 0$ is the set

$$\left\{x \in \mathbf{R}^N : \sum_{i\in N} x_i = v(N), x_i \geq 0 \text{ for all } i \in N, \sum_{j\in R(i)} x_j \geq v(R(i)) \text{ for all } i \in N \backslash \{1\}\right\}. \quad (2)$$

Table 2 shows this reduced core description for the peer group game arising from the situation depicted in Fig. 5. Recall that $v(\{1\}) = b_1 = 0$ is assumed and $v(N) = B = \sum_{i\in N} b_i$.where $b(Q(4)) = \Sigma_{i\in Q(4)} b_i$ denotes the sum of the missing benefits.

Observe that only $8 + 7 + 1 = 16$ linear constraints of the simplified core system (2) are needed to determine the core in any 8-player peer group game. In contrast, in a generic 8-player convex game all constraints related to the $2^8 - 1 = 255$ nonempty coalitions are essential in core system (1).

The following statement holds in any peer group game.

1. *If the individual benefit number for all leaf players is positive, then the core of the peer group game has a nonempty relative interior.*

Statement 1. is a corollary of Statement 6 (proven in subsection 4.4), which asserts that under the same conditions, the Shapley allocation lies within the relative interior of the core.

4.2. Nucleolus

The core, if not empty, typically contains infinite payoff vectors which, in terms of stability, are "good" outcomes. In such cases, "the most stable" outcome(s) among these good ones is searched. First, it needs to be specified when outcome x is considered "more stable than" outcome y. Following Schmeidler [98], for both x and y the satisfactions of all coalitions $S \neq \varnothing, N$ are arranged in a non-decreasing order (ties are broken arbitrarily) and get the ordered vectors $F(x) = [\ldots \leq f(S,x) \leq f(S',x) \leq \ldots]$ and $F(y) = [\ldots \leq f(T,y) \leq f(T',y) \leq \ldots]$ are obtained. Then $F(x)$ and $F(y)$ are compared lexicographically by taking the corresponding entries from left to right. If $f(S,x) > f(T,y)$ in the first pair in which the two satisfactions are different, x is considered "more stable than" y, and if the two satisfactions are equal in all pairs, x and y are considered "equally stable". Schmeidler [98] proves that if the imputation set of a cooperative game is not empty, then there is a unique imputation, called the *nucleolus*, which lexicographically maximizes the non-decreasingly ordered vectors of satisfactions over the imputation set; moreover, if (the relative interior of) the core is not empty, the nucleolus always belongs to (the relative interior of) the core. To find the location of the nucleolus, Maschler et al. [99] provide a general framework, called the *lexicographic center procedure*. Most of the known nucleolus algorithms for general cooperative games are implementations of this procedure.[6]

Although the definition of the nucleolus contains all nonempty coalition values, Reijnierse & Potters [100] prove that in any game, there are always linearly many coalitions which, in fact, determine the nucleolus but finding them is as difficult as computing the nucleolus itself. Brânzei et al. [97]. [7] show that when the relative interior of the core of a peer group game is not empty, the nucleolus is determined by the same set of the linearly many coalitions which determine the core, namely, the single-player coalitions $\{i\}$ for all $i \in N$ and the coalitions $R(i)$ for all $i \in N \backslash \{1\}$. Brânzei et al. [97] present an algorithm that computes the nucleolus of a peer group game with positive leaf benefits directly from the parameters of the underlying peer group situation without calculating any of the coalitional values and show that for an n-player case, the algorithm requires $\mathcal{O}(n^2)$ time.

Next, an informal description of the algorithm is presented, and an illustration on Fig. 5 example is given. The key observation is that for any Pareto-efficient payoff vector x and any partition $N = N_1 \cup \ldots \cup N_k$ of the grand coalition, the equality $\sum_{i=1}^{k} f(N_i,x) = v(N) - \sum_{i=1}^{k} v(N_i)$ holds. Thus, the satisfactions always sum up to a constant that is specific to the partition. It is called the *efficiency gap* of the partition because it expresses the loss in total efficiency when the grand coalition breaks up into several smaller coalitions. The efficiency gap is positive whenever the interior of the core is nonempty. If the smallest satisfaction of the partition members is to be maximized over the core, all satisfactions must be equal, that is $f(N_i,x) = \frac{v(N) - \sum_{i=1}^{k} v(N_i)}{k}$ for each $i = 1,\ldots,k$. The primary goal of the nucleolus is to maximize the smallest satisfaction for all coalitions, but each coalition S is in several partitions, including the partition $N = S \cup (N \backslash S)$. It follows that at the nucleolus, the satisfaction of S cannot be higher than half of the efficiency gap of this 2-member partition, that is, $f(S,Nu) \leq \frac{v(N) - v(S) - v(N \backslash S)}{2}$. There are, however, many other similar upper bounds for $f(S,Nu)$, and not just for one particular S but for all coalitions. Determining all of them and finding the minimal one is computationally demanding in general. Besides, after maximizing the smallest satisfaction for all coalitions, the nucleolus also maximizes the second smallest satisfaction for those coalitions for which the satisfactions can still be increased, and so on, until the satisfactions for all coalitions are fixed at a unique imputation, the nucleolus.

In peer group games, this procedure is much simpler, because in peer group game (N,v) with nonempty core interior induced by peer group situation $(N,T,(b_i)_{i\in N})$ with $b_1 = 0$, the nucleolus is determined by the core-defining coalitions $\{i\}$ for all $i \in N$ and $R(i)$ for all $i \in N \backslash \{1\}$ [97]. It is easily checked (see the core system in Table 2) that from this pool of $2n-1$ coalitions only n partitions can be formed, namely $\Pi_i = R(i) \cup \bigcup_{j \in Q(i)} \{j\}$ for each $i \in N$. Let π_i denote the number of coalitions in partition Π_i, that is $\pi_1 = n$ (because $R(1) = \varnothing$ and $Q(1) = N$) and $\pi_i = 1 + q_i$ for $i \geq 2$, where q_i denotes the number of players in $Q(i)$. Since $v(\{j\}) = 0$, for all players $j \in N$, the efficiency gap of partition Π_i is $g(\Pi_i) = v(N) - v(R(i)) - \sum_{j \in Q(i)} v(\{j\}) = v(N) - v(R(i)) = \sum_{j \in Q(i)} b_j$. Then the highest level of the smallest satisfaction among the $2n-1$ nucleolus-defining coalitions over the core is equal to $\min_{i \in N} \frac{g(\Pi_i)}{\pi_i}$. Since $\frac{g(\Pi_j)}{\pi_j} = \frac{b_j}{2}$ for any leaf player j, the maximum satisfaction guaranteed for all coalitions over the core cannot be higher than $\min_{j\ leaf} \frac{b_j}{2}$. Since satisfaction is equal to payoff, i.e. $f(\{i\},x) = x_i$ for all players $i \in N$, it follows that

2. *in any peer group game, the nucleolus payoff is at most half of the potential benefit, $Nu_j \leq b_j/2$ for any leaf player j.*

For the adjustments needed to compute the second smallest satisfaction, then the third smallest one, and so on, till all nucleolus payoffs are found, the algorithm in Ref. [97] can be consulted. Based on that algorithm Oishi et al. [101] provide an axiomatic characterization of the nucleolus mapping on the class of peer group games. Both these papers present illustrative numerical examples for the computation of the nucleolus in peer group games.

For the peer group game arising from the situation depicted in Fig. 5, the first iteration of the lexicographic optimization algorithm computes the maximum over the core of the minimum satisfaction among the nucleolus-defining $2n-1$ coalitions as

$$\min_{i \in N} \frac{g(\Pi_i)}{\pi_i} = \min\left\{\frac{B}{8}, \frac{b_2}{2}, \frac{b_3}{2}, \frac{b_4 + b_5 + b_6 + b_7 + b_8}{6}, \frac{b_5}{2}, \frac{b_6}{2}, \frac{b_7}{2}, \frac{b_8}{2}\right\}. \tag{3}$$

Notice that in formula (3) the minimum is attained by the leaf player (s) with the smallest benefit because in Fig. 5 both non-leaf players 1 and 4 are superiors of several leaf players, thus $Nu_j = b_j/2$ *for leaf player(s)* j *with the smallest potential benefit* b_j in any peer group game associated with the tree graph in Fig. 5, irrespectively of the individual potential benefits $b_1 = 0, b_2, \ldots, b_8$.

4.3. Gately value

Like the core and the nucleolus, the single-valued solution concept initiated by Gately [102] is also based on the satisfaction of coalitions with an imputation. In contrast to the nucleolus, however, the Gately value only depends on the values of the one-player and the all-but-one-player coalitions. Further differences are that stability against deviations only of players (and not of all coalitions) is considered, and ratios of the satisfactions are used to "measure" the players' inclination to deviate. The Gately value mapping is well-defined for a very broad class of games[8] which includes peer group games with positive leaf benefits.

Player i's *propensity to disrupt* outcome x is the ratio $pd(i,x) = \frac{f(N \backslash i,x)}{f(i,x)}$ of the satisfaction loss i can inflict on the complement coalition $N \backslash i$ over his own satisfaction loss.[9] For any Pareto-efficient x, it holds that $f(N \backslash i, x) + f(i,x) = v(N) - v(N \backslash i) - v(i) = g_i$, a player-specific number independent of the payoff vector. Notice that g_i is the *gap* between the

[6] For a review and comparison (supported by simulation results) of general-scope nucleolus algorithms and a state-of-the-art implementation of the lexicographic center procedure, see Ref. [123].

[7] For an alternative discussion, see Ref. [124]. For similar results on weighted versions of the nucleolus, see Ref. [125].

[8] Details and an overview of the related literature can be found in Ref. [104].

[9] For brevity, braces are omitted, and it is written $v(i)$, $S \cup i$, and $N \backslash i$ instead of $v(\{i\}), S \cup \{i\}$, and $N \backslash \{i\}$, respectively.

Table 3
Calculation of gaps and Gately payoffs related to Fig. 5.

	1	2	3	4	5	6	7	8	total
$Q(1)$	$b_1 = 0$								b_1
$Q(2)$	b_2	b_2							$2b_2$
$Q(3)$	b_3		b_3						$2b_3$
$Q(4)$	b_4			b_4					$2b_4$
$Q(5)$	b_5			b_5	b_5				$3b_5$
$Q(6)$	b_6			b_6		b_6			$3b_6$
$Q(7)$	b_7			b_7			b_7		$3b_7$
$Q(8)$	b_8			b_8				b_8	$3b_8$
g_i	$B = b(Q(1))$	b_2	b_3	$b(Q(4))$	b_5	b_6	b_7	b_8	$G = \sum_{i \in N} g_i$
Ga_i	$B \bullet \frac{B}{G}$	$b_2 \bullet \frac{B}{G}$	$b_3 \bullet \frac{B}{G}$	$b(Q(4)) \bullet \frac{B}{G}$	$b_5 \bullet \frac{B}{G}$	$b_6 \bullet \frac{B}{G}$	$b_7 \bullet \frac{B}{G}$	$b_8 \bullet \frac{B}{G}$	$B = \sum_{i \in N} Ga_i$

marginal contributions of player i to the complement coalition $N \backslash i$ and to the empty coalition $\varnothing$. Following Littlechild & Vaidya [103], the outcomes are only taken from the interior of the core, so all propensity to disrupt ratios and all gap values are well-defined positive numbers. For $x \in int\, Core(N, v)$, it holds that $pd(i, x) = \frac{g_i}{f(i,x)} - 1$. For stability of an outcome, small propensity to disrupt values are desired. Littlechild & Vaidya [103] show that if the largest individual propensity to disrupt value is to be minimized over the interior of the core, the uniquely best outcome is the imputation where all propensity to disrupt values are equal. It means that there is a number $r > 0$ such that $1 + r = \frac{g_i}{f(i,x)}$ for all players $i \in N$, implying $x_i - v(i) = \frac{g_i}{1+r}$. Pareto-efficiency of x implies $v(N) - \sum_{i \in N} v(i) = \frac{\sum_{i \in N} g_i}{1+r}$, thus the Gately payoff to player $i \in N$, denoted by $Ga_i(v)$, is

$$Ga_i(v) = v(i) + \frac{g_i}{\sum_{j \in N} g_j}\left[v(N) - \sum_{j \in N} v(j)\right]. \tag{4}$$

It is clear from reformulation $f(i, Ga) = \frac{g_i}{\sum_{j \in N} g_j} \sum_{j \in N} f(j, Ga)$ that the Gately value allocates the grand coalition value $v(N)$ among the players in such a way to make the satisfactions proportional to the individual gaps.

In games with $v(i) = 0$ for all $i \in N$, formula (4) simplifies to

$$Ga_i(v) = \frac{g_i}{\sum_{j \in N} g_j} v(N). \tag{5}$$

It is easily checked that for the peer group game (N, v) induced by peer group situation $(N, T, (b_i)_{i \in N})$ with $b_i = 0$, the gap of player $i \in N$ is $g_i = b(Q(i)) := \sum_{k \in Q(i)} b_k$, the sum of the *dependent benefits* of i, because the potential benefits of players in $Q(i)$ are realized only if i is also present in the coalition. Notice that $g_1 = B$ for the root player 1 because $Q(1) = N$; all players are dependents of 1. For any other player $i \in N \backslash \{1\}$, the gap is readily obtained from the right hand side of the corresponding inequality in the simplified core system (2), because $g_i = \sum_{k \in Q(i)} b_k = \sum_{k \in N} b_k - \sum_{k \in R(i)} b_k = B - v(R(i))$ for all $i \in N \backslash \{1\}$. For the sum of all gaps formula G $= \sum_{i \in N} g_i =$ B + [sum of gaps of level 2 players] + [sum of gaps of level k $\geq$ 3 players] can also be used. Since the union of the disjoint dependent sets of the level 2 players is the grand coalition, the sum of gaps of the level 2 players equals the sum of benefits of all players, i.e. [sum of gaps of level 2 players] = B. This implies $G \geq 2B$, thus

3. *in any peer group game, the Gately payoff is at most half of the potential benefit, $Ga_j \leq b_j/2$ for any leaf player j.*

This is illustrated in Table 3 with the peer group game arising from the situation depicted in Fig. 5, where the notation $b(U) = \sum_{j \in U} b_j$ is used for any nonempty $U \subseteq N$.

Observe that $N = Q(1)$ as well as $N = Q(2) \cup Q(3) \cup Q(4)$, the union of the disjoint dependent sets of the level 2 players. It follows that $B = b(Q(1)) = g_1$ as well as $B = b(Q(2)) + b(Q(3)) + b(Q(4)) = g_2 + g_3 + g_4$. This implies $G = (g_1 = B) + (g_2 + g_3 + g_4 = B) + (g_5 = b_5) + (g_6 = b_6) + (g_7 = b_7) + (g_8 = b_8)$, thus $G \geq 2B$. Moreover, since there are level 3 players, $G > 2B$ if the potential benefit for all leaf players is positive.

In allocation problems proportionality is (very likely) the most frequently used principle. It is widely considered a "fair method" that is easy to understand and calculate. The key question in each setting is "what should be the weight of each individual"? As mentioned above, in games (with a nonempty interior core) the minimization of the maximum individual propensity to disrupt leads to a particular proportional allocation. The weight of an individual must be the efficiency loss the deviation of this player from the grand coalition would cause, that is not just the potential benefit of this player but also the sum of the potential benefits of all the dependent players (if any).

Despite of these appealing properties, the Gately value mapping has drawbacks. Since it only relies on the 1-player, $(n-1)$-player, and the n-player coalition values and thus explicitly ignores all other coalition values that might provide useful information on individual contributions in various group settings, the Gately allocation could fall outside the core even for convex games [104]. However, in a subclass of peer-group games, which includes the ones associated with the tree graph depicted in Fig. 5, the inclusion is proved below.

4. *If the tree graph has at most 3 levels and the individual benefit for all leaf players is positive, the Gately payoff vector is in the relative interior of the core of the peer-group game. Thus, the dependent-proportional allocation in such peer-group situations is stable.*

Proof of 4. Assume that the underlying tree graph has at most 3 levels, $b_k > 0$ for all leaf players k, and as standard, $b_1 = 0$. Since the Gately payoff vector is Pareto efficient, it is to be seen that all the $2n-1$ inequalities in the simplified core description (2) hold strictly. Since $G \geq 2B > 0$ and $Q(i)$ contains at least one leaf player for all $i \in N$, it follows that $Ga_i = \frac{B}{G} \sum_{j \in Q(i)} b_j > 0 = v(\{i\})$ for all $i \in N$. It is then left to be shown that $\sum_{j \in R(i)} Ga_j > \sum_{j \in R(i)} b_j = v(R(i))$, or equivalently, since $Q(i) \cup R(i) = N$ for all $i \in N$, that $\sum_{j \in Q(i)} Ga_j < \sum_{j \in Q(i)} b_j = g_i$ for all players $i \geq 2$. First, if i is a leaf player, $Q(i) = \{i\}$, then $Ga_i = \frac{B}{G} b_i \leq \frac{1}{2} b_i < b_i$ because $G \geq 2B$ and $b_i > 0$. Second, if i is a not leaf player, then it is a level 2 player with at least one level 3 dependent player, so $Q(i) \backslash \{i\} \neq \varnothing$. Since any level 3 player must be a leaf player, $g_j = b_j$ for all $j \in Q(i) \backslash \{i\}$. Thus, $0 < b(Q(i) \backslash \{i\}) \leq b_i + b(Q(i) \backslash \{i\}) = g_i$. On the other hand, $0 < B < B + b(Q(i) \backslash \{i\}) \leq B +$ [sum of gaps of all level 3 players] $= G - B$. It follows that $B \bullet b(Q(i) \backslash \{i\}) < (G - B) \bullet g_i$. Adding $B \bullet g_i$ to both sides gives $B \bullet \sum_{j \in Q(i)} g_j < G \bullet g_i$, that is just a rearranged form of the claimed strict inequality. This concludes the proof of 4.

4.4. Shapley value

The best-known single-valued solution concept is due to Shapley

Table 4
Computation of the Shapley allocation in Fig. 5 example

	1	2	3	4	5	6	7	8	total
$b_1 Sh(u_{P(1)})$	$b_1/1$								b_1
$b_2 Sh(u_{P(2)})$	$b_2/2$	$b_2/2$							b_2
$b_3 Sh(u_{P(3)})$	$b_3/2$		$b_3/2$						b_3
$b_4 Sh(u_{P(4)})$	$b_4/2$			$b_4/2$					b_4
$b_5 Sh(u_{P(5)})$	$b_5/3$			$b_5/3$	$b_5/3$				b_5
$b_6 Sh(u_{P(6)})$	$b_6/3$			$b_6/3$		$b_6/3$			b_6
$b_7 Sh(u_{P(7)})$	$b_7/3$			$b_7/3$				$b_7/3$	b_7
$b_8 Sh(u_{P(8)})$	$b_8/3$			$b_8/3$				$b_8/3$	b_8
$Sh(v)$	$\sum_{k\in Q(1)} \frac{b_k}{p_k}$	$b_3/2$	$b_2/2$	$\sum_{k\in Q(4)} \frac{b_k}{p_k}$	$b_5/3$	$b_6/3$	$b_7/3$	$b_8/3$	$B = \sum_{i\in N} b_i$

Table 5
Individual decarbonization potential for the hydrogen supply chain agents in the treated case

Node or Agent (i)	Agent (technology) name	e_i: emissions per agent (kg $CO_{2\text{-eq}}$ /kgH2)	Reference	$b_i = e_i$-sq_i	Comment
Status quo (e_sq$_i$)	Production: SMR	10.30	[91]	0	Reference technology for gray H_2 (no benefit)
	Gaseous storage	1.00	Assumption	0	Can be used for any H_2 color. Gaseous (pipeline) or liquid hydrogen shipping
	Gaseous transportation	1.00			adds another 1.5 or 1.8 kg $CO_{2\text{-eq}}$ per kg H_2, respectively [3]
1	Gaseous storage	1.00	Assumption	0	no benefit
2,7	Electrolysis + solar power	3.08	[91]	7.22	Median green hydrogen production emissions is estimated as 2.9 kg $CO_{2\text{-eq}}$ per
3,8	Electrolysis + wind power	0.98	[92]	9.32	kg H_2 (0.8–4.6 kg $CO_{2\text{-eq}}$ kg per H2, 95% confidence interval) [3]
4	Gaseous transportation	1.00	Assumption	0	no benefit
5	Electrolysis + nuclear power	2.15	[92]	8.15	
6	SMR + CCS	3.40	[91]	6.9	
Total emissions of the system (nodes 1–8)		15.67 kg $CO_{2\text{-eq}}$			

[105]. It is based on marginal contributions of the players to all coalitions they can join and not on satisfactions of coalitions with given outcomes like the nucleolus and the Gately value. The Shapley value mapping is defined for all games, but it needs not give a core allocation even if the core of the game is not empty. For convex games, however, the Shapley value is always in the core, in fact, in the relative interior when it is not empty [96].

In game (N, v) the *Shapley payoff* to player $i \in N$, denoted by $Sh_i(v)$, is

$$Sh_i(v) = \sum_{S\subseteq N\setminus i} \frac{s!(n-1-s)!}{n!} [v(S\cup i) - v(S)] \tag{6}$$

where s, n denotes the number of players in coalitions S, N, respectively. Since $\sum_{S\subseteq N\setminus i} \frac{s!(n-1-s)!}{n!} = 1$, the Shapley payoff is the weighted average of all marginal contributions of the given player. Shapley [105] proves that on the domain of all cooperative games the only value mapping which satisfies four basic axioms[10] is the above one. The explicit formula makes the impression that the Shapley payoffs are "easy to compute", but notice that to calculate formula (6), all exponentially many marginal contributions are needed (that requires the computation of all coalitional values from the underlying situation) for each player since all the weights are positive. So, unlike the nucleolus and the Gately allocation, the Shapley allocation is sensitive to changes in all coalitional values.

Any game (N, v) can be expressed as a linear combination of the unanimity games with a unique system of coefficients.[11] Brânzei et al. [84] show that for peer group game (N, v) induced by peer group situation $(N, T, (b_i)_{i\in N})$ this linear combination only consists of linearly many terms, namely $v(S) = \sum_{i\in N} b_i\, u_{P(i)}(S)$ for all $\varnothing \neq S \subseteq N$. By linearity of the Shapley value mapping, the Shapley payoff vector is $Sh(v) = \sum_{i\in N} b_i\, Sh(u_{P(i)})$. The other three properties of the mentioned axiomatization uniquely determine the payoffs in the unanimity games. By the "equal treatment of equals" axiom, in unanimity game $u_{P(i)}$ the Shapley payoffs to all players $j \in P(i)$ superior to i must be the same. By the "null player" axiom, $Sh_k(u_{P(i)}) = 0$ for all other players $k \in N\setminus P(i)$. Finally, by the Pareto-efficiency axiom, the Shapley payoffs must sum up to $u_{P(i)}(N) = 1$. It follows that the Shapley payoff to players $j \in P(i)$ superior to i in unanimity game $u_{P(i)}$ must be $Sh_j(u_{P(i)}) = \frac{1}{p_i}$, where p_i denotes the number of players in path $P(i)$. Therefore, again by linearity, in peer group game (N, v) the Shapley payoff to player $i \in N$ must be $Sh_i(v) = \sum_{k\in Q(i)} \frac{b_k}{p_k}$, that is the sum of the per-capita benefits for all path coalitions $P(k)$ which contain i. Notice that the Shapley allocation can be directly obtained from the parameters of the underlying peer group situation, there is no need to calculate the exponentially many coalitional values and the coefficients in the linear decomposition of the game.

The following two statements hold in any peer group game.

5. *For any leaf player k, the Shapley payoff is at most half of the potential benefit, $Sh_k \leq b_k/2$. Moreover, equation holds for level 2 leaf players.*
6. *If the individual benefit number for all leaf players are positive, then the Shapley payoff vector belongs to the relative interior of the core of the peer group game.*

Proof of 5. Let k be a leaf player. Then $Q(k) = \{k\}$ and $p_k \geq 2$ since $k \neq 1$. It follows that $Sh_k \leq b_k/2$.

Proof of 6. Assume that $b_k > 0$ for all leaf players k and, as standard, $b_1 = 0$. Since the Shapley payoff vector is Pareto efficient, it is to be verified that all the $2n-1$ inequalities in the simplified core description (2) hold strictly. First, since $Q(i)$ contains at least one leaf player for all $i \in N$, it follows that $Sh_i = \sum_{j\in Q(i)} \frac{b_j}{p_j} > 0 = v(\{i\})$ for all $i \in N$. Second, since $p_i \geq 2$ and $Q(i)$ does not contain root player 1 for all $i \geq 2$, in the

[10] The Shapley value mapping has been characterized by many different sets of axioms. For details on the best-known axiomatizations on the unrestricted domain, consult the textbooks listed in footnote 4. It is important to emphasize, however, that on a smaller class of games, the same set of axioms need not determine the value mapping uniquely. It is left for further research to find axiomatizations for the value mapping. In the class of peer group games, the Shapley value mapping is characterized by Oishi et al. [101].

[11] For details see the textbooks listed in footnote 4.

sum $\sum_{j\in Q(i)} Sh_j = \sum_{j\in Q(i)} \sum_{k\in Q(j)} \frac{b_k}{p_k}$ the term $\frac{b_k}{p_k}$ appears at most $p_k - 1$ times for each $k \in Q(i)$. It follows that $\sum_{j\in Q(i)} Sh_j \le \sum_{k\in Q(i)} \frac{(p_k-1)b_k}{p_k} < \sum_{k\in Q(i)} b_k$ for all $i \ge 2$. Since $Q(i) \cup R(i) = N$ for all players, the obtained $\sum_{j\in Q(i)} Sh_j < \sum_{j\in Q(i)} b_j$ is equivalent to the claimed $\sum_{j\in R(i)} Sh_j > \sum_{j\in R(i)} b_j = v(R(i))$ for all players $i \ge 2$. This concludes the proof of 6.

Table 4 summarizes the calculations for Fig. 5 example and illustrates the above two general statements.

Observe that in any peer group game associated with the tree graph in Fig. 5, for level 2 leaf players $k = 2, 3$ the Shapley payoff is $Sh_k = b_k/2$, and for level 3 leaf players $k = 5, 6, 7, 8$ the Shapley payoff is $Sh_k = b_k/3 \le b_k/2$. For statement 6, notice that if $b_k > 0$ for all leaf players k, then all Shapley payoffs (the values in the last row of Table 4) are positive, and for any $i \ge 2$, the submatrix in the intersection of the rows and columns corresponding to $j \in Q(i)$ does not contain the entries in the (second) column containing the shares of root player 1, thus the sum of the Shapley payoffs to coalition $Q(i)$ (the sum of the entries in the $Q(i)$ submatrix) is smaller than the sum of the benefits (the entries in the last column) of players in $Q(i)$.

5. Results and discussion

In this Section, Steps 5 and 6 of Fig. 3 are developed. They correspond to the performance of calculations (Step 5) and the comparison of results using the HSC cooperation toolbox (Step 6).

5.1. Environmental benefit

Decarbonization risk is widely considered in the context of non-green hydrogen solutions; however, as illustrated by the case, it exists even in green HSCs. By using a functional unit of 1 kg H_2 for each production agent (i.e., 6 kg H_2 for the whole system – Fig. 5), the potential individual environmental benefit for all technologies is presented in Table 5. The functional unit can be easily scaled up to the required hydrogen demand. The production, storage, and transportation of low-carbon hydrogen are not entirely free of emissions. The actual benefit offered by each production agent (b_i) can be calculated regarding SMR, which is considered the status quo technology. From Tables 5 and it can be highlighted that the production's largest environmental benefit is given by wind electrolysis, followed by nuclear electrolysis, solar electrolysis, and finally, SMR + CCS. Both wind and solar options are available in centralized or decentralized configurations. The total maximum benefit, understood as decarbonization potential, for the 8-node coalition is 78% when compared to the status quo technology just by measuring the production technology nodes, meaning that this coalition fulfills the emissions reduction requirements (>70%) to participate, for example, in international auctions [90]. Financial support is needed to accelerate the deployment of low-carbon HSCs because low-carbon hydrogen costs are still not competitive with those of gray hydrogen or other fuels [56]. This might explain diverting investments to hydrogen solutions with higher CO_2 emissions [43]. Both subventions and carbon prices can accelerate the expansion of hydrogen technologies, but capacity constraints related mainly to energy sources might incentivize agents' cooperation to achieve both economic and environmental benefits through synergies. The social cost-benefit was used previously to provide an economic evaluation that integrates also hidden costs or benefits, referred to as externalities [7]. An environmental externality refers to the situation when negative environmental consequences are not or not fully internalized by the market agents [106,107].

In a transparent environment, all coalition agents having a unique sequence of superiors should be aware of their potential individual values, as well as their need to cooperate if their capacity is not enough. In the treated case, if the agents decide to work independently, they have a zero benefit, even if they have a positive potential individual benefit b_i, because the basic assumption is that the agents have limited capacity, which would not allow them to fulfill a required demand on their own. The agents should also be conscious of the potential implications of a hierarchy where higher-level agents possess "critical resources" and might block the efficient implementation and realization of system-level objectives, be it economic or environmental. Having access to such a critical resource is necessary for being able to materialize the potential capabilities of lower-level agents. Table 5 displays the individual environmental benefits for the agents. For the proposed case, "wind + electrolysis" agents in nodes 3 and 8 offer the highest benefit with a reduction of 9.32 kg $CO_{2\text{-eq}}$ /kgH_2. Based on these results, agents are ready to start the bargaining process. To support this, six allocation rules are used to investigate what could be the best way to allocate the benefit in low-carbon HSCs that display a peer group game structure, as developed in Sections 5.2 and 5.3.

5.2. Case specification and allocations

In the peer group game model associated with a peer group situation, the value of a coalition is defined as the sum of the individual potential benefits of those members who are connected to the root member having a critical resource (gaseous storage for the proposed case) via other members within the coalition. Table 6 describes the rooted tree structure by specifying the unique immediate superior node $t(i)$ for each node i (except the root node 1) and gives the potential benefit values $b(i)$ as well as the gap values $g(i)$ for the nodes. Table 6 shows that the maximum total benefit achievable by the eight agents, that is, the value of the grand coalition is $v(N) = B = \sum_i b(i) = 48.11$ kg $CO_{2\text{-eq}}$.

The allocation of the grand total benefit value (48.11) was computed for the six allocation rules and is displayed in Table 7. The naïve rules (PE, AE, and BP) offer higher shares to production, but the hierarchical aspect is not captured. In the "producers equally" (PE) and "benefit proportional" (BP) rules, a zero share is allocated to transportation and storage. Only the "all equally" (AE) rule gives some gains to those nodes among the naïve rules, but it ignores the benefit differences of the production agents. In contrast, the game theoretic rules consider both types of individual differences and give a joint assessment in line with the normative idea underlying the solution concepts.

In the case of the game theoretic allocation rules, the highest share always goes to agent 1 who represents the critical resource (storage). The second largest share goes to agent 4 (transportation) who leads four agents in the centralized production configurations. These results might seem contra intuitive if only the benefit in CO_2 emission is taken into consideration because both transportation and storage offer a zero individual decarbonization benefit. However, this clearly indicates how important the role and position of these agents are in achieving the

Table 6
Structure of the hierarchy and emission saving benefit for the agents

Agent		Storage	Solar + Electr.	Wind + Elect.	Transport	Nuclear + Electr.	SMR + CCS	Solar + Elect.	Wind + Elect.	Grand coalition
Agent number	i	1	2	3	4	5	6	7	8	NA
Direct superior node number	t(i)	–	1	1	1	4	4	4	4	NA
Benefit (emission savings)	b(i)	0.00	7.22	9.31	0.00	8.15	6.90	7.22	9.31	B = sum b(i) = 48.11
Dependent benefit (gap)	g(i)	48.11	7.22	9.31	31.58	8.15	6.90	7.22	9.31	G = sum g(i) = 127.8

Table 7
Allocated shares (reference unit: benefit in kg $CO_{2\text{-eq}}$ per agent)

Agent number	i	1	2	3	4	5	6	7	8	Total
Production equally	PE	0.00	8.02	8.02	0.00	8.02	8.02	8.02	8.02	48.11
All equally	AE	6.01	6.01	6.01	6.01	6.01	6.01	6.01	6.01	48.11
Benefit-proportional	BP	0.00	7.22	9.31	0.00	8.15	6.90	7.22	9.31	48.11
Gately (gap-prop.)	Ga	18.11	2.72	3.50	11.89	3.07	2.60	2.72	3.50	48.11
Nucleolus	Nu	16.16	3.61	4.66	7.90	4.08	3.45	3.61	4.66	48.11
Shapley	Sh	18.79	3.61	4.66	10.53	2.72	2.30	2.41	3.10	48.11

Table 8
Satisfaction and propensity to disrupt values for the six allocations

Coalition values needed for computation of Gately allocation and checking core memberships of allocations									
Coalition	{1}	{2}	{3}	{4}	{5}	{6}	{7}	{8}	*
v(i)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	
Coalition	N\{1}	N\{2}	N\{3}	N\{4}	N\{5}	N\{6}	N\{7}	N\{8}	{1,2,3}
v(N-i) = v(N)-g(i)-v(i)	**0**	**40.89**	**38.8**	**16.53**	**39.96**	**41.21**	**40.89**	**38.8**	**16.53**
Allocations									
Share of player	1	2	3	4	5	6	7	8	{1,2,3}
PE: only producers share equally, PE(i)=B/6 for producer i, and =0 for infrastructure agents									
Satisfaction: f(N-i,PE)	48.11	−0.80	1.29	31.58	0.13	−1.12	−0.80	1.29	−0.49
f(i,PE) = PE(i)	0	8.02	8.02	0	8.02	8.02	8.02	8.02	
Propensity to disrupt: pd (i,PE)	Infinite	−0.10	0.16	Infinite	0.02	−0.14	−0.10	0.16	
AE: All agents share equally, AE(i)=B/8 for all i									
f(N-i,AE)	42.10	1.21	3.30	25.57	2.14	0.89	1.21	3.30	1.51
f(i,AE) = AE(i)	6.01	6.01	6.01	6.01	6.01	6.01	6.01	6.01	
pd(i,AE)	7.00	0.20	0.55	4.25	0.36	0.15	0.20	0.55	
BP: benefit proportional shares from the sum of benefits, so BP(i)=b(i) for all i									
f(N-i,BP)	48.11	0	0	31.58	0	0	0	0	0.00
f(i,BP)==BP(i) = b(i)	0	7.22	9.31	0	8.15	6.9	7.22	9.31	
pd(i,BP)	Infinite	0	0	Infinite	0	0	0	0	
Ga: Gately = shares are in proportion to the dependent benefits									
f(N-i,Ga)	30.00	4.50	5.81	19.69	5.08	4.30	4.50	5.81	7.80
f(i,Ga)==Ga(i)	18.11	2.72	3.50	11.89	3.07	2.60	2.72	3.50	
pd(i,Ga)	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	
Nu: nucleolus									
f(N-i,Nu)	31.95	3.61	4.66	23.69	4.08	3.45	3.61	4.66	7.90
f(i,Nu) = Nu(i)	16.16	3.61	4.66	7.90	4.08	3.45	3.61	4.66	
pd(i,Nu)	1.98	1.00	1.00	3.00	1.00	1.00	1.00	1.00	
Sh: Shapley									
f(N-i,Sh)	29.32	3.61	4.66	21.05	5.43	4.60	4.81	6.21	10.53
f(i,Sh) = Sh(i)	18.79	3.61	4.66	10.53	2.72	2.30	2.41	3.10	
pd(i,Sh)	1.56	1.00	1.00	2.00	2.00	2.00	2.00	2.00	

**In the last column the satisfaction value of coalition* {1,2,3} is listed

maximum decarbonization objectives of the grand coalition. In other words, if the hydrogen produced cannot be made accessible to the market (assumed to be close to storage), the global decarbonization goals might be infeasible or highly risky. On the other hand, since the storage and transportation agents are assumed to have limited capacity to provide their services to other clients (e.g., manage gray H_2 instead of low-carbon H_2), they might have significant influence in defining certain contractual conditions or in selecting whom to cooperate with. Identifying critical resources and preparing for bargaining strategies are essential tasks for all agents to successfully deploy low-carbon HSCs. Allocating benefits to key superior agents might ensure collaboration.

Going further in the comparison of the game-theoretical allocation rules, it is possible to distinguish similar results for the Gately and Shapley allocations. Nucleolus, on the other hand, offers higher benefits to the wind nodes, which might be considered a more acceptable approach; however, it does not differentiate the level for those technologies when used in the centralized and decentralized setup as it is done in the Gately and Shapley allocations. To compare the rules and the resulting allocations of shares in the proposed case, four key aspects are considered: (1) allocation value, (2) stability level, (3) satisfaction level, and (4) propensity to disrupt level. These concepts from cooperative game theory describe fairness of the allocation for some rules. It is highlighted that the concept of fairness in other contexts might be subject to different criteria or to subjective interpretation [108]. In terms of the three types of distributional fairness principles discussed by Soares et al. [95] (cf. subsection 3.3), the Shapley rule is clearly a meritocratic one because it allocates to the players the weighted average of their marginal contributions. Since the nucleolus allocation is

Table 9
Allocated shares per unit volume (reference unit: benefit in kg $CO_{2\text{-eq}}$ per kg H_2 in node *i*)

Node number	i	1	2	3	4	5	6	7	8
H_2 volume (kg)		6	1	1	4	1	1	1	1
Production equally	PE	0.00	8.02	8.02	0.00	8.02	8.02	8.02	8.02
All equally	AE	1.00	6.01	6.01	1.50	6.01	6.01	6.01	6.01
Benefit-proportional	BP	0.00	7.22	9.31	0.00	8.15	6.90	7.22	9.31
Gately (gap-prop.)	Ga	3.01	2.72	3.50	2.97	3.07	2.60	2.72	3.50
Nucleolus	Nu	2.69	3.61	4.66	1.98	4.08	3.45	3.61	4.66
Shapley	Sh	3.13	3.61	4.66	2.88	2.72	2.30	2.41	3.10

computed to maximize (in a lexicographic way) the satisfaction of the minimally satisfied coalitions, the nucleolus rule embodies the max-min fairness principle. Similarly to the "producers equally" PE rule, the Gately rule also shows that the fairness principles are not exclusive. Although the Gately value is defined to minimize the maximum disruptive propensity of players, a genuine example of max-min fairness in allocating bads. As shown in subsection 4.3, in peer group games, it turns out to be a proportional allocation, a typical example of meritocratic fairness, where the weights of the players measure in a natural way the "nullifying power" of the infrastructure agents in the HSC. Since, in this work, cooperative and naïve rules are compared, "acceptability" is used instead of "fairness".

To analyze the acceptability of allocations, their stability, satisfaction levels, and propensity to disrupt levels (concepts developed in Section 4) are used. First, the core is not empty, and it is possible to evaluate the satisfaction and propensity to disrupt by using the calculations from Table 8. The value of all single-player coalitions is zero, so the satisfaction values are equal to the payoffs, $f(i,x) = x_i$ for all agents i and allocations x. Here f can be considered a satisfaction metric that measures the difference of the allocated share of coalition S and the total

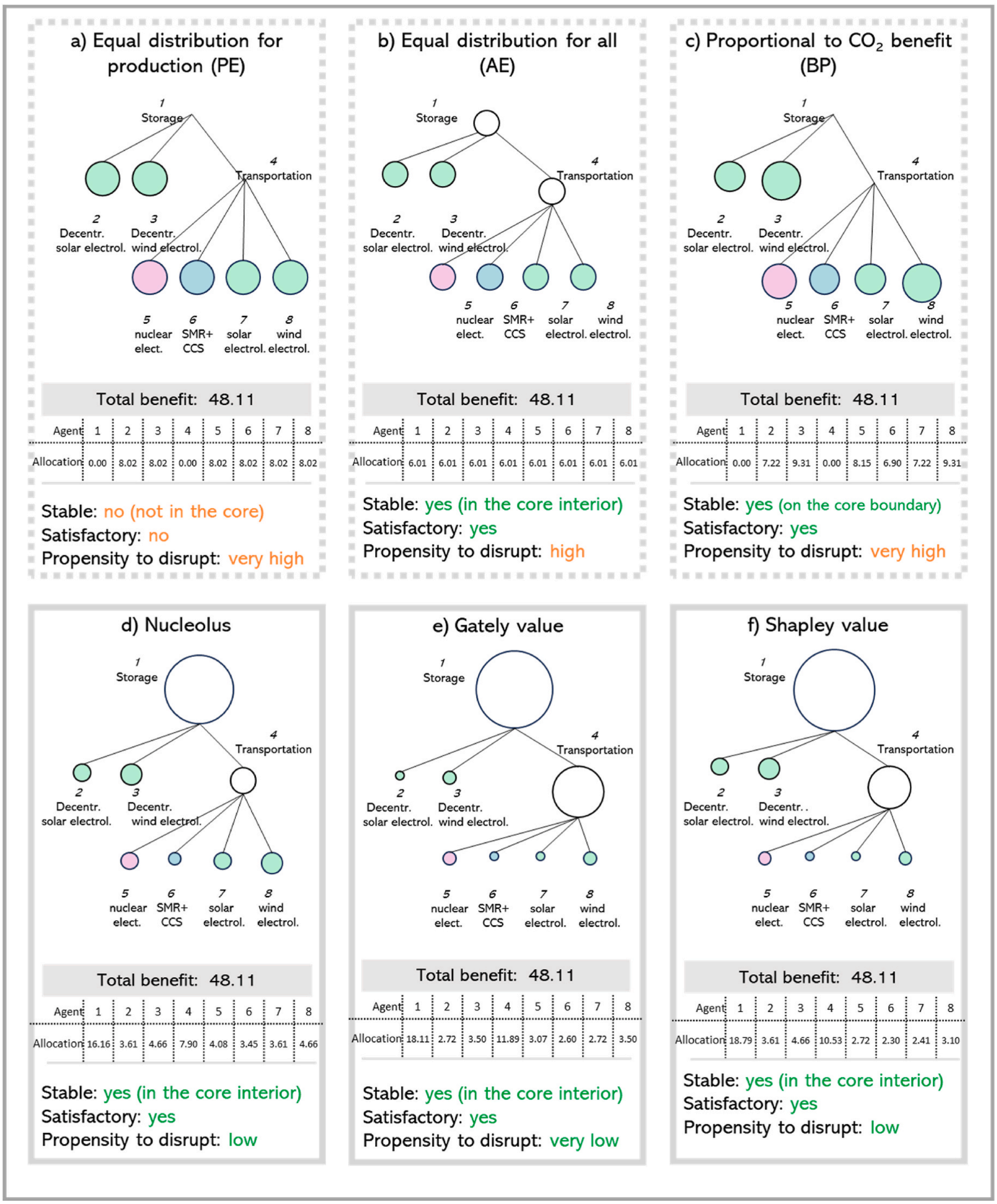


Fig. 7. Results of the proposed toolbox for decision-makers - the general low-carbon HSC scenario (total benefit allocation per agent). Scale: Node size represents the agent's allocation value. Font colors: orange: bad for the grand coalition threatening its viability; green: good for the grand coalition. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

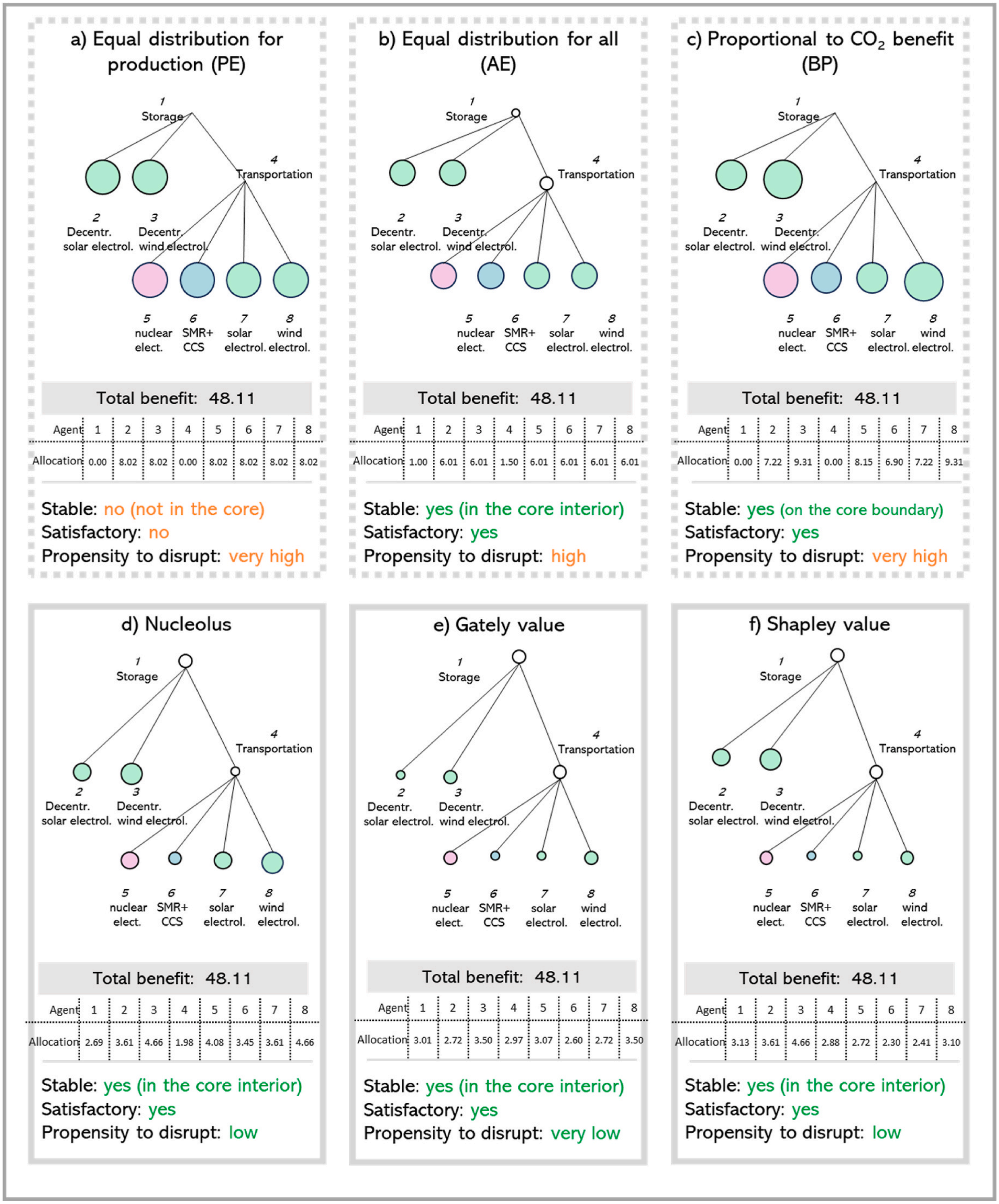


Fig. 8. Results of the proposed toolbox for decision-makers - the general low-carbon HSC scenario (benefit allocation per kg H_2 per agent).

benefit it can achieve on its own without the other agents. If it is not negative, coalition S has no incentive not to participate in the grand coalition N. The core allocations, where no smaller coalition has an incentive to break away, are thus considered stable. The propensity to disrupt (pd) is also a measure showing the degree of acceptability. Values of coalitions $N\backslash\{1\}$ and $N\backslash\{4\}$ are only needed for computing the Gately allocation, whereas value of coalition $\{1,2,3\}$ is only needed for checking core membership. For the treated case, only allocation PE is not stable (e.g., $f(\{6\},PE)<0$), the other five allocations are in the core (Table 8). In a generic peer group game, however, only the Gately, Nucleolus, and Shapley allocations are guaranteed to be in the interior of the core when all leaf players have positive potential benefits. The nucleolus allocation provides the highest satisfaction for all coalitions over the core, $\max_{x\in Core}\min_S f(S,Nu) = 3.45 = f(\{6\},Nu) = f(N\backslash\{6\},Nu)$; for all other allocations there is some coalition with lower satisfaction. The Gately allocation provides the lowest propensity to disrupt value for all players over the core interior, $\min_{x\in int\ Core}\max_i pd(i,Ga) = 1.66 = pd(i,Ga)$ for all $i\in N$; for all other allocations, there is some player with a higher propensity to disrupt (Table 8). Notice that due to the inner positions of the nucleolus and the Shapley value in the core, the highest propensity to disrupt value for these allocations is always expected to be not "much higher" than for the Gately value. In this case, $pd(4,Nu)=3.00$ and $pd(4,Sh)=2.00$, whereas for the three naïve allocations this is $pd(1,AE)=$

7.00 and even infinite for *PE* and *BP*, reflecting the "global" veto power of root agent 1, and the "local" veto power of non-leaf agent 4 over the dependent agents 5,6,7, and 8.

In closing this section, clarification is needed regarding the hydrogen volumes handled by the different agents based on their position in the supply chain. While each production agent handles 1 kg H_2, transportation handles 4 times more and storage 6 times more, which is also captured in the allocated values for the game theoretical rules displayed in Table 7. For example, from the total coalition benefit of 48.11 units, 37% (18.11 units) is allocated to storage (agent 1) by the Gately rule, compared to 3.5 units allocated to the wind decentralized electrolysis production (agent 3); however, the former treats 6 kg H_2 and the latter only 1 kg H_2, then the allocation for the storage agent is indeed 3.01 units per kg H_2. All results can be presented by using the same functional unit of 1 kg as displayed in Table 9.

5.3. A toolbox for facilitating smart policy decisions in low-carbon HSCs

Although the focal concept of the paper is cooperation, low-carbon HSC agents have a "coopetitive" relationship. Using the classic "pie metaphor" [109], agents cooperate to increase the size of the pie, for this case, the environmental benefit, which can translate into financial gain. To increase the size of the pie, agents must invest in resources (e.g., expanding capacity, building new installations, or dedicating infrastructure to low-carbon hydrogen). Then, agents turn to competitors to get as much from the pie as possible for themselves. Such coopetition is always paradoxical [110], loaded with potential tension, which can threaten the realization of common goals, like maximized decarbonization and demand fulfillment. Managing coopetition needs efficient means to overcome this inherent tension [111]. The operationalization of the low-carbon HSC coalition as a peer group game and the comparison of potential allocation schemes using the six allocation rules can help find an acceptable cooperation strategy for all agents. In this context, the methodology suggests using the proposed toolbox (see Figs. 7 and 8) to inform agents about the impact of each allocation scheme. The toolbox can be used to support smart investment decisions in real-world HSC bargaining processes but does not aim to specify a single allocation rule as the most appropriate choice, generally. Rather, the solutions for each rule allow the analysis and discussion and give the possibility to include the agents' preferences in the decision-making by exploring alternative allocation rules.

The toolbox is designed to simultaneously display the six allocation rules, categorized as naïve (top section of Figs. 7 and 8) or game-theoretical (bottom section). For each rule, the following elements are presented: the rule name, the structure (with agent sizes proportional to allocated benefits), and the maximum benefit of the coalition and individual allocations in numerical values (which can serve as a proxy of the allocation of financial means). The toolbox also reports three game-theoretical concepts to evaluate the acceptability of the schemes: (1) stability level, (2) satisfaction level, and (3) propensity to disrupt. These are closely related, complementary measures contributing to understanding how viable a specific allocation is. Numerical values for these concepts are presented in Table 8, and the coding is based on the analysis in Section 5.2. As detailed in the methodological section, the property of stability is conceptualized on the coalition level. It shows the "level of resistance" of the grand coalition against deviations by smaller groups of agents, including single agents as well, benefitting all members of the deviating group. This resistance of single agents (and not of all coalitions) is called satisfaction and is used to "measure" the agents' inclination to deviate. For stable allocations, small individual propensity to disrupt values are reported too. From Figs. 7 and 8, an allocation with high stability and satisfaction level and with low propensity to disrupt means that there is a very low risk for agents to leave the grand coalition, making it a viable alliance. On the contrary, allocations having low stability and satisfaction levels but high propensity to disrupt values are unlikely to be acceptable by all agents.

The visual representation of the toolbox facilitates data analysis. For instance, Figs. 7 and 8 quickly reveal that game-theoretical rules outperform naïve ones in terms of acceptability, even though the latter may be considered intuitively fairer by some decision-makers. This aligns with recent research findings, which show that the intuitive preferences of decision-makers do not always lead to optimal outcomes [112]. Fig. 7 highlights the impact of hierarchical positioning, showing a clear difference between naïve and game-theoretical rules. This difference mainly comes from how benefits are allocated to storage (agent 1) and transportation (agent 4), with game-theoretical rules considering the position and volume handled by each agent. In that sense, decision-makers may question why the allocation by the game-theoretical rules in Fig. 7 is so large for agents 1 and 4 when their individual contribution to CO_2 emissions reduction is zero. This can be explained by two main reasons. The first one is the importance of the hierarchy in the peer group game situation, e.g., storage (agent 1) would probably veto an allocation unacceptable using its hierarchical position within the grand coalition. In other words, if low-carbon hydrogen is produced but there is no dedicated storage capacity, the storage agent becomes a bottleneck, obstructing successful delivery to end customers. This limits the capacity utilization of production and transport agents, ultimately preventing the achievement of maximum environmental benefit. The second reason is the volume; the production agents are assumed to process the same volume (functional unit: 1 kg H_2), and in the centralized coalition, the transport agent handles the output from four production agents, while in the grand coalition, the storage agent manages the volume from all producers. These aspects are ignored in the current setup of the naïve rules and might explain their higher propensity to disrupt. For comparison purposes, the analysis is simplified through the per-unit representation shown in Fig. 8, which reveals the gain per kg of H_2 for each agent in each scheme. By comparing elements from the toolbox, agents can discuss the specificities of a particular scenario and agree on the best trade-off solution that ensures both the effective operation of the low-carbon HSC and the maximization of environmental benefits.

6. Conclusions and perspectives

Low-carbon hydrogen is considered a key element in the energy transition due to its energy storage capability, flexibility, and decarbonization potential. A low-carbon HSC is a network connecting different stakeholders (institutional or infrastructure agents). In the next decades, a massive development of low-carbon hydrogen infrastructure is projected, making agents cooperation a key enabler. The main objective of this research was to use a systems and cooperative game theory approaches for analyzing the maximum decarbonization potential of a generalized low-carbon HSC scenario that captures multiple agents' particularities (type, decarbonization potential, hierarchical position, and capacity) to analyze the effects of cooperation under different benefit allocation schemes. Based on the literature review, cooperation has been widely explored in the last years with direct or indirect relationships to hydrogen. Game theory has been found useful in analyzing the effects of cooperation in multiple case studies; however, the paper identified five research gaps that are used now for elaborating contributions.

First, more research is needed to define the HSC structure, which is crucial for benefit allocation, especially in decarbonization. In this research, a hypothetical case with infrastructure agents (i.e., electrolysis using solar, wind, or nuclear power, SMR with CCS, gaseous transportation, and storage) was developed based on assumptions justified by recent reports and articles to find a generic structure for low-carbon HSCs. The case was designed with three main requirements: (1) to highlight the potential capacity constraints, mainly related to renewable energy sources availability, (2) to capture the individual differences in environmental benefits provided by each technology, treated as agents, and (3) to achieve a total system-level decarbonization benefit of more than 70% with regards to the status quo technology. Only global warming potential ($CO_{2\text{-eq}}$) was considered, and 1 kg of hydrogen is the functional unit to allow easy scalability for the proposed calculations. At this stage of the research, the main objective was to develop a generic case that allows to illustrate and test the proposed methodology. The development of realistic case studies is not a trivial task due to the inherent complexity. As a perspective, the definition of a real case study is being explored.

Second, most of the agents are treated equally in available models, with no agent having veto power over another's payoff. This paper argued for cooperation in a systems perspective by analyzing the low-carbon HSC. It is characterized by sequential dependency among the infrastructural agents using a hierarchical representation, resulting in unique sequences of superiors with critical resources, having blocking potential. The position of an agent might affect the acceptability to participate in a coalition, resulting in a high risk if the veto agent(s) leave the alliance. In this research, the structure of the so-called "peer group game" has been identified as useful for operationalizing cooperation in such structures.

Third, the dependency aspect is crucial and requires additional research. HSC agents should be conscious of their individual decarbonization potential, capacity constraints, and positions in a coalition. They depend on each other to achieve the decarbonization benefit of at least 70%. Dependency can be differentiated by the existence of coalitions inside the grand coalition, e.g., centralized or decentralized electrolysis production using wind or solar power. The infrastructure agents' dependency and hierarchical position were analyzed by comparing naïve and game theoretical allocation rules that displayed important allocation differences that might affect the coalition's viability. A special type of transferable-utility game model was used in this research to integrate the dependency aspect and the individual heterogeneity appropriately.

Fourth, in analyzing cooperative TU games, besides the Shapley value and the Nucleolus, additional game-theoretical solution concepts remain underexplored. In the context of the peer group game model of HSCs, in addition to the Shapley value and the Nucleolus, the Gately value is also found appropriate for analysis because it provides an easily computable, highly stable allocation of the benefits that are proportional to the disruption potential of the agents. The properties and the computation of these three game-theoretical rules are thoroughly explained and justified in the paper. They were also compared to three naïve rules (similar to those used in real cases) to illustrate the added value of game-theoretical tools in decision-making.

The fifth gap is related to the lack of visualization tools. This paper proposes a toolbox with the six allocation rules to identify acceptable allocation option(s) and provides a visualization solution, too. Fairness is often seen as a key evaluation criterion in game theory. However, it is difficult to generalize, especially due to its subjective and diverse cultural connotations. In this work, the evaluation of the HSC coalition acceptability is done by using game-theoretical measures, like allocation share, stability, satisfaction, and propensity to disrupt, which can affect the viability of a cooperation. The proposed "acceptability criteria" could influence how much coalitions are eligible for financial support designed to avoid decarbonization risk and maximize its potential.

From the numerical results, it can be concluded that among the stable allocations, the Nucleolus offers the highest satisfaction level while the Gately value provides the lowest propensity to disrupt. For the naïve rules, the results are very different. The "equal distribution only for producers" has the highest risk because this option is out of the core. The other two naïve options, namely the "equal shares for all agents" and the "shares proportional to individual benefits" allocations, although in the presented case are stable, but offer rather marginal results in terms of the other two evaluation criteria. This research does not conclude on the best allocation scheme, instead offers a toolbox for agents to debate and agree on the best trade-off solution that guarantees the achievement of the grand coalition objectives in the medium or long term.

Contributions of the paper are mainly methodological and related to:

1. *System-level decarbonization assessment in the energy transition.* The proposed methodological solution is capable of measuring system-level decarbonization potential and its distribution among HSC agents. Calculations were presented using a general scenario to promote understanding.
2. *Cooperation and decision-making in hydrogen systems.* The proposed set of methodologies can be used as a decision-making toolkit by HSC agents and other stakeholders, facilitating efficient decision-making and cooperation. It is useful to the industrial community of the hydrogen economy and financial institutions facilitating its development but also to policymakers. It helps understand the systemic challenges and make better decisions, develop sophisticated financial support schemes that can facilitate conflict resolution, and work on synergies to avoid decarbonization risk while investing in a low-carbon hydrogen economy.
3. *Coalition's needs.* The case results prove the value of cooperation-related studies in the context of HSC to avoid market failures, which can be associated with tensions, lack of coordination, and environmental failures. Specifically, it emphasizes

a. *Coordination.* The urgent need to consider coordination in decision making. The realization of system-level maximum benefit is not straightforward, and it can be risky in the absence of coordination efforts based on understanding of potential synergies around decarbonization.

b. *Risk mitigation and financial support.* Decarbonization risk is widely considered in the context of non-green hydrogen solutions. However, as this study demonstrates, it exists even in low-carbon HSCs. Mitigating both risk types might include innovative financial constructs to help the market players in their cooperative efforts. However, decarbonization risk represents an externality to market agents; thus, well-designed government policies seem to be necessary to achieve ambitious system-level decarbonization objectives. Thus, on the one hand, this work can help policymakers develop appropriate incentive schemes to achieve both financial and climate objectives. Finally, it can help the cooperating agents to calculate the needed financial support for the coalition to be feasible.

4. *Cooperation and decision-making in other energy supply chains.* The methodology was applied to HSCs but is not limited to it. The proposed toolbox can be used in other energy supply chain problems representing a peer group situation and looking for collaboration.
5. *Cooperative game theory.* New findings for solutions of any peer group game were identified and highlighted as numbered statements in Section 4.
6. *Coopetition.* Agents of low-carbon HSC compete for limited resources but are also forced to cooperate. Thus, the paper pinpoints that the notion of coopetition needs to be introduced in the hydrogen economy implementation analysis. As discussed, managing coopetition needs an efficient management of decisions loaded with tension [111]. Still, little is known concerning the nature and materialization of this paradox [113], and there is a lack of understanding of how tension in coopetitive relationships manifests and how these might affect outcomes [114]. The work from Ref. [115] presents a game-theoretical operationalization capable of doing that in the context of dyadic coopetitive relationships. This paper adds to this discussion by providing an operationalization for HSCs as complex systems where cooperation and competition might be present parallelly.

Some limitations and perspectives have also been identified:

1. A general low-carbon hydrogen scenario was addressed. Future research is needed to develop specific scenarios embedded in real-life development projects. The proposed hierarchy, with hydrogen

storage at the top level, should be further discussed. In future research, the methodology can be applied to HSC configuration derived from optimization models.
2. In respect of the applied methodology, new value functions could be explored quantitatively, e.g., financial benefit allocation.
3. Only six allocation rules were applied. Future work can integrate more rules embedded in real case agents' concrete situations.
4. The proposed metrics to evaluate the goodness of allocation rules must be developed further. So far, the criteria from game theory and their associated measures have been considered; however, depending on local realities, cultural values, business practices, and the level of exigency in reaching the targets, new aspects could be added. Empirical research is especially valued in this regard.
5. Coopetition can be further explored, with a special focus on the temporal behavior of agents, by including, for example, a multi-period approach.

CRediT authorship contribution statement

Sofía De-León Almaraz: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Andrea Gelei:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Tamás Solymosi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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List of abbreviations

AbbreviationDefinition

AE: All equally
bi: Potential individual benefit of agent i
BP: Benefit proportional
CCS: Carbon Capture and Storage
DSO: Distribution system operator
Gai(v): Gately payoff to player i
GHG: Greenhouse gases
gi: Gap between the marginal contributions
H2: Hydrogen
HSC: Hydrogen Supply Chain
i: Agent or node
j: Leaf of the tree T
k: Level
N: Set of agents
P(i): Set of nodes on the unique *path* from i to 1
pd(i,x): Propensity to disrupt
PE: Producers equally
Q(i): *i*-rooted subtree of the 1-rooted tree T
Q(j): *j*-rooted subtree of the 1-rooted tree T
r: Leaf benefit
R(i): Set of agents who are not a dependent of agent i
S: Coalition
Shi(v): Shapley payoff to player i
SMR: Steam methane reforming
T: Tree graph on agents set N
TU game: Transferable utility cooperative game
TSO: Transmission system operators
TU: Transferable utility
v(i): Agent's value
v(S): Coalition value
x(i): Allocation for agent i