



Strategic dynamics in hydrogen deployment: A game-theoretical review of competition, cooperation, and coopetition

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ABSTRACT

As hydrogen products emerge as a promising energy alternative in multiple sectors, low carbon hydrogen supply chains require concerted efforts among a diverse array of stakeholders. Within an evolving energy transition landscape, stakeholders' competition and cooperation play a critical role in expediting the deployment of the hydrogen economy. In this review, different strategies referred to as *Hydrogen Competition, Cooperation, and Coopetition* (H2CCC) dynamics are analyzed from the lenses of game theory. The study employs hybrid literature review methodology, integrating both bibliometric and structured review approaches. The study reveals that competition and cooperation represent a contrasting but interconnected dynamics that drive the energy transition. Coopetition models are less common. Furthermore, it is observed that Integrated Energy Systems are mainly used in cooperative and coopetitive approaches while H₂ technologies and Hydrogen Supply Chains are more explored in competitive approaches. Industrial and mobility sectors are present in H2CCC dynamics with technological players more present than institutional entities. Maps, definitions, gaps and perspectives are developed. These insights may be valuable for policymakers, industry stakeholders, modelers, and researchers. There remains a need for further empirical H2CCC case studies and applications of pure cooperative games.

1. Introduction

The Sustainable Development Goal 7 from the United Nations aims at providing affordable, reliable, sustainable and modern energy for all by 2030 [1]. For the past decades, efforts have been made towards transitioning into clean energy since it offers numerous advantages over the use of fossil fuels [2]. Low-carbon hydrogen (H₂) offers the possibility to store overproduction of renewable energy sources, creating greater flexibility in energy systems [3]. Hydrogen is also praised for its usefulness as a clean energy carrier capable of decarbonizing multiple sectors, like mobility, industry, and residential heating. While low-carbon hydrogen has the potential to enhance energy security and support decarbonization efforts, its unit cost remains prohibitively high through 2025. Low-carbon hydrogen production requires the upscaling of hydrogen supply chains (HSCs), i.e., networks that link institutional and technological stakeholders [4]. Institutional stakeholders refer to groups representing institutions (e.g., government, industry, regulatory bodies, academia), including specific agents such as countries, public and private companies, policymakers and regulators, universities, etc.

[4]. Technological or infrastructure stakeholders refer to the various technologies involved across the hydrogen supply chain, such as production, storage, and distribution. These include infrastructure agents (e.g., wind energy, electrolysis, SMR, pipelines, gas storage, refueling stations, and fuel cell electric vehicles). A list of interests for institutional and technological (infrastructure) stakeholders and agents is provided in Ref. [4]. In graphical representations, the HSC agents are typically connected by arrows, illustrating their relationships and interdependencies [4]. Low-carbon HSCs face significant challenges, including substantial financial investment requirements and high economic risk in a market characterized by uncertainty and stringent regulations [5]. Nonetheless, collaborative H₂ roadmaps and national plans for developing the hydrogen economy have been established, with important targets from 2030 [6]. Hydrogen must not only deliver environmental benefits [5] but also remain affordable [1], for the associated supply chains (feedstock, fuel, or technology) [7].

Strategic, tactical and operational decision levels are classically considered in supply chain related to different time horizons [8]. There are multiple modeling approaches to design HSCs: 1) optimization

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(single- [9] or multi-objective [17]; deterministic [9] or stochastic [10]; linear [97] and non-linear [11]; single- or multi-period [12]); 2) simulation [13]; 3) spatial-based approaches (GIS-supported models [14]); 4) behavioral and strategic models (e.g., game theory and agent-based models); and 5) hybrid models (e.g., optimization + GIS or optimization + game theory). In optimization models, the most competitive options are proposed as the best solutions, as these models aim to identify optimal configurations that minimize cost or environmental impact [9,15]. More sophisticated optimization models prioritize sustainability by simultaneously optimizing economic, environmental, and social aspects; however, trade-offs in HSCs are inevitable and the costs remain high [16,17].

Optimization has been the most used approach in the last decades [18] but from the stakeholder behavior point of view, optimization is mainly related to competition and the approach assumes a single decision maker approach (centralized decision). Recently, increasing attention has been given to the use of game theory in optimizing resource allocation [19], and many prospective HSC models employ methods that imply competition among technologies [20–23] or resources [24] during the design phase. Stakeholders might also compete to increase the market share, attract investments through favorable policies, incentives, and regulatory frameworks with the primary goal of reducing cost and improving profit [25].

Cooperation is also crucial at the current stage to defeat barriers such as high infrastructural costs and regulatory compliance in low-carbon HSC scaling-up efforts. Roadmaps emphasize the need for *cooperation* and coordination among multiple HSC stakeholders to accelerate low-carbon HSCs deployment and argue for de-risking, risk-sharing, and customized financing solutions [26]. Coalitions among various stakeholders are also necessary to build production facilities, distribution pipelines, storage, and refueling stations. Collaboration is needed to promote best practices, advocate for favorable policies, and to establish international partnerships to build a global hydrogen market [4] needed for stable demand and supply of hydrogen energy. *Cooperation* has been analyzed using several theories such as evolution theory [27,28], social exchange theory [29], network analysis [30], behavioral theory [31,32], cooperation for innovation [33], tragedy of the commons [34,35], Rawls' theory of justice (fairness) [36], complexity theory (agent-based modeling) [37], systems analysis, stakeholders and resource dependence theory [38,39], game theory [40,41]. Cooperation is often examined at regional and national levels [42,43], focusing on both industrial [44] and technological collaboration [45,46].

Another important strategy is *coopetition* [47] (a blend of cooperation and competition) which can be understood as a coordinated and balanced approach to addressing the challenges posed by inter-sectoral rivalry over hydrogen supplies and infrastructure. In this context, stakeholders collaborate in specific areas while maintaining competitive advantages in others [48–50]. By embracing *coopetition*, stakeholders might overcome conflict by balancing short-term competitive interests with long-term collective goals to accelerate the deployment of HSCs [51]; e.g., hydrogen producers might cooperate on large scale electrolysis projects to share capital costs but compete on pricing and market access [52]. *Coopetition* can be modeled using game theory [47,48].

Strategic interactions among stakeholders in HSCs have been partially and scarcely explored [4]. This work aims to investigate the modeling of stakeholders' behavior in HSCs with particular emphasis on establishing clear boundaries to facilitate rigorous analysis. A review on the social aspects of HSCs identified that modeling cooperation by using game theory in HSC can be further explored [53], and Zhang et al. [54] concluded that game theory-based models are better suited to account for the different economic goals of stakeholders and to simulate the interactions between them. Unlike optimization approaches, game theory adopts a multi-decision-maker perspective, which is crucial for modeling stakeholder behavior in supply chains. Moreover, in solutions of game theoretic models, the descriptive and predictive analysis of a complex multi-agent system (what are the feasible outcomes, which

state of the system is likely to emerge?) is always coupled with the prescriptive aspect of the analysis (what to do to influence or achieve a preferred outcome?). Considering the reasons outlined above, together with the growing relevance of game theory in analyzing supply chain dynamics and the rapidly expanding body of literature employing it (often in combination with other frameworks), this study delimits its scope to game theoretic models in HSCs. Nevertheless, this focus should not be interpreted as implying that game theory is inherently more suitable than other approaches for studying stakeholders' behavior.

Previous review papers are presented in Table 1. Some of them have explored modeling approaches from HSC to hydrogen system integration [54,55]. The concept and patterns in supply chain competition are presented in Ref. [56]. Review papers on cooperation focus on power systems, e.g., microgrids clusters [57] using cooperative game theory [58], and more recent work reviewed both cooperative and non-cooperative game theory used in renewable energy systems [57, 59]. As displayed in Table 1, to the best of our knowledge, there is no work that has mapped the game theoretical application in *Hydrogen Competition, Cooperation, and Coopetition* (H2CCC) dynamics (Table 1).

This study aims to investigate how game theory research has been used to analyze the behavior of institutional and technological stakeholders in hydrogen and energy systems, with particular focus on cooperation, competition, and *coopetition* dynamics (Fig. 1). Specifically, three research questions are listed.

- RQ1: How is game theory applied to H2CCC dynamics?
- RQ2: What are the main trends and focus areas in H2CCC research?
- RQ3: What are the research gaps and future directions in H2CCC?

To this end, this research develops a hybrid systematic literature review combining bibliometric (topic identification) and structured approaches (formal analysis) [60]. As shown in Table 1, *coopetition* in energy and hydrogen supply chains remains unexplored. The initial hypothesis is that there is limited effort in modeling *coopetition* and a limited empirical implementation of *coopetition* strategies in low-carbon HSC modeling.

This paper is organized as follows: Section 2 presents a brief background by explaining the main concepts used in game theory and in energy systems where hydrogen is an important component. The methodology used in this hybrid literature review is given in Section 3. The consolidated results from both the bibliometric and structured reviews are presented in Section 4, followed by the detailed analysis based on the structured review (Section 5). The research gaps, limitations, and future perspectives are listed in Section 6. The conclusions of this review are available in Section 7.

2. Background

Energy stakeholders are numerous and vary depending on the energy system, supply chain, or network. The interests of stakeholders within the HSC are often complex and dynamic. In Section 2.1, the context and important methodologies/terms of game theory are summarized. Section 2.2 provides the context of energy and HSC systems and points out some of the main stakeholders identified in the literature.

2.1. Game theory

Game theory has emerged as a viable approach for studying various stakeholder dynamics [61]. It is defined as a formal, mathematical discipline that studies situations of competition and cooperation between several involved parties [62]. In game theory, stakeholders' strategic interactions are akin to games where each stakeholder is a player and acts either in its own interest or for the mutual benefit of a coalition the player is a member of. The outcome of the game is determined by how stakeholders act (compete or cooperate). In Fig. 1, the left side depicts the various stakeholders (agents or players) and their

Table 1
Previous review papers.

Previous Reviews	Sectoral coverage			Review scope						
	Energy	HSC	Other	Modeling methods	Stakeholder dynamics	Game theory	Cooperation	Competition	Coopetition	Comment
[54]	*	*		*	*					Investigate the system integration of hydrogen
[55]	*			*	*	*	*	*		Peer-to-peer multi-energy trading
[56]			*		*				*	Maps supply chain coopetition.
[57]	*			*	*	*	*			Microgrid clusters cooperation
[58]	*			*	*	*	*			Power systems
[59]	*			*	*	*	*	*		Competitive, cooperative, and strategic interactions among different stakeholders
[53]		*			*		*	*		Social aspects. Importance of cooperation
This review	*	*		*	*	*	*	*	*	Focus on HSCs, hydrogen technologies, integrated energy systems, game theory, and stakeholders' dynamics



Fig. 1. Proposed review of *Hydrogen Competition, Cooperation, and Coopetition (H2CCC) dynamics*. Icons: flaticon.com.

potential interactions. Each stakeholder brings different resources, technologies, and interests to the table.

In game theory, competition and cooperation are mostly modeled as non-cooperative and cooperative games. Solution concepts in game theory are formal rules used by each game model to identify a set of stable or desirable outcomes. Table 2 summarizes the most used: i) type of game theoretical models; ii) game forms; and iii) solution concepts. In a *non-cooperative game (NCG)* model, two or more players (here also called stakeholders) with their potential set of decisions engage in strategic interactions with other stakeholders such that the benefit (payoff) received by each stakeholder is dependent on the decision(s) or action(s) taken by all other stakeholders [63]. NCGs can appear in several forms (Table 2, Fig. 2).

Normal form games are represented by a bimatrix (for two players with finite action sets), or a multi-dimensional array (for more than two players), that consists of the configurations (vectors) of players' payoffs for all possible combinations (profiles) of players' actions (moves). From Fig. 2, P1 and P2 are players 1 and 2, respectively. Each player has two actions (pure strategies): comply or defect. The numbers in each cell represent the payoffs of the row and column player, respectively. For instance, if player one complies, and player 2 defects, player 1 gets

0 payoff, but player 2 gets a payoff of 5.

The extensive form game is a sequential move game with two or more players, e.g., on the right in Fig. 2 a two-player extensive form is presented. The game starts at the top node, labelled as 1. Player 1 has three possible actions to choose from (action A, B, or C). If player 1 chooses action A or B, the game moves to the next node where player 2 gets to play. If player 1 plays A, the game reaches the second node, where player 2 has two actions. Action *l*, leads to an outcome with payoffs (4, 1) while action *r*, leads to an outcome with payoffs (7, 2). Similarly, if player 1 plays B and then player 2 chooses action *l* or *r*, and the game stops with payoffs (6, 3) or (4, 0), respectively. If player 1 chooses action C, the game moves to a node where the player with the next move is chosen according to a known random distribution. With probability 1/4, player 2 can choose action *L* or *R*, then the game stops with payoffs (0, 0) or (8, 4), respectively. With probability 3/4, however, player 1 moves again and terminates the game with payoffs (8, 8) or (0, 8), in case action *a* or *b* is chosen, respectively. In general, these sequential moves continue until a last node is reached, where the payoffs are achieved.

How a player's behavior evolves over time can be modeled based on evolutionary game theory [68]. Repeated games consist of a one-shot

Table 2
Game theoretical models, forms and solution concepts.

I. Non-cooperative game theory (NCGT)	
a) Game types	Key features/concepts
<i>Normal form</i>	Represented by a bimatrix (for two players with finite action sets), or a multi-dimensional array (for more than two players), that consists of the vectors of players' payoffs for all possible profiles of players' actions (moves) [40,64].
<i>Extensive form</i>	Sequential move game with two or more players that continue until the last node, where the payoffs are achieved [62,64].
<i>Evolutionary</i>	Captures long-term strategic adjustments to understand the evolution of players behaviors and strategies [27]. Relaxes the assumption that players are rational.
<i>Repeated</i>	A one-shot stage game played multiple times by the same set of players. Players observe the outcomes of previous rounds and adjust their strategies based on the history of the moves observed in previous rounds [62].
<i>Special types:</i> <i>Stackelberg</i>	Sequential move game where one player (leader) chooses the first action after which the follower(s) make their own choice based on the leader's action [62]. Often modeled in a hierarchical structure.
<i>Cournot</i>	Model of oligopoly games where few firms simultaneously compete on the quantity to produce a homogeneous product [65].
<i>Bertrand</i>	Model of oligopoly games where few firms simultaneously compete by setting prices for identical products [66].
<i>Auction</i>	Study bidder behavior and identify optimal strategies across auction formats and information conditions [67].
b) Solution concepts	Nash equilibrium is the main solution concept [41]. Others include Bayesian Nash equilibrium, Sequential equilibrium (for extensive games), Stackelberg equilibrium (for Stackelberg games), MiniMax strategies (for constant-sum games) [62,67], evolutionary stable strategies (for evolutionary games) [68].
II. Cooperative game theory (CGT)	
a) Game types	Key features/concepts
Transferable utility (TU)	Utilities or benefits generated by a coalition can be summed up in a single numerical value that can freely be allocated among its members [67] without loss.
Non-transferable utility (NTU)	Utilities can be redistributed among members of a coalition, but each member's utility is personal and cannot be compared and summed up in a single numerical value. For each coalition, the set of jointly achievable utility profiles describes the feasible outcomes [62].
b) Solution concepts	Nash bargaining solution prescribes a division of the surplus generated by cooperation that maximizes the product of the players' utility gains over the disagreement values, the players can expect to receive if negotiations break down [41,69]. Core, a set of payoff allocations such that no sub-coalition has an incentive to break away from the grand coalition [64]. Nucleolus [70], a unique allocation that lexicographically minimizes the maximum dissatisfaction among all coalitions over the payoff allocations [71]. Shapley value [72], allocates payoffs to each player based on their marginal contribution to all possible coalitions [73]. Gately value [74], is the Pareto-efficient compromise between a pessimistic and an optimistic payoff allocation. It minimizes the maximum relative disruption an individual player can cause by exiting from an agreement [4]. Kernel [75] is a set of allocations where bargaining power of players is balanced between pairs so that neither player can convincingly argue for more payoff transferred from the other player [76].
III. Mixed (Biform) Games	
a) Biform game	Hybrid noncooperative-cooperative game model designed to formalize business strategy for situations with both competitive and cooperative elements. It has a two-stage structure: the first (noncooperative) stage models the competitive strategic moves to favorably shape the second (cooperative) stage where the payoffs are determined in the resulting environment [77].

stage game played multiple times by the same set of players [62]. Some special types of non-cooperative games are Stackelberg, Cournot, Bertrand oligopoly games, and auction games which explore concepts in game theory and industrial organization (Table 2). The aim of every game model is to predict or prescribe how a game will be played. More details about concepts and classification of NCGT can be found in Ref. [62].

In *cooperative game theory (CGT)*, the fundamental units of analysis are the coalitions, that is, subsets of players who agree to cooperate to achieve a common goal. The game is typically defined as a characteristic function that assigns a value (measured on a monetary or utility scale) to every possible coalition. This value represents the total or synergistic benefits. CGT focuses on feasible coalitions to analyze the stability and dynamics of the coalition formation process. Typically, the grand coalition consisting of all players is (or assumed to be) formed, and the generated total benefit is to be distributed among the members in a "fair and stable manner" (reasonable and resistant to deviations by subgroups of players). The general assumption is that a binding agreement exists among the players within the coalition. It is also assumed that a perfectly divisible commodity exists that can be used to freely exchange the individual utilities among the coalition members if compensation is needed to support the agreement on the coordinated actions. Special types of cooperative games are transferable utility (TU) games where all individual utility scales have the same measurement unit. Without this condition on the uniform exchange rates, the cooperative game is called a non-transferable utility (NTU) game. The main solution concepts are listed in Table 2. Additional details about the key definitions and results can be found in Refs. [62,65,67].

Finally, for *cooperation* [47], the biform games can be used [77]. A review by Ref. [78] outlines the developments of the biform game model and its applications. It is important to highlight that the use of an NCGT model does not mean antagonistic competition modeling (some cooperative aspects could be present even in NCGT models and solutions). Similarly, representing cooperation is not the same as forming CGT models [62].

2.2. HSCs and integrated energy systems (IES)

Although hydrogen is the most abundant element in the universe, it is rarely available in its pure form on Earth. HSCs are complex networks of processes and infrastructure that generally include energy source, production, storage, distribution, and market sector [3] (Fig. 3). The scale-up of low-carbon HSCs is not a trivial task due to the large number of interdependencies among resources and market uncertainty [79,80]. Hydrogen can be produced from various energy sources through water electrolysis, gasification, steam methane reforming (with or without carbon capture and storage -CCS-, etc.) [Fig. 3a, b]. Hydrogen can be conditioned in various forms (gas, liquid, and even solid (metal hydrides)), then be used, stored, or transported through various means (pipelines, tube trailers, tanker trucks, ships) to various storage centers or refueling stations. It can be used in industrial, mobility, and residential applications [7]. Hydrogen derivatives (e.g., e-methanol, e-methane, and e-ammonia) can also be used to "facilitate" its distribution.

Hydrogen products can be categorized into three main types based on their final use [Fig. 3c]: H₂ feedstock, H₂ fuel, and H₂ technology/component [7]. As a feedstock, hydrogen can be used in hard-to-abate sectors such as the refinery, chemical, and ammonia industries (ammonia's most common use is in fertilizers [81]). As a substitute for fossil-derived products, it can be used to produce synthetic fuels, ammonia, and other chemicals [82]. As fuel, hydrogen can be used for heating, cooking, and electricity generation. Also, as fuel, hydrogen has the potential to play a significant role in the mobility sector, being used in fuel cell electric vehicles (FCEVs) [83]. It is also expected to play a substantial role in internal combustion engines (heavy-duty cars, rails, maritime, and aviation) [84]. Hydrogen technologies such as

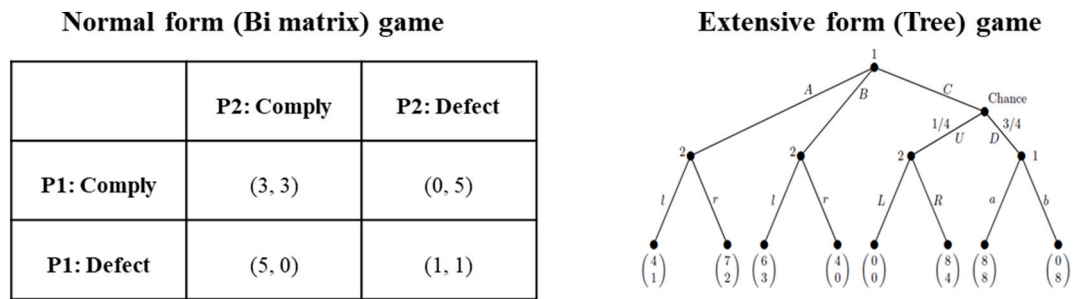


Fig. 2. Games in Normal and Extensive forms (P: player)

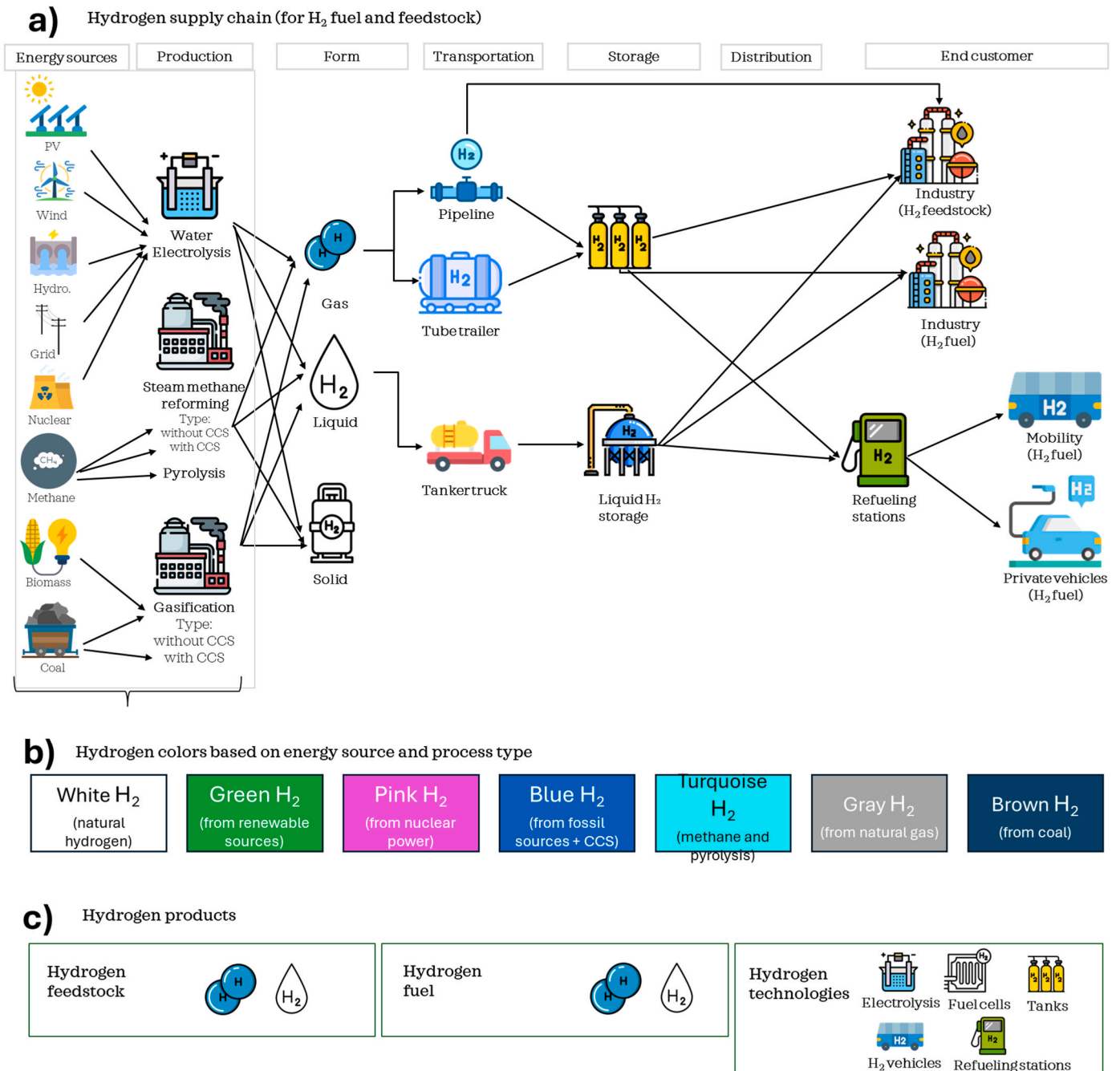


Fig. 3. Hydrogen Supply Chain generics. Adapted from [7].

electrolysis, fuel cells, hydrogen refueling stations (HRS), hydrogen vehicles, etc., are recognized as hydrogen technological products [Fig. 3c].

IESs can include different energy sources, the grid, and various storage means to increase operational flexibility [85]. HSCs can serve as a link between renewable energy sources (RES), energy storage systems, and end-use applications. HSCs interact with energy systems in ways that enhance overall IES performance since hydrogen acts as an energy carrier that can be produced from various sources [19,86]. Production of hydrogen via electrolysis allows for the storage and integration of RES into the energy system, and its long storage capabilities complement short-term storage solutions like batteries and balance seasonal variations in energy demand and supply [87]. Similarly, the integration of hydrogen into multiple energy systems allows for judicious use of existing infrastructure and enables sectoral energy flows [88].

As previously introduced, in HSCs and IESs, stakeholders can be categorized as institutional stakeholders or technological/infrastructure ones [79,89,90], and their roles and interests are described in Ref. [4]. The need for collaboration among companies, institutions, and neighboring countries has been highlighted in Ref. [91]. Technological stakeholders can be represented by all the technologies from the HSC or IES, as presented in (Fig. 3). Stakeholder interests within energy systems often differ and evolve rapidly. This study aims to investigate H2CCC dynamics to identify how strategic interactions of stakeholders in hydrogen systems are incorporated into game-theoretical models (Fig. 1). To this end, the methodology is presented in the following section.

3. Methodology

A hybrid systematic literature review is proposed, combining PRISMA guidelines [92] with bibliometric, and structured approaches [60]. Three review stages are distinguished (Table 3): 1) PRISMA, 2) Hybrid Review, and 3) Results and Discussion.

Table 3
Methodological phases.

Phases	Content
1. PRISMA	
Research topic	<ul style="list-style-type: none"> • Competition, Cooperation, and Coopetition in the Deployment of the Hydrogen Supply Chain using Game Theory
Objectives	<ul style="list-style-type: none"> • Analyze how game theory is used to study H2CCC • Identify the general trends, insights and focus areas for H2CCC • List research gaps, and propose future research avenues
Keywords	<ul style="list-style-type: none"> • Hydrogen (H₂) + competition, cooperation, coopetition, game theory
String	<ul style="list-style-type: none"> • (“hydrogen” AND “game theory”) OR (“hydrogen energy” AND “game theory”) OR (“hydrogen” AND “game”) OR (“hydrogen economy” AND “game theory”) OR (“hydrogen supply chain” AND “game theory”) OR (“hydrogen energy” AND “competition”) OR (“hydrogen energy” AND “cooperation”) OR (“hydrogen energy” AND “coopetition”)
Databases	<ul style="list-style-type: none"> • Scopus and Web of Science
2. Hybrid Literature Review	
a) Bibliometric Review	
Bibliometric maps	<ul style="list-style-type: none"> • Topic identification by using VOSviewer software
b) Structured Review	
Review matrix table	<ul style="list-style-type: none"> • Created Excel table to summarize and synthesize all articles • Refined themes and categorizations • Coded “researchers keywords” from the summarization and categorization • Created final maps based on the researcher keywords
3. Results and discussions	
	<ul style="list-style-type: none"> • Discussion of main topics • Gaps and perspectives

In the PRISMA stage, the topic and research questions are defined allowing the identification of relevant keywords used in Scopus and Web of Science (Table 3). The flow diagram displays the identification criteria, the screening criteria, and the inclusion criteria (Fig. 4). Research articles strictly on hydrogen (H₂), cooperation, competition, coopetition, and game theory were collected and analyzed (final string is listed in Table 3). Articles from this query retrieved relevant game-theoretical papers for further categorization. The literature search was carried out in February 2025, with no limit to the time range. Data was collected and saved in Excel CSV format. The search across Scopus database resulted in 789 records while Web of Science resulted in 591 records. The combination of the two databases accumulated 1380 articles (Fig. 4). After the screening phase, 180 articles were retained for bibliometric analysis and 87 articles for structured review.

In the *Hybrid Literature Review* stage, the starting point was the Bibliometric Review. The 180 articles were mapped based on title, abstract, and keywords analysis using VOS viewer [93] to identify the general topics (Section 4.1). As a next step, an expert-based approach was employed to screen and validate the applicability of the papers. Two researchers independently analyzed titles, abstracts, and keywords, discussing ambiguous cases to reduce bias. This process narrowed the set from 180 to 87 papers. The common criterion applied was that the paper’s focus addressed H2CCC and game theory. For the *Structured Review*, an Excel review matrix was developed to summarize and synthesize the 87 papers selected (see Fig. 4). Categories or filters used for the structures are defined in Section 2 and summarized in Section 4.2. At this step, all authors revise the review matrix for validity and reliability reasons. Based on the review matrix, “researcher keywords” (proposed by the authors to group synonyms and similar words from the original papers) are used to create a Sankey diagram for the structured review and to develop the full analysis (Section 4.2). In Section 5 (detailed results), the three research questions are addressed based on the findings from the structured review phase.

4. Consolidated results

4.1. Topic mapping from the bibliometric literature review

The initial map from the sample of the screened 180 papers is presented in Fig. 5. In terms of general mathematical approaches, “optimization”, “game theory” and “evolutionary game theory” have a similar presence. For NCGT, “Stackelberg games” and “Nash equilibrium” are also present while for cooperative games, “Nash bargaining” is the main solution concept applied. The main phrases for system or technologies are “integrated energy systems”, “RES – renewable energy sources”, “hydrogen storage”, “energy storage”, “fuel cells”, “fuel cell electric vehicles”, “CCS”. Some of the papers explore “policy”, “pricing”, “innovation” and “energy management” topics. With this initial map, however, it is not possible to conclude which are the main H2CCC approaches treated in the literature. To better understand the dataset results, these initial outcomes are developed further and compared to the results of the structured literature review.

4.2. Structured literature review: overall results

A total of 87 articles were deeply analyzed; all the papers include game-theoretical models. The structure for the analysis consists of several categories or filters (identified and defined in Section 2), including methodological aspects: 1) the *Approach* (Cooperation, Competition, Coopetition); 2) the *Game Theory (GT) type* (i.e. CGT, NCGT or mixed); 3) *GT Model* outlining the theoretical foundation and structural framework used (e.g., NTU, Evolutionary game, Normal form, Extensive form, etc.); 4) the *GT Solution concepts* (e.g., Nash equilibrium, Nash bargaining solution, Stackelberg equilibrium, Shapley value, etc.). Additional methodologies that complement the game theory aspects in the state of the art, like optimization, are also identified. The

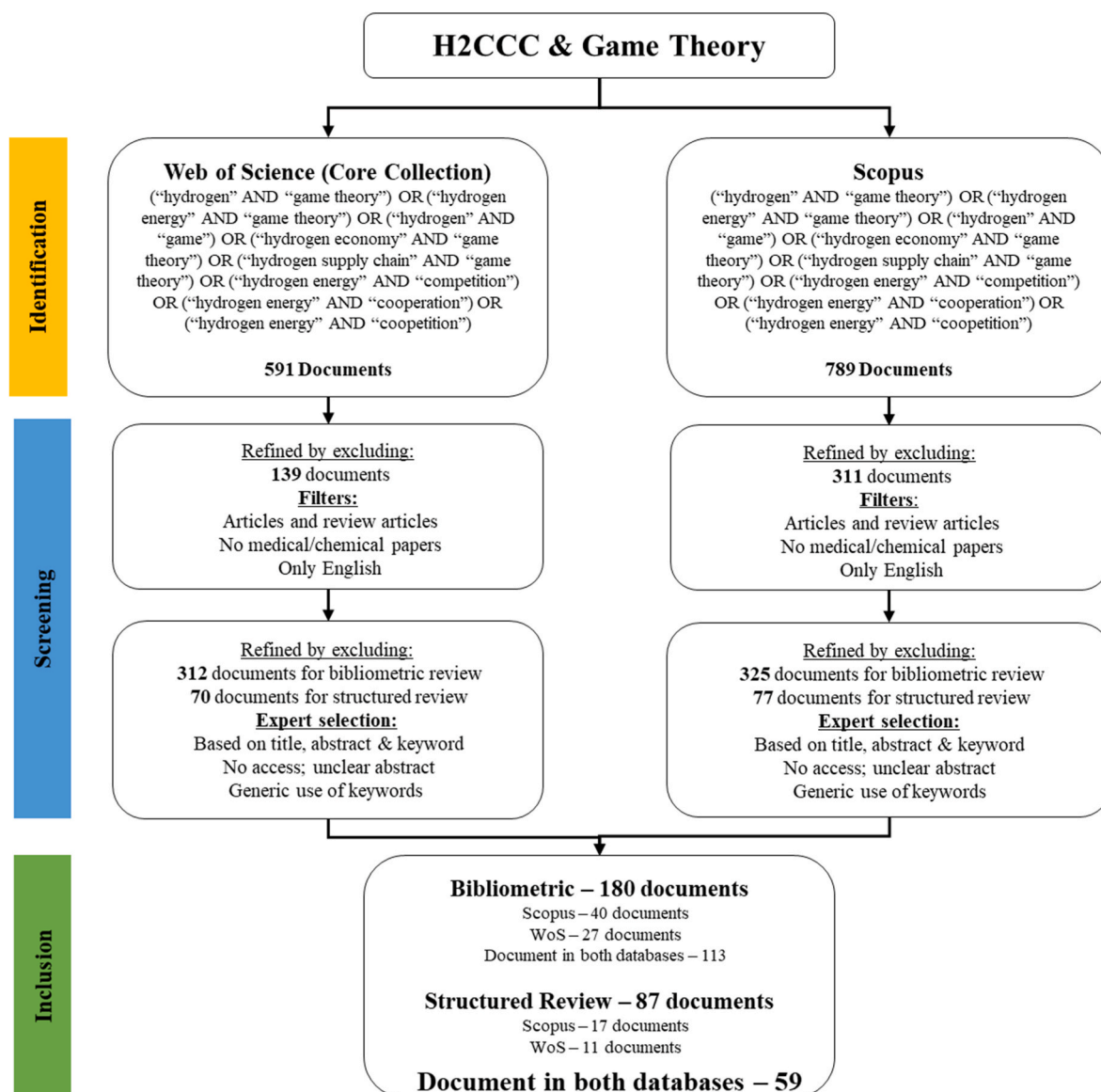


Fig. 4. Database Search and Appraisal based on PRISMA guidelines

categorization also includes aspects of case studies, i.e., 5) the *Scale of the study* (IES, HSC, H₂ technology); 6) the *Technologies* involved, offering clarity on the scope and technical components; 7) the *Application sector* (Mobility, Industry, Residential or Several); 8) the *Country* for the case study (when available); the authors propose 9) the *Researcher keywords* to summarize the core themes and topics addressed in the paper by using the predefined codes to develop the final Sankey diagram (Fig. 6); and finally, 10) the *Focus of the paper*, which highlights the specific aims of the articles. In Table 4, the results for categories 1–8 are summarized, highlighting the trends.

Table 4, Figs. 6 and 7 allow the identification of cross-cutting issues, which are briefly explained in this section, while details for each H2CCC strategy are provided in Section 5. Cooperation approaches are slightly more prevalent than the competition ones (43 % vs 40 %) while competition (as defined in the hypothesis) is the least addressed (17 %).

Fig. 6 shows that NCGT (64 %) is more used than CGT (28 %) or mixed games (5 %); Nash equilibrium (21 %), ESS (20 %), Stackelberg (18 %), are applied to the three H2CCC dynamics, and are followed by solution concepts from CTG like Nash bargaining (14 %) and Shapley value (9 %). Other CGT solution concepts are less frequent, and biform games are not used. For each H2CCC strategy, solution concepts are

listed in Table 4 and displayed in Fig. 7(a–c, e). In terms of applicability, studies using NCGT solution concepts (Nash equilibrium, Stackelberg, etc.) value tractability and stability, often defaulting to Nash equilibria (a stability arrangement against individual deviations). In cases where H₂ technology adoption and demand uncertainty are being addressed, the Bayesian game is applied. Similarly, the ESS is used when bounded rationality and adaptive learning is crucial. On the other hand, Shapley value and the Core are frequently applied in cooperative game problems due to its perceived fairness and axiomatic properties (rationality, symmetry, additivity, divisibility, etc.) in allocating costs/benefits and coalition stability across coalition members. Nucleolus and Gately, which yield different equity or stability outcome solves the convenience model bias in model construction. The Kernel solution concept has largely been ignored, probably due to its computational complexity and applicability. Biform games are not used so far. In cases where hydrogen infrastructure projects involve heterogeneous actors with asymmetric bargaining power, the Nash bargaining game is applied. Notwithstanding, while each model and solution concept may resolve theoretical limitations, none fully captures the complex realities of HSC deployment. It is worth noting that the choice of game model and its solution concepts is case specific. Therefore, it is not possible to provide a general

Table 4
H2CCC dynamics - key insights and trends.

Aspects/Shares	Approach		
	Competition	Cooperation	Coopetition
	40 %	43 %	17 %
Game theory type, model, solution concepts	Mainly NCGT: Evolutionary games (28 %), Stackelberg (28 %), and Nash equilibrium (23 %)	Mainly CGT with NTU (Nash bargaining – 32 %) and TU (Shapley – 22 %). For NCGT, evolutionary games (ESS – 13 %)	Mainly NCGT with Nash equilibrium (53 %), Stackelberg (13 %), ESS (13 %). For CGT: Fuzzy Shapley (7 %)
Scale and key sector	1 H ₂ technol. (54 %) <ul style="list-style-type: none"> • Mobility (58 %) • Several applications (42 %) 2 IES (26 %) <ul style="list-style-type: none"> • Several applications (100 %) 3 HSC (20 %) <ul style="list-style-type: none"> • Several applications (86 %) • Mobility (14 %) 	1 IES (49 %) <ul style="list-style-type: none"> • Industry (67 %) • Several applications (28 %) • Mobility (6 %) 2 HSC (30 %) <ul style="list-style-type: none"> • Industry (45 %) • Several applications (36 %) • Mobility (18 %) 3 H ₂ technologies (22 %) <ul style="list-style-type: none"> • Mobility (50 %) • Industry (25 %) • Several applications (25 %) 	1 IES (47 %) <ul style="list-style-type: none"> • Industry (43 %) • Several applications (43 %) • Mobility (14 %) 2 H ₂ technologies (33 %) <ul style="list-style-type: none"> • Mobility (100 %) 3 HSC (20 %) <ul style="list-style-type: none"> • Industry (67 %) • Mobility (33 %)
Top 7 technological stakeholders (in alphabetic order)	1 FCEV (26 %) 2 HRS (13 %) 3 Microgrid (10 %) 4 Fuel cell (8 %) 5 CCS (5 %) 6 H ₂ production (5 %) 7 Battery (3 %) Other (30 %)	1 P2P – heat, elect. (18 %) 2 RES (15 %) 3 H ₂ storage (9 %) 4 H ₂ production (7 %) 5 CCS (4 %) 6 FCEV (4 %) 7 H ₂ transportation (4 %) Other (39 %)	1 RES (21 %) 2 Battery (11 %) 3 H ₂ storage (8 %) 4 FCEV (8 %) 5 HRS (8 %) 6 H ₂ production (5 %) 7 Fuel cell (5 %) Other (34 %)
Decision structures	Hierarchical interactions and dynamic strategy adaptation	Coalition formation of rational decision makers	Hierarchical interactions and dynamic strategy adaptation and coalition formation
Often used:	Optimization models		
Geographic and Policy coverage	Mostly global with regional focus on China and some European countries. Policies are modeled via subsidies and carbon pricing		Mostly global with regional focus on China

recommendation on which model to use. Rather, it is the modeler's task to select the most appropriate model based on the characteristics and structure of the case study, the strategy (H2CCC), the research questions, and the properties of the game model. Multidisciplinary collaboration is highly recommended in these efforts.

Scale and key sectors also vary for each H2CCC strategy (Table 4 and Fig. 7b–d, f). The IES scale is the most used one for cooperation (49 %) and coopetition (47 %) while for competition the H₂ technologies (54 %) are more frequent. HSCs scale could be further explored. The main trends and technological stakeholders in the case studies for each strategy are presented in Table 4, and the corresponding maps are available in the Supplementary Material. A summary is provided below.

- Competition trends:
 - o 1) H₂ technologies → mobility focus (58 %); several applications (42 %).
 - o 2) IES → several applications (100 %)
 - o Stakeholders: FCEV (26 %), HRS (13 %), Microgrid (10 %), Fuel cell (8 %).
- Cooperation trends:
 - o 1) IES → Industry (67 %)
 - o 2) HSC → Industry (45 %)
 - o Stakeholders: power to power technologies, including heating and electricity (18 %), RES (15 %) and H₂ storage (9 %).
- Coopetition trends:
 - o 1) IES → Industry (43 %)
 - o 2) H₂ technologies → mobility focus (100 %)
 - o Stakeholders: RES (21 %), Batteries (11 %) and H₂ storage (8 %).

Geographically, Chinese research and academic institutions lead the research landscape in game theoretical models related to energy or hydrogen technologies and systems (55 %). Green innovation, now central to China's energy reform, drives energy transition projects and research [94]. Europe has also some contributions focusing mainly on renewable hydrogen and policy-driven innovations (6 %). Finally, 26 %

of the studies do not report a country.

5. Hydrogen competition, cooperation and coopetition dynamics

Detail results for H2CCC dynamics are presented in this section. The other concepts presented in Fig. 6 are discussed in detail for Competition, Cooperation, and Coopetition in Sections 5.1-3.

5.1. Competition

Businesses are inherently competitive. As displayed in Fig. 6, around 40 % of the papers employed competitive strategies and almost all of them use NCGT. Within the NCGT type, most of the studies employed normal, extensive and special form games. The main solution concepts are (Fig. 7a): evolutionary games (28 %), Stackelberg (28 %) and Nash equilibrium (23 %). Cournot (6 %), Auction (3 %), Bayesian (3 %) and MinMax (3 %) are less used. NCGT is very often coupled with optimization models. Many of the studies (91 %) utilize theoretical and simulation-based approaches in modeling competition while a few (9 %) employ hypothetical case studies with partial empirical data.

5.1.1. Game type used

Evolutionary game theory (and ESS) has been applied to model the diffusion of hydrogen-related technologies and to simulate how stakeholders (local governments, consumers, and manufacturers) [95] respond to subsidies, carbon trading and taxes over time. Unlike the classical NCGT models, evolutionary games model accounts for the dynamic evolution of strategies often driven by payoff performance and behavior adaptation over time [65]. The work of [96] employed ESS to explore the competitiveness of hydrogen technology in air transport considering factors such as policy interventions, market dynamics, and movement impacts. Evolutionary dynamics reflect policy robustness [97] by analyzing subsidy impacts, adoption rates and infrastructural development to determine whether policies met promotion targets in

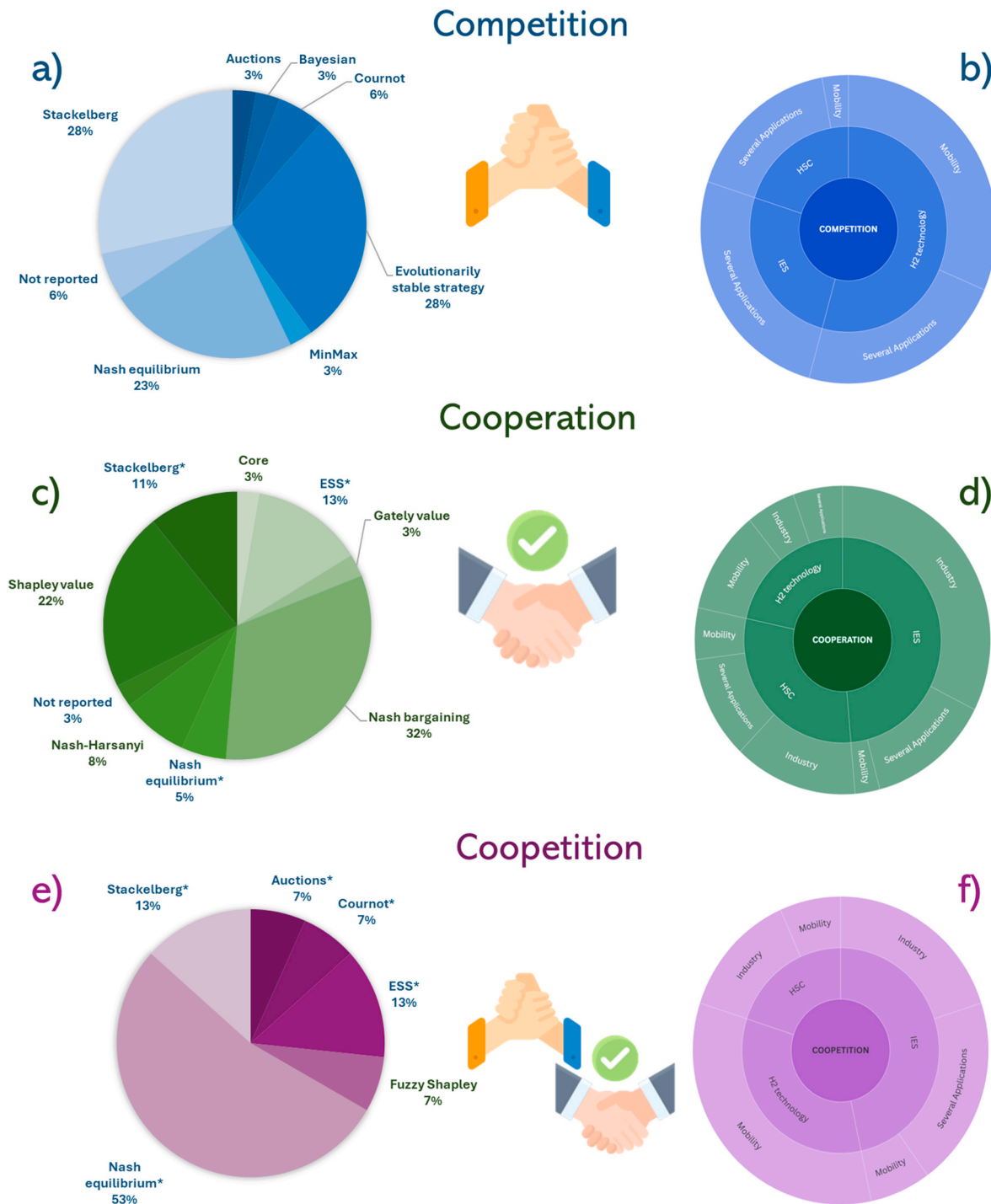


Fig. 7. Game theoretical solution concepts (left) and type of case studies (right) in H2CCC. (* is used when NCGT solution concepts are used in cooperation or coopetition).

promoting FCEV [98]. Similarly [99,100], applied ESS to investigate the interactions between local government and coal-fired power plants operators over the adoption and dissemination of CCS technologies. The evolutionary nature of this model enables policy makers to speculate on future deviations in policy outcomes. Tripartite evolutionary game theory extends the main concepts of evolutionary games to scenarios involving three distinct interacting populations. The papers [98,101], show this by simulating interactions among three stakeholders (government, private investors, and consumers) to highlight the difficulties in aligning heterogeneous interests to achieve shared objectives such as emission reduction and FCEV deployment. Although studies utilizing

evolutionary game theory is mostly centered on policy, the works of [102,103] investigate micro-level decision in energy storage and fuel cell durability efficiency improvements, while [96,104] prove that evolutionary game theory is instrumental in evaluating how market actors adjust strategies in response to shifting regulatory landscapes, energy prices, and social influence over time.

Stackelberg games are used to model hierarchical decision-making in scenarios where the leaders optimize, e.g., pricing or investment while the followers adapt their strategies accordingly [105], and Stackelberg equilibrium is the main solution concept applied. For example, a bi-level master slave game where the HRS agent acts as a leader by setting

pricing strategies to optimize profits while the FCEVs operators act as followers minimizing fuel costs is modeled in Ref. [104]. Stackelberg game was used to identify strategic equilibria where electrolysis firms, acting as leaders, engage in decision-making in energy, hydrogen, and ancillary services markets [106]. This game has also been used to analyze the strategic behavior of critical raw material exporters, particularly platinum exporters, in light of the EU's 2030 hydrogen target [107]. The authors analyzed these asymmetric trade dynamics to highlight how dominant exporters can shape market outcomes under geopolitical conditions and economic interdependence. In microgrid operations [108], utilized Stackelberg games to develop energy management strategies under islanding constraints and hybrid energy storage. Similarly [109], used this same model to analyze microgrid clusters under dynamic hydrogen pricing and demand-side uncertainties by integrating user behavioral responses to pricing signals. A multi-energy ecosystem as has been modeled by Ref. [110] to optimize the operations between IES and electricity-hydrogen hybrid charging stations. The authors model IES as the leader optimizing supply under uncertainty while the charging station adjusts demand accordingly. Regional integrated hydrogen-electricity market [111], community energy systems [75], and interactions between distributed energy systems and hydrogen-powered vehicles [74] signify the suitability of Stackelberg game models to cross sectoral systems.

Nash equilibrium has been widely applied to optimize strategies in energy systems [113,114]. It has been used to analyze the equilibrium state of supply-demand flow in a regional hydrogen market [115]. It has also been used to explore system planning of hydrogen-gas-power [113] and cluster optimization for IESs [114].

Beyond the models that have been discussed, recent contributions have expanded the scope by incorporating special game types such as auction theory and Cournot models. For instance Ref. [116], developed a Stackelberg–Auction model by incorporating Vickrey–Clarke–Groves (VCG) auction mechanism to model hierarchical decision making between shared energy storage systems (SESS) and microgrids (MGs). This hybrid modeling captures SESS as the leader while the followers (MGs) participate through auction bids. The study by Ref. [117] explores a classic Cournot competition setting to analyze how hydrogen storage influences equilibrium outcomes and investment incentives in electricity markets. Bayesian games which incorporate incomplete information when modeling strategic interactions have been applied to address informational asymmetries in mode selection and financing risk estimation for energy automobile enterprises [118] and microgrid planning [119]. The use of mixed-strategy Bayesian Nash equilibria [118,119] aids these models in capturing the uncertainty surrounding private belief and hidden strategies that are central in the hydrogen economy.

5.1.2. Focus areas

In Fig. 7b, the scale and sectors are displayed. Competition papers focus mainly on “H₂ technologies” and the main specific sector is *mobility* but most of the papers include *several applications* which is the main sector when including also the “IES”. The special focus on the mobility sector stems from the earnest desire to decarbonize transport and the complex coordination challenges among automakers, energy suppliers, and regulators. Within this sector, several studies centered on HRS, particularly on hydrogen cars [103,118,120], HRSs [104,121,122], energy management strategies for FCEVs [123], and hydrogen technologies in air transport [96]. The dominance of this sector encourages fuel cell and refueling station players to compete to capture market share, often through innovations in cost reduction, profit and efficiency improvement strategies. This drives investments in H₂ mobility technologies leading to improvements in fuel cell durability in hybrid electric vehicles and further exploration of hydrogen in the aviation market (aircrafts). However, this can lead to fragmentation in vehicle types, fuel cell designs and HRS infrastructure and services for different H₂ technologies within the HSC. The concentration of H₂

mobility technologies in China and Europe with supportive policies and incentives fragments the global market. These hinder H₂ scalability and potentially slow down global H₂ mobility technology diffusion, particularly in underdeveloped regions.

For “IESs” complex systems like microgrids and P2G are analyzed and the final products can be used in several sectors. Several studies mainly focused on profitability and economic viability tackling issues ranging from pricing [11,105,112], profit maximization and cost reduction [104,115], to market growth [107,111]. For instance, Ref. [25] explored profitability of green hydrogen production while [104] explored energy pricing of the HRSs highlighting how early adopters can gain strategic advantage by lowering operational costs. For IES [111], explored the energy management strategy for a regional integrated electricity-hydrogen market. In the industrial and residential sectors, authors focused on integrated electricity-hydrogen markets [110,111] and microgrid optimization [102,108,109,119]. Additionally, the exploration of market dynamics and trading behavior of hydrogen investors in a competitive market was also highlighted [101,115]. A significant number of studies address the IES with the aim of optimizing the multi-energy interactions within the electricity [110,111], hydrogen, and thermal energy sources [101,113]. They do this by developing robust flexible systems capable of managing demand-side uncertainties.

Table 4 shows the main technological stakeholders in competitive models. Some examples of technology investment on hydrogen production and storage, and FCEVs are available in Refs. [84,103,124,125] reflecting commitment to both upstream and downstream technologies. Papers by Refs. [98,126] evaluated government regulations and subsidy policies for FCEVs to assess the efficiency of government interventions in promoting hydrogen technologies. A subset of literature centered on sustainability and efficiency [103,120] of energy systems with special emphasis on carbon emission reduction [85,86], energy security and fuel cell durability [120,123] among many others.

5.2. Cooperation

Within the cooperative approach, 43 % of the studies used collaborative approaches among stakeholders to benefit from win-win situations. Cooperation uses both CGT, NCGT and mixed models (Fig. 6).

5.2.1. Game type used

Within the CGT models, NTU game models dominate, with 32 % of the papers employing the Nash bargaining model and solution concept (Fig. 7c). In cooperative game theory, the Nash bargaining solution and the Nash–Harsanyi solutions are used interchangeably in literature. These models are widely used in contexts where utilities cannot be easily transferred between players to balance cost, risk, and environmental benefits in multi-agent energy systems [129,130]. Nash bargaining is used for modeling negotiation processes between two or more players aiming to reach a mutually beneficial agreement [62]. Nash bargaining has proven to be effective in several case studies. It has been used to model energy sharing among virtual power plants, load aggregators, and energy storage operators [131] where stakeholders negotiate over surplus distribution under individual rationality and Pareto efficiency constraints. It has been applied to equitably allocate cooperation costs and benefits among hydrogen–ammonia industrial systems in different regions [82], to develop cooperative electricity–hydrogen trading model [132], and to optimize the overall performance of the multiple agents (wind, hydrogen, and heat systems) [130]. Similarly, it is used in cooperative operation of a multi-park integrated energy system that integrates hydrogen produced from electricity into existing natural gas networks to enhance the integration of hydrogen energy into multi-park energy system [132]. The distributed algorithm based on the alternating direction method of multipliers (ADMM) has been the main computation technique used to solve Nash bargaining game models [130,133] across various hydrogen-related cases. The approach of [130,133] has also

been used in Ref. [88] to examine low-carbon planning for IESs. The simulation results show that Nash bargaining solutions significantly improved the benefits for all participants. Some studies extend the Nash framework to incorporate weighted bargaining formulations [88] to allow for flexible modeling of power asymmetries, strategic preferences, or stakeholder-specific utility functions. Both solutions have been used to analyze 2-player [131], 3-player [129,134], 4-player [133], and 16-player [82] interactions among stakeholders to reduce cost, increase renewable energy integration, and profit-cost sharing. The Nash–Harsanyi solution has been used to design a hierarchical coordinated energy management strategy for electricity-hydrogen integrated charging stations and distribution system operators to address the uncertainty of photovoltaic generation by designing a risk-aversion robustness model [135].

Calculating the Nash bargaining solution is a complex optimization problem (cf. e.g., Ref. [136]). This involves maximizing the product of utility gains while ensuring Pareto efficiency within a constrained feasible set. To tackle these challenges, various computational methods have been developed, including direct, indirect, and distributed approaches. These methods often utilize advanced convex optimization or approximation techniques, depending on the specific mathematical properties of the utility functions involved.

The Nash bargaining solution has several desirable properties ([41, 69]), but it may not always align with certain natural expectations. To address this, various alternative solutions for the cooperative Nash bargaining model have been proposed and characterized through axioms [137]. Among these alternatives, the Raiffa-Kalai-Smorodinsky solution, for example, appears to be more computationally manageable [138], yet it is completely ignored in the surveyed literature.

Under the TU models, coalition benefits (or costs) are assumed to be transferable in one-to-one trade-off ratios among players [64]. A broad array of studies involving TU game models mostly employed Shapley value as a solution concept to provide equitable allocation schemes grounded in axiomatic fairness, symmetry, and additivity principles [62]. The Shapley value has been applied to coalition formation problems and benefit sharing in IES such as electricity-heat-hydrogen infrastructures [86,139,140], P2G and P2P trading [141,142], and multi-microgrid systems [143]. In some of the studies, the coalition value for the Shapley allocation comes from optimization [86,141]. Other studies employed more than one solution concepts to offer valuable insights in settings of unstable coalitions, strategic uncertainty, or heterogeneous player capabilities. For instance Ref. [139], utilized a combination of the Shapley value and the core solutions to examine cost allocation and profit sharing among 3-player coalitions (electricity, gas, heat and hydrogen). Similarly [144], developed a flexible energy supply scheduling strategy for isolated islands using power-to-gas technology by using the same solution concepts. The reliance on the Shapley value has also limited the exploration of alternative solution concepts such as the Gately value or the nucleolus. A recent paper provides a comparison toolbox using the Shapley value, the Gately value, and the nucleolus in lower-carbon HSC to identify stable and fair payoff distributions across technological stakeholders within the HSCs (with critical resources) and compares game theoretical allocation rules to naïve ones to facilitate comparison and decision making [4].

Just like the Nash bargaining solution is dominant for NTU models, the Shapley value is the preferred single-valued solution for TU games in the applications reviewed. However, scalability issues already emerge in medium-sized scenarios (see, for example, [145]). The well-known closed formula for calculating Shapley payoffs can be misleading; while it only requires basic arithmetic operations, the number of operations needed increases exponentially as the number of agents grows. This can quickly deplete computational resources or result in excessively long processing times.

As displayed in Fig. 7c, NCGT models were also used to examine cooperation among stakeholders (i.e., Evolutionary and Stackelberg). Evolutionary games follow the “logic of the animal conflict” which sets

the tone for evolutionarily stable strategies - ESS [68]. ESS has been used to solve complex cooperative structures under uncertainty and variability. All the papers that employed evolutionary game theory in modeling cooperation utilized a three-player evolutionary game analysis. For instance Refs. [146,147], apply ESS to simulate interactions among three core agents (e.g., governments, private investors, and consumers) highlighting the complexity of aligning heterogeneous interests to achieve shared objectives like emission reduction or HRS deployment. These models offer nuanced insights into the conditions under which cooperation emerges or fails, particularly when incentives are asymmetrical or when the agents operate under limited rationality [148,149]. Stackelberg games have been used to examine cooperative strategies in hierarchical decision-making structure to capture leader-follower dynamics [150,151] in pricing, cost or profit-sharing among coalition agents while others tackle uncertainties in IESs [152]. A mixed approach using Shapley value (cooperative) and Stackelberg model (non-cooperative) is presented in Ref. [153] to analyze benefit allocation mechanisms for hydrogen energy storage systems.

5.2.2. Focus areas

With regards to scale and sector, the cooperation approach is mostly used in “IESs” with focus on *industrial and several applications* (Fig. 7d). For industrial applications, studies focused on cooperative strategies to promote sector coupling (e.g. power-to-ammonia) [82] and to enable resource optimization [152]. Within this sector, efforts to replace the high demand for fossil fuels with hydrogen in energy intensive industries have been a key focus [88,131]. Carbon neutralization and environmental sustainability have been a concern. For instance Ref. [127], discusses the role of hydrogen in achieving significant reductions in industrial carbon emissions to align with global decarbonization goals. The study by Ref. [154] emphasizes that higher quality syngas with better yield support efficient energy and hydrogen production, which is essential for industrial fuel and chemical feedstocks. Cooperative strategies across multiple sectors emphasized the need for synergy between hydrogen, electricity, and gas (mixing electrolytically produced hydrogen with other gases) and IES to promote the utilization of hydrogen energy in the industrial, commercial, and residential sectors [132]. Studies have leveraged hydrogen energy as a viable carrier for residential heating [155], energy storage [153], and power generation [134], offering a sustainable alternative to traditional fossil fuels. Another case of application is market design and system integration developed in Refs. [86,116,132]. These studies highlight the role of market mechanisms in facilitating cooperation among renewable energy companies, storage providers, and power distribution entities. Policy analysis has largely explored the impact of government policies and technological advancement with special emphasis on photovoltaic hydrogen production in promoting CCS [147]. The use of cooperative models in “H₂ technology” (mainly mobility applications) and “HSCs” (mainly *industrial* applications) accounts for half of the reviewed papers (Fig. 7d). The mobility sector cooperation plays a crucial role in advancing HRSs [146] and FCEVs [151]. Studies have also emphasized the need to develop risk management strategies [116,156] while developing innovative technologies for hydrogen mobility to ensure compatibility and interoperability across systems [157], and [11] proposed a dynamic collaborative pricing strategy for managing refueling demand of FCEV. A strand of literature discussed how stakeholders collaborate in ensuring emission reduction (CCS) [88,131,147], profit allocation and cost reduction strategies [129,132], risk management and trading strategies [142,158] and policy analysis [146,147].

Most of the papers consider technological stakeholders. From the total number of listed technologies, the top 7 are presented in Table 4. Institutional stakeholders are presented in Ref. [146] that analyzed the development of HRS to highlight strategic interactions among government, investors, and operators.

5.3. Cooperation

The initial hypothesis that there is limited empirical studies of cooperative strategies in HSC modeling holds. Out of the 87 papers selected for the systematic review, only 17 % followed the cooperation approach (without explicitly naming it as such). Cooperation is a hybrid approach to analyze multi-agent situations where cooperation and competition are more-or-less equally important, in contrast to situations where either the conflict in the individual interests or the jointly achievable common benefit is the dominant feature. Although the standard game models and their solutions capture both aspects to some extent, but neither the non-cooperative nor the cooperative models formalize explicitly both the conflict and the coherence in the agents' interests. The biform game is one of the first attempts to formally include both aspects in the model itself, but it has not yet developed enough to become a kind of canonical model of cooperation. NCGT was mostly used as displayed in Fig. 6; with Nash equilibrium, ESS and Stackelberg, the main solution concepts (Fig. 7e) applied in many of the studies.

5.3.1. Game type used

Although pure biform games have not been used to model cooperation, some studies applied mixed approach (i.e., CGT with NCGT models or with optimization). Nash equilibrium has been used in Ref. [159] which proposed a hybrid framework combining competition-cooperation control with predictive modeling to optimize the lifetime performance of fuel cell hybrid buses. The authors employ bi-level game theory where manufacturers and operators compete to maximize their respective objectives while cooperating to prolong fuel cell and battery life. In a similar study [160], the Nash equilibrium and bi-level optimization model are combined to solve energy supply challenges by integrating solar, hydrogen, and battery storage systems in charging stations. In this study, the first level employs Nash equilibrium for non-cooperative demand-side management, while the second level uses peer-to-peer energy trading strategies for cooperative operations. The multi-layered Nash solution has been used alongside other optimization models to analyze cooperative methodologies [161,162].

Evolutionary game involving three agents has been used to study government regulations [126] and policy impact [163] on FCEVs industry over time. In these studies, three agents (government, FCEV enterprises, and technology enterprises) engage in strategic interactions. Government is responsible for formulating and implementing subsidy policies to promote FCEV adoption. FCEV enterprises are manufacturers of FCEVs, and their strategies are influenced by subsidies and market dynamics while technology enterprises provide technological innovations and support essential for FCEV development. Each stakeholder selects strategies based on their payoffs which are influenced by subsidies, research and development investments and technological risks. The model assumes bounded rationality; as a result, stakeholders adjust their strategies over time through learning and imitation, leading to ESS.

Stackelberg and evolutionary games (NCGT) and the Shapley value (CGT) are used to design an optimal business model for distributed HRS system that considers both hierarchical and centralized approaches to operate either individually or as a coalition to supply hydrogen [157]. Similarly [164], designed a single-leader multiple-followers Stackelberg game with an iterative solution algorithm to capture the interactions between a hydrogen auctioneer and several HRSs.

An international study developed a framework to analyze strategic interactions between the US and a group of countries adhering to the COP21 Paris agreement to address global policy challenges [165]. The authors blend the Cournot game and the Nash equilibrium solution to model a somewhat cooperative bargaining process where stakeholders negotiate emission reduction targets. The asymmetric model assumes that the players have different market power and production capacity and thus, can influence market prices more significantly, forcing the other player to adapt its strategy accordingly. Similarly [166], used the

same model framework (Cournot and Nash equilibrium) to investigate competition and alliances in fuel-cell powertrain development. The auction model has been used to address competitive dynamics while promoting efficient resource management. For instance Ref. [167], designed an auction model for a group of buyers and sellers (electric transaction manager, electric response agents, and industrial users). The model focuses on the demand response trade considering cost and benefit allocation among the stakeholders.

5.3.2. Focus areas

Similar to the cooperation approach, with regards to scale and sector, the cooperative approach is mostly used in "IESs" with focus on *industrial* and *several applications* (Fig. 7f). The need to enhance reliability and efficiency in energy management and decentralized systems are crucial in cooperative studies. In the paper [162], the authors examined energy management and control in autonomous poly-generation microgrids while [159] investigated degradation adaptive energy management for fuel cell hybrid buses. This study addresses fuel cell and battery performance while maximizing hydrogen efficiency. Other studies have explored RES integration [124,161,168] to address energy supply changes and social welfare maximization. Cooperative studies have also addressed intermittency [79] and variability [169] in IESs.

For competition in "H₂ technologies", *mobility* applications are very relevant. For "HSC" and cooperative studies focus first on the *industrial* sector followed by *mobility*. The industrial sector is represented in areas such as eco-industrial parks [161], and multi-energy hubs [167,169] where stakeholders within the energy system both compete in the market and share carbon reduction goals. Within the mobility sector, studies explored fuel cell hybrid bus [159], FCEV market growth [170], and HRS [157]. For the studies spanning across several sectors, environmental sustainability and climate change [165], as well as microgrids were well addressed. The role of government regulations (penalties, subsidies), and infrastructure investment in FCEVs industry development and carbon neutrality has also been explored [126].

5.4. Policy implications for H2CCC strategy

Studies on green and blue H₂ by Ref. [97], energy storage by Ref. [95], and CCS in coal-to-hydrogen production in the works of [100] consistently emphasize competition as a policy challenge that requires carefully balanced incentives. Under tradable green certificate by Ref. [101] for instance, competition between renewable and thermal power plants shapes trading behavior, with market efficiency hinging on certificate prices and regulation quotas. In a similar study by Ref. [128], technology substitution was conditioned on the competitiveness between fuel cell and battery forklifts under discounted surplus electricity.

From policy perspective, static subsidies fail to account for dynamic efficiency, as witnessed in the works of [97] where blue hydrogen remained attractive even under green hydrogen subsidies due to carbon market interactions. Studies under competition further highlight the risk of technology lock-in if incentives disproportionately favor one pathway and advocate for adaptive policy frameworks linked to carbon prices if policies are to keep pace with rapid technological improvements and cost reductions.

In contrast, cooperation emphasizes the need for interdependence in early infrastructure development and technology diffusion. A study by Ref. [146] demonstrates this by showing that cooperation among public sector, private investors and consumers in HRS diffusion is crucial for overcoming the chicken-or-egg problem. The work of [149] affirms this highlighting that cooperation between coal-to-hydrogen firms and oil fields players in CCS deployment is hampered by asymmetric risk-sharing, often requiring carefully designed subsidies to incentivize collaboration. From these, it is clear that willingness to cooperate is as important as financial incentives just as it is found in the study of [146] that boosting initial probabilities to cooperate is often more effective

compared to subsidy provision, highlighting the role of trust-building, regulation enforcement, and long-term contractual mechanisms in policy design.

Perhaps, the most compelling set of findings on policy studies emerge from a study adopting co-competition. Tuofu et al. [163] analyze China's "Replace Subsidy with Awards" mechanism for FCEVs and suggest that central and local governments may diverge in incentives. According to the authors, central regulators aim for technological upgrading, while the local authorities prioritize industrial competitiveness, forcing enterprises to simultaneously cooperate with policymakers while competing for market share. This mirrors broader multi-level governance challenges in hydrogen policy where co-competition highlights the dual role of markets, thus, encouraging competition through innovation and cooperation through standardization, infrastructure alignment and social acceptance.

In terms of market relevance, competition is pronounced at technology readiness levels, suggesting that competition dominates in mid-

stage commercialization, cooperation is crucial in early pre-commercialization diffusion and co-competition in mid-to-late stage ecosystem integration. Aligning policy instruments with these stages can accelerate faster development of sustainable HSCs.

6. Research gaps, perspectives and limitations

Gaps and perspectives are listed in Table 5.

As with all types of literature reviews, this study has some limitations. A potential limitation of this review lies in the search query (Table 3). Some relevant papers addressing competition, cooperation, and co-competition from game theoretical lenses may not have been retrieved due to the refinement of the query. Other papers may have been missed out if they were not included in the title, abstract, or keywords.

The analysis represents the authors' perspective. To mitigate potential bias in the H2CCC categorization, experts with backgrounds in game theory and HSC performed the categorization task, aiming for a more balanced and improved review. In this sense, the titles, abstracts, and keywords of the selected documents were analyzed for applicability to ensure that the papers fell within the scope of H2CCC dynamics. However, this review does not include a formal assessment of the quality, rigor, or replicability of the studies considered. Future research could benefit from incorporating quality appraisal criteria to reduce bias. Despite these challenges, this review article attempts to generate a reliable identification of the current status and gaps in research related to the H2CCC economy.

7. Conclusions

This review paper summarizes studies that employed game theory to analyze competition, cooperation, and co-competition in hydrogen and energy systems. Identification, categorization, and analysis were carried out using a hybrid literature review with the PRISMA framework to develop both bibliometric (180 articles) and structured reviews (87 articles).

Game-theoretical models from Non-Cooperative Game Theory (NCGT) are among the most widely used in literature. They are applied not only to competitive scenarios but also to cooperative and co-competitive dynamics within hydrogen supply chains (HSCs) and integrated energy systems (IESs). The cooperative approach emerges as the most frequently explored, appearing in 43 % of the papers (using both NCGT and CGT). Competitive dynamics receive slightly less attention (40 %), despite their significant role in real-world economic systems. Many models exploring competition combine optimization and game theory in several ways, e.g., multi-level solutions strategy. Co-competition is the least examined (17 %). It is, however, important to highlight that several models could offer a more explicit explanation and details about the game theoretical formulations to be able to replicate the results.

Most of the IESs case studies use hydrogen technologies as stakeholders due to the need for renewable energy storage, energy decarbonization, and energy system flexibility. The HSCs mainly involve the analysis of technological stakeholders (energy sources, production, etc.). The HSC scale can be applied more extensively to analyze H2CCC dynamics. Users, countries, organizations and other institutional stakeholders could be studied more in game-theoretical models. Only a limited number of studies address topics such as policy and geopolitics. Furthermore, factors like trust, fairness, attitudes, behavior, and preferences require deeper investigation to better understand their influence on decision-making processes. Empirical case studies on H2CCC are scarce.

The policy and regulatory environment can have an important role in the promotion of cooperative or competitive dynamics. A realistic feature for some models has been the consideration of evolutionary or dynamic behaviors around cooperation or competition using evolutionary games but more efforts are needed. Developing multi-period

Table 5
H2CCC gaps and perspectives.

Strategy	Research gaps	Perspectives
All	1 Empirical case studies are rare	1 Real case studies to be developed
	2 HSC approach can be further explored	2 Systems approach can be used [38,39]
	3 Investigate H2CCC tensions overtime	3 Multi-period, ESS and repeated games [62]
	4 Investigate geographical impact: currently Chinese cases (55 %) or unreported (26 %)	4 New policy environments can be considered.
	5 Explore modeling transferability to other regions or case studies	5 Game theoretic models, like other types of symbolic models using mathematical formalism, are abstract in nature. Applying them to the analysis of particular situations or systems is rather a matter of knowledge, expertise, research interest, and financial support than of geographic location.
	6 Improve and refine game theory modeling and reporting	6 Multidisciplinary team with a game theory expert is recommended
	7 Model new roadmaps priorities using H2CCC with game theory	7 E.g., hard-to-abate sectors, hydrogen ports, regional alliances, or the use of critical raw materials
	8 Cooperation may fail in practice, as behavioral, trust, and negotiation dynamics are rarely modeled	8 Try new methodologies to model H2CCC (e.g., agent-based simulation [37])
	9 H2CCC properties can be further discussed	9 Fairness, stability and satisfaction [4,171] can be analyzed
	10 Policy implications are missing in many papers	10 Include formal representations of regulatory mechanism and policy representation [94,147, 163].
	11 Results reporting can be improved and policy makers can be involved	11 Improve results reporting to facilitate analysis and decision making
Co-competition specific	1 Lack of pure co-competitive approaches	1 Biform games [77] can be used
Cooperation specific	1 Mobility sector is less treated	1 Mobility market research development
	2 Gately value or Nucleolus are underexplored	2 Can be compared to other solution concepts if applicable [4].
	3 Scalability and computational tractability limitations	3 Raiffa-Kalai-Smorodinsky solution can be tried [138] for bargaining solutions comparison

game-theoretical models that studies early-stage cooperation followed by competition might offer a broader insight into the strategic behaviors influencing the upscaling of hydrogen technologies. The hierarchical aspects are also critical in decision making. Stackelberg games and evolutionary games (NCGT) were mostly applied to reflect the impact of hierarchical decision-making structures and the dynamic learning environments, respectively. More research can be developed to include hierarchical and critical resources aspects in coalitions (CGT).

Industrial and mobility sectors are present in H2CCC dynamics emphasizing hydrogen's critical role in both sectors. Coordinated investment and continuous innovation to support scalable hydrogen deployment are underlined in the articles. The analysis of competition and cooperation has shown to be both contrasting and interconnected, collectively shaping the evolution of the hydrogen economy. Cooperation, as an emerging concept, offers a strategic pathway for balancing these two approaches, enabling stakeholders to pursue shared objectives while maintaining healthy market rivalry in other domains. Pure cooperative games have not yet been applied to investigate H2CCC dynamics. Gaining a better understanding could enable more refined game-theoretical modeling aimed at enhancing the efficiency, sustainability, stability and resilience of future energy systems.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2025.116293>.

Data availability

Data will be made available on request.

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