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Towards sustainable hydrogen production: An integrated approach for Sustainability, Complexity, and Systems Thinking in the energy sector

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ABSTRACT

The energy sector constitutes a dynamic and complex system, indicating that its actions are influenced not just by its individual components but also by the emergent behavior resulting from interactions among them. Moreover, there are crucial limitations of previous approaches for addressing the sustainability challenge of the energy sector. Changing, transforming, and integrating paradigms are the most relevant leverage points for transforming a given system. In other words, nowadays the integration of new predominant paradigms in order to provide a unified framework could aim at this actual transformation looking for a sustainable future. This research aims to develop a new unified framework for the integration of the following three paradigms: (1) *Sustainability*, (2) *Complexity*, and (3) *Systems Thinking* which will be applied to achieving sustainable energy production (using hydrogen production as a case study). The novelty of this work relies on providing a holistic perspective through the integration of the aforementioned paradigms considering the multiple and complex interdependencies among the economy, the environment, and the economy. For this purpose, an integrated seven-stage approach is introduced which explores from the starting point of the integration of paradigms to the application of this integration to sustainable energy production. After applying the Three-Paradigm approach for sustainable hydrogen production as a case study, 216 feedback loops are identified, due to the emerged complexity linked to the analyzed system. Additionally, three system dynamics-based models are developed (by increasing the level of complexity) as part of the application of the Three-Paradigm approach. This research can be of interest to a broad professional audience (e.g. engineers, policymakers) as looks into the sustainability of the energy sector from a holistic perspective, considering a newly developed Three-Paradigm model considering complexity and using a Systems Thinking approach.

1. Introduction

The dynamic nature of the world, shaped by emerging situations and unforeseen events, needs a consideration of these factors in endeavors toward sustainable development. Effectively addressing the complex challenges is essential for comprehending, describing, and studying the intricacies of our global environment. Despite the awareness of living in a complex world, conventional decision-making has often relied on static, narrow, and reductionistic mental models (Ball and Wietschel, 2009). In other words, to propose an effective decision-making approach, it is needed to provide a holistic perspective considering this dynamic complexity.

The global energy sector constitutes a dynamically complex system (Birol, 2022), suggesting that its behavior is influenced not only by its independent components but also by the emergent behavior arising from its agent interactions (Laimon, et al., 2022). Due to this fact, there are several and crucial limitations of previous approaches (Nanjundaswamy Vasist and Krishnan, 2023) for addressing the sustainability challenge of

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the energy sector (Zhao et al., 2023). At the same time, it is important to highlight that sustainability includes environmental protection, societal advancements, but also, economic development (Meraj et al., 2023). For this reason, the proposed solutions must be economically viable, otherwise, it is not possible to talk about real sustainable development.

Therefore, in this point, it is of paramount importance to propose a holistic framework by integrating the following aspects for sustainable development: (1) an effective decision-making process, (2) the dynamic behavior of the energy sector, and (3) the complexity linked to the sustainability of the energy sector. Additionally, there is a gap in integrating into the same approach the complex interdependencies among technical issues and social, economic, and political decisions related to the energy sector which need to be studied and modeled in order to adopt the right policies in the long-term run. For this purpose, it is needed to propose effective ways of intervention in a given complex system (as is the energy sector), but how to do so?

A possible answer to this concern is that changing paradigms and changing the way of adopting them could lead to achieving actual changes in a given complex system. According to Meadows (1999) the most effective places to intervene in a system are (1) the power to transcend paradigms, (2) the mindset or paradigm from which the system arises; and (3) the goals of the system. “There is yet one leverage point that is even higher than changing a paradigm” (Meadows, 1999). Therefore, nowadays the integration of new predominant paradigms in order to provide a unified framework could aim at this actual transformation looking for a sustainable future.

The second question to be addressed is which paradigms really need to be integrated for this purpose. The complexity paradigm allows to identify the interactions and interdependencies among the economy, the environment, and the society. A Systems Thinking approach leads to adopt an effective decision-making process consistent with the complex causalities identified (Delikhoon et al., 2022). Finally, sustainability naturally emerged as the result of combining these paradigms. In other words, sustainable energy production needs this integration, and for this reason, this study has a high interdisciplinary component, where the role of collaborative thinking has been highlighted in the proposed framework.

This research aims to fill the aforementioned gaps by developing a new unified framework for the integration of the following three paradigms: (1) *Sustainability*, (2) *Complexity*, and (3) *Systems Thinking* which will be applied to achieving sustainable energy production (using hydrogen production as a case study). The main objective of this research is to provide a holistic perspective of sustainable hydrogen production using this proposed integration of paradigms. For this purpose, it is crucial to analyze the multiple and complex interdependencies among the economy, the environment, and the society. Hence, the novelty of this research can be summarized in the following aspects:

➢ Developing a new framework for integrating three paradigms into the same approach: (1) *Sustainability*, (2) *Complexity*, and (3) *Systems Thinking*.
➢ Applying the new Three- Paradigm (3P) model to the sustainability of the energy sector using sustainable hydrogen production as a case study.
➢ Proposing new conceptual models (both Causal Loop Diagrams and System Dynamics) linked to sustainable hydrogen production.
➢ Proposing guidelines for future research and practical applications of the 3P approach.

Using as a framework the proposed integration of paradigms, a seven-stage methodology will be proposed by addressing the identified gaps providing a holistic approach to sustainable hydrogen production. Hydrogen has been chosen as a case study as it is one of the fuels with the potential to be produced sustainably.

By providing a holistic perspective through the integration of the aforementioned paradigms it is possible to consider the multiple and complex interdependencies among economy, environment, society, sustainability, and safety. At the same time, integrating these paradigms will contribute to adopting long-term solutions in the near future by assuring the effectiveness of these policies.

Furthermore, the archival value of the expected results is linked to the fact of proposing a unified framework by integrating Sustainable Development, Complexity, and Systems Thinking into the same holistic approach. Additionally, the conceptual models developed as well as the proposed guidelines will allow to analyze the dynamic behavior of the energy sector by studying the effectiveness of different policies.

This research article is divided as follows: Section 2 provides the conceptual framework and the current literature state from which the necessity of the integration of paradigms emerged. In this section, the research questions linked to this research are presented. Section 3 focuses on the methodology for developing the holistic framework needed for energy sustainability. A detailed description of the new Three Paradigm model is provided. Section 4 contains the results and discussion of the development and implementation of the proposed framework for sustainable hydrogen production as well as the future research lines that can be performed from this approach. Finally, conclusions are exposed in section 5.

2. Conceptual framework

This section has been developed to address the following questions:

(1) Why choose hydrogen production and applications as a case study in the sustainability of the energy sector? (Q1)
(2) Why a Systems Thinking approach is adopted over other well-known approaches such as Complex Adaptive Systems Theory and Softy Systems Modelling? (Q2)
(3) What are the links and common points among the Complexity, Systems Thinking, and Sustainability paradigms? (Q3)
(4) How a Systems Thinking approach has been applied to achieve energy sustainability? (Q4)

Fig. 1 shows the links among the aforementioned research questions. Starting with the general idea about how to provide a holistic framework towards energy sustainability, other concerns arise such as understanding the role of hydrogen in the energy sector, and how would be possible to address the complexity linked to it for achieving sustainability.

That is why, in this section, the most relevant concepts for developing this research are exposed and a brief literature review is conducted mainly focused on the following ideas:

➢ Hydrogen sustainable production role in the energy sector.
➢ Comparing Complex Adaptive Systems Theory, Soft Systems Modeling, and Systems Thinking approaches.
➢ Systems Thinking approach considering Causal Loop Diagrams, System Archetypes, leverage points, and System Dynamics-based models.
➢ *Complexity* linked to *Sustainability* in the energy sector from a *Systems Thinking* perspective.

2.1. Hydrogen sustainable production role in the energy sector

Renewable energy sources are expected to be a sustainable replacement for fossil fuels (Chien et al., 2021). Notwithstanding, their inconsistent and discontinuous characteristics require efficient and safe storage methods. Renewable energy can be stored in chemical (such as hydrogen) or electrical energy sources. On the one hand, electrical energy is generally exploited as an energy storing choice and it is widely used daily. On the other hand, hydrogen has been gaining consideration as a result of its positive characteristics as an energy carrier. Thus, to

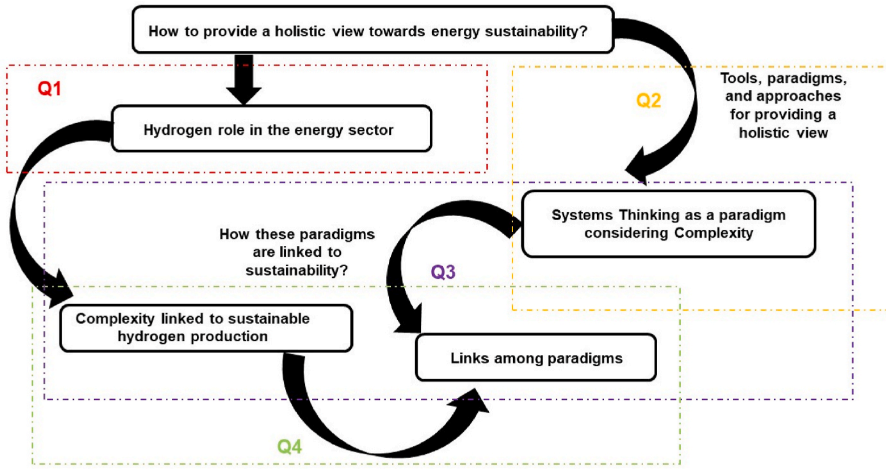

Fig. 1. Links among the research questions in this conceptual framework.

ensure sustainable development and address environmental, economic, and social concerns, both electricity and hydrogen must be produced from renewable energy sources (Acar and Dincer, 2018).

Hydrogen is a vital energy carrier in the energy sector for the following reasons: (1) it has good exchange effectiveness; (2) it can be produced from water with zero emissions; (3) it can be stored using different pathways (gaseous, liquid, or metal hydrides) (Hassan et al., 2021); (4) it can be transformed into other energy ways by more methods than those of every other fuel; and (5) it possesses a higher heating value than the majority of traditional fossil fuels. Overall, hydrogen has the potential to mitigate the adverse effects of climate change; reduce pollutant emissions; and explore alternatives to reducing reliance on fossil fuel sources (Acar and Dincer, 2018).

Nowadays, there are four main shades of hydrogen in which the majority of hydrogen production pathways can be included: gray (Gray-H), blue (BH), turquoise (TH), and green (GH). Gray-H primarily originates from fossil fuels and results in significant CO_2 emissions, rendering these technologies unsuitable for achieving a net-zero emissions pathway. BH is obtained in the same way as Gray-H but adding carbon capture and storage (CCS). It has the potential to foster the expansion of the hydrogen market, given that 75% of current hydrogen is derived from natural gas, which would consequently alleviate the burden on renewable energy capacity installation for producing GH (Castelvecchi, 2022).

Numerous industrial processes, including steel production, demand a constant supply of hydrogen. BH can serve as the initial solution to meet this demand, with GH gradually scaling up its production and storage capacity to fulfill the requirement for a continuous hydrogen supply (Ikram et al., 2021). Furthermore, the constraints of BH encompass reliance on finite resources (fossil fuels), vulnerability to price fluctuations in fossil fuels, energy insecurity, and social acceptance issues (related to additional costs for CO_2 transport, storage, and monitoring) (Lagioia et al., 2023). Other concerns are related to CCS capture inefficiencies (around 5–15% of CO_2 is still emitted), and methane leakages upstream (which is significantly more potent as a GHG per molecule than CO_2). Therefore, BH fails to meet the criteria for a net-zero future and should be regarded only as a short-term transition to facilitate the integration of GH into the net-zero emissions pathway (Dhayal et al., 2023).

One of the most crucial challenges of the energy sector in this regard is related to the hydrogen economy (Demartini et al., 2023). According to Cozzi & Gould (2022), capital flows indicate where investors and companies can see real opportunities in the next years; the capital spent on hydrogen electrolyzer projects was around USD 1.5 billion, which represented more than three times the 2020 capital; also, two of the world's largest electrolyzers started operations in 2022. Reliable long-term demand for low-emissions hydrogen will be the main driver of investment for scaling up (Cozzi and Gould, 2022).

2.2. Comparing Complex Adaptive Systems Theory, Soft Systems Modeling, and Systems Thinking approaches

In this section three most important approaches are compared: a Complex Adaptive Systems Theory (CAS), Soft Systems Modeling (SSM), and a Systems Thinking (ST) approach. In the supplementary materials, there is a table containing detailed information about the advantages and disadvantages of adopting a Complex Adaptive Systems Theory, Soft Systems Modeling, and Systems Thinking approaches. Table 1 shows a brief comparison of these methods.

In general, these paradigms offer different lenses for understanding and solving complex problems. The choice of the adopted approach will depend on the nature of the problem, the context, and the specific factors that need attention. In this research a Systems Thinking approach is adopted due to its ability to capture the interdependencies of a given system, considering their dynamic evolution and possible interactions. By adopting a Systems Thinking approach, both qualitative and quantitative perspectives can be modeled for analyzing the interdependencies linked to sustainable hydrogen production.

Table 1
Comparison among the CAS Theory, SSM, and Systems Thinking approach.

Parameter	CAS Theory	SSM	ST
Scope	Primarily focused on complex adaptive systems in nature and society.	Primarily applied to human activity systems.	Applicable across a wide range of systems.
Approach	Emphasizes adaptability and emergence.	Human-centric and emphasizes stakeholder perspectives.	Holistic approach considering system interdependencies.
Modeling	Focuses on understanding and describing system behavior.	Involves creating rich pictures and conceptual models.	Involves system diagrams and feedback loops.
Applicability	Well-suited for natural and social systems.	Effective for addressing unstructured human activity systems.	Applicable across various domains and industries.
References	Holland (1992); Holden (2005).	Hindle (2011).	Garcia (2009); Sterman (2002).

2.3. Systems Thinking and Complexity paradigms. Main ideas and concepts

This section aims to explain the main concepts of Systems Thinking and Complexity paradigms and how they are linked. A Systems Thinking approach contains the development of Causal Loop Diagrams and System Dynamics models. The Causal Loop Diagram (CLD) serves as a highly effective tool for comprehending the dynamics and complex behavior of a particular system. Moreover, it aids in identifying leverage points that can enhance system performance (Haraldsson et al., 2006). Although discovering these leverage points may not be straightforward, System Archetypes (SAs) can assist in their identification (Haraldsson and Sverdrup, 2021).

System Dynamics (SD) allows the development of models after a really careful assessment of the elements of the complex system and its interconnections and interdependencies (Bala et al., 2017). Using an SD approach, the internal logic of the model can be extracted and knowledge then can be gained for a long-term dynamic evolution of the system (Sterman, 2002). The key issue for the model construction is the analysis of the internal logic and the structural relationships within the system (Guzzo et al., 2023). Therefore, the main application of SD is in the field of complex defined environments (McAvoy et al., 2021).

As complex systems can be studied using a Systems Thinking approach (Sterman, 2002), it is necessary to understand which phenomena can emerge in complex systems (as part of its integration in thee 3P model). The most important properties of complex systems are analyzed below.

Complex systems (CS) are constantly changing, even if it appears to remain static for some time, over a long-term period, they are going to evolve. These changes happen at different time scales, and these scales often interact with each other. CS are also tightly coupled which is translated into strong interactions with the world, and governed by feedback from where dynamic behavior emerges. Nonlinearity is another characteristic of complex systems, wherein effects are seldom proportional to their causes, and local occurrences in a system often do not hold true for distant regions. This aspect is exceptionally crucial to consider, especially when multiple factors interact in decision-making processes. CS are history-dependent, meaning that choosing one particular path can preclude other options, leading to a state of path-dependence that determines the system's final outcome (Sterman, 2002).

Furthermore, CS are self-organizing, giving rise to dynamic patterns spontaneously from their internal structure. Random perturbations are often amplified by the feedback structure, resulting in the emergence of new spatial and temporal patterns. Another distinctive trait of CS is their adaptability. The capabilities and decision rules of the agents within these systems undergo changes over time. Consequently, evolution plays a role in selecting and propagating certain agents while causing others to become extinct (Garcia, 2009).

Moreover, complex systems are marked by trade-offs, and time delays in feedback patterns can result in long-term responses to a given intervention. In CS, cause and effect can exhibit distant relationships in both time and space, leading to counter-intuitive behavior. As a result, identifying high-leverage policies becomes a challenging task. CS are also prone to snowballing and cascading effects. Additionally, they frequently display policy resistance behavior, where seemingly straightforward solutions may fail or even exacerbate the problem (Guzzo et al., 2023).

Once the links between Complexity and Systems Thinking paradigms have been studied, it is only needed to explore their connections with the Sustainability paradigm in the context of the energy sector. This is addressed in the following section.

2.4. Sustainability in the energy sector from a Systems Thinking perspective

In this section, a brief literature review of the most relevant studies which proposed a solution from a Systems Thinking perspective to sustainable energy production is exposed. This subsection aims (1) to understand that a Systems Thinking has been effectively used for decision-making in sustainable development, and (2) to demonstrate that despite this use, there are still complex concerns that have not been addressed, highlighting the importance of our proposed integration of paradigms.

A new conceptual model was developed by Laimon et al. (2022) for studying the energy sector in Australia by analyzing the potential consequences of current energy development policies. One important conclusion was that while the classical linear thinking approach focuses solely on symptom treatment with quick-fix solutions, disregarding the intricacies and challenges of sustainability in the energy sector, the Systems Thinking approach takes a different path.

This idea was additionally supported by the review article of Rebs et al. (2019) and the research study by Guzzo et al. (2023). The authors concur that system dynamics modeling is a potent method for representing the intricate interplay and dynamic connections among various causal factors in sustainability and that the dynamic complexity arises from the interdependent relationships among system elements and how these interactions evolve.

Moreover, there are some previous studies which explored the sustainability of the energy sector linked to cleaner production. Silva et al. (2020) proposed a new index for computing energy sustainability considering five main dimensions: environmental, economic, social-cultural, political-territorial, and technological. The utilization of green hydrogen synergy has the potential to foster the clean and sustainable growth of offshore and coastal industries by creating new opportunities for clean energy expansion (Kumar et al., 2023). Furthermore, Saleh and Brem (2023) addressed the question: "How can creativity foster sustainability?" through an exhaustive literature review of the sustainability literature. Their research revealed four distinct levels of creativity for sustainability, namely, at the individual, community, organizational, and institutional levels.

Regarding the hydrogen production pathways sustainability, the research proposed by Li et al. (2022) focused on identifying which GH subsidy methods the Chinese government should adopt. Based on this study, there is a present requirement to enhance policy support in three key aspects of Green Hydrogen (GH) subsidy policies: (1) technology readiness, (2) market penetration, and (3) market growth (Ahmadi and Khoshnevisan, 2022).

A similar research was developed by Gao & An (2022) which focused on the assessment of China's coordinated development capacity (CDC) of the hydrogen energy industry chain from 2015 to 2021 by using a combination of different methods such as the entropy model, partial least squares regression (PLS), and system dynamics model. The main purpose was to simulate the functioning of China's hydrogen chain spanning the period from 2016 to 2030 (Zhang, 2021). Overall, the study suggested that building a science and technology innovation system is necessary to improve the policy and institutional guarantee system, and to encourage the development of hydrogen energy infrastructure and the diverse utilization of hydrogen energy. Precisely, the research proposed in this paper addresses this gap by integrating the necessary paradigms for providing a holistic understanding of hydrogen sustainability.

Other studies were developed by building conceptual models based on a Systems Thinking perspective. Yusaf et al. (2022) proposed a conceptual model for hydrogen energy using a Systems Thinking approach, with a particular focus on the hydrogen use pathways. Moreover, this study showed the demand growth of hydrogen energy until 2050 using a system dynamics approach applied to the Australian energy system. Yang et al. (2023) introduced a System Dynamics model to analyze China's green hydrogen production industry. The findings revealed that even with a 25% income tax and no installation subsidy, the production capacity of the GH industry struggles to meet the demand across various demand scenarios (Falcone et al., 2021).

Overall the Systems Thinking paradigm has been applied to the sustainability of the energy sector, using Causal Loop Diagrams and System Dynamics-based models (depending on the research aim as described above). However, previous studies focused more on individual concerns linked to energy sustainability rather than on providing a holistic view of the problem. That is why the complexity paradigm is needed as there is an emergent behavior (from the interactions among the economy, society, and the environment) directly linked to the sustainability paradigm that needs to be addressed.

Even when a Systems Thinking approach has been applied to achieving Sustainability in these aforementioned studies, there are still many complex constraints and interdependencies that were not considered before. For this reason, a new integration of paradigms is proposed. Based on these concepts, and in the developed feedback loops, CLDs, and SD model, a new seven-stage approach is described, from the development of a Three-Paradigm model to the application of this new methodology to the sustainability of the energy sector.

3. Methodology

This research is divided into seven main stages (Fig. 2). Firstly, an extensive literature review was carried out to understand the basics of a Systems Thinking approach: Causal Loop Diagrams (CLD), Forrester Diagrams (SD), common phenomena in complex systems, System Archetypes, and limiting and key factors.

Then, a new three-paradigm (3P) model considering a holistic perspective for achieving sustainability (Sustainability-Complexity-Systems Thinking) is proposed. In order to analyze the new 3P model, a CLD and an SD models are developed considering System Archetypes (SAs). The second stage is linked to the application of these SAs to the hydrogen-sustainable production and applications.

From this perspective, the necessary factors and causalities related to energy-sustainable production are obtained; and the understanding of the Systems Thinking approach for addressing the complexity. The third stage is focused on the identification of the previously studied feedback loops reported in the literature, for a posterior integration in the proposed CLD. After that, the application of the developed CLDs to hydrogen production will be developed (fourth stage). The fifth step aims to develop an integrated CLD for hydrogen-sustainable production using the previous feedback loops.

The sixth stage focuses on developing SD-based models for addressing the emerged complexity due to the multiple interdependencies in the developed CLD. Finally, future research and challenges related to the application of the 3P approach and sustainable hydrogen production are presented. The general methodology is shown in Fig. 2.

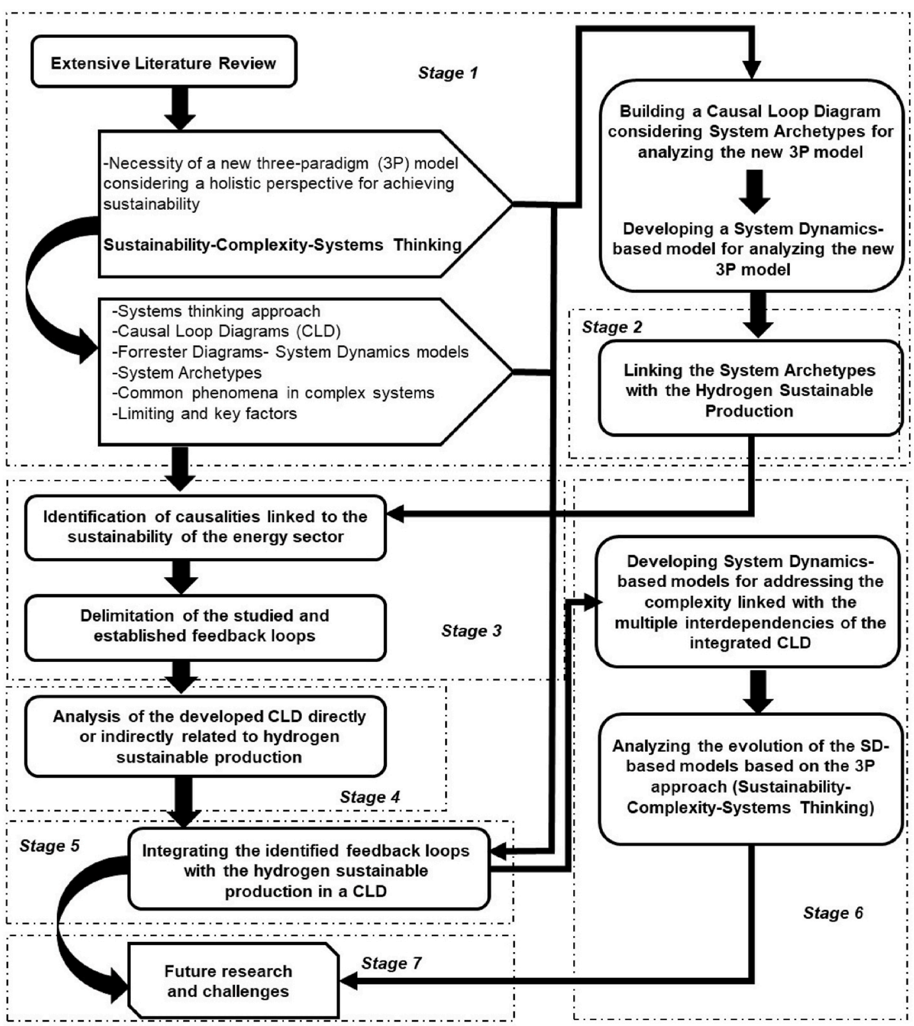

Fig. 2. Proposed methodology in this research framework.

3.1. Stage 1: Exploring the necessity of a Three-Paradigm model using a Systems Thinking approach for achieving Sustainability

The first step into this stage is to seek in the literature which studies already developed CLDs, SDs, or both applied to sustainable energy production. All the studies reported in the Web of Science were considered in the last 30 years, with a special focus on the last 5 years. The final papers (described in detail in the Supplementary Materials) were selected based on the application of a Systems Thinking approach for achieving sustainable energy efficiency.

The second step of this stage is presenting a new three-paradigm (3P) model considering a holistic perspective for achieving sustainability. Table 2 shows the advantages of using each paradigm in the same approach as well as the challenges linked with the use of each one.

Traditional approaches often treat systems as static entities, failing to capture their dynamic nature and the interplay of feedback loops over time. By integrating Systems Thinking, Sustainability, and Complexity paradigms, it is much better understood how complex systems evolve, adapt, and respond to changes in their environment. Therefore, considering the dynamic nature of the systems is crucial to studying the interconnections among the economy, the environment, and the society linked to energy sustainability.

The integration of these paradigms has itself many challenges, some of which will be addressed in this research (such as the role of collaborative thinking, and the way for dealing with multiple interdependencies), the others have been outlined as future research lines.

At the same time, these paradigms are intrinsically related. Fig. 3 shows the general picture of this 3P (Sustainability-Complexity-Systems Thinking) model. The development of a Systems Thinking approach is needed for addressing the complex phenomena related to all the possible interactions in order to achieve sustainability. The complexity of the sustainability paradigm relies on the emergent behavior of the interdependencies among economic development, environmental respect, and societal implications. At the same time, a Systems Thinking algorithm provides an effective decision-making framework which leads to effective policies for sustainable production.

The most effective way for capturing these interrelations and causalities is through the Systems Thinking paradigm (CLDs plus Forrester diagrams). Additionally, common properties related to the complexity paradigm challenge applying a Systems Thinking approach (such as the non-linear dynamics, multidirectional relations, feedback loops, multiscale properties, and inherent uncertainty). However, these properties are inherent in most complex systems, which are necessary to consider for implementing effective decisions (using a Systems Thinking approach) for achieving sustainable development.

Moreover, the Systems Thinking approach provides many advantages such as the identification of leverage points, the design of effective interventions, and the prediction of the system behavior which leads to long-term viability (necessary for sustainable development) and promotes adaptive management. Using this adaptive management will minimize undesirable outcomes or consequences, assuring sustainability.

Hence, for integrating these three paradigms into a new model, it is necessary to develop interdisciplinary research and a collaborative mindset among environmental and social sciences, economics, and engineering. As part of this stage, a CLD and an SD-based model will be proposed for understanding the advantages and limitations of the proposed 3P approach.

Table 2
Advantages and challenges of integrating each paradigm in the same model.

Paradigms	Advantages	Challenges
Sustainability	Analyzing effective long-term policies for sustainable development considering the economic, environmental, and societal impacts.	Emerged complexity linked to the economic (Dueñas Santana et al., 2022), environmental, and societal impacts (Dueñas Santana et al., 2021) as well as their synergic effect.
Complexity	Considering the common phenomena of complex systems, and the complex relations among the environment, the economy, and the society.	Dealing with multi-agent networks and multiple interdependencies and causalities.
Systems Thinking	Providing a decision-making approach for analyzing the dynamic behavior of a given system.	Collaborative thinking in the framework of emerged complexity due to multiple interrelations.

3.2. Stage 2: System Archetypes in the context of the 3P model

The second stage aims to link the SAs to sustainable hydrogen production in the context of the 3P model. SAs are structures which help to identify unintended consequences, hidden effects, and feedback loops that influence the effectiveness of different solutions to a given problem. Using these archetypes is crucial for understanding how really achieve sustainability in the energy sector.

3.3. Stage 3: Identification of causalities and loops linked to the sustainability of the energy sector

This stage focuses on the identification of the main feedback loops, and causalities of the interactions among sustainable energy production, applications, and their impact on the environment, society, and economy. This procedure selects the interactions which directly or indirectly affect the sustainability of the energy sector from the literature. The previously studied feedback loops were selected (in a qualitative way) based on their relationship to the sustainability of the energy sector.

3.4. Stage 4: Analysis of the previous developed CLDs and SD-models

In this stage, the main CLDs and SD models are analyzed to identify the main interdependencies and the way that the previous studies applied a Systems Thinking approach. This stage aims to select the most relevant feedback loops using the same procedure as in Stage 3. Also, from this stage, it is important to understand how to connect the existing relevant loops with the newly proposed ones for achieving sustainability.

3.5. Stage 5: Developing a CLD model for hydrogen sustainability

This stage aims to develop a new CLD model containing the aforementioned causalities and loops linked to the sustainability of hydrogen production and applications. CLDs are conceptual models which help to the understanding of the interdependencies of a given system. When it is applied in the context of the 3P approach, a high complexity associated with it is expected due to the multiple interdependencies and impacts on society, environment, and economy as well.

3.6. Stage 6: Developing SD-based models for addressing the complexity of the developed CLD

This stage aims to develop new SD-based models for addressing the complexity of the developed CLD for hydrogen sustainable production. For this purpose, stocks, flows, auxiliary variables, and delays are proposed, all of them elements of a System Dynamics model. Additionally, the evolution of the SD models is analyzed. In this way, the application of the 3P approach allows to address the *Complexity* (emerged in the developed CLD), for achieving *Sustainability* (the main focus of the developed models), using a *Systems Thinking* approach (using CLDs and SD-based models).

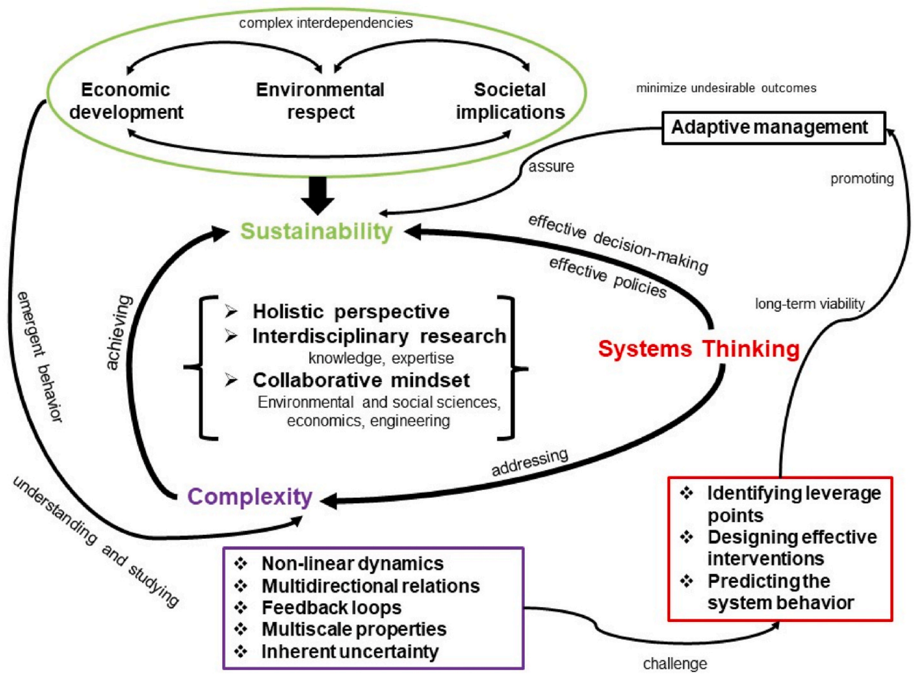

Fig. 3. General picture of the new proposed three-paradigm model (Sustainability-Complexity-Systems Thinking).

3.7. Stage 7: Future research and challenges

This stage outlines the future research and challenges linked with the application of the new proposed 3P model and the sustainability of the energy sector as well. Ideas are clearly provided for understanding the new emerging gaps in this sense. Overall, after adopting this seven-stage approach it is expected that the new proposed 3P model will capture the complexity linked to sustainability through a Systems Thinking approach.

4. Results and discussion

In this section, the results obtained from the seven-stage methodology proposed in this research framework are discussed. The main idea is to provide a guideline for the application of the 3P approach in the context of sustainable energy production. Firstly, the new three-paradigm (3P) model considering a holistic perspective for achieving sustainability (Sustainability-Complexity-Systems Thinking) is clearly explained through a CLD and an SD model. Additionally, the application of System Archetypes (SAs) to sustainable hydrogen production is provided. After that, the CLDs reported in the literature related to energy-sustainable production are presented; and, the integrated CLD for hydrogen sustainable production is proposed considering complex interactions. Moreover, three SD-based models for addressing this emerged complexity. Finally, future research lines and challenges are indicated.

4.1. CLDs and SD-based model for the proposed 3P approach (Stage 1)

In this section, a new CLD and an SD-based model for the proposed 3P approach are discussed. This section addresses the challenge of using collaborative thinking in the framework of emerged complexity due to multiple interrelations in the 3P model. Fig. 4 shows a developed CLD for analyzing the factors linked to the integration of paradigms. In this CLD, there are two feedback loops: a reinforcing loop (R1), and a balancing loop (B2). The R1 contains the idea that the efforts for interdisciplinary research will increase the integration of paradigms in this context, and that, at the same time, this integration (due to the positive results and effective sustainable decisions) will lead to more efforts for interdisciplinary research. In this sense, collaborative thinking plays an essential role, setting a starting point for discussion and analysis which leads to more interdisciplinary applications. However, the integration of paradigms has limitations. The SA "Limit to Success" gives the opportunity to explore these constraints in the 3P framework. As the integration of paradigms increases, there is high consumption of resources such as time, funding, and expertise, and this can lead to putting less effort into this integration (represented by B2).

This CLD can be transformed into an SD-based model considering the integration of paradigms as a stock (accumulation). Fig. 5 shows the SD-based model for describing this integration in the context of the 3P

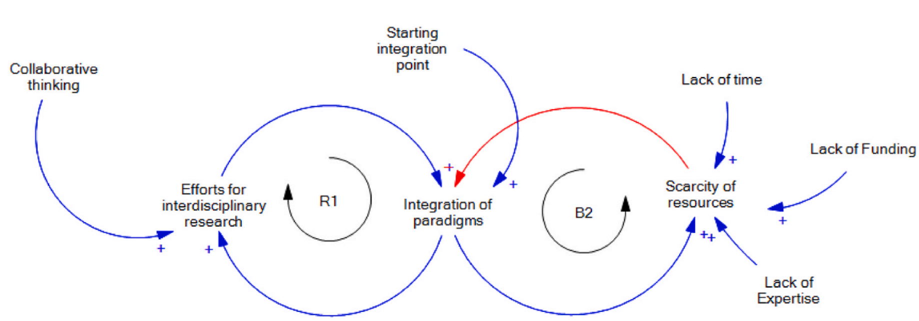

Fig. 4. CLD for analyzing the integration of paradigms in the 3P context.

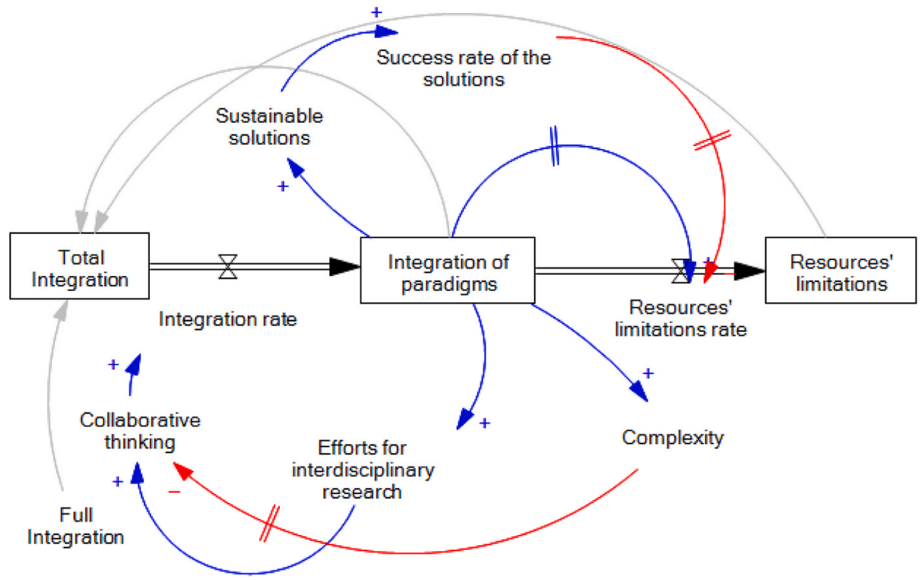

Fig. 5. SD-based model for analyzing the integration of paradigms in the 3P context.

model. The integration of paradigms will lead to more sustainable solutions, and the success of these, after a given time (for checking such success and for resource distribution) will increase the resources' availability (in the model it decreases the resources' limitations rate). At the same time, the integration increases the efforts for interdisciplinary research, the collaborative thinking, and this directly pushes up the integration rate; and therefore the integration of paradigms. However, this integration will lead to more complexity, and this could lead to periods of frustration or misunderstanding among the experts, affecting the collaborative thinking effect after a given time. Hence, this SD-based model allows to understand the risks associated with the application of the 3P model proposed in this research and its limitations as well.

Setting the Integration of Paradigms in a range from [−100-100] and running a simulation using the model, Fig. 6 is obtained. The minimum value (−100) represents no integration at all, while the maximum value (100) represents the full or complete integration of paradigms. Also, (0) represents the common or usual integration of paradigms in a normal collaborative thinking framework. In this sense, the efforts for the integration can be measured as the values above 0.

In the dynamic evolution of the Integration of Paradigms, it can be noted that there are periods of poor integration followed by periods of good integration in general. Also, the periods of good integration are each time of better integration considering the proposed scale. The oscillations are due to the delays that are part of the system, between the

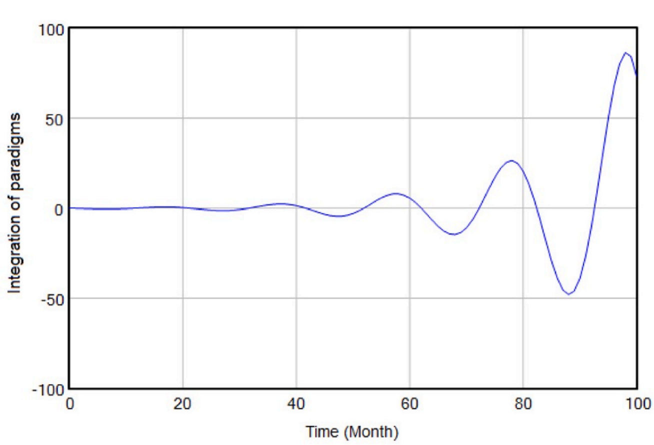

Fig. 6. Dynamic behavior of the Integration of Paradigms.

studied parameters. The main interpretation of this behavior is that a minimum starting effort for integrating paradigms will lead in a given time to higher values of integration even knowing the limitations of resources. These concerns will be addressed through the effectiveness and success of sustainable and effective measures in the long-term period. These solutions will bring more funding, more experts, and more time for the integration of paradigms.

There are practical implications that emerged from the proposed integration of paradigms. Firstly, by simulating various policy scenarios, policymakers can identify strategies that maximize positive outcomes while minimizing negative trade-offs. Industry stakeholders can use their simulation results to make informed investment decisions that align with sustainability goals. For example, by simulating the long-term impacts of investing in renewable energy infrastructure versus traditional fossil fuel projects, stakeholders can assess the financial and environmental risks associated with each option.

Moreover, the proposed paradigm integration can help stakeholders anticipate and mitigate risks associated with sustainability initiatives. By simulating worst-case scenarios and conducting sensitivity analyses, stakeholders can identify vulnerabilities and develop contingency plans to address potential challenges. The simulation results can serve as a basis for stakeholder engagement and collaboration. By providing stakeholders with a visual representation of complex systems and their interactions, the simulation model can facilitate dialogue, consensus-building, and collective action toward shared sustainability goals.

The limitations of the proposed paradigm integration, due to high resource consumption, raise important considerations for policy and practice in addressing sustainability challenges. One way to mitigate the limitations of high resource consumption is to prioritize resource efficiency strategies. Policies can encourage industries to adopt cleaner production. Additionally, investing in technological innovation can enable the development of cleaner and more efficient technologies that reduce resource consumption and environmental impact.

Finally, policymakers can adopt integrated policy frameworks that consider the interconnectedness of environmental, social, and economic factors in decision-making processes. Addressing the limitations of high resource consumption requires collaboration across sectors, disciplines, and stakeholders. Policymakers can facilitate multi-stakeholder partnerships that bring together government, industry, academia, and civil society to co-create solutions and implement coordinated action plans for sustainability.

Table 3
System Archetypes in the context of sustainable hydrogen production and applications.

System Archetype	System Archetype description	Application to sustainable hydrogen production
Fixes that Fail	This archetype describes a situation where a given problem is addressed using a short-term (or quick) solution, which seems effective, but, in the end, it produces unintended consequences that worsen the problem over time. The reinforcing loop of fixes is the core of this SA.	Symptomatic solution: Using a readily available but unsustainable energy source (e.g. fossil fuels) to meet immediate energy needs. Unintended consequences: Increased carbon emissions and environmental degradation, leading to a global climate crisis and environmental impact. Short-term focus: Stakeholders in the hydrogen production industry may prioritize meeting short-term demands without considering the long-term environmental consequences. Feedback loops (FL): FL can exacerbate the problem. For example, as carbon emissions increase, there may be more public and regulatory pressure to address environmental concerns, leading to stricter rules and an emphasis on sustainability. Continuation of symptomatic solution: Even considering the growing awareness of the environmental consequences, the continued use of unsustainable energy sources can persist due to economic factors, existing infrastructure, and inertia.
Shifting the Burden	This archetype represents a situation where a quick or symptomatic solution is adopted over a fundamental, or systemic solution, which can lead to long-term problems.	Symptomatic Solution (Quick Fix): Focusing on immediate, short-term solutions that address energy and environmental issues without fundamentally changing the system. Fundamental Solution (Systemic Change): Necessity for a long-term systemic change in energy production and consumption practices through transitioning to renewable energy sources, improving energy efficiency, and adopting sustainable hydrogen production methods. Symptomatic Reinforcement Loop: As the symptomatic solution is adopted, it temporarily alleviates environmental concerns or energy needs. In other words, using BH and/or Gray-H may provide a quick energy solution. Side Effects (Unintended Consequences): Increased carbon emissions, resource depletion, or other environmental problems. Shifting the Burden: The symptomatic solution may become the primary approach to address energy and environmental concerns. This shift can create dependency on his solution, making it difficult to transition to a more sustainable and fundamental solution. Delayed or ineffective fundamental solution: While the symptomatic solution may provide short-term relief, it delays or hinders the adoption of a fundamental, sustainable solution.
Growth and Underinvestment	In a Growth and Underinvestment case, growth gets a limit that might be eliminated or postponed if capacity investments were applied. Instead, as a result of policies or even delays inside the system, the demand or performance is degraded, limiting further growth. This declining demand leads to further withholding of investment or reductions in capacity, triggering worse performance.	Rapid Industry Growth: As the demand for clean energy sources grows, the hydrogen industry experiences rapid expansion. Increased Energy Demand: The need for hydrogen as an energy carrier escalates due to potential applications in various sectors, such as transportation, industry, and power generation. Insufficient Sustainable Production Investments: Despite the growth in the industry demand for clean hydrogen, investments in sustainable hydrogen production methods, such as renewable energy-based production or advanced technologies, may not keep pace with the increasing demand. Reliance on Less Sustainable Methods: Due to the underinvestment in sustainable production, there may be a continued reliance on less sustainable hydrogen production pathways, such as hydrogen production from fossil fuels, to meet immediate energy demands. Capacity and Quality Issues: Underinvestment can lead to capacity constraints and quality issues, potentially impacting the reliability and availability of sustainable hydrogen production. Economic viability concerns: The underinvestment may also be influenced by economic factors, such as the cost-effectiveness of sustainable production methods in comparison to less sustainable options.
Limit to Success	This archetype suggests that as a system or technology grows or scales up, it may encounter inherent constraints which hinder its ability to expand indefinitely.	Initial Success: Sustainable hydrogen production methods (e.g. renewable energy-based production or advanced hydrogen technologies) experience success and gain traction due to their environmental benefits, encouraging policies, tax reduction, and growing demand for clean energy. Resource Constraints: The availability of renewable energy sources (such as solar or wind) may be limited in some regions, or the supply of critical materials for advanced production technologies can become restricted. Environmental or Regulatory Constraints: As sustainable hydrogen production increases, it may find more stringent environmental requirements, particularly in areas where its environmental benefits were initially a driving force. Reduction in Growth Rate: Due to these constraints, the rate of growth in sustainable production may slow down, limiting the ability to completely replace less sustainable production pathways. Continued Use of Unsustainable Methods: In response to these constraints, there could be a continued reliance on less sustainable hydrogen production methods, such as hydrogen production from fossil fuels, to meet energy demands.
Drifting Goals	This archetype suggests that, over time, initial goals and objectives may lose clarity or be altered. This potentially affects the trajectory of a given system to reach its goals.	Initial Goals: The hydrogen production industry sets initial goals to transition to sustainable production methods, which are driven by environmental impact concerns, carbon emissions, and the necessity of

(*continued on next page*)

Table 3 (*continued*)

System Archetype	System Archetype description	Application to sustainable hydrogen production
		cleaner energy solutions. Technology evolution: As technology evolves and new methods for hydrogen production are available, there may be shifting priorities within the industry. For instance, advancements in carbon capture and sequestration (CCS) technology may change the focus from sustainable production to cleaner utilization of hydrogen produced from fossil fuels. Changing objectives: The evolving landscape may lead to changing objectives, with a shift from prioritizing sustainable hydrogen production methods to other priorities such as cost reduction, economic viability, or short-term energy supply. Feedback Loops: Feedback loops within the industry can influence the direction of investments, research, and policy priorities, potentially moving away from the initial production goals. Loss of Alignment: Over time, these evolving goals and objectives may result in a loss of alignment with the initial sustainability goals, potentially leading to a slowdown in the transition to sustainable hydrogen production.
Success to the Successful	In this archetype, two or more agents are competing for a limiting pool of resources to achieve success. When one of them starts to be more successful than the others, it tends to gain more resources, increasing the probability of continued success. So, its starting success justifies moving more resources while robbing the other alternatives of resources, and opportunities to build their own success.	Established Hydrogen Production Methods: Certain established and successful hydrogen production methods, which may include conventional methods like steam methane reforming (SMR) or well-established electrolysis techniques, have a strong presence in the hydrogen market. More investment and resources: These established methods receive a significant share of investment, research, and resources due to their proven track record, reliability, and market dominance. Innovation and Emerging Technologies: Innovative and emerging sustainable hydrogen production technologies, such as advanced electrolysis, and novel catalysts, struggle to compete with the resources allocated to established methods. Crowding out innovation: The dominance and investment in established methods can crowd out innovation and the development of sustainable production technologies, potentially slowing down the transition to more sustainable hydrogen production. Sustainability Concerns: As the dominance of less sustainable methods continues, it may raise some sustainability concerns linked with more carbon emissions, resource depletion, or environmental impacts.
Escalation	This archetype occurs when one party's actions are perceived by another party to be a threat. Then, the second party responds similarly, increasing the threat. The outcome results in threatening actions by both parties, which grow exponentially over time.	Competition and Investment: The hydrogen industry experiences increased competition among various stakeholders, including companies, regions, and nations, vying for market share and dominance in hydrogen production and utilization. Resource consumption: The escalating competition drives higher resource consumption, including energy, water, and materials, to meet the growing hydrogen demand. This can lead to resource scarcity and depletion. Environmental impact: The increased resource consumption and production volume can result in a higher environmental impact, such as carbon emissions, water usage, or land utilization. Feedback loops: Competitive forces drive more investments in hydrogen production, potentially leading to a self-reinforcing cycle of escalating competition and resource consumption. Sustainability challenges: The rapid escalation can create sustainability challenges, making it difficult to achieve long-term sustainability goals in hydrogen production and utilization.
Tragedy of the Commons	This archetype detects the causal connections between agent actions and their collective results in a closed system. The total usage of a common resource starts to be too great for the system to support, then the commons will be overloaded and every agent will experience diminishing benefits.	Shared resources: Certain resources essential for hydrogen production, such as water, energy, and critical materials, are shared among multiple stakeholders in the hydrogen industry. Overuse and depletion: The lack of effective management, regulations, or limitations on resource use can lead to the overuse and depletion of these shared resources by individual stakeholders. Environmental impact and sustainability challenges: This overuse can result in water scarcity, increased energy consumption, and damage to ecosystems, which may compromise sustainability goals.

4.2. Linking System Archetypes with sustainable hydrogen production (Stage 2)

After analyzing the 3P model, it is important to develop a bridge between this approach and the sustainability of the energy sector (with a relevant focus on hydrogen) using precisely the tools that this idea offers. One of these tools is the System Archetypes (SAs), therefore, in this section, these SAs are seen from a hydrogen sustainable production perspective considering complex concerns. Table 3 provides a guideline for understanding and applying the SAs in the context of sustainable hydrogen production.

4.2.1. Fixes that fail archetype

The "Fixes that Fail" archetype (in the context of energy-sustainable production) leads to a situation where the industry becomes increasingly unsustainable and environmentally damaging. The continued use of symptomatic solutions can hinder progress toward more sustainable production pathways including the use of renewable energy sources, advanced production technologies, and carbon capture and storage methods. In order to consider this archetype in the context of the 3P model, it is essential for stakeholders to recognize the long-term consequences of symptomatic solutions, and prioritize investments and policies that support a cleaner energy production transition. In the end, balancing short-term energy needs with long-term sustainability goals is crucial for mitigating the "Fixes that Fail" dynamic.

4.2.2. Shifting the Burden archetype

The “Shifting the Burden” archetype is linked with the preference for using fossil fuels for hydrogen production (because of immediate availability), despite the negative environmental impact. This can delay the transition to a more sustainable approach that relies on renewable energy sources or low-carbon production methods. In order to address this archetype it is important to recognize the long-term benefits of sustainable solutions and develop strategies and policies that promote their adoption.

4.2.3. Growth and Underinvestment archetype

The “Growth and Underinvestment” archetype in hydrogen sustainable production can lead to a situation where the rapid growth of the hydrogen industry outpaces the necessary investments in sustainable production methods and infrastructure. This can result in continued reliance on less sustainable production methods, hindering progress toward a fully sustainable hydrogen production system. To address this archetype, it is essential for stakeholders to anticipate and plan for the necessary investments in sustainable production technologies and infrastructure to keep up with the industry’s growth. This involves creating a supportive policy environment, incentivizing research and development, and aligning economic factors to make sustainable hydrogen production methods more competitive and cost-effective.

4.2.4. Limits to success archetype

The “Limits to Success” archetype can lead to a situation where the transition to sustainable methods reaches certain inherent limits. This results in continued reliance on less sustainable methods to meet energy needs, which delays progress toward a fully sustainable hydrogen production system. In order to address this archetype, it is essential to recognize the potential constraints early in the transition process. Some strategies can be directed to diversifying sustainable production sources, investing in research to overcome resource constraints, and working with regulators to create a supportive policy environment that encourages sustainable hydrogen production despite potential limitations. Additionally, this archetype highlights the importance of proactive planning and adaptation as the hydrogen industry scales up its sustainable production efforts to avoid reaching insurmountable constraints.

4.2.5. Drifting Goals archetype

The “Drifting Goals” archetype can lead to a situation where the industry’s focus shifts away from its original sustainability aims. This may result in reduced emphasis on sustainable production methods and a potential increase in the use of less sustainable pathways. To address this archetype it is crucial to regularly reassess and reaffirm sustainability goals and priorities within the industry. This can involve continued investments in research and development of sustainable production technologies, as well as fostering a supportive policy environment that maintains a focus on sustainability despite evolving technology and priorities.

4.2.6. Success to the successful archetype

The “Success to the Successful” archetype in hydrogen sustainable production can lead to a situation where established and successful hydrogen production methods maintain their dominance, while innovative and sustainable methods struggle to gain a foothold. This can potentially hinder the transition to more sustainable hydrogen production, even when such methods offer environmental benefits and long-term sustainability advantages. To address this archetype it is important to develop an environment that supports innovation and emerging sustainable technologies. This can include directing resources and incentives toward research and development in sustainable methods, fostering collaboration between industry stakeholders, and aligning policies and regulations with sustainability goals.

4.2.7. Escalation archetype

The “Escalation” archetype in hydrogen sustainable production can lead to a situation where the industry experiences heightened competition, resource consumption, and environmental impacts, potentially hindering progress toward long-term sustainability objectives. To address this archetype, it is important to encourage cooperation and coordination among industry stakeholders, regions, and nations to manage resource consumption and mitigate potential environmental impacts. This can involve setting standards, regulations, and agreements that promote sustainable practices and resource efficiency. Overall, recognizing the potential for escalation and its consequences is essential for ensuring that the rapid growth of the hydrogen industry is managed in a way that aligns with long-term sustainability goals. Therefore, balancing competition with sustainability is crucial for the industry’s success in providing clean and sustainable energy solutions.

4.2.8. Tragedy of the commons archetype

The “Tragedy of the Commons” archetype can lead to a situation where resources are overused or depleted, causing negative environmental impacts and sustainability challenges. This can potentially hinder progress toward long-term sustainability objectives. To address this archetype it is essential to establish effective resource management, regulations, and agreements among industry stakeholders and governments. These measures can ensure that shared resources are used in a sustainable and equitable manner, safeguarding the environment and the long-term viability of the hydrogen industry. Recognizing the

Table 4
Causal Loop Diagram and Forrester diagrams related to the sustainability of the energy sector reported by the literature.

No.	Title	Aim	Reference
01	Hydrogen vehicle-infrastructure	To model the simple relationship between complementary goods in a vehicle-fueling station	Meyer and Winebrake (2009)
02	The Bass diffusion model	Creating a model for predicting the timing of initial purchases of new products.	(Bass, 1969; Meyer and Winebrake, 2009; Sterman, 2002)
03	Hydrogen Vehicle and Infrastructure Simulator for Integrated and Operational Transportation Networks (H_2 VISION)	To simulate the diffusion paradigm related to H_2 Fuel Cell Vehicles and refueling infrastructures.	Meyer and Winebrake (2009)
04	The CLD of the Australian energy sector	Designing a conceptual model of the energy sector. Analyzing the potential consequences of current energy development policies using the model. Offering suggestions for improving policies towards sustainable energy development.	Laimon et al. (2022)
05	Modeling the development of the Green Hydrogen industry in China under diverse subsidy scenarios.	Simulating the development of the Green Hydrogen industry in China while considering various subsidy scenarios.	Li et al. (2022)
06	Coordinated Development Capacity (CDC) of China’s hydrogen energy industry chain	Simulating the CDC of the hydrogen energy industry chain in China from 2016 to 2030.	Gao and An (2022)
07	Hydrogen energy (Australia and Global)	To model the hydrogen energy system.	Yusaf et al. (2022)
08	System dynamics model for Green Hydrogen industry development	To study the policy impact under different terminal demand scenarios in China.	Yang et al. (2023)

potential for this archetype and implementing appropriate resource management strategies is crucial for maintaining a balance between resource use and sustainability.

Applying System Archetypes to hydrogen sustainable production can help stakeholders anticipate and address sustainability challenges by identifying underlying dynamics, avoiding common pitfalls, and promoting systemic solutions. By leveraging these insights, stakeholders can enhance the sustainability of hydrogen production practices and contribute to a more resilient and equitable energy transition. Additionally, SAs aim to identify feedback loops, facilitate stakeholder dialogue, and design resilient policies and strategies.

Overall, these archetypes provide a guideline for decision-makers to consider hidden effects and unintended consequences linked with the sustainability of the energy sector. In this way, the 3P approach offers the opportunity to deeply look inside sustainable hydrogen production considering complexity from a Systems Thinking perspective.

4.3. Causal Loop Diagrams (CLDs) and system dynamics (SDs) related to the sustainability of the energy sector (Stages 3–4)

After analyzing how System Archetypes can bring a huge advantage in the use of the 3P model, it is time to explore which CLDs and SDs were already proposed in the literature. From these, the most relevant feedback loops were chosen and linked to sustainable hydrogen production.

A review of the developed CLDs linked with the sustainability of the energy sector is reported by the literature is shown in Table 4. An extended version of this table can be found in the Supplementary Materials.

The most relevant feedback loops were taken from those studies and connected to hydrogen sustainable production. Table 5 shows the feedback loops integrated into the model.

4.4. An integrated CLD for hydrogen sustainable production (Stage 5)

Based on the previous CLDs developed in the aforementioned research, an integrated CLD for achieving hydrogen-sustainable production is proposed. The proposed CLD (Fig. 7) has a core which consists of the following variables: (1) economic growth, (2) environmental sustainability, (3) social acceptance, (4) energy safety, and (5) effectiveness of government policies. In general, this integrated CLD captures the interdependencies among sustainable hydrogen production and: (1) Economic-social relations, (2) reliability of intermittent RE sources, (3) fuel cell pathways, (4) environmental sustainability of fuel cell pathways, (5) advantages of hydrogen as a net-zero fuel, (6) emissions, (7) economic growth of non-renewable and renewable energy, (8) capacity bankruptcy, (9) market supply and demand, (10) energy insecurity, (11) energy production capacity (EPC), (12) capacity-social relationships, (13) environmental-investment relations, (14) environment-emissions relations.

Fig. 8 shows the causes tree of the variable Hydrogen Sustainable Production (H_2 Sust. Prod.) obtained using Vensim. Causal Tracing proves to be a potent tool for navigating through a model, identifying the factors responsible for driving changes. It illustrates the main factors directly related to the sustainability of hydrogen production such as the economic profits, the effectiveness of government policies, energy safety, environmental sustainability, investment in renewable energy, and social acceptance. Simultaneously, the main variables linked to these aforementioned factors are exposed.

After building the new conceptual CLD model for sustainable hydrogen production as a case study considering the feedback loops reported in the literature (Table 5) for the sustainability of the energy sector, 216 loops are identified (starting with the variable H_2 Sust. Prod). This quantity is significantly larger than the reported in previous studies. This is due to the fact that when the interdependencies are considered (among the economy, the environment, and the society), the complexity of this system emerges, and therefore, more reinforcing and

Table 5
Feedback loops integrated in the CLD model.

No.	Loop name	Feedback loop	Meaning	Impact on hydrogen sustainability
01	R1	H_2 Sustainable Production (SP) — + Economic growth — + Jobs — + Social Acceptance — + H_2 SP	Economic-social interdependency	Potential for a self-reinforcing cycle where sustainable hydrogen production not only contributes to economic growth and job creation but also strengthens social acceptance and further investment in sustainable practices.
02	R2	H_2 SP — + Integration with other RE sources — + Reliability of intermittent RE resources — + Investment in RE — + H_2 SP	RE integration reliability	Potential for a mutually reinforcing relationship between sustainable hydrogen production and renewable energy sources. By integrating hydrogen production with other renewable energy systems, improving reliability, and increasing investment in renewable energy infrastructure, the sustainability of hydrogen production can be enhanced, further promoting the transition to a cleaner and more sustainable energy system.
03	R3	Fuel cells pathway — + Zero emission pathway — + The adoption of H_2 as a net zero fuel — + Fuel cells pathway	Fuel cells pathway advantages	Reinforcing cycle where the adoption of hydrogen fuel cells, coupled with the recognition of hydrogen as a net-zero fuel, contributes to sustainability by providing a zero-emission energy pathway. This supports efforts to mitigate climate change, reduce air pollution, and transition towards a more sustainable energy future.
04	R4	Environmental sustainability — + Fuel cells pathway — + Zero emission pathway — + Environmental sustainability	Relation of fuel cells with environmental sustainability	By prioritizing sustainable production methods and promoting zero-emission technologies, hydrogen plays a vital role in mitigating climate change, reducing air pollution, and advancing environmental conservation efforts.
05	R5	Environmental sustainability — + The adoption of H_2 as a net zero fuel — + Environmental sustainability	Sustainable adoption of H_2 as a net zero fuel	
06	B1	Environmental sustainability — + Fuel cells pathway — + Zero emission pathway — -	Interdependencies among fuel cells, emissions and environmental sustainability	By prioritizing policies and investments that encourage emissions reduction and promote clean energy

(*continued on next page*)

Table 5 (*continued*)

No.	Loop name	Feedback loop	Meaning	Impact on hydrogen sustainability
		Emissions — + Environmental deterioration — + Policy encouraging reduction in emissions — + Investments in RE — + Environmental sustainability		technologies, it is possible to mitigate environmental degradation and advance toward a more sustainable future.
07	R6	New non- RE capacity — + Economic growth — + Energy production capacity — + New non-RE capacity	Non-RE capacity relation with the economic growth	Balancing economic growth with environmental sustainability requires careful consideration of transitioning towards cleaner and more sustainable energy sources such as renewable energy and implementing energy efficiency measures.
08	R7	Energy Production Capacity (EPC) — + New RE capacity — + Economic growth — + EPC	New RE capacity relation with the economic growth	To capture the interconnectedness of energy production capacity, market dynamics, economic growth, and their implications for hydrogen production sustainability. Balancing the expansion of renewable energy capacity with market stability and demand-side considerations is crucial for promoting sustainable energy systems and accelerating the transition towards a low-carbon economy.
09	B2	EPC — + Capacity bankruptcy — - EPC	Capacity bankruptcy	
10	R8	EPC — + Supply — - Market price — - Demand — + EPC	EPC relation with market supply and demand	
11	R9	Energy insecurity — + Effectiveness of government policies (EGP) — + Energy dependency — + Risk of supply disruptions — + Energy insecurity	Energy insecurity relations	The importance of effective government policies, investment in renewable energy, and diversification of energy sources in promoting energy security and sustainability, including in the context of hydrogen production. By addressing energy insecurity through strategic policies and investments, countries can mitigate risks, enhance resilience, and accelerate the transition to a more sustainable energy future.
12	R10	Energy insecurity — + EGP — + Supply — + Gas exports — + Energy insecurity	Energy insecurity relation with gas exports	
13	B3	Energy insecurity — + EGP — + Supply — - Energy insecurity	Energy insecurity relation with energy supply	
14	B4	Energy insecurity — + EGP — + Investment in RE —(delay)— + EPC — -Energy insecurity	Energy insecurity relation with EPC	
15	B5	Energy insecurity — + EGP — + Investment in RE —(delay)— - Demand — + Energy insecurity	Energy insecurity relation with energy demand	
16	R11	Emissions — + Environmental deterioration — + Policies encouraging reduction in emissions — + Investments in RE — + EPC — + Combustion pathway — + Nitrogen oxides — + Emissions	Emissions relations with investments in REB	The importance of policies encouraging emission reduction, investments in renewable energy, and the development of sustainable energy production pathways to mitigate environmental deterioration and promote hydrogen production sustainability. By prioritizing cleaner energy technologies and reducing emissions associated with hydrogen production processes, countries can advance towards a more sustainable and environmentally friendly energy future.
17	B6	EPC — + Combustion pathway — + Nitrogen oxides — + Risk of adoption of hydrogen as a combustion fuel — - EPC	Risk of adoption of hydrogen as a combustion fuel relation with the EPC	Potential trade-offs and challenges associated with using hydrogen in combustion pathways. While hydrogen offers the potential for clean combustion and reduced greenhouse gas emissions, the formation of NOx and other pollutants presents a significant challenge to its widespread adoption. Balancing the benefits and risks of using hydrogen in combustion processes requires careful consideration of emission control technologies, regulatory measures, and technological advancements to ensure sustainable hydrogen production and utilization.
18	R12	EPC — + Employment opportunities — + Immigration — + Population — + Demand — + EPC	Capacity-social interdependencies	This feedback loop illustrates how the expansion of energy production capacity can stimulate economic growth, attract immigrants, and contribute to population growth, which in turn drives up energy demand and reinforces the need for further expansion of EPC. However, it's essential to consider the sustainability

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Table 5 (*continued*)

No.	Loop name	Feedback loop	Meaning	Impact on hydrogen sustainability
				implications of this cycle, including environmental impacts, resource depletion, and the transition to cleaner energy sources, to ensure long-term energy security and environmental stewardship.
19	R13	Net CO_2 emissions — + Atmospheric Green House Gases concentrations — + Global warming — + Impacts — + Concerns — + Policy encouraging reductions in CO_2 emissions — + Investment in RE — + Uncertainty unfulfilling demand growth — + Inversion in non-RE — + Net CO_2 emissions	Environmental-investment interdependencies	These feedback loops underscore the complex interactions between CO_2 emissions, climate change impacts, policy interventions, investment decisions, and uncertainties in shaping the sustainability of hydrogen production and the broader energy system. Achieving long-term sustainability requires concerted efforts to reduce CO_2 emissions, transition to renewable energy sources, and address concerns about climate change through informed policies, strategic investments, and international cooperation.
20	B7	Net CO_2 emissions — + Atmospheric Green House Gases concentrations — + Global warming — + Impacts — + Concerns — + Policy encouraging reductions in CO_2 emissions — + Investment in RE — - Net CO_2 emissions	Environmental-investment relations	
21	B8	Net CO_2 emissions — + Atmospheric Green House Gases concentrations — + Global warming — + Impacts — + Concerns — + Policy encouraging reductions in CO_2 emissions — - Net CO_2 emissions	Environmental-emission relations	

balancing loops appear. This proves that the newly proposed three-paradigm model is able to capture the complexity of the energy sector (as a complex system considering hydrogen sustainable production as a case study) using a system-thinking approach (a list of all the loops can be found in the Supplementary Materials).

Fig. 9 shows the relationship between the length of each loop and the absolute frequency of each length. The average is around 13, which means that around 27% of the variables are involved in each loop by average. However, the length range is wide between 3 and 24, having 9, 14, and 15 lengths the highest frequencies.

This CLD is only the first step in applying the 3P approach to understanding the complex interrelations of sustainable hydrogen production with society, the economy, and the environment.

4.5. System dynamics-based model for hydrogen sustainability and their evolution in the 3P approach framework (Stage 6)

In order to address the complexity that emerged from the interconnected system for hydrogen sustainable production and applications, SD-based models are developed. Fig. 10 shows the first two models considering Hydrogen Production (H2P main stock) from Sustainable Sources (inflow) and Fossil Fuels (inflow). The production of other energy ways (not linked to hydrogen) for meeting the global energy demand, is the way of decreasing the stock H2P.

The first model (SD1) is proposed only considering the hydrogen production from different sources (distinguishing between fossil fuel and sustainable sources). After that, SD2 contains additionally, the environmental impact of each source on the hydrogen production. For this purpose, the stock Environmental Impact (EI) is connected to the previous model, considering the carbon emissions as an inflow and the environmental management for zero emissions target as the outflow.

The carbon emissions rate is increased by the hydrogen production from fossil fuels and the energy produced from other sources (non-sustainable). For closing these loops, the environmental impact leads to a decrease in hydrogen production from fossil fuels and other energy sources and an increase in hydrogen production from sustainable sources after a given time (delays).

For considering other relevant parameters in the 3P framework, a third SD model is developed (SD3). Fig. 11 shows the SD for hydrogen production considering the following parameters as stocks:

- ➢ Environmental Impact (EI).
- ➢ Sustainable Production Technology Development (SPTD).
- ➢ Economic Viability (EV).
- ➢ Public Awareness (PA).
- ➢ Government Policies and Incentives (GPI).

The model SD3 contains the main feedback loops of the developed CLD translated to the structure of a Forrester Diagram (or System Dynamics model). This model contains the loops and delays reported in the previous ones such as the environmental impact interdependencies. In addition, hydrogen production will lead to economic viability (EV) improvements and a part of this profit can be used for sustainable production technology development after a given time (considering a delay). These new technologies will lead to better environmental management, decreasing the environmental impact, which directly affects the different shades of hydrogen production. At the same time, part of the profits can be used for CCS implementation, which decreases carbon emissions, being this a balancing factor for producing hydrogen from fossil fuels using this technology. Furthermore, the environmental impact will increase public awareness, which directly influences government policies and incentives for moving towards more environmentally friendly solutions. However, investment can be made in more CCS technology, supporting the production of hydrogen from fossil fuels. This is not a contradictory policy in the short-term, because this can lead to the hydrogen to a better hydrogen penetration for producing more GH in a long-term perspective.

The development of CLDs, SD, and SAs provides a deeper understanding of the sustainability of the energy sector due to the inclusion of complex issues such as feedback loops, special patterns, accumulation (by using stocks), and delays. The main advantage of this integration regarding the existing approaches (such as Yusaf et al., 2022; Yang et al., 2023) is that the complexity linked to sustainability is captured. For

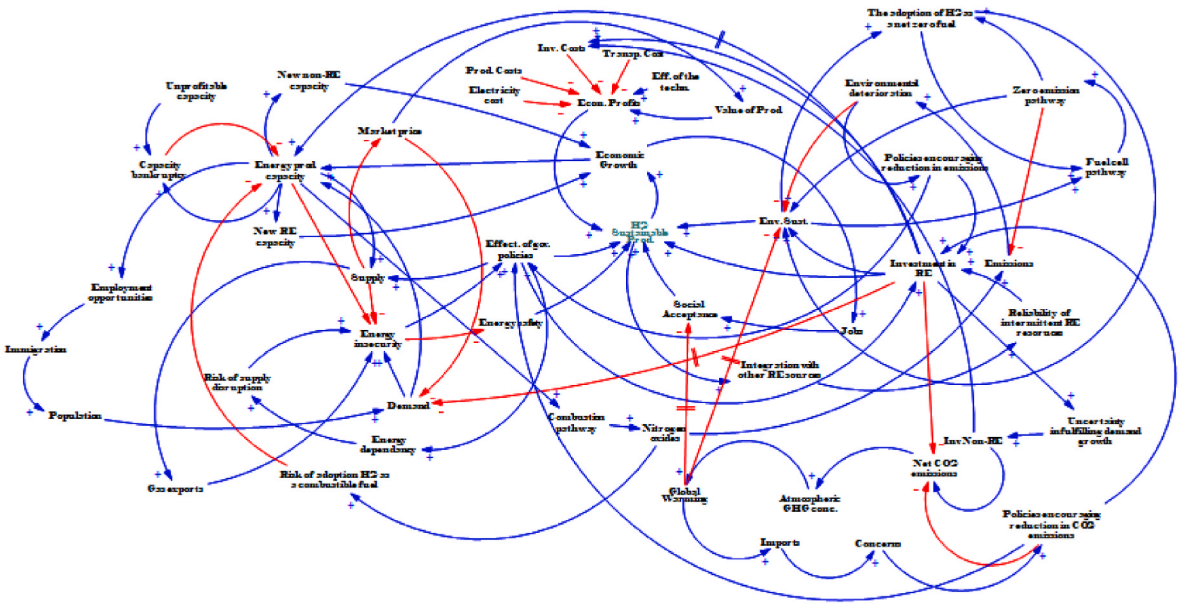

Fig. 7. Integrated CLD for hydrogen sustainable production.

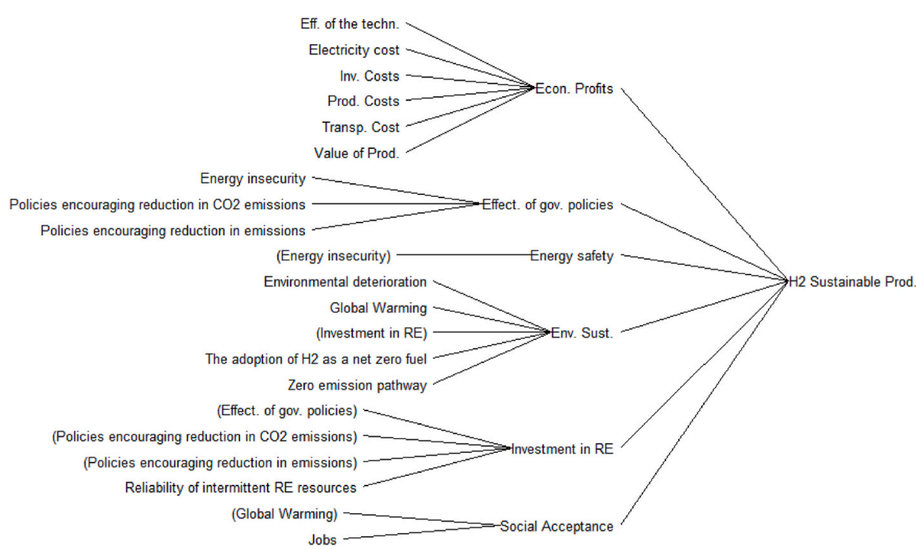

Fig. 8. Causes tree for hydrogen sustainable production.

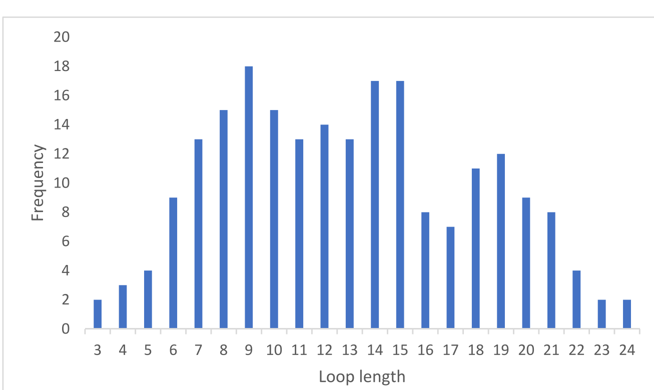

Fig. 9. Relationship between the loop length and absolute frequency.

policymakers, this represents a huge advantage as the decision-making process performed from the previously developed models is based on the consideration of complex characteristics and long-term (essential for sustainability).

Hence, the 3P approach gives the opportunity to explore the complex interdependencies among the economy, the environment, and the society from an holistic perspective, for achieving sustainability through a Systems Thinking approach. To sum up the main outlines of this research, Fig. 12 shows how the 3P model has been applied to the hydrogen sustainability.

After finding in the literature the main causalities and feedback loops a new CLD model is built by connecting the economic, societal, political, and environmental interdependencies all together in the same model. Next to these connections, the number of feedback loops were increased from 21 to 216, due to the emerged complexity linked with the sustainability itself. For addressing this complexity, the model is split into system dynamics-based models (by increasing complexity) using the proposed 3P. This can be used for decision-making and to get effective

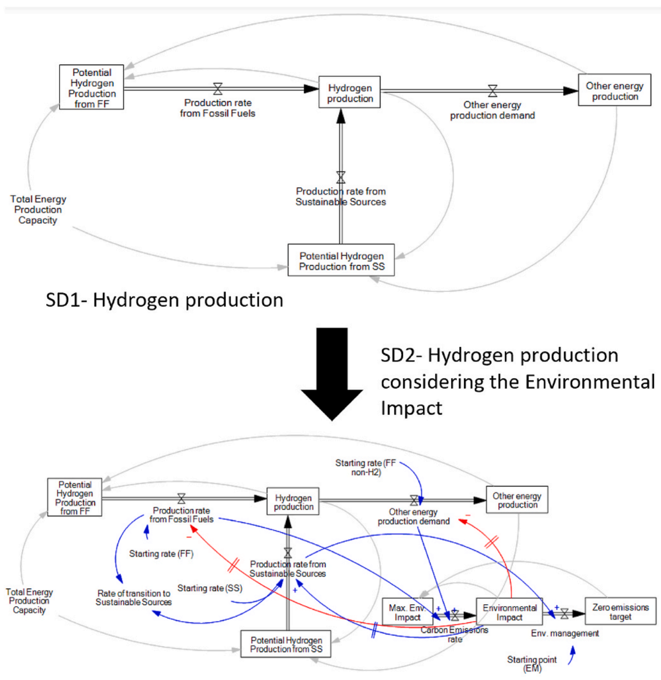

Fig. 10. SD-based models (SD1 and SD2) for hydrogen production.

long-term policies.

4.6. Future research and challenges (Stage 7)

In this research, a new 3P model is presented for achieving sustainable energy production addressing complexity and using a Systems Thinking approach. There are limitations of the current approach that were previously discussed, and new questions or gaps to be solved in future research as the following:

1. As subjectivity could influence the development of models, the combination of the 3P perspective with tools can allow the computation of subject criteria of different experts (such as Fuzzy logic or others).
2. The integration of the 3P model into a Risk Assessment-Safety Management framework for the process industries.
3. To identify which variables can be directly controlled, and their influence on the whole complex system.

Additionally, there are still concerns about the sustainability of the energy sector and in that regard, it is proposed:

1. To extend the proposed 3P model to other fuels in the energy sector such as natural gas, fossil fuels, methanol, ammonia; and other renewable and non-renewable energy production pathways; as well as their coexistence or integration in order to predict which solutions or combinations would be certainly effective in the long-term.
2. To simulate the proposed models using real data for decision-making purposes.
3. To develop a new sustainability indicator considering the 3P approach and to compare it with current sustainability indicators.

These aforementioned open research lines will be addressed in an upcoming research paper.

4.7. Implications for theory and practice on cleaner production and sustainability

The link between this research (which proposes a new three-paradigm integrating the Systems Thinking approach, the complexity theory, and sustainability) with cleaner production lies in their shared focus on holistic and interconnected perspectives for guaranteeing accurate long-term solutions to economic, environmental, and social challenges. Using a Systems Thinking approach involves considering hydrogen production and applications as a part of a larger interconnected complex system. It takes into account the interdependencies and feedback loops within the energy sector, considering the environmental, social, and economic aspects. Therefore, applying Systems Thinking in the context of energy production can lead to a more comprehensive understanding of the potential impacts and benefits; for instance, it can help identify opportunities for integrating renewable energy sources in hydrogen production, optimizing distribution networks, and designing sustainable hydrogen-powered applications.

Additionally, the theory and practice of cleaner production and

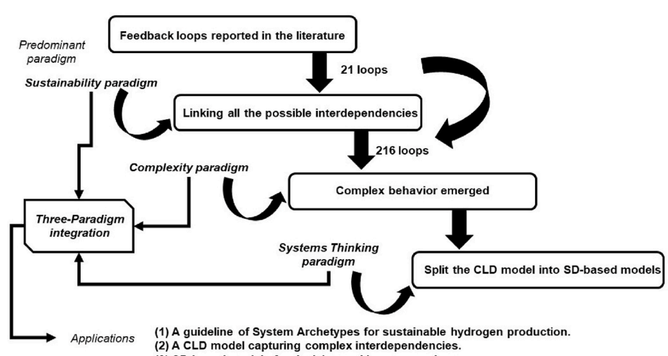

Fig. 12. Flowchart of the application of the Three-Paradigm approach to the hydrogen sustainability.

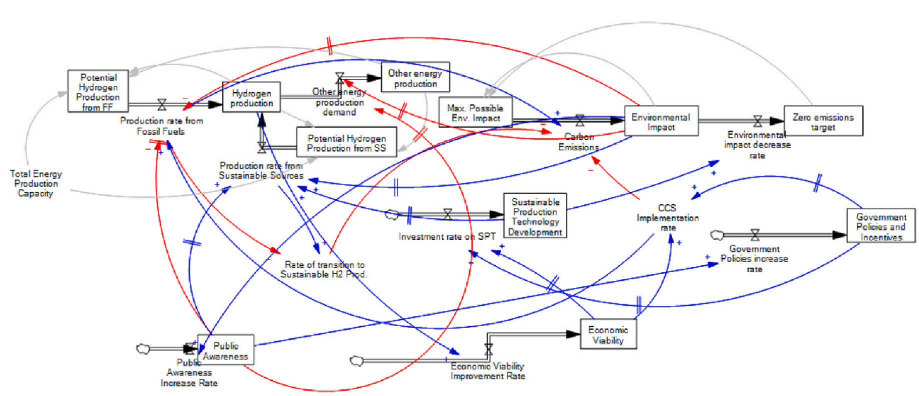

Fig. 11. SD3 for hydrogen production considering the evolution of the model.

sustainability encompass a wide range of strategies to reduce environmental pollution and promote sustainable development. It involves adopting cleaner and more efficient processes, minimizing waste, and integrating renewable resources. Moreover, understanding the interconnectedness of hydrogen systems can lead to innovative solutions that align with broader sustainability goals. Hence, this research allows for a more comprehensive and integrated perspective on the challenges and opportunities associated with hydrogen utilization, which promotes more informed decision-making, and strategic and adaptive management across the energy sector.

5. Conclusions

A new Three-Paradigm (3P) model using a Systems Thinking approach for addressing Complexity linked to Sustainability is proposed. For this purpose, an integrated seven-stage approach is introduced which explores from the starting point of the integration of paradigms to the application of this integration to sustainable hydrogen production. New models are developed which can help to gain an understanding of the complex interdependencies linked to the sustainability of the energy sector and to develop a future decision-making approach using the 3P model.

A new Causal Loop Diagram (CLD) was developed for sustainable hydrogen production considering complex interdependencies among economic, environmental, and societal aspects. The complexity associated with sustainability led to an increase in the number of feedback loops from 21 to 216. The core of the newly developed model is the relations among economic growth, environmental sustainability, energy safety, social acceptance, the effectiveness of government policies, and hydrogen-sustainable production. Hence, the 3P approach allows exploring the complex interdependencies among the economy, the environment, and the society from a holistic perspective, for achieving sustainability through a Systems Thinking approach, being the first stage of application of the 3P approach.

Moreover, System Archetypes (SAs) were introduced in the context of sustainable hydrogen production and applications. System Dynamics-based models were developed to capture the evolution of a simple model (for hydrogen production) using the 3P approach considering the multiple and complex interactions identified in the CLD. In general, regarding the application of the 3P model to hydrogen sustainable production, this research offers (1) a guideline of System Archetypes for sustainable hydrogen production, (2) a CLD model capturing complex interdependencies, and (3) SD-based models for decision-making approach.

Overall, the real effectiveness of different policies for sustainable development will mostly depend on how these policies or interventions were developed, and in this sense, the 3P approach offers a holistic pathway for achieving efficient long-term solutions by considering complex interdependencies. The newly proposed 3P model can capture the complexity of the sustainability of the energy sector using a Systems Thinking approach.

CRediT authorship contribution statement

Julio Ariel Dueñas Santana: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Almerinda Di Benedetto:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Orelvis González Gómez:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Ernesto Salzano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, 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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.141751.

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