Applied Energy 377 (2025) 124616

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Market diffusion of Power-to-X fuels in Germany: A cognitive approach with robust reasoning for policy support

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ARTICLE INFO

Keywords:
Power-to-X fuels
Energy transition
Fuzzy Z-numbers
Fuzzy cognitive mapping
Market diffusion

ABSTRACT

The European Union has set the target to reduce greenhouse gas (GHG) emissions by 55% by 2030 (compared to 1990) and to achieve climate neutrality by 2050. While GHG emissions have fallen in most areas, efforts to reduce them in transport have been largely unsuccessful. Power-to-X (PtX) fuels are renewable fuels with significant potential to reduce emissions in parts of the transport sector that are not well suited for electrification. However, the market diffusion of PtX fuels is a complex process influenced by multi-dimensional factors. Overcoming these complexities requires a comprehensive approach in order to improve the governance dynamics of the regulatory framework. To systematically analyze the diffusion of PtX fuels, a cognitive approach based on Fuzzy Cognitive Mapping (FCM) is developed and enhanced using the extended Z-numbers theory. The extended Z-numbers theory provides a realistic and robust reasoning framework for decision analysis in complex systems by involving decision makers to determine the interrelationships in the FCM and experts to evaluate the decision makers' opinions. A case study is conducted to investigate the market diffusion of PtX fuels in the German transport sector from a system perspective. Extensive sensitivity analyses are performed to understand the system's behavior under different scenarios. The results indicate a high importance of cross-sectoral factors influencing the complex diffusion of PtX fuels.

1. Introduction

1.1. Climate goals and Power-to-X fuels

As a result of key European legislation such as the Fit for 55 package and the European Union (EU) Green Deal, two key targets have been set: to reduce greenhouse gas (GHG) emissions by 55% by 2030 and to achieve climate neutrality by 2050 [1–3]. In line with the EU, in Germany, even more ambitious targets were officially included in the Climate Action Plan, mandating a 65% reduction in GHG emissions by 2030 and achieving climate neutrality by 2045 — five years ahead of the EU's target [4]. According to the German Environment Agency (Umweltbundesamt), most sectors have progressed in decreasing their GHG emissions compared to 1990 [5]. However, the transport sector has recorded the most modest decrease, falling short of meeting the previous objectives over the past three decades. As the transport sector is responsible for almost a fifth of GHG emissions, it causes significant energy and climate-related problems and thus presents an ongoing challenge to the German government's emissions reduction efforts [6,7]. In this context, the dependence on fossil fuels, in particular oil, is one of the biggest challenges for the sector, contributing significantly to current GHG emissions. In addition to high GHG emissions, Germany's reliance on non-renewable energy sources and the related import dependency makes it more vulnerable to supply disruptions and price instability caused by external geopolitical events [8].

To reduce GHG emissions, renewable fuels are seen as future clean alternatives and have recently been included in the EU and national fuel planning frameworks [9,10]. Power-to-X (PtX) fuels, also known as e-fuels or electricity-based fuels, are viable fuel alternatives to reduce emissions in parts of the transport sector, especially those with low suitability for electrification, such as aviation and maritime [11–14]. PtX fuels are produced by converting electricity, preferably from renewable sources, water and carbon (as well as bio-based carbon feedstock) into various end products (X) as gaseous or liquid fuels. They hold great promise for the aviation and maritime sectors, given their ability to reduce GHG emissions without requiring major changes to the existing transport infrastructure and internal combustion engines in these sectors. This in turn reduces transition costs and increases acceptance [13].

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https://doi.org/10.1016/j.apenergy.2024.124616
Received 22 March 2024; Received in revised form 18 September 2024; Accepted 29 September 2024
Available online 23 October 2024
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Understanding the policy paradigm is essential to grasp the dynamics of the shift to PtX fuels in aviation and maritime. In this context, the Renewable Energy Directive (RED) III is a key policy within the EU and Germany, as it plays a major role in supporting the utilization of renewable energies [15,16]. The Fit for 55 Package identifies aviation and maritime as responsible for roughly 28% of GHG emissions in the EU transport sector. To improve the deployment of renewable fuels, the ReFuelEU Aviation and FuelEU Maritime were launched. The ReFuelEU sets a target of 2% sustainable aviation fuel (SAF) use by 2025 and 6% by 2030, which eventually should increase to 63% by 2050. Moreover, it urges a minimum share of 1.2% PtX fuels in aviation which increases eventually to 35% by 2050. On the other hand, the FuelEU Maritime aims for a 6% annual average carbon intensity reduction by 2030, increasing to 75% by 2050. To comply with the EU policies and national strategies, Germany develops the essential frameworks for successful deployment of PtX fuels in transport [17,18]. Meeting the long-term goals of climate neutrality, however will require further facilitated and optimized market diffusion of these fuels especially in selected hard-to-abate sectors.

1.2. Market diffusion of Power-to-X fuels

Market diffusion is the process by which a new product, technology or concept spreads throughout a market or society. Within the energy landscape, the need for environmentally sustainable and renewable energy sources has brought the market diffusion of fuels, particularly renewable fuels, into the spotlight in recent years [19–21]. Renewable fuels such as PtX fuels have become more widely used as a result of a variety of factors, including environmental concerns, social impacts, regulations, and technological breakthroughs [22–25]. In this context, the market diffusion of PtX fuels in aviation and maritime transport is a critical challenge considering the complexity of energy market dynamics as well as economic viability, scalability, and infrastructure limitations. The high cost of PtX fuels is a primary barrier to their adoption and diffusion, as it currently exceeds the cost of conventional fossil fuels, limiting their market attractiveness. However, as the price of renewable energy sources such as solar and wind continues to fall, the price of producing PtX fuels is expected to fall as well [26,27]. Government incentives and regulations are discussed as further options to reduce the price of PtX fuels and increase their market competitiveness. Given the high costs, currently PtX fuels are produced only on small scale. However, it is expected that larger scale PtX production facilities will emerge in response to technological developments and increasing demand for renewable fuels. PtX fuels are predicted to become more competitive in the marketplace as production scale increases and production costs decrease [17,28].

Aviation and maritime expect noticeable shares of renewable fuels, particularly PtX fuels, to mitigate their GHG emissions [13,17,29]. Therefore, facilitating the success of ongoing projects in commercializing PtX fuels requires a comprehensive consideration of the technical, regulatory, social, environmental, and economic dynamics that influence the market diffusion of PtX fuels. Such insights are significant for informed and strategic policy formulation. Thus, understanding the behavior of different factors in a complex system under different circumstances and by different stakeholders is of high significance to address major challenges related to the market diffusion of PtX fuels in Germany [30]. We thus propose a reliable and comprehensive approach to reflect the real-life circumstances in understanding how the diffusion process is influenced by various factors.

1.3. Contributions

To investigate the market diffusion of PtX fuels in a complex system, this study develops a cognitive approach by improving the traditional Fuzzy Cognitive Mapping (FCM) [31–33]. FCM is a well-known soft computing tool with system perspective for real-world strategic decision-making such as policy-making in non-linear complex and uncertain systems [34–37]. FCM builds a model based on the concepts and associated causal interrelationships to investigate behavior of different components under different scenarios. Empirical data is usually used as input for the FCM, which enables incorporating stakeholders. FCM uses fuzzy logic to consider the uncertainty in data provided by stakeholders [38]. Compared to other similar approaches such as system dynamics, FCM integrates qualitative expert knowledge with quantitative analysis through fuzzy logic, which enables handling the uncertainty and vagueness inherent in emerging technologies where empirical data may be limited. Moreover, FCM's visual and intuitive representation of causal relationships makes it accessible to a broad range of stakeholders, facilitating interactive scenario analysis and decision support. While system dynamics offers rigorous policy testing capabilities, its data-driven nature and complexity can be limiting when detailed data is scarce or when qualitative insights are necessary to be included.

Recently, Abbaspour Onari et al. [39] and Babroudi et al. [40] introduced a new version of FCM, where not only uncertain information was collected from decision-makers but decision-makers were also enabled to express the degree of certainty for their expressed information using Z-numbers [41] (ZFCM). Nevertheless, all of the previous versions of FCM have focused on the incorporation of decision-makers' opinions without considering internal and external experts or upper-level managers and policymakers as a way for data validation. In real-world cross-sectoral decision-making problems, decision-makers' opinions are subject to judgment of upper-level managers or key role-players in every organization. Consequently, employing either internal or external experts to assess the validity of the data provided by decision-makers can prove instrumental in generating promising solutions. To address this challenge, this study develops a novel FCM using the extended Z-numbers theory [42], where a two-step data collection is considered to collect decision-makers' opinions on the causal relationships along with the certainty degrees. Later, a group of experts are incorporated to reflect their judgments on the provided data by decision-makers. Using the developed approach, the market diffusion of PtX fuels is investigated for the German transport sector. To do so, technical, economic, social, environmental, and regulatory aspects are considered to examine their interrelationships on the diffusion process. Furthermore, extensive sensitivity analyses are conducted through various scenarios to understand the behavior of the model under different circumstances.

The contributions of this study can be summarized as follows:

- Developing a cognitive approach by extending the traditional FCM using the extended Z-numbers theory, where a group of experts are considered in the decision-making process to judge the information provided by decision-makers.
- Applying the developed approach to investigate the market diffusion of PtX fuels in Germany.
- Identifying the most critical factors affecting the market diffusion process under social, technical, regulatory, economic, and environmental perspectives.
- Investigating behavior of the identified factors with a system perspective under different scenarios.
- Proposing recommendations to support the market diffusion of PtX fuels in Germany.

The remainder of the paper is organized as follows. Section 2 presents a comprehensive literature review on the German and the EU legislation associated with renewable fuels, specifically PtX fuels, as well as applications of FCM for renewable fuels. The developed approach and its preliminaries are presented in Section 3. Context definition of the market diffusion problems is introduced in Section 4. Section 5 presents the results, followed by various scenario analyses. Managerial insights are discussed in Section 6. Finally, concluding remarks are provided in Section 7.

2. Literature review

2.1. Renewable fuels: Legal frameworks in Germany and the EU

The German policy framework for renewable energy adopts EU policies and proposes amendments based on national concerns. Several policies have been adopted in different contexts for different renewable fuels, including Renewable Fuels of Non-Biological Origin (RFNBOs) such as PtX fuels. In the context of PtX fuels, relevant policies directly affecting them are summarized in Table 1.

By 2030, key goals include significant reductions in GHG emissions (e.g., 65% by the German Climate Action Plan, 55% by the EU Green Deal) and increased use of renewable energy in transport (e.g., 42.5% in RED III, 2% renewable fuels in aviation). For the 2045 and 2050 targets in Germany and the EU, the focus shifts to achieving climate neutrality, with further advancements in zero-emission technologies and increased use of renewable hydrogen and fuels in sectors such as aviation and maritime. The policies highlight a strong push towards infrastructure development and research to support these goals.

While understanding the regulatory frameworks governing PtX fuels lays the foundation for examining their diffusion, suitable approaches from a systems perspective, such as FCM, are essential to capture the dynamics of diffusion within a complex system. FCM enables understanding how different factors influencing the diffusion actually interact and affect one another. In this way, it helps to gain insights into the dynamics of interplay of factors, making it a viable tool for decision-making in policy formulation for the diffusion of PtX fuels.

2.2. Applications of FCM for renewable fuels

Considering the efficiency of FCM in addressing complex systems with a high number of variables, it has been applied for various decision-making problems in the supply chain of renewable fuels. In one of the earliest applications of FCM for renewable fuels, Kontogianni et al. [43] investigated the market adaptation of low-carbon transport using hydrogen with participation of a lay group and experts from industry. Concepts for the FCM were collected from both groups where the lay people group provided 37 concepts, while experts defined 52 concepts. Later, individual FCM models were developed. Their results indicated that consumer information, social acceptance, private demand for hydrogen, and hydrogen use safety are the most important identified concepts.

Falcone et al. [44] investigated the policy mix related to sustainability transition in the biofuels sector in Italy using FCM considering various crisis scenarios. Several concepts were identified related to crisis, policy, and technical aspects. Public procurement, knowledge level in biofuels, investments and infrastructural subsidies, and tax relief and production incentives had the highest impact on other concepts. Konti and Damigos [34] used FCM to analyze the weaknesses and strengths of producing bioethanol from biowaste in Greece. A survey was conducted among 9 experts suggesting 65 concepts. The final FCM model was built on 28 most important concepts where legislation and political willing were found as the most crucial concepts. Falcone et al. [35] conducted a survey among 5 experts to analyze the networking dynamics of the Italian biofuels sector during crisis considering the policy mix. The study identified 19 main concepts for the production of biodiesel and bioethanol in various plants in Italy. In the following year, Falcone et al. [45] used FCM and social network analysis for policy formulation in liquid biofuels (first and second generations) in Italy. Naeini et al. [46] suggested an integrated approach based on strength-weakness-opportunity-threat (SWOT), step-wise weight assessment ratio analysis (SWARA), FCM and weighted aggregated sum product assessment (WASPAS) to investigate the development of third-generation biodiesel production from microalgae in Iran. A SWOT analysis was used to identify the critical factors affecting biodiesel production. Importance of the identified factors were determined by SWARA and FCM. Finally, WASPAS was applied to prioritize various potential strategies to promote the production of third-generation biodiesel.

While several studies have aimed to investigate the market adoption and diffusion of renewable fuels, there remains a notable gap, as no study has been dedicated to exclusively scrutinizing the market adoption and diffusion of PtX fuels from a system perspective. It is important to highlight that diverse methodologies have been employed in previous research to address this multi-dimensional challenge. As previously discussed, FCM has held a prominent position as a method for assessing the interplay of factors that influence the diffusion process within complex systems. Nonetheless, earlier versions of FCM have faced limitations in constructing a realistic environment capable of accurately capturing experts' judgments and decision-makers' viewpoints on causal relationships. For this purpose, this study improves the traditional FCM by providing a robust reasoning framework to build a FCM model and determine corresponding causal interrelationships. In this regard, an improved FCM is developed, where experts (upper-level managers, policymakers, or decision-makers with high experience) express their judgments over decision-makers' opinions in order to enhance the reliability of the data, build a more realistic FCM model, and therefore generate more reliable outcomes.

3. Methodology: FCM based on extended Z-numbers

Complex systems can be represented and analyzed using a form of decision support tool called FCM. As a development of the cognitive map, a network is used to show causal linkages between concepts that influence each other [31]. To model ambiguous or inaccurate causality between concepts and the weights assigned to them, FCM makes use of the fuzzy logic. FCM can aid in the understanding of the potential effects of various management or policy initiatives and is particularly beneficial for complex system analysis when several elements interact non-linearly. Considering its high applicability in real-world problems, FCM has been utilized in various fields such as renewable energy management [47], and climate change & environmental management [48, 49]. Within this context, the utilization of FCM presents an apt method for investigating the diffusion of PtX fuels through a systemic lens. This enables policymakers to gain a profound comprehension of the interplay among variables that influence real-world diffusion dynamics.

FCM is constructed using concepts that represent a system's components and causal relations that show interlinkage among the concepts. Fig. 1 represents a FCM model based on concepts C_i, and causal relationships denoted by w_{ij}, which shows causal relation between C_i and C_j with a value in range of [−1,1]. Three types of causal relationships are as follows:

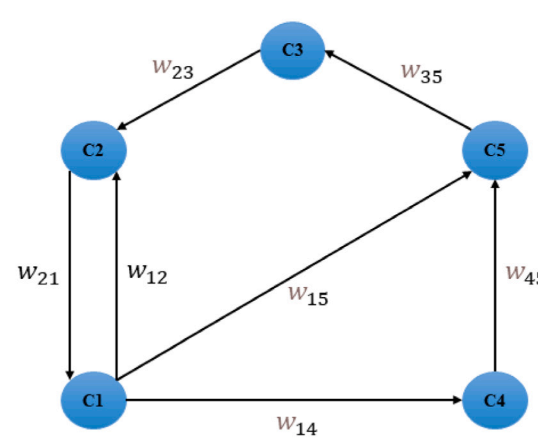


Fig. 1. An example FCM model based on C_i concepts and w_{ij} weights.

Table 1
A summary of relevant policies, policy packages and transport-related targets.

Policy	Measures for 2030	Measures for 2045 (2050 EU)
Climate Action Plan[DE]	– 65% GHG emission reduction compared to 1990. – Supporting PtX fuels through research & development project and governmental investments.	– Reaching climate neutrality.
EU Green Deal	– 55% decrease in GHG emissions. – A minimum of 30 million zero-emission cars and 80,000 lorries. – Increasing transport by maritime by 25%.	– Reaching climate neutrality. – Developing zero-emission aircrafts.
RED III	– Achieving at least a 42.5% share of renewable energy in the EU's final energy consumption. – A minimum of 29% share of renewables for transport sector. – Increase in share of RFNBOs by 5.5%. – A minimum of 1% share of RFNBOs in form of hydrogen.	–
AFIR	– Enhancing infrastructural capacities for recharging & refueling of hydrogen and renewable fuels.	–
ReFuelEU Aviation	– Minimum share of renewable fuels by 2%.	– Minimum share of renewable fuels by 63%.
FuelEU Maritime	– Reducing GHG emissions intensity by 6% (compared to 2020).	– Reducing GHG emissions by 75% (compared to 2020).
EU Hydrogen Strategy	– A minimum of 40 GW of renewable hydrogen electrolysers. – Increasing the production capacity to 10 million tons of renewable hydrogen (green hydrogen).	– Reaching technology maturity for large-scale development. – Necessity to increase share of renewable electricity due to its role in the production of green hydrogen. – Using hydrogen-based synthetic fuels, gaseous and liquid for aviation and maritime as well as urban buses and rail.
German Hydrogen Strategy[DE]	– Producing 90 to 110 TWh of hydrogen. – Creating a domestic market for hydrogen economy. – Devising a regulatory framework for hydrogen development & expansion. – Extending international partnerships to support hydrogen economy.	–
Renewable Energy Act (EEG)[DE]	– Increasing the share of electricity generation out of renewable sources by at least 80%.	–
National Platform for Future Mobility[DE]	– A minimum share of 21% share of renewable fuels including e-fuels. – Increasing national electrolysers capacity to 20 GW and importing 20 GW.	–
Mobility and Fuels Strategy[DE] (MFS)	– Increasing share of renewable energies for 18% of gross final energy consumption by 2020.	– Increasing share of renewable energies for 60% of gross final energy consumption.
PtL Roadmap for Aviation[DE]	– Utilizing a minimum of 200,000 tons of PtL Kerosene in aviation.	–
GHG Reduction Quota (37. BImSchV)[DE]	– Crediting of electricity-based fuels and processing biogenic oils on the GHG quota. – Gradual increase of the GHG quota to 25%. – Reducing share of 1st gen. biofuels, and gradual increase of the minimum share of advanced biofuels to 2.6%.	–

DE denotes German Policies.

- $w_{ij} > 0$ denotes positive causality between C_i and C_j. Positive causality means that increasing C_i causes the C_j to be increased by w_{ij},
- $w_{ij} = 0$ represents no relationship between C_i and C_j,
- $w_{ij} < 0$ shows negative causality between C_i and C_j. Negative causality means that decreasing C_i causes the C_j to be increased by w_{ij}.

Considering the uncertain nature of information provided by the decision-makers on the w_{ij}, Abbaspour Onari et al. [39] and Babroudi et al. [40] extended the traditional FCM using Z-numbers to consider the certainty (reliability) values for determining optimal w_{ij}. Although FCM under Z-numbers provides more flexible and well-grounded environment for decision-makers to express their opinions on w_{ij}, the credibility of the expressed information by decision-makers still can be biased and subjective. For this purpose, this study presents a novel extension of FCM using the extended Z-numbers theory, which improves the decision-making environment by including judgments of an expert group on the information provided by the decision-makers.

The term Z-number refers to a pair of fuzzy numbers with the denotation $Z = (A, B)$, where the A component denotes the variable of the fuzzy restriction of the domain X and the B component denotes a reliability assessment of A via triangular fuzzy numbers (TFNs) [41, 50,51]. The fuzzy restriction $R(X) : X$ is A is a probabilistic constraint, which indicates the possible distribution based on Eq. (1).

$$R(X) : X \quad \text{is} \quad p \rightarrow \text{Prob}(u \leq x \leq u + du) = p(u)du \tag{1}$$

Components A and B are linked through a hidden probability according to Eq. (2).

$$\sum_{i=1}^{n} \check{V}_A(x_i) p_{x_A}(x_i) \rightarrow b_i \tag{2}$$

To calculate the fuzzy number, the reliability component is first converted to a real number via Eq. (3) and later multiplied to component A.

$$\beta = \frac{\int x \check{V}_B dx}{\int \check{V}_B dx} \tag{3}$$

Tian et al. [42] highlighted the potential subjectivity of reliability values expressed by decision-makers for a real-life complex decision-making problem. Therefore, Tian et al. [42] extended the traditional Z-numbers using a voting method for a group of experts based on Eq. (4).

$$\zeta = ((A, B), E) \tag{4}$$

where $E = (Y, N, \mu)$ and Y denotes the number of experts who agree with evaluated Z-numbers, N indicates the number of experts who disagree with the provided reliability values by decision-makers, and μ

Table 2
Linguistic terms for causal relationships.

Linguistic term	TFN
Extremely Low (EL)	(0, 0.1, 0.2)
Very Low (VL)	(0.1, 0.2, 0.35)
Low (L)	(0.2, 0.35, 0.5)
Medium (M)	(0.35, 0.5, 0.65)
High (H)	(0.5, 0.65, 0.8)
Very High (VH)	(0.65, 0.8, 0.9)
Extremely High (EH)	(0.8, 0.9, 1)

Aforementioned terms can be shown as negative and positive by adding N and P to the beginning of them such as NEL: negative extremely low, PH: positive high, and PM: positive medium.

Table 3
Linguistic terms for reliability parameter.

Linguistic term	TFN
Very Low Certainty (VLC)	(0, 0, 0.3)
Low Certainty (LC)	(0.1, 0.3, 0.5)
Medium Certainty (MC)	(0.3, 0.5, 0.7)
High Certainty (HC)	(0.5, 0.7, 0.9)
Very High Certainty (VHC)	(0.7, 1, 1)

shows the total number of experts who neither agree or disagree (neutral) with the provided reliability values by decision-makers. Using the collected judgments of the experts, new reliability values are calculated as Eqs. (5)–(6).

$$Q = \begin{cases} b_i^* = b_i(1+R), & R < 0 \\ b_i^* = b_i, & R = 0 \\ b_i^* = 1-(1-b_i)(1-R), & R > 0 \end{cases} \tag{5}$$

where b_i^* is the modified reliability value, and R can be determined as follows.

$$R = \frac{Y-N}{n-\mu} \tag{6}$$

where n denotes total number of the participants.

Based on the definitions of the extended Z-number theory, an outline of the developed FCM using the extended Z-numbers is provided below.

Step 1. Construction of the FCM model by identifying relevant concepts and causal relationships based on a literature review, historical data, decision-makers, and experts.

Step 2. Determination of causal relationship values for each pair of concept as well as the type of the causal relationship (negative or positive) using the linguistic terms in Table 2. Next, decision-makers determine their reliability or certainty values for their expressed opinions on w_{ij} using the linguistic terms in Table 3.

Step 3. Experts are invited to express their judgments through agreeing, disagreeing, or neutrality on the outgoing values for each concept provided by decision-makers. According to the extended Z-numbers theory, optimal reliability values are determined based on the decision-makers' reliability values and experts' judgments. To determine the final w_{ij} values, the generated Z-numbers are converted to a TFN and then are combined. Finally, the combined TFNs are converted to real numbers.

Step 4. For an FCM model with C_i concepts and corresponding w_{ij} causal relationships, identified concepts represent the state vector $A = [A_1, A_2, A_3, \dots, A_n]$. The state matrix A is later updated through several transitions in the weight matrix. Eq. (7) is used to determine the state vector A for each concept C_i.

$$A_i^t = f\left(A_i^{t-1} + \sum_{j \neq i, j=1}^{N} A_j^{t-1} w_{ji}\right) \tag{7}$$

where A^t represents the value of concept C_i at iteration t, A^{t-1} denotes the value of concept C_i at iteration $t-1$. The function $f(x)$ is an activation which aims to determine the value by converting to a number in the preferred range of [0,1] or [−1,1]. Sigmoid function and hyperbolic tanget function are the most common and frequently used functions for the FCM (Eqs. (8)–(9)) [52].

$$f(x) = \frac{1}{1+e^{-\lambda x}} \tag{8}$$

where $\lambda \in (0, +\infty)$ is a slope parameter. The function resembles to a linear function when λ is low while, it turns to a discrete function when λ is high.

$$f(x) = \tanh \lambda x = \frac{e^{\lambda x} - e^{-\lambda x}}{e^{\lambda x} + e^{-\lambda x}} \tag{9}$$

There exist several software tools for modeling FCM such as Mental Modeler [53] and FCM Expert [54], which are both used in this study.

4. Problem definition

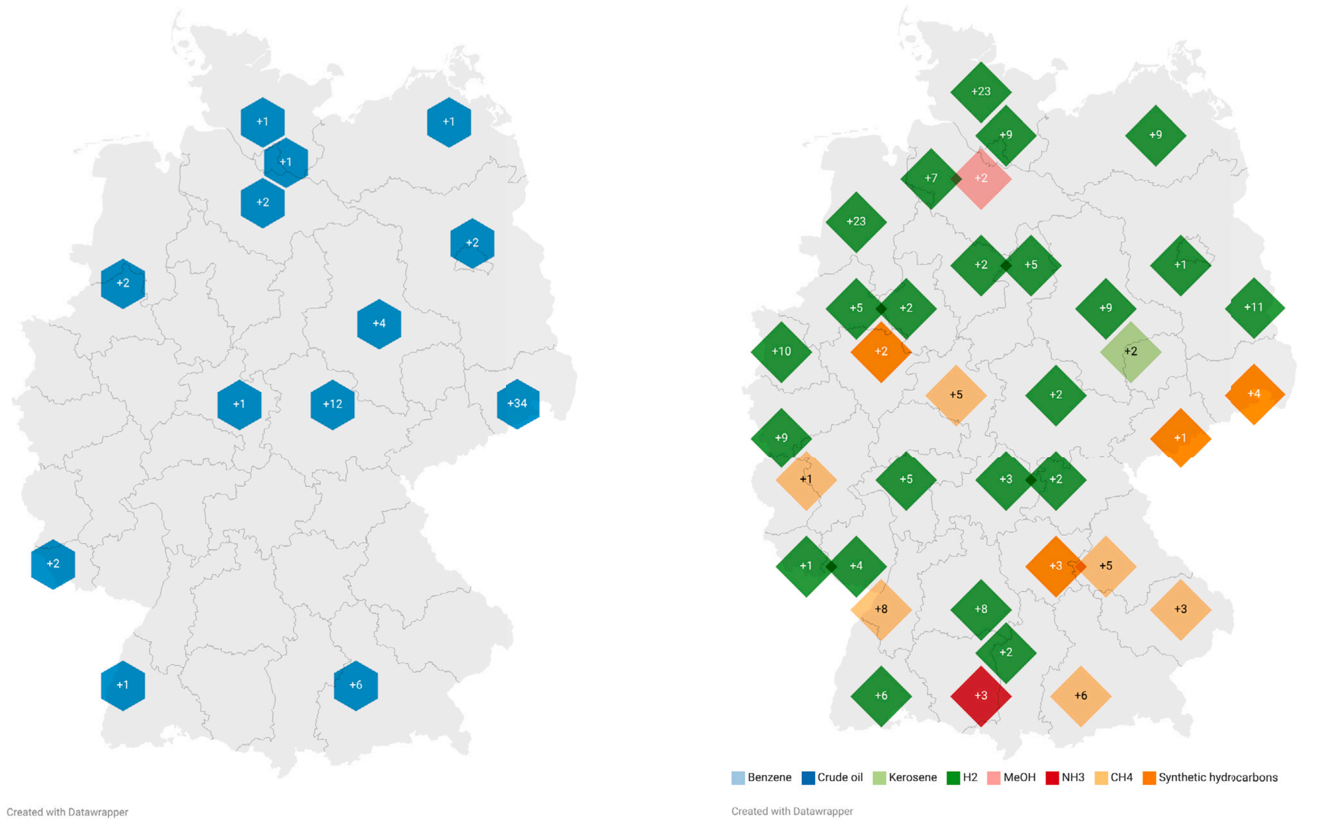
4.1. PtX fuels in Germany

PtX fuels are sustainable alternatives to fossil fuels in response to the concerns raised by the EU Green Deal and the Fit for 55 Package regarding the emission reduction. In general, the PtX process begins with the electrolysis of hydrogen, preferably powered by renewable sources of electricity. The hydrogen produced then undergoes several refinement stages to produce synthetic fuels such as methane, methanol, or liquid hydrocarbons. PtX fuels can be categorized into two types: power-to-liquid (PtL) and power-to-gas (PtG). In cases where bio-based feedstocks are utilized within the production process, for example bio-based carbon feedstock, the resulting fuel is referred to as Power-to-Biomass-to-X (PBtX) or bio-hybrid fuels. The European Union (EU) has also categorized these fuels under the term "e-biofuels", defining them as fuels that incorporate synthetic gas derived from biomass gasification during the production [55,56]. However, a significant challenge within these definitions in the EU regulatory frameworks is the lack of clarity surrounding non-biological sources and the absence of provisions addressing potential shortfalls in the availability of these sources to meet fuel production demands. This ambiguity presents challenges for consistent interpretation and application of the regulations across various sectors, thereby creating uncertainty regarding compliance and scalability. Furthermore, it elevates the potential role of organic waste utilization, as the lack of clarity on non-biological sources may shift focus towards bio-based feedstocks to fill gaps in meeting production demands [57–59].

Germany has established a target of achieving a 28% share of renewables including e-fuels and hydrogen in the transport sector by 2030 [60]. To achieve this ambitious target, the German government has put forth substantial investments in the development and implementation of renewable energy sources, such as wind and solar power. This strategic move guarantees a sustainable supply of renewable electricity for the production of PtX fuels. The government has also proposed the creation of a PtX fund through the Federal Ministry for Economic Cooperation and Development (BMZ), which would provide financing for the construction of PtX plants and infrastructure as well as funding for hydrogen value chains [61]. The current status quo of PtX fuels in Germany is promising, with several projects and demonstration plants in operation.

Fig. 2 illustrates the distribution of PtX plants and R&D projects across Germany. Key map details can be succinctly summarized in the following manner:

- North Rhine-Westphalia, Lower Saxony, and Schleswig–Holstein have the highest production capacities, with 2276 MW, 2121 MW, and 1758 MW, respectively, followed by Saxony-Anhalt, Mecklenburg-Vorpommern, Brandenburg, and Hamburg.



(a) PtX R&D projects in Germany.

(b) PtX facilities in Germany.

Fig. 2. An overview of PtX fuels in Germany [62].

- Hydrogen is a primary component or an integral part of the final products in the majority of the plants (127 plants), followed by CH_4 in 37 plants, NH_3 in 4 plants, MeOH in 12 plants, and synthetic hydrocarbons in 19 plants.
- Eighty-nine of these plants were established before 2020, while 85 were either established after this date or are planned for future establishment. Currently, 35 of the 85 plants are undergoing feasibility analysis.
- North Rhine-Westphalia has the highest carbon potential for PtX production, with 168 Mt per year, followed by Brandenburg with 50 Mt.
- Saxony, Thuringia, and Bavaria stand out as leading states with a significant number of R&D projects focused on PtX.
- The Federal Ministry for Economic Affairs and Climate Action (BMWK), the Federal Ministry of Education and Research (BMBF), and the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) have funded large investments in these projects.

Given the pioneering nature of PtX fuels and technologies, the initiation of projects is not the sole determinant of their success. Understanding the dynamics and complexities of the market is a fundamental prerequisite for the diffusion and therefore the success of PtX projects.

4.2. Context definition

The energy market in the aviation and maritime sectors is quite different from the road and rail sectors, given the limited suitable fuel alternatives and the required fuel characteristics. Considering the high energy consumption in the German aviation and maritime sectors, PtX fuels are potential fuel alternatives, requiring low modification and infrastructure costs, and are more compatible with the associated regulations and engines. However, commercial utilization of PtX fuels in the German aviation and maritime is hindered by various obstacles. The predominance of fossil fuels in the energy market and the influence of pro-fossil fuel political lobbies can be identified as the main barriers to progress [63,64]. Thus, further analyses are required to understand the dynamics of the market in a multi-perspective system to succeed in using PtX fuels in the aviation and maritime sectors.

For this purpose, an initial FCM model is built based on a comprehensive literature review as well as regulatory documents in the German and EU policy paradigms. The inclusion criteria consisted of identifying factors contributing to the diffusion of PtX fuels in terms of social, environmental, regulatory, economic, and technical aspects. A large part of this stemmed from the discussion in policy documents regarding the challenges for RFNBOs, and the need to address them through the introduced regulatory instruments. The initial model consists of 23 concepts within social, technical, environmental, regulatory, and economic aspects. Table 4 presents the identified concepts where 4 social concepts, 7 economic, 3 environmental, 3 regulatory, and 5 technical concepts are considered. The objective is to understand effect of cross-sectoral factors on the market diffusion of PtX fuels.

The initial FCM model is constructed using the identified concepts and potential relationships to facilitate the involvement of different stakeholders with different backgrounds (with different levels of knowledge about renewable fuels and market diffusion) (Fig. A.1). In this step, all causal relationships are all assumed to be equal at this point, which will be determined later based on the decision-makers' opinions and experts' judgments. The initial FCM model was used in the first survey, where participants were asked to update the model through adding or removing concepts and relationships. In the second survey, causal relationships were to be determined for a finalized FCM model.

Table 4
Concepts of the initial FCM model based on a literature review.

No.	Concept	No.	Concept	No.	Concept
C1	Public acceptance	C9	Bioeconomy policies	C17	Volatility in availability of biomass
C2	Job creation	C10	Governmental incentives for renewable fuels	C18	Volatility in availability of CO2 feedstock
C3	Public trust	C11	Competitiveness of PtX fuels against fossil fuels	C19	Volatility in availability of renewable electricity supply
C4	Knowledge in benefits of renewable energy	C12	Economic Sustainability	C20	Market regulations
C5	Fuel price	C13	GHG emissions	C21	Infrastructural capacity for renewable fuels
C6	New businesses	C14	Air and environmental pollution	C22	Fuel availability
C7	Transition cost	C15	EU and German policies on sustainable transport and renewable fuels	C23	Market diffusion of PtX fuels
C8	Subsidies/tax on fossil fuels	C16	Environmental sustainability		

4.3. Data collection

To build an empirically-based FCM model with realistic causal relationships, a two-fold survey was designed. Several stakeholders were invited from diverse backgrounds and industries, all of whom have direct or indirect involvement in the production, transport, storage, R&D, or policymaking of PtX fuels. This approach ensured the incorporation of a wide range of perspectives and expertise, contributing to the model's robustness and the accuracy of the identified causal relationships.

In the first step, the initial FCM model in Fig. A.1 was presented to the participants. Three main questions were included in the first survey:

- Which absent concepts, in your view, have the potential to influence the diffusion of PtX fuels?
- What are irrelevant concepts in the initial FCM that you believe do not influence the diffusion of PtX fuels?
- What are missing and irrelevant causal relationships, considering the newly added and removed concepts?

Experts were primarily identified from R&D teams involved in PtX projects in Germany, as well as from key participants in industrial projects within the country. This selection ensured that the survey captured insights from professionals with firsthand experience and expertise in both the technological development and practical implementation of PtX fuels. In the first round, 54 participants were identified and contacted via email. A follow-up reminder email was subsequently sent to ensure a higher response rate and encourage participation from those who had not yet responded. Twenty participants accepted our invitation and took part in the first survey. In order to maintain a high level of quality, we decided to build the model with participants who have expertise in the field as each participant brings a wealth of experience that can significantly influence the model's accuracy and reliability. Moreover, this number allows for a comprehensive exploration of the topic while still being manageable for analysis and interpretation. Table A.1 presents an overview of the participants' profiles.

At the end of the first survey, participants were asked whether they were interested to participate in the second part of the survey. Out of the twenty respondents, twelve expressed their willingness to be contacted again for the second survey. In the second round, the consenting participants were contacted, where seven out of twelve decided to actually participate in the survey. Following a discussion between authors regarding the background and expertise of the participants, two individuals were designated as decision-makers, mainly involved in the R&D of PtX fuels. The remaining five participants with higher experience and expertise in the field, were classified as experts.

5. Results

5.1. Model structure and analysis

The primary objectives of the initial survey were to refine the focus by highlighting relevant concepts and to broaden the scope by including previously overlooked concepts. Given the diverse backgrounds of the participants, the decision to keep or eliminate a concept in the model depended on the use of the majority rule. Similarly, the majority rule was used to decide whether or not to add a new concept to the model. This was done to reduce the bias and subjectivity of favoring the opinions of certain participants over others. All in all, the concepts of the updated FCM model are completely listed in Table 5. Here, concepts shown with S, P, E, EC, and T can be categorized as social, regulatory, environmental, economic, and technical concepts.

In the next step, participants who agreed to take part in the second survey were contacted. Decision-makers were invited to express their opinion on causal relationships using Tables 2 and 3. Upon completion of this phase, the collected data was shared with the experts. The experts expressed their judgment about the decision makers' opinions on the relationships of each component to others (outgoing edges) in a three-way decision by deciding to agree, disagree, or have a neutral judgment. An example of the collected data, expressed by the degree of causal relationships determined by the first decision maker, is shown in Table 6.

In Table 6, each pairwise component with a value denotes a connection between two concepts, unless a "–" is used for those concepts with no effect on each other. For pairwise values of concepts affecting each other, expressed linguistic opinions are shown for example as (PM,MC), which denotes the effect of social acceptance & trust (S1) on the diffusion process (C). Here, the first term indicates the degree that social acceptance & trust (S1) affects the diffusion (C). In this case, it is "PM" where, P denotes positive effect and M shows medium effect based on Table 2. For negative degrees, N is added to the linguistic terms in Table 2. Furthermore, the second terms reveals reliability or certainty of the decision-maker on the expressed degree which is "MC" indicating medium certainty based on linguistics terms in Table 3.

Subsequently, the data gathered from both decision-makers was passed to the panel of experts. Then, the experts expressed their judgment on the outgoing vector of each component by choosing whether they agree, disagree, or have neutral opinion. Table A.2 shows an overview of the experts' judgments on each component. Each value signifies the cumulative count of experts who expressed identical judgments. According to the collected data, both decision-makers show strong agreement with experts in public acceptance and trust (S1), public knowledge (S3), PtX supportive market regulations (P1), EU and German energy policies (P2), GHG emissions (E1), climate change policies (E2), air pollutants (E3), incentives for renewable fuels (EC1),

Table 5
FCM model generated based on the first survey.

No.	Concept	No.	Concept	No.	Concept
C	Market Diffusion of PtX fuels	E5	Direct and indirect land changes	T2	Renewable fuels demand
S1	Public acceptance & trust	E6	Shift to Bioeconomy	T3	Volatility in availability of biomass
S2	Job creation	EC1	Incentives for renewable fuels	T4	Volatility in availability of CO_2
S3	Public knowledge about renewable energy benefits	EC2	Competitiveness of PtX fuels against other renewable fuels	T5	Fuel availability
S4	Population growth	EC3	PtX fuel price	T6	Volatility of renewable electricity supply
P1	PtX supportive market regulations	EC4	Lowered subsidies/increased tax on fossil fuels	T7	Potential for availability of Infrastructure for PtX fuels
P2	EU/German energy policies	EC5	Competitiveness of PtX fuels against fossil fuels	T8	Process efficiencies
P3	External political impacts (i.e. war)	EC6	Payback period	T9	Research data availability
E1	GHG emissions	EC7	Transition cost (vehicle modification cost)	T10	Biomass origin
E2	Climate Change policies	EC8	Economic Sustainability of PtX fuels	T11	Food competition
E3	Air pollutants	T1	Driving range	T12	Risk perceptions
E4	Environmental Sustainability of PtX fuels				

Table 6
First decision-maker's opinions on the degree of causal relationships.

	C	S1	S2	S3	S4	P1	P2	P3	E1	E2	E3	E4	E5	E6	EC1	EC2	EC3
C	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
S1	(PM,MC)	–	–	–	–	–	–	–	–	–	–	–	–	(PM,MC)	–	–	–
S2	–	(PVL,VLC)	–	–	(PL,LC)	–	–	–	–	–	–	–	–	–	–	–	–
S3	–	(PM,LC)	–	–	–	–	(PL,LC)	–	–	–	–	–	–	–	–	–	–
S4	–	–	–	–	–	–	–	–	(PH,HC)	–	(PM,MC)	(NH,MC)	(PH,HC)	–	–	–	–
P1	(PVH,HC)	(PL,VLC)	(PM,MC)	(PM,MC)	–	–	–	–	(PM,LC)	–	(PL,VLC)	–	(PM,MC)	(PH,HC)	(PH,HC)	(PH,HC)	(PH,MC)
P2	(PH,VLC)	–	–	(PM,MC)	–	(PM,VLC)	–	(NH,VLC)	(PH,MC)	–	–	(NL,LC)	(PL,LC)	–	(PH,MC)	–	–
P3	–	(PL,LC)	–	(PM,MC)	–	–	(PL,LC)	–	–	–	–	–	–	–	(PH,MC)	–	–
E1	(PL,LC)	(PL,LC)	–	(PH,MC)	–	(PM,VLC)	(PM,HC)	–	–	(PM,HC)	–	(NVH,HC)	–	(PL,LC)	–	–	–
E2	–	–	–	(PL,VLC)	–	–	(PVH,HC)	(NL,VLC)	(PH,MC)	–	(NL,LC)	(PH,LC)	(PL,LC)	(PL,LC)	(PH,LC)	–	–
E3	–	–	–	–	–	–	–	–	–	–	–	(PH,HC)	–	–	–	–	–
E4	(PM,HC)			–	–	–	–	(NL,MC)	–	–	–	–	–	–	–	–	–
E5	–	–	–	–	–	–	–	–	–	–	–	(NH,VHC)	–	(PH,HC)	–	–	–
E6	–	(PL,LC)	(PM,MC)	–	–	–	–	–	(PM,LC)	–	–	(PH,MC)	(PM,MC)	–	(PL,LC)	–	–
EC1	(PH,MC)	(PL,LC)	–	(PH,HC)	–	–	–	–	(NM,MC)	–	(NL,LC)	(NL,LC)	(PM,LC)	(PM,HC)	–	(PM,MC)	(NM,MC)
EC2	(PH,HC)	(PM,MC)	(PM,MC)	–	–	–	–	–	(NL,LC)	–	(NL,LC)	(PL,LC)	(PL,LC)	(PM,MC)	–	–	(NM,MC)
EC3	(NH,HC)	(PH,HC)	–	–	–	–	–	–	–	–	–	–	–	(NL,LC)	–	(PM,HC)	–
EC4	–	–	–	–	–	–	–	(NL,VLC)	(NH,MC)	–	(NL,LC)	(PL,LC)	–	–	–	(PM,MC)	–
EC5	(PH,HC)	(PM,MC)	(PM,MC)	–	–	(PL,LC)	–	–	(NL,LC)	–	(NL,LC)	(PL,LC)	(PL,LC)	(PM,MC)	–	(PM,MC)	–
EC6	–	–	–	–	–	(PL,LC)	–	–	–	–	–	–	–	–	–	–	(NL,LC)
EC7	–	(NM,LC)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
EC8	(PL,LC)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T1	–	(PVL,MC)	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T2	–	–	(PL,MC)	–	–	–	–	–	(NL,LC)	–	–	–	(PL,LC)	(PM,MC)	–	(PL,MC)	(NL,LC)
T3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T5	(PM,MC)	(PM,MC)	–	–	–	–	–	(NL,VLC)	(NL,LC)	–	(NL,MC)	(PL,MC)	(PL,LC)	(PM,MC)	–	(PM,MC)	(NM,MC)
T6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	(NH,MC)	(PM,LC)
T7	(PM,MC)	(PM,MC)	–	–	–	–	–	(NL,VLC)	(NL,LC)	–	(NL,MC)	(PL,MC)	(PL,LC)	(PM,MC)	–	(PM,MC)	(NM,MC)
T8	(PM,MC)	(PM,MC)	(PM,MC)	–	–	–	–	(PM,MC)	(NM,MC)	–	(NL,LC)	(PM,MC)	–	(PM,MC)	–	(PM,MC)	(NM,MC)
T9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T10	–	–	–	–	–	–	–	–	–	–	–	–	(NM,MC)	(PM,MC)	–	–	–
T11	(NEH,VHC)	(NEH,VHC)	–	–	–	(NEH,VHC)	(NEH,VHC)	–	–	–	–	(NEH,VHC)	(NEH,VHC)	(NEH,VHC)	(NEH,VHC)	(NEH,VHC)	–
T12	(NH,HC)	(PH,HC)	–	–	–	–	–	–	–	–	–	–	–	(NH,HC)	–	–	–

	EC4	EC5	EC6	EC7	EC8	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
C	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
S1	–	–	–	–	–	–	(PM,HC)	–	–	–	–	–	–	–	–	–	(NH,HC)
S2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
S3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	(NM,MC)
S4	–	–	–	–	–	–	(PH,HC)	(PH,HC)	–	–	–	–	–	–	–	–	–
P1	–	(PH,HC)	(NH,HC)	–	–	–	–	(PH,HC)	–	(PH,HC)	–	(PH,HC)	(PH,HC)	–	–	–	(NL,LC)
P2	(PH,MC)	–	–	–	(PL,LC)	–	(PL,HC)	–	–	–	(NL,LC)	(PH,LC)	–	–	–	–	–
P3	–	–	–	–	(NVH,VHC)	–	–	(PH,HC)	–	–	–	–	–	–	–	(PH,LC)	–
E1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
E2	–	–	–	–	(PL,LC)	–	(NL,LC)	–	–	–	(NL,LC)	–	–	–	–	–	–
E3	–	–	–	–	(NEL,MC)	–	–	–	–	–	–	–	–	–	–	–	–
E4	–	–	–	–	(PM,HC)	–	–	–	–	–	–	–	–	–	–	–	–
E5	–	–	–	–	–	–	–	(PL,LC)	–	–	–	–	–	–	–	(PH,LC)	–
E6	–	–	–	–	(PM,MC)	–	–	–	–	–	–	–	–	–	–	–	(NL,MC)
EC1	–	(PH,MC)	(NM,MC)	–	(PL,LC)	–	–	(PH,LC)	–	(PH,MC)	–	(PH,MC)	(PM,LC)	–	–	(PVL,LC)	–
EC2	–	(PM,MC)	(NM,MC)	–	(PM,MC)	–	(PH,HC)	(PH,LC)	–	(PH,MC)	–	(PH,MC)	(PM,LC)	–	–	(PVL,LC)	–
EC3	–	(NH,HC)	(NM,MC)	–	(NM,MC)	–	(NVH,MC)	–	–	(NH,MC)	–	(NH,MC)	(PM,LC)	–	–	–	–
EC4	–	(PL,LC)	(NM,MC)	–	(PM,MC)	–	(PL,LC)	–	–	–	–	–	(PVL,LC)	–	–	–	–
EC5	–	–	(NM,MC)	–	(PM,MC)	–	(PH,HC)	(PH,LC)	–	(PH,MC)	–	(PH,MC)	(PM,LC)	–	–	(PVL,LC)	–
EC6	–	–	–	–	(PL,LC)	–	–	–	–	–	–	–	–	–	–	–	–
EC7	–	(PL,LC)	(PL,LC)	–	(NM,LC)	–	(NM,MC)	–	–	(NH,MC)	–	(NM,LC)	–	–	–	–	(PM,LC)
EC8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T1	–	–	(NL,LC)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
T2	–	–	–	–	–	–	–	(PL,LC)	–	–	–	(PH,LC)	(PH,MC)	–	–	(PVL,LC)	–
T3	–	–	–	–	–	–	–	–	–	(NM,LC)	–	–	(NM,LC)	–	–	–	–
T4	–	–	–	–	–	–	–	–	–	(NM,LC)	–	–	(NM,LC)	–	–	–	–
T5	–	(PM,MC)	–	–	(PH,MC)	–	–	–	–	–	–	(PM,MC)	(PM,MC)	–	–	(PVL,LC)	(NL,LC)
T6	–	(NH,MC)	–	–	–	–	–	–	–	(NH,MC)	–	–	(NL,MC)	–	–	–	(PVL,LC)
T7	–	(PM,MC)	–	–	(PH,MC)	–	–	–	–	(PM,MC)	–	–	(PM,MC)	–	–	(PVL,LC)	(NL,LC)
T8	–	(PM,MC)	(NM,MC)	(NM,LC)	(PM,MC)	(PM,MC)	–	–	–	(PM,MC)	–	(PM,MC)	–	–	–	–	–
T9	–	–	–	–	–	–	–	–	–	–	–	–	(PH,MC)	–	–	–	–
T10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	(NVH,HC)	–
T11	–	–	–	–	–	–	(NH,VHC)	(NH,MC)	–	(NH,MC)	–	–	–	–	(NEH,VHC)	–	–
T12	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

driving range (T1), potential for availability of infrastructure for PtX fuels (T7), and biomass origin (T10). On the other hand, one or both decision-makers have strong disagreement on job creation (S2), population growth (S4), PtX fuel price (EC3), payback period (EC6), volatility in availability of CO2 (T4) and volatility of renewable electricity supply (T6). Concepts such as S1, P1, EC1, T1, and T7 show strong agreement between experts and both decision-makers. While, concepts such as S2, S4, EC3, EC6, T4, and T6 show significant disagreement, indicating

Table 7
An example of the Extended Z-number calculations based on the first decision-maker's opinions.

		C	S1	…	P1	…	E1	…	EC1	…	T2
C	A	–	–	…	–	…	–	…	–	…	–
	B	–	–	…	–	…	–	…	–	…	–
	B^*	–	–	…	–	…	–	…	–	…	–
	ζ	–	–	…	–	…	–	…	–	…	–
S1	A	(0.35,0.50,0.65)	–	…	–	…	–	…	–	…	(0.35,0.50,0.65)
	B	(0.30,0.50,0.70)	–	…	–	…	–	…	–	…	(0.50,0.70,0.90)
	B^*	(0.72,0.80,0.88)	–	…	–	…	–	…	–	…	(0.80,0.88,0.96)
	ζ	(0.31,0.44,0.58)	–	…	–	…	–	…	–	…	(0.32,0.46,0.60)
…	…	…	…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…	…	…	…
P2	A	(0.50,0.65,0.80)	–	…	(0.50,0.65,0.80)	…	*(0.50,0.65,0.80)*	…	(0.50,0.65,0.80)	…	*(0.20,0.35,0.5)*
	B	(0.10,0.30,0.50)	–	…	(0.50,0.70,0.90)	…	*(0.50,0.70,0.90)*	…	(0.30,0.50,0.70)	…	*(0.10,0.30,0.50)*
	B^*	(1,1,1)	–	…	(1,1,1)	…	*(1,1,1)*	…	(1,1,1)	…	*(1,1,1)*
	ζ	(0.50,0.65,0.80)	–	…	(0.50,0.65,0.80)	…	*(0.50,0.65,0.80)*	…	(0.50,0.65,0.80)	…	*(0.20,0.35,0.5)*
…	…	…	…	…	…	…	…	…	…	…	…
EC3	A	*(0.50,0.65,0.80)*	*(0.50,0.65,0.80)*	…	–	…	–	…	–	…	*(0.65,0.80,0.90)*
	B	*(0.50,0.70,0.90)*	*(0.50,0.70,0.90)*	…	–	…	–	…	–	…	*(0.30,0.50,0.70)*
	B^*	*(0.25,0.35,0.45)*	*(0.25,0.35,0.40)*	…	–	…	–	…	–	…	*(0.15,0.25,0.35)*
	ζ	*(0.29,0.38,0.47)*	*(0.29,0.37,0.48)*	…	–	…	–	…	–	…	*(0.32,0.40,0.45)*
…	…	…	…	…	…	…	…	…	…	…	…
EC8	A	*(0.20,0.35,0.50)*	–	…	–	…	–	…	–	…	–
	B	*(0.10,0.30,0.50)*	–	…	–	…	–	…	–	…	–
	B^*	*(0.05,0.15,0.25)*	–	…	–	…	–	…	–	…	–
	ζ	*(0.07,0.13,0.19)*	–	…	–	…	–	…	–	…	–
…	…	…	…	…	…	…	…	…	…	…	…
T5	A	(0.35,0.50,0.65)	(0.35,0.50,0.65)	…	–	…	*(0.20,0.35,0.5)*	…	–	…	–
	B	(0.30,0.50,0.70)	(0.30,0.50,0.70)	…	–	…	*(0.30,0.50,0.70)*	…	–	…	–
	B^*	(1,1,1)	(1,1,1)	…	–	…	*(1,1,1)*	…	–	…	–
	ζ	(0.35,0.50,0.65)	(0.35,0.50,0.65)	…	–	…	*(0.20,0.35,0.5)*	…	–	…	–

Italic values denote negative causal degrees.

areas of contention or differing perspectives. Experts indicate significant disagreement on first decision-maker's opinions regarding PtX fuel price (EC3), economic sustainability of PtX fuels (EC8) and biomass origin (T10). For the second decision-maker, experts state strong disagreement on payback period (EC6), research data availability (T9), GHG emissions (E1) and air pollutants (E3).

After all R values have been determined, new reliability values can be determined using Eq. (5). In this regard, Table 7 shows an example of the Z-number calculations based on the first decision-makers' opinions. Once more, for the sake of clarity, the process of calculating the influence of social acceptance and trust (S1) on the diffusion process (C) is described using four values: A representing the fuzzy degree, and B denoting the initial reliability value provided by the decision-maker. Then, the new reliability is determined using Eq. (5) as $b^*_{S1} = 1 - (1 - b_{S1})(1 - 0.6) = (0.72, 0.80, 0.88)$

Later, new reliability B^* and final fuzzy Z-number value ζ are determined as follows. According to Table A.2, the R value for S1 is 0.6. Then, the new reliability is determined using Eq. (5) as (0.72, 0.80, 0.88). Next, the new reliability is defuzzified using Eq. (3) as 0.80. The final fuzzy Z-number is calculated based on Eq. (3). $(\sqrt{0.80} \times 0.35, \sqrt{0.80} \times 0.50, \sqrt{0.80} \times 0.65) = (0.31, 0.44, 0.58)$

In accordance with this approach, all Z-numbers are calculated. In the last step, the calculated fuzzy Z-numbers are defuzzified to construct the final FCM model (Eq. (3)). Fig. 3 illustrates a traditional visualization of the FCM model with the complete set of components and causal degrees. For better visualization of the final FCM, Fig. A.2 demonstrates the relationships between components within a chord diagram. To grasp a detailed overview of the causal degrees between concepts, Fig. A.3 presents a heat map by categorizing the causal degrees into several groups.

Gaining insight into the attributes and configuration of the FCM requires a clear explanation of the model, its components, and their interconnections, which provides valuable information. In this regard, Table 8 summarizes the profile of all components based on their network characteristics including indegree, outdegree, centrality, and type. The diffusion of PtX fuels (C) is the only receiver component, and research data availability (T9) is the only driver concept of the model while, the remaining concepts are ordinary. According to Table 8, food competition (T11), process efficiencies (T8), fuel availability (T5), competitiveness of PtX fuels against other renewable fuels (EC2), incentives for renewable fuel (EC1), shift to bioeconomy (E6), PtX supportive market regulations (P1), and competitiveness of PtX fuels against fossil fuels (EC5) have high centrality values denoting their key roles in the model. In general, the FCM model consists of 34 components, 260 connection, a density of 0.231, and 7.64 connection per concept.

According to the categorization of the concepts, Fig. 4 demonstrates the overall characteristic of the concept categories based on the aforementioned metrics. In this regard, political concepts have the lowest indegree value, followed by social concepts, economic, environmental, and technical. This indicates that most regulatory concepts affect other concepts, rather than being affected by them. On the other hand, social concepts have the lowest outdegree, followed by political, environmental, economic, and technical concepts. This signifies that social concepts affect other concepts less than other concepts while, technical concepts influence other more. The graph shows high importance of technical and economic concepts on the model based on their high interconnections within themselves as well as with other concepts.

For a comprehensive examination of the model, the quantity of connections within each category serves as a valuable metric to comprehend the model's behavior. In this context, components in economic and technical categories have the highest links to themselves with 7 links. Between categories, technical concepts have the highest connectivity to economic concepts with a total of 28 links, and in the same way economic components affect the technical components through 27 links. In the social category, the highest impact is made on the environmental category with a total of 5 links. The same value for political

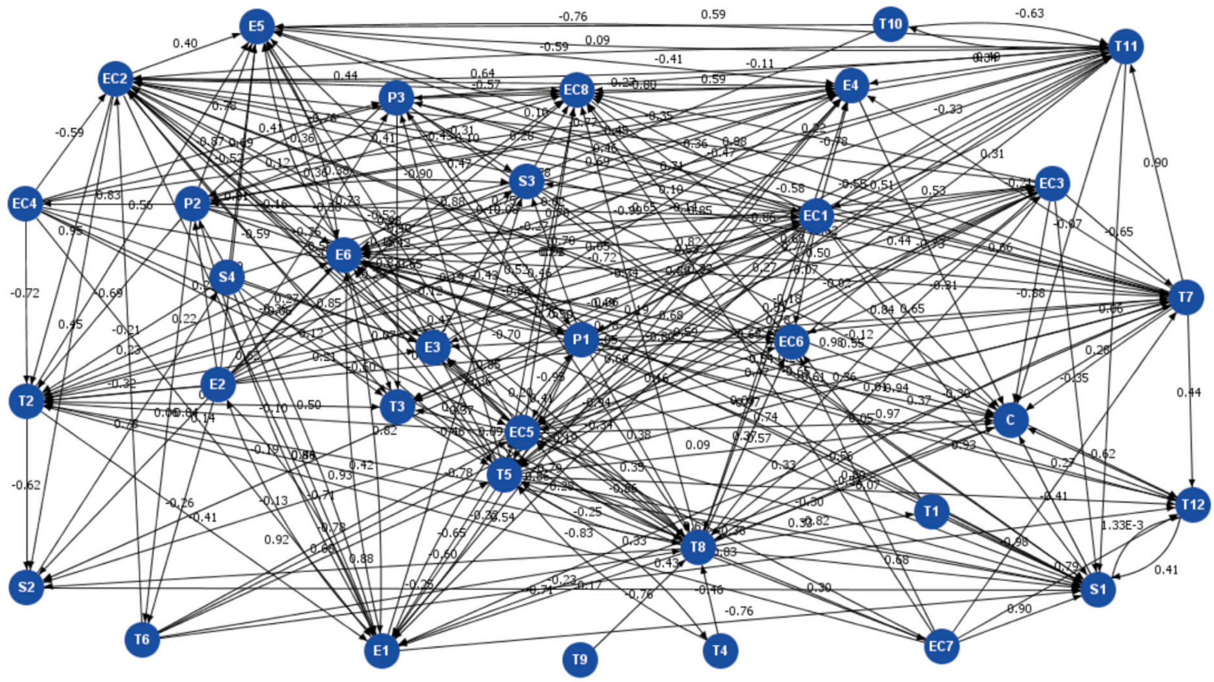


Fig. 3. Traditional illustration of the final FCM model with finalized causalities.

Table 8
Input, output, centrality degree, and type of model's components.

Component	Indegree	Outdegree	Centrality	Type	Component	Indegree	Outdegree	Centrality	Type
C	8.55	0.00	8.55	Receiver	EC4	0.60	3.51	4.11	Ordinary
S1	7.50	2.22	9.72	Ordinary	EC5	5.22	6.50	11.72	Ordinary
S2	2.53	0.46	2.99	Ordinary	EC6	3.88	0.49	4.37	Ordinary
S3	2.77	1.26	4.03	Ordinary	EC7	0.45	3.47	3.92	Ordinary
S4	0.25	3.21	3.46	Ordinary	EC8	7.25	0.19	7.44	Ordinary
P1	2.48	9.92	12.41	Ordinary	T1	0.47	0.58	1.05	Ordinary
P2	2.98	5.74	8.72	Ordinary	T2	4.80	2.34	7.14	Ordinary
P3	2.60	4.14	6.74	Ordinary	T3	4.35	1.07	5.42	Ordinary
E1	5.91	3.40	9.30	Ordinary	T4	0.79	1.08	1.87	Ordinary
E2	0.52	6.50	7.02	Ordinary	T5	6.13	7.20	13.33	Ordinary
E3	2.52	0.18	2.70	Ordinary	T6	0.70	3.01	3.70	Ordinary
E4	7.06	1.29	8.35	Ordinary	T7	5.09	5.33	10.42	Ordinary
E5	5.54	2.30	7.84	Ordinary	T8	5.78	7.56	13.33	Ordinary
E6	7.86	4.42	12.28	Ordinary	T9	0.00	0.49	0.49	Driver
EC1	4.05	8.83	12.88	Ordinary	T10	0.88	1.30	2.18	Ordinary
EC2	4.87	8.36	13.23	Ordinary	T11	3.14	10.32	13.47	Ordinary
EC3	2.61	4.69	7.31	Ordinary	T12	3.22	2.02	5.24	Ordinary

components' effect is made on economic and technical components, both with a total of 10 links. Next to affecting components through the whole model, environmental components have highest number of links to the components in their own category. Fig. 5 illustrates a complete overview of the interactions among concept categories.

Furthermore, Kosko's activation rule (Eq. (7)) is applied to report the optimal activation values for all components. Fig. A.4 and Table A.3 present the results of the inference analysis using the Kosko's activation function after 11 iterations. The final activation values in Table A.3 represent the relative strength of influence or importance of each concept within the FCM. Results indicate that environmental sustainability of PtX fuels (E4), driving range of PtX-fueled vehicles (T1), GHG emissions (E1), competitiveness of PtX fuels against other renewable fuels (EC2), payback period (EC6), EU/German energy policies (P2), and public knowledge about renewable energy benefits (S3) are concepts with higher importance, which strongly contribute to the diffusion of PtX fuels.

5.2. Scenario analysis

A sensitivity analysis of the FCM is considered to enable policymakers in grasping the impact of changes in the value of specific concepts on other concepts and the objective concept. The goal is to understand the impacts of changes on the other concepts and compare the results to the base scenario. In the next step, the scenario analysis is conducted through several scenarios supported by different policies.

Two scenarios are assumed to measure impacts of potential changes in the fuel demand and production requirements as follows:

- Policy Scenario I: Within the context of the EU Green Deal and the Fit for 55 Package, renewable energies are garnering heightened focus across all sectors, aimed at replacing conventional fossil alternative. Consequently, an upsurge in demand for renewable fuels within the transport sector is anticipated. In light of this, our objective is to assess the repercussions of an augmented demand for renewable fuels.

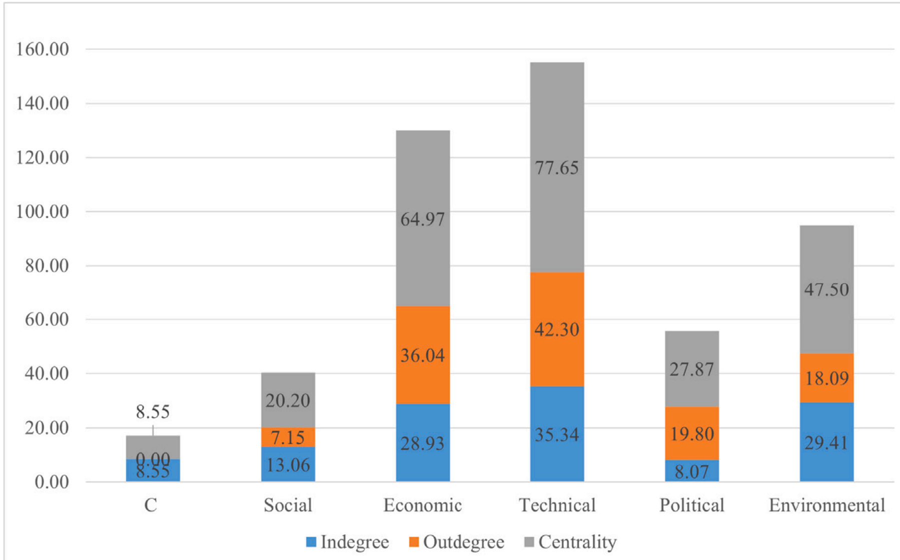


Fig. 4. Overview of components in five main categories (*C* denotes the diffusion of PtX fuels).

- Policy Scenario II: As previously outlined, the production of PtX fuels is intricately tied to the availability of bio-based feedstock, renewable electricity, and carbon. Undoubtedly, any fluctuations or deficits in the availability of these resources would result in diminished fuel production and reduced availability within the energy market. In this context, we contemplate a scenario wherein a 25% decline in biomass availability and renewable electricity generation occurs due to non-compliance with goals and standards linked to the relevant policies.

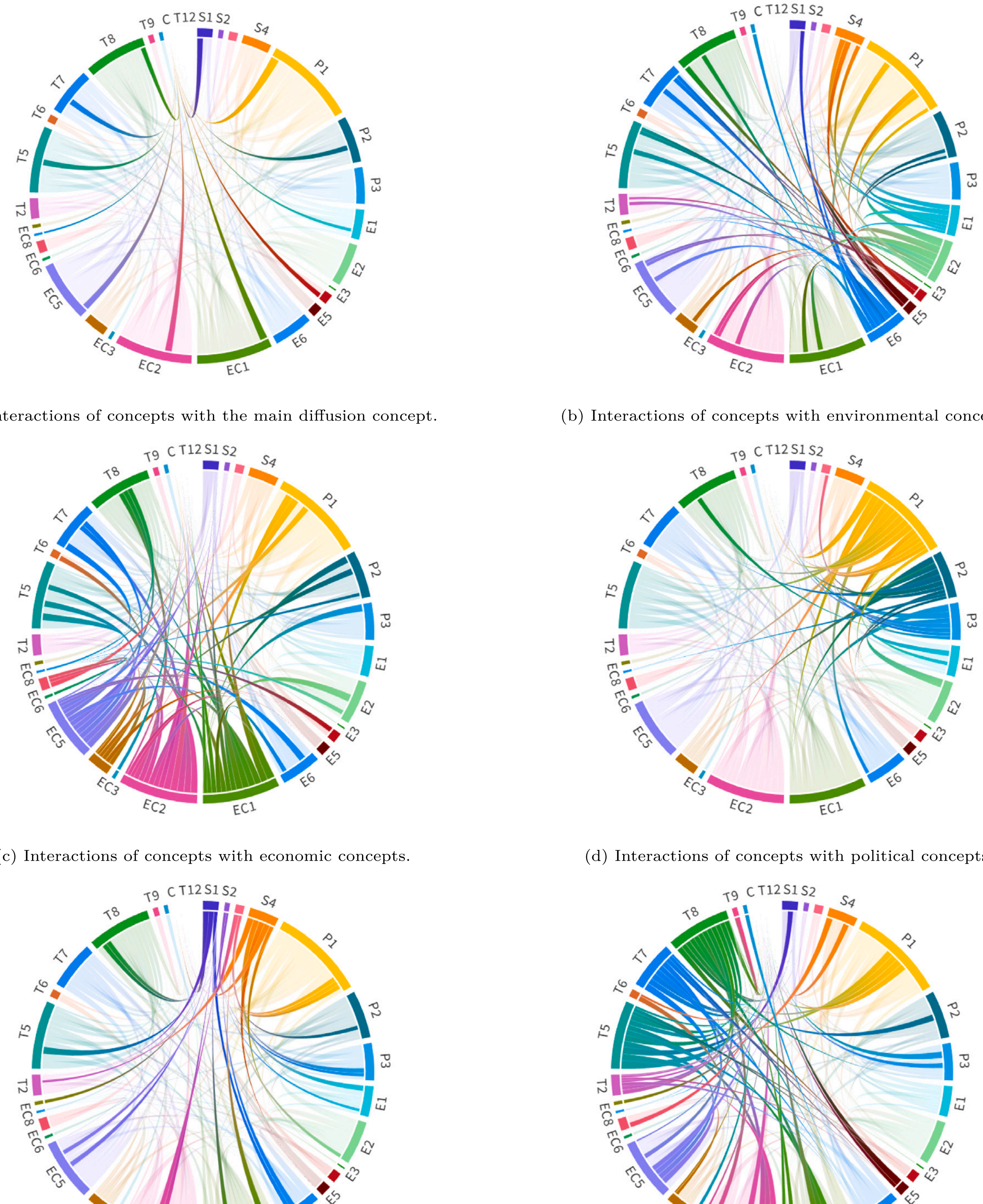
Fig. 6(a) depicts the potential status quo of the model, accounting for a sudden 20% surge in demand for renewable fuels (T2). Given the complex nature of the energy system, fuel properties, and their economic attributes, such rapid spike in demand can exert a substantial impact on the system. In this context, favorable changes are anticipated in terms of reduced GHG emissions (E1) and air pollutants (E3). To meet the heightened demand, an increase in fuel production is expected, potentially leading to a rise in direct or indirect land-use change (E5) due to increased biomass utilization, likely driven by increased investments and support for PBtX fuels. Likewise, the transition towards a bioeconomy is likely to be catalyzed, considering the role of PBtX fuels. A significant negative effect of −15% suggests that, contrary to expectations, there might be challenges in reducing GHG emissions in the short term, even with an increase in demand. This could be due to transitional inefficiencies, such as the continued use of fossil fuels during the ramp-up of renewable fuel production, or the carbon intensity associated with certain renewable fuel production methods. Ultimately, the diffusion process is projected to see a positive enhancement of 5%.

Fig. 6(b) presents an overview of the repercussions stemming from an increase in the volatility of the essential components necessary for PtX fuel production. It is evident that such deficiencies result in adverse outcomes, notably diminished social acceptance and trust (S1). A negative shift of −23% suggests that the public's trust and acceptance of PtX fuels could decline due to perceived unreliability in the availability and production of these fuels. Reduced GHG emission reduction (E1), decreased competitiveness against other renewable fuels and fossil fuels (EC2 & EC5), and, most critically, a 48% decline in fuel availability, subsequently causing a 35% reduction in the diffusion process are further changes in the model under this scenario. In contrast, in these circumstances, both direct and indirect land-use change and food competition experience a decrease of 12% and 8%, respectively. The availability of all three requisite components emerges as a notable concern for the diffusion process, given the seasonality and instabilities in resource maintenance throughout the year.

Economic factors are pivotal for the diffusion of PtX fuels, as their cost competitiveness relative to fossil fuels and other renewables is crucial. Government policies, subsidies, and market demand are also influenced by economic considerations, impacting PtX adoption. Ultimately, PtX fuels must offer a compelling economic value to gain traction in the market. For this purpose, two scenarios are built based on policies regulating price of PtX fuels as well as monetary incentives for renewable fuels.

- Policy Scenario III: One of the current challenges hindering the diffusion of PtX fuels is their high price compared to fossil fuels. Both the EU and Germany have explored various strategies to achieve cost competitiveness for PtX fuels, a critical step in advancing the energy transition and reducing reliance on fossil fuels. Carbon and renewable electricity are playing more crucial roles in price of PtX fuels compared to biomass. Currently, the EU is using Emission Trading System (ETS), Carbon Border Adjustment (CBA), and RED III for emission pricing. On the other hand, renewable electricity price is regulated by various policies including the RED III, EU ETS, EU Green Deal, Energy Efficiency Directive (EED) as well as different funds such as European Structural and Investment Funds (ESIF). In an ideal scenario, price parity would be attained, resulting in a reduction in fuel costs. Consequently, in this scenario, we evaluate the effects of a 35% reduction in PtX fuel prices within the model.
- Policy Scenario IV: A key economic factor influencing the diffusion of renewable fuels is the provision of monetary incentives aimed at motivating users to embrace these sustainable fuel alternatives. As the monetary incentives play a key role, a scenario is considered, where policies such as the RED III in its future amendments or new revisions of the ReFuelEU Aviation, and the FuelEU maritime increase monetary incentives by 35% compared to the current rate.

Fig. 7(a) demonstrates the prospective alterations in PtX fuel diffusion resulting from a 35% reduction in fuel price. Presently, the economic sustainability and affordability of PtX fuels are subjects of uncertainty, given their elevated costs in comparison to fossil fuels. This stands as a significant impediment to their widespread adoption



(a) Interactions of concepts with the main diffusion concept.

(b) Interactions of concepts with environmental concepts.

(c) Interactions of concepts with economic concepts.

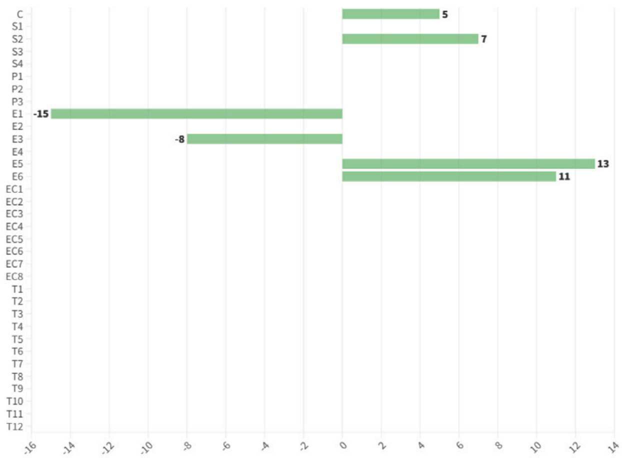
(d) Interactions of concepts with political concepts.

(e) Interactions of concepts with social concepts.

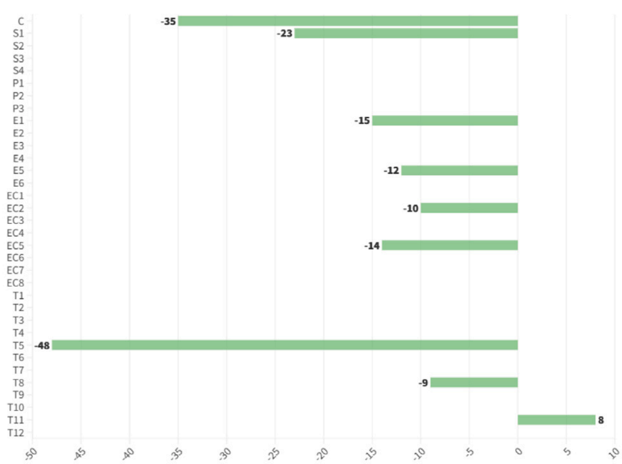
(f) Interactions of concepts with technical concepts.

Fig. 5. Detailed illustration of interactions among concept categories.

within the current energy market. According to the results, a decrease in price causes an increase in many concepts, specifically renewable fuel demand (T2), fuel availability (T5), competitiveness against other renewable fuels and fossil fuels (EC2 & EC5), economic sustainability of the fuel (E6), social acceptance & trust (S1), and therefore, the diffusion process. The findings verify the crucial role of PtX fuels in their diffusion process, demand, and economic competitiveness to their rival fossil fuels. The increase in market diffusion of PtX fuels (C) suggests that the reduction in PtX fuel prices has a profound effect on the market diffusion, making these fuels more attractive and accessible. Lower prices likely lead to higher adoption rates, greater market penetration, and an overall boost in the use of PtX fuels as a viable alternative to fossil fuels. In the same way, the price reduction brings PtX fuels closer to price parity with fossil fuels, making them a more competitive

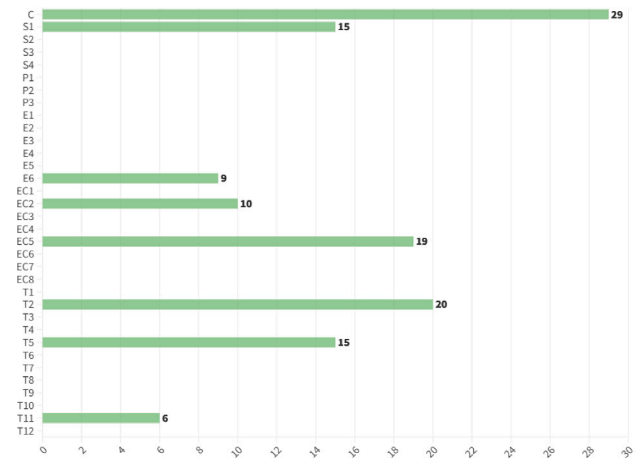


(a) Effects of 20% increase in demand.

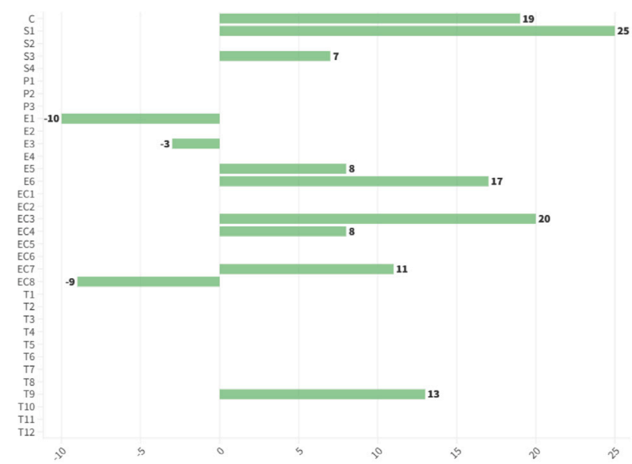


(b) Effects of 25% increase in the possibility of volatility in availability of biomass, renewable electricity, and CO_2.

Fig. 6. Effects of changes in technical components under different policy scenarios.



(a) Effects of 35% decrease in PtX fuel price.



(b) Effects of 25% increase in incentives for renewable fuels.

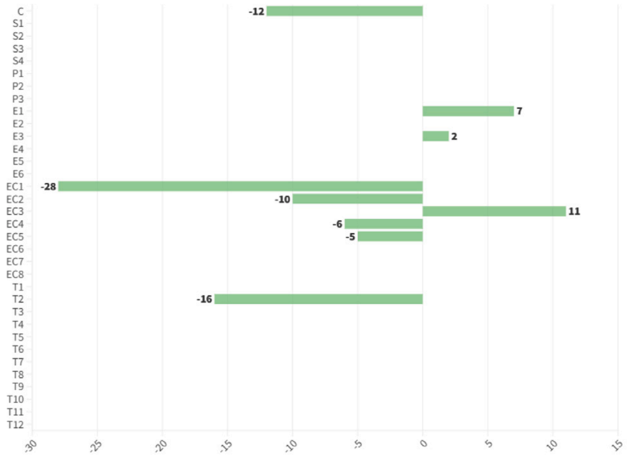
Fig. 7. Effects of changes in economic components under different policy scenarios.

option in the energy market. This improvement in cost competitiveness is crucial for the broader acceptance and use of PtX fuels. Of course, lower prices drive higher demand (T2), as more airlines and consumers are willing and able to switch from fossil fuels to PtX fuels.

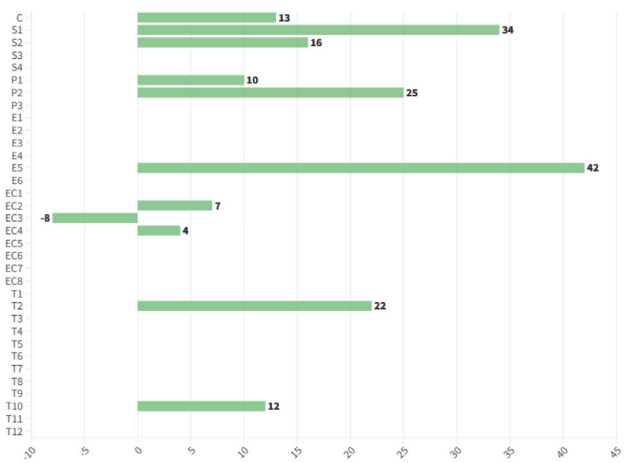
Fig. 7(b) reveals changes caused by a 35% increase in incentives for renewable fuels. In such circumstances, noticeable effects are visible in the social acceptance & trust (S1), PtX fuel price (EC3), the diffusion of PtX fuels (C), environmental sustainability of PtX fuels (E6), and transition cost (EC7). The increase in the diffusion of PtX fuels (C) indicates that the enhanced monetary incentives are highly effective in boosting the market diffusion of PtX fuels, as they make these alternatives more financially attractive to consumers and industries, leading to higher adoption rates. Next, public acceptance and trust (S1) increase by 19%, showing that higher incentives encourage more people to switch to renewable fuels. Financial benefits likely enhance public perception and trust in the sustainability and viability of these fuels, making them a more appealing choice. Competitiveness against fossil fuels and other renewable fuels are further significant effects of an increase in incentives. Negative effects are reflected in GHG emissions (E1) considering the possibility of allocation of such incentives to renewable fuels, emitting GHG emissions. Also, this could indicate that while incentives boost the adoption of PtX fuels, there may be short-term increases in emissions due to the transition phase or due to the specific production processes of certain PtX fuels. Moreover, such incentives also put the economic sustainability of PtX fuels under question by potentially creating economic sustainability challenges if the aviation and maritime sectors become too reliant on these financial supports, raising concerns about long-term viability without continued incentives.

Environmental concepts play significant roles in the diffusion of PtX fuels considering the overall climate change targets on the emission reduction. For this purpose, two scenarios are designed to understand impacts of policy modifications on lowering the environmental sustainability of PtX fuels and a significant increase in bioeconomy policies as follows.

- Policy Scenario V: Environmental sustainability is a pivotal consideration in the diffusion of PtX fuels. The historical use of synthetic fuels, including PtX fuels generated from non-renewable electricity sources, has raised concerns about their ecological impact. Therefore, the environmental sustainability of PtX fuels holds a crucial position in influencing their widespread adoption. While the RED III may serve as a significant policy governing the environmental aspects of PtX fuels, it is important to note that policies from diverse domains, including electricity generation, bioeconomy, and carbon capture, collectively exert substantial influence in this regard. To understand the failure of policies



(a) Effects of 25% decrease in environmental sustainability of PtX fuels.



(b) Effects of 75% increase in supporting bioeconomy.

Fig. 8. Effects of changes in environmental components under different policy scenarios.

aiming to improve the environmental sustainability of PtX fuels, a scenario is considered to measure a failure of relevant policies in form of 25% (slightly worse scenario) lower than their current standards.

- Policy Scenario VI: By the launch of the EU Green Deal, the EU's previous efforts on highlighting role of biomass was intensified strongly. Despite all potential challenges in this regard, bioeconomy is currently considered a viable plan for a sustainable future. Now, the bioeconomy is supported through various policies, but mainly through the EU bioeconomy as well as a national bioeconomy strategy in Germany. At the current rate, improvements in extending bioeconomy to different sectors and industries is expected. For this purpose, a scenario is developed to measure effects of an enhancement in success rate of bioeconomy-related policies by 75% (relatively best scenario).

Fig. 8(a) illustrates the outcomes resulting from Policy Scenario V, which leads to a 12% reduction in the diffusion of PtX fuels. This scenario is accompanied by a 28% decline in incentives for renewable fuels (EC1), subsequently diminishing the competitiveness of PtX fuels against other renewable alternatives (EC2) and fossil fuels (EC5). Policymakers and investors may be less inclined to support these fuels if they are not meeting environmental standards, leading to a potential reduction in financial or regulatory support. Another important effect is reflected on decrease in demand of renewable fuels (T2). Such a decrease in demand indicates that as PtX fuels become less environmentally sustainable, the overall demand for renewable fuels declines. Airlines and consumers and industries may turn to other renewable alternatives that offer better environmental benefits (e.g., advanced biofuels).

Next, Fig. 8(b) illustrates dramatic changes caused by improving the support for the bioeconomy. This indicates that the intensified support for the bioeconomy has a profound effect on driving the transition towards bio-based industries and practices. The success of bioeconomy-related policies significantly accelerates this shift, promoting sustainable development across aviation and maritime sectors. Diffusion of PtX fuels improves by 13% as bio-based production processes and supply chains become more established, PBtX fuels are likely to become more prevalent and accessible in the market. Other concepts such as social acceptance & trust (S1), EU/German energy policies (P2), and demand of renewable fuels (T2). Supporting the bioeconomy in such scale would strongly increases direct and indirect land-use changes (E5) and PtX fuel price (EC3).

Social factors and regulatory frameworks are important elements in the diffusion of PtX fuels. Thus, three scenarios are considered to measure impacts of possible changes in both categories.

- Policy Scenario VII: The EU has launched the Social Climate Fund (SCF) and different funds to support its policies regarding the energy transition to achieve the 2030 emission reduction target. The SCF aims to support households and individuals negatively affected by through the energy transition. Since societies hold a significant sway in the embrace of sustainable practices during the transition process, a dearth of social acceptance for new regulations, technologies, and fuels can impede progress, while a positive reception can foster further advancements. Therefore, we assume a scenario where implementation of the SCF has been successful and enhanced social acceptance & trust regarding the renewable fuels.
- Policy Scenario VIII: Energy security stands as a matter of paramount importance for the EU. The recent conflict between Ukraine and Russia vividly highlighted the dire consequences it can have on both the warring parties and neighboring EU member states. Being depended to oil and gas imports from Russia, its energy systems was strongly affected. Therefore, in this scenario, we aim to measure the impacts of a 20% increase in importance of external political events on the diffusion process.
- Policy Scenario IX: EU and German energy policies (P2), such as RED III, and PtX supportive regulations (P1), exemplified by the EU Hydrogen Strategy, wield substantial influence within the regulatory framework that supports PtX fuels. The RED III has set specific targets for PtX fuels within the category of renewable fuels of non-biological origins (RFNBOs) for 2030. Similarly, the EU Hydrogen Strategy has devised an array of measures and actions to stimulate the market growth of PtX fuels, including green hydrogen. Given the pivotal role of PtX fuels, there exists a notable likelihood that the EU may propose revisions to its current relevant policies to fortify energy and market policies in favor of these fuels. To gauge the potential impact of such an event, a scenario is considered, where the importance of both P1 and P2 is augmented by 50%.

Fig. 9(a) shows effects of potential social support through the SCF and other relevant policies on the model. Maximizing the social acceptance & trust (S1) strongly affect the diffusion process by +34%, followed by job creation (S2) by 3%, EU and German policies (P2) by 9%, shift to bioeconomy (E6) by 13%, GHG and combustion related emissions (EC1) by 12%, lowered subsidies for renewable fuels and increased tax on fossil fuels (EC4) by 7%, competitiveness of PtX fuels with fossil fuels (EC5) by 5%, and fuel demand by 17%.

Simultaneously, we observe that such a support in a social aspect lead to 5% decrease in risk perception. According to the results, social acceptance & trust play a significant role in the diffusion process and have noticeable influence on important components of the model.

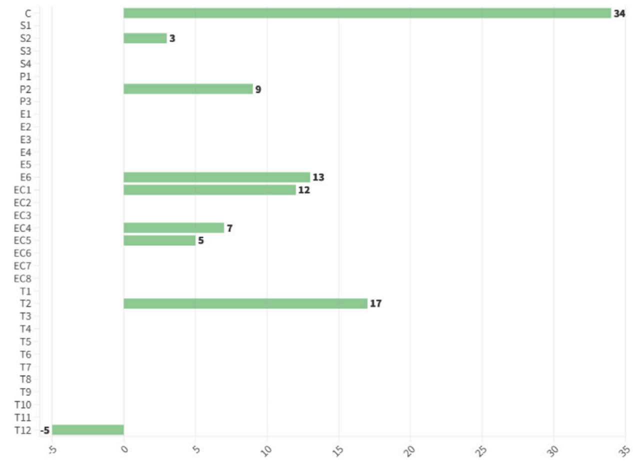
The EU's energy sector heavily relies on imports. Consequently, the absence of resilience and energy security within the energy sector can lead to substantial and costly repercussions in particular situations, such as during times of conflict or pandemics. Fig. 9(b) represents the model under a 55% increase in possibility of any external political event which may affect the model. In such circumstances, a noteworthy consequence is the heightened significance of PtX regulations (P1) and EU and German policies (P2). This is a logical response to decreased imports resulting from such events, compelling the EU to bolster its renewable energy capacity to meet the demand across various sectors. This would be followed by providing incentives through different policies to convince the society to change their energy options. Of course, under such circumstances, the scarcity of requirements for PtX fuels would also be another matter due to the sudden increase in the fuel demand; thus, the PtX fuel price could expect an increase in early years of such events.

Impacts of enhancing the support to PtX fuels through EU and German energy policies as well as PtX supportive market regulations are reflected in Fig. 9(c). As per the findings, this considerable level of support has a pronounced positive impact on PtX fuel diffusion. It leads to substantial enhancements in social acceptance and trust (S1), environmental sustainability (E6), incentives for renewable fuels (EC1), competitiveness of PtX fuels against fossil fuels (EC5), as well as fuel demand and availability (T2 & T5). Furthermore, it results in a noteworthy reduction in GHG emissions (E1), air pollutants (E2), and notably, PtX fuel prices (EC3). These results underscore the potential for significant effects to be achieved through the strengthening of the regulatory framework.

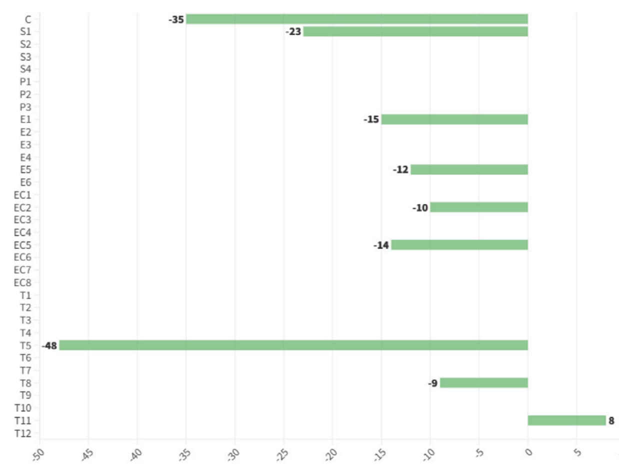
6. Discussions

In this study, we applied a novel cognitive approach to investigate the market diffusion of PtX fuels for policy support in achieving the 2030 and climate neutrality targets. The diffusion of PtX fuels heralds a paradigm shift towards sustainable and clean energy sources. However, the transition is filled with complexities and hurdles that necessitate a comprehensive evaluation. According to the structure of the FCM model, our results highlight the following perceived challenges.

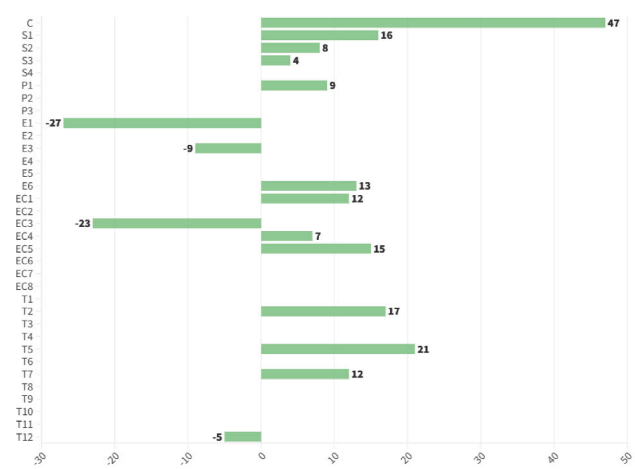
- Based on our findings, the fundamental difficulty with PtX fuels is their economic viability. PtX fuels require significant initial financial investment. In addition, it is economically difficult to achieve cost parity and promote market acceptance when competing with well-established fossil fuel-based alternatives. Important factors that will determine whether PtX fuels are successfully deployed include economic viability, scalability, conversion challenges and process efficiencies and cost effectiveness.
- While PtX fuels have the potential to reduce emissions and environmental impacts in support of the EU policies, it is important to consider environmental sustainability through the fuel life-cycles. To achieve a favorable environmental outcome, it is essential to comprehensively assess the full range of environmental implications, including resource utilization, water consumption, direct and indirect land-use, as well as potential unforeseen consequences. A critical aspect in this context is related to the utilization of electricity derived from renewable sources, as opposed to non-renewable ones. This is crucial for making PtX fuels environmentally friendly and bringing them closer to near-zero emissions. This principle similarly applies to direct air capture facilities, which have faced challenges due to their substantial costs. Simplifying the establishment of direct air capture facilities will play a key role in promoting the diffusion of PtX fuels and thus advancing the defossilization of the transport and other sectors.



(a) Effect of maximize increase in social acceptance & trust on the model.



(b) Effects of 55% increase in external political events.



(c) Effects of 50% increase in PtX market regulations, and EU/German energy policies.

Fig. 9. Effects of changes in social and regulatory components under different policy scenarios.

- A major obstacle is the lack of defined standards specifically designed for PtX fuels. The regulatory framework should encourage innovation, provide incentives for the deployment of PtX fuels, and establish clear sustainability standards. For a sustainable market diffusion, it is essential to align international and national legislation to simplify market entry and stimulate investment. The PtX economy is currently being indirectly shaped by a limited number of policies e.g., the RED III, whereas the EU needs stronger and better designed policies to strengthen its renewable fuel production capacity.
- Social acceptance and trust of PtX fuels are critical components of successful diffusion. According to the results, improving public perception, understanding and acceptance of these green fuels, particularly by addressing potential misconceptions and concerns, is critical to their widespread adoption. Stakeholder engagement and public education campaigns are effective ways to increase social acceptance. Currently, one of the major barriers to the social acceptance of PtX fuels is related to their higher cost and lower range.
- A significant barrier is the technical complexity of PtX technologies. R&D efforts are needed to address technology maturity, scale-up issues, efficiency improvements, and optimization of the overall PtX process. Successful diffusion depends on bridging the gap between laboratory-scale developments and scalable, commercially viable solutions.
- The findings reveal stakeholders' concerns about the origin of biomass used for PBtX fuels and the potential risk of competition with food production. These concerns are further amplified by the lack of a clear definition for RFNBOs, discussed in Section 4.1, and the possibility of volatility or shortages in non-biological biomass to meet the growing demand for PBtX fuels. This uncertainty raises critical questions about the long-term sustainability and scalability of PBtX production, particularly in balancing energy needs with food security. Future revisions on the relevant policies need to address this concern in order to mitigate the controversy about biomass origin.

According to the results, the FCM model effectively builds up a comprehensive model of factors influencing the diffusion PtX as well as their interrelationships. Initial results revealed the importance of specific factors including food competition (T11), process efficiencies (T8), fuel availability (T5), competitiveness of PtX fuels against other renewable fuels (EC2), incentives for renewable fuels (EC1), shift to bioeconomy (E6), PtX supportive market regulations (P1), and competitiveness of PtX fuels against fossil fuels (EC5). In this context, our goal is to conduct an in-depth exploration of each of these factors and subsequently provide well-founded recommendations. To begin, we will delve deeper into the intricacies of these crucial elements.

The successful diffusion of PtX fuels depends heavily on rigorous research and advances in process efficiency within the production process. Energy conversion efficiency is a key metric in production systems. The improvement of energy conversion efficiency in PtX processes is enabled by research. Understanding the fundamental chemical and electrochemical processes enables the development of catalysts and technological advances that promote more effective energy conversion, resulting in higher yields and lower energy consumption. In their production systems, electrolysis plays an important role in converting electricity into chemical energy stored in fuels. To reduce energy losses during the electrolysis process and ultimately increase efficiency, research can help improve electrolyzer designs, electrolyte properties and electrode materials. In addition, research is focused on developing sustainable PtX production processes that minimize the energy and resource footprint. On the other hand, carbon capture and utilization through PtX technologies can be used to produce fuels and chemicals. Funding research programs to optimize carbon capture efficiency, identify efficient catalysts, and explore novel pathways for CO_2 conversion to PtX fuels is essential.

The use of biomass as a feedstock for PtX production ensures a sustainable, carbon-neutral pathway, as the CO_2 released during consumption is offset by the CO_2 absorbed during biomass growth. In addition, the diversity of biomass feedstock sources, such as agricultural residues, forest residues, algae, and organic wastes, diversifies the resource for PtX production, thereby improving the resilience and sustainability of the production process and stabilizing it in the event of feedstock availability and price shortages. In addition, PtX fuels serve as a bridge between the established fossil fuel economy and the emerging bioeconomy. By using PtX technology to convert biomass into fuels, we gradually move towards a sustainable bioeconomy where renewable resources are preferred to other resources in the production of energy and chemicals. Highlighting the role of biomass feedstock for PtX production would also lead to economic benefits such as job creation in the supply chain.

As discussed above, economic sustainability and affordability are critical barriers that currently prevent the diffusion of PtX fuels. To increase the commercial viability of PtX fuels, incentives and subsidies are essential. They can help offset high capital costs, lower production costs, and increase the parity of PtX fuels with traditional substitutes. Improving investor trust and encouraging private sector involvement in PtX projects can be achieved through the implementation of subsidies and incentives. Such measures could accelerate the commercialization of emerging technologies and their subsequent deployment. In addition, incentives are essential to promote market entry and growth, foster innovation, and facilitate the deployment of PtX infrastructure. In this way, the economic competitiveness of PtX fuels with renewable and fossil fuel counterparts can be strongly supported. Subsequently, by supporting their environmentally friendly characteristics (in resource utilization within the production process), their competitiveness can be enhanced to a stable point required for price parity.

The regulatory framework is currently a big obstacle ahead of PtX fuels. PtX fuels are mandated mainly by the RED III. The RED III in its most recent revision, explicitly included PtX fuels under RFNBOs category for the transport and industry sectors. Most relevant policies regulating PtX fuels in the EU and Germany is supported by the EU Hydrogen Strategy and the German National Hydrogen Strategy. Most recently, Germany launched a roadmap for power-to-liquid (PtL) fuels, supporting sustainable aviation fuels. Beyond this initiative, the rest of regulatory principles are covered in the Climate Action Plan, and the NPM. In this regard, development of required policies exclusively for PtX fuels can enhance their market diffusion. For this purpose, feed-in-tariffs and subsidies can play key roles in regulating the market. Government subsidies and feed-in-tariffs for PtX fuels can significantly reduce their production costs, enhancing their competitiveness against fossil fuels. These financial incentives promote investment and innovation in PtX technology. Moreover, providing a reliable environment for investments of private sector in PtX can be supported via proper policy design in form of tax and financial credits. Moreover, various costs occur to the individuals through the energy transition. The SCF, launched by the EU, mainly focuses on electrified transport while, PtX fuels are not included in its main plans. Therefore, a similar initiative can be considered to financially support sectors willing to adopt PtX fuels, specifically in aviation and maritime.

All in all, addressing market diffusion requires reliable tools to formulate the problem in a perfect and realistic way, thus avoiding falsehoods and biased results that can negatively affect policy making. Addressing the market diffusion of PtX fuels by examining its influencing factors is improved in accuracy, reliability, and comprehensiveness thanks to the developed cognitive approach, which provides a robust reasoning framework by consolidating experts' judgments over decision-makers' opinions. By using the developed approach, decision makers and stakeholders can gain crucial insights into the critical factors influencing the diffusion process in a complex system. For the PtX market diffusion, a robust and comprehensive approach to model all potential entities within the system is highly required to be able to use the results to propose required strategies and policies. This would play a key role in shaping the future of renewable fuels in the transport sector as well as the policy paradigm.

7. Conclusions

Renewable fuels, in particular PtX fuels, hold promise as alternative options to replace fossil fuels, and contribute to the defossilization of parts within the transport sector that are not suitable to electrification. While Germany has made significant efforts to promote renewable fuels in its quest to reduce GHG emissions and achieve climate neutrality, the marginal reduction in emissions within the transport sector underscores the importance of PtX fuels. However, the diffusion of PtX fuels encounters obstacles due to the dominance of fossil fuels in the market, coupled with technical, economic, social, environmental, and political challenges. Moreover, the involvement of multiple stakeholders from different sectors adds to the complexity and challenges associated with the diffusion of PtX fuels.

To examine the interconnections among cross-sectoral factors that affect the diffusion process, leveraging empirical data within a multi-stakeholder setting, a novel cognitive approach is developed based on the extended Z-numbers theory to investigate the market diffusion of PtX fuels in Germany. The developed approach empowers policymaking with a reliable and accurate cognitive framework through incorporating decision-makers and experts. Using the developed approach, a real case study was conducted for the diffusion of PtX fuels in the German transport sector, mainly aviation and maritime. For this purpose, a two-fold survey was proposed to collect the required data to build the FCM model. The first survey aimed to build the FCM model based on different stakeholders' opinions. The second survey aimed to determine weight of interrelationships based on decision-makers' opinions and experts' judgments.

Results showed that the FCM built by stakeholders for investigating the diffusion of PtX fuels consists of 34 concepts, which are interconnected through 260 links. The FCM model aims to analyze the factors that potentially influence the diffusion process from different perspectives. In this regard, observations show that the diffusion of PtX fuels in Germany is predominated by technical and economic concepts. Furthermore, social, regulatory, and environmental concepts show lower authoritative effect on the diffusion compared to technical and economic concepts. Initial results reveals high significance of different concepts, specifically process efficiency in the production of PtX fuels, fuel availability, food competition for the biomass usage, competitiveness of PtX fuels against fossil fuels and other renewable fuels as well as monetary incentives for renewable fuels and PtX-favored market regulations. Several scenarios are considered to measure the effects of changes in different concepts under different circumstances.

Although this study addresses an important problem in the German transport and energy sector, there are several limitations that can be addressed in future studies. The diffusion of PtX fuels is a complex problem and future studies can integrate different diffusion models such as the Bass diffusion model with FCM or system dynamics to incorporate innovation adoption dynamics and improve policy analysis. Learning algorithms can play an important role in FCM models by refining the weights. Future studies can use population-based, Hebbian-based or hybrid algorithms to determine the optimal weights of relationships. In addition, understanding the importance of concepts and clustering them into the same groups with concepts that show similar behaviors can provide useful information about the performance of the model. Thus, different clustering algorithms can be applied to identify concepts with similar behaviors. Moreover, a large-scale decision-making process could also be approached by involving a greater number of stakeholders for the same model. Another way to reflect social perceptions on the diffusion process is to build a model based on data gathered from social media through natural language processing algorithms. This would allow for a more comprehensive analysis of public sentiment and broader stakeholder engagement, providing additional insights into the potential challenges and opportunities related to the use of PtX fuels. In addition, the developed FCM model can be adopted and modified to analyze the market diffusion of different renewable fuels through modifying the diffusion factors.

CRediT authorship contribution statement

Ali Ebadi Torkayesh: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sandra Venghaus:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition.

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.

Acknowledgments

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – Cluster of Excellence 2186 "The Fuel Science Center" – ID: 390919832.

Appendix

See Tables A.1–A.3 and Figs. A.1–A.4.

Table A.1
Participant information.

Category	Detail	Count
Gender	Male	7
	Female	6
	Not disclosed	7
Professional sector	Academia	12
	Transport	2
	Fuel and Chemical Engineering	1
	Not disclosed	5
Professional role	Researchers (Ph.D., leaders)	9
	Full Professor	1
	Master's Student	1
	Technical Engineer	1
	Energy Consultant	1
	Fuel Specialist	1
	Not disclosed	6
Years of experience	Over 10 years	2
	1–3 years	6
	3–8 years	6
	Not disclosed	6
Academic Degrees	Ph.D.	5
	MA/MSc	8
	BA/BSc	2
	Not disclosed	5

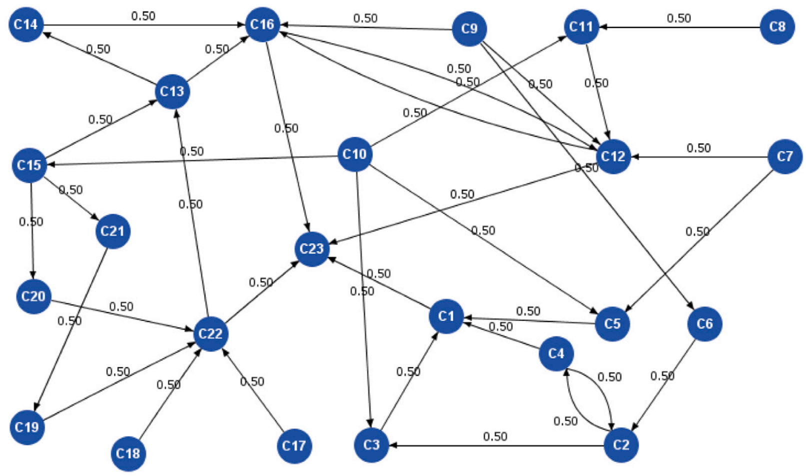


Fig. A.1. Initial FCM model based on a literature review, where C_i shows the concepts with primary edge weights set to 0.5.

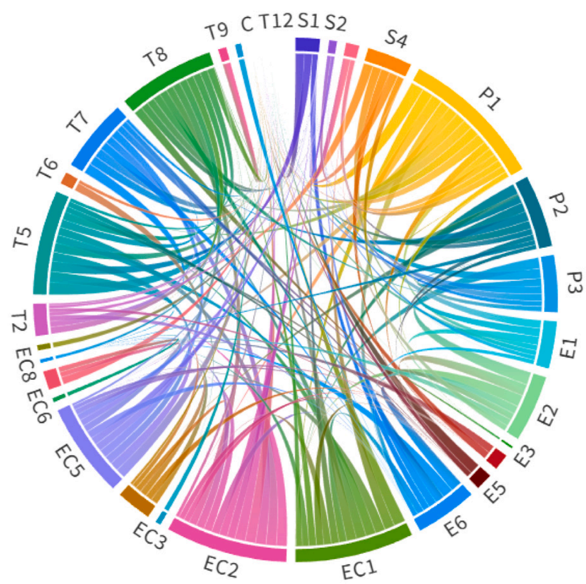


Fig. A.2. The final FCM model with finalized causalities.

Table A.2
Experts' judgments over decision-makers' opinions.

	First decision-maker				Second decision-maker					First decision-maker				Second decision-maker			
	Agree	Disagree	Neutral	R	Agree	Disagree	Neutral	R		Agree	Disagree	Neutral	R	Agree	Disagree	Neutral	R
C	5	0	0	1	1	1	3	0	EC4	1	1	3	0	4	0	1	1
S1	4	1	0	0.60	5	0	0	1	EC5	1	1	3	−0.33	3	0	2	1
S2	3	0	2	1	1	2	2	−0.33	EC6	2	0	3	1	1	4	0	−0.60
S3	4	1	0	0.60	4	0	1	1	EC7	5	0	0	1	4	1	0	0.60
S4	5	0	0	1	1	2	2	−0.33	EC8	1	3	1	−0.50	1	3	1	−0.50
P1	3	1	1	0.50	4	1	0	0.60	T1	1	0	4	1	1	1	3	0
P2	5	0	0	1	2	2	1	0	T2	2	1	2	0.33	1	3	1	−0.50
P3	5	0	0	1	4	1	0	0.60	T3	4	1	0	0.60	2	0	3	1
E1	4	0	1	1	1	3	1	−0.50	T4	2	0	3	1	3	0	2	1
E2	4	0	1	1	4	0	1	1	T5	5	0	0	1	4	0	1	1
E3	4	1	0	0.60	1	3	1	−0.50	T6	5	0	0	1	5	0	0	1
E4	4	0	1	1	3	1	1	0.50	T7	4	0	1	1	4	0	1	1
E5	3	0	2	1	5	0	0	1	T8	5	0	0	1	3	1	1	0.50
E6	3	0	2	1	5	0	0	1	T9	2	0	3	1	1	3	1	−0.50
EC1	3	0	2	1	4	1	0	0.60	T10	1	3	1	−0.5	4	1	0	0.60
EC2	4	0	1	1	4	0	1	1	T11	1	1	3	0	1	1	3	0
EC3	1	3	1	−0.50	4	1	0	0.60	T12	2	0	3	1	3	0	2	1

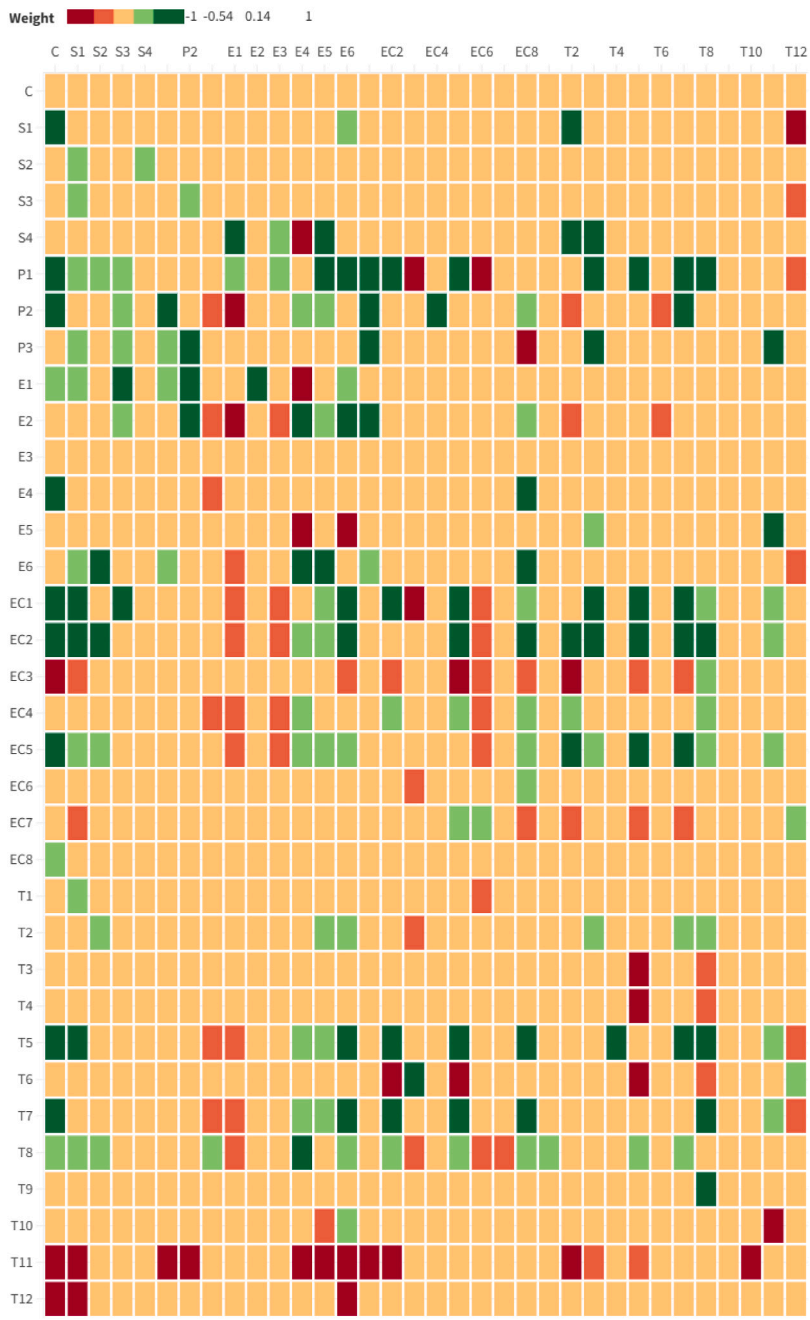


Fig. A.3. A heatmap of the final FCM model based on the causal degrees.

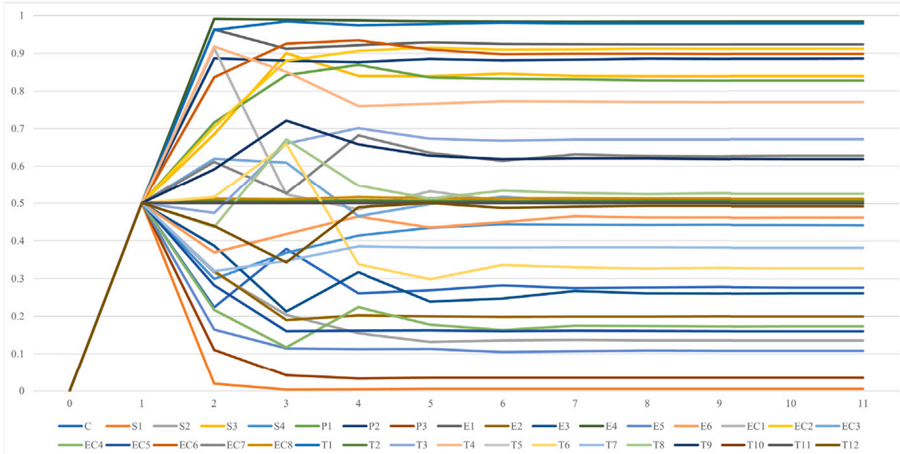


Fig. A.4. Inference analysis of components (x-axis represents iterations, and y-axis shows the activation value).

Table A.3
Results of inference analysis.

Iteration	$i = 0$	$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$	$i = 7$	$i = 8$	$i = 9$	$i = 10$	$i = 11$
C	0	0.5	0.22	0.38	0.26	0.27	0.28	0.27	0.28	0.28	0.28	0.28
S1	0	0.5	0.02	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
S2	0	0.5	0.32	0.20	0.15	0.13	0.14	0.14	0.14	0.14	0.14	0.14
S3	0	0.5	0.69	0.90	0.84	0.84	0.85	0.84	0.84	0.84	0.84	0.84
S4	0	0.5	0.30	0.37	0.41	0.43	0.44	0.44	0.44	0.44	0.44	0.44
P1	0	0.5	0.72	0.84	0.87	0.84	0.83	0.83	0.83	0.83	0.83	0.83
P2	0	0.5	0.89	0.88	0.88	0.89	0.88	0.88	0.89	0.89	0.89	0.89
P3	0	0.5	0.11	0.04	0.03	0.04	0.03	0.03	0.04	0.04	0.04	0.04
E1	0	0.5	0.96	0.91	0.92	0.93	0.92	0.92	0.92	0.92	0.92	0.92
E2	0	0.5	0.32	0.19	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
E3	0	0.5	0.39	0.21	0.32	0.24	0.25	0.27	0.26	0.26	0.26	0.26
E4	0	0.5	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.98
E5	0	0.5	0.16	0.11	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.11
E6	0	0.5	0.37	0.42	0.46	0.44	0.45	0.46	0.46	0.46	0.46	0.46
EC1	0	0.5	0.91	0.52	0.48	0.53	0.51	0.50	0.51	0.51	0.51	0.51
EC2	0	0.5	0.71	0.88	0.91	0.92	0.91	0.91	0.91	0.91	0.91	0.91
EC3	0	0.5	0.62	0.61	0.46	0.50	0.52	0.51	0.51	0.51	0.51	0.51
EC4	0	0.5	0.22	0.12	0.22	0.18	0.16	0.17	0.17	0.17	0.17	0.17
EC5	0	0.5	0.28	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
EC6	0	0.5	0.84	0.93	0.93	0.91	0.90	0.90	0.90	0.90	0.90	0.90
EC7	0	0.5	0.61	0.53	0.68	0.64	0.61	0.63	0.63	0.63	0.63	0.63
EC8	0	0.5	0.51	0.51	0.52	0.51	0.51	0.51	0.51	0.51	0.51	0.51
T1	0	0.5	0.96	0.99	0.97	0.98	0.98	0.98	0.98	0.98	0.98	0.98
T2	0	0.5	0.51	0.50	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
T3	0	0.5	0.47	0.66	0.70	0.67	0.67	0.67	0.67	0.67	0.67	0.67
T4	0	0.5	0.92	0.85	0.76	0.77	0.77	0.77	0.77	0.77	0.77	0.77
T5	0	0.5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
T6	0	0.5	0.52	0.66	0.34	0.30	0.34	0.33	0.33	0.33	0.33	0.33
T7	0	0.5	0.32	0.35	0.39	0.38	0.38	0.38	0.38	0.38	0.38	0.38
T8	0	0.5	0.44	0.67	0.55	0.51	0.53	0.53	0.52	0.53	0.53	0.53
T9	0	0.5	0.59	0.72	0.66	0.63	0.62	0.62	0.62	0.62	0.62	0.62
T10	0	0.5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
T11	0	0.5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
T12	0	0.5	0.44	0.34	0.49	0.50	0.49	0.49	0.49	0.49	0.49	0.49

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