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Mapping the hydrogen transition in the Netherlands: A sociotechnical multi-system event sequence analysis

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ABSTRACT

Hydrogen is considered a promising energy carrier that can potentially contribute to low-carbon energy systems and achieving climate goals. Its introduction, however, is complex, involving multiple emerging niches and developments across various sociotechnical systems. Despite its significance, the multi-system nature of hydrogen has received limited attention in sustainability transition scholarship. This paper addresses this knowledge gap by examining the emerging hydrogen transition in the Netherlands from a multi-system sociotechnical perspective. To achieve this, we adopted a framework that considers multiple niches and sociotechnical systems in parallel, using Event Sequence Analysis (ESA). The analysis provides a systematic reconstruction of (niche-)processes as networks of events for analysing hydrogen niche formation from 2001 to 2020 across four sociotechnical systems: industry, electricity, transport, and the built environment. The results reveal that, despite positive discourse and ambitious plans, investments and implementation remained limited. We provide possible explanations for this progress through a multi-system lens.

1. Introduction

Hydrogen is increasingly considered a promising energy carrier with significant potential to support the transition to low-carbon energy systems and help achieve climate goals (Chapman et al., 2019; Parra et al., 2019; Hanley et al., 2018; UNFCCC, 2015). Attention towards hydrogen is expected to remain high, as liquid and gaseous energy carriers are projected to play a key role in future sustainable energy supply (Li et al., 2010; Uhrig et al., 2020). Additionally, hydrogen is often regarded as a highly promising option compared to alternative solutions (Staffel et al., 2019; Parra et al., 2019; Hanley et al., 2018). If produced carbon-free,[1] hydrogen can contribute to decreasing carbon dioxide emissions in multiple sociotechnical systems, such as electricity (e.g., seasonal storage), industry (e.g., as raw material or high-temperature heating), transport (e.g., fuel-cell vehicles) and the built environment (e.g., in heat

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[1] Hydrogen can be subdivided into different colours indicating its production process; Grey hydrogen is produced from fossil fuels. Blue hydrogen is produced from fossil fuels with carbon capture and storage. Green hydrogen is produced from renewable energy, usually through electrolysis.

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supply). In this paper, sociotechnical systems refer to linkages between a large variety of social and physical elements necessary to fulfil societal functions (Geels, 2004; Markard, 2011). Our definition of 'sociotechnical system' encompasses sectors, regimes, and industries.

Due to its potential, hydrogen niches are emerging globally, particularly in industrialised countries. This emergence is often supported by ambitious visions of transitioning to a hydrogen-based society where hydrogen becomes the primary energy carrier (Chaube et al., 2020; European Commission, 2020; Australian government, 2019; IEA, 2021a). For example, the Dutch government pursues hydrogen as a central energy carrier through simultaneous introduction in the four systems mentioned above, emphasising an 'all-encompassing approach' (Government of the Netherlands, 2020a). This highlights hydrogen's role as a complex multi-system energy carrier, involving numerous emerging niches, including different technologies and end-uses across various systems that potentially contribute to a broader hydrogen transition (Kovač et al., 2021; Züttel et al., 2010; Mazloomi and Gomez, 2012). Here, 'multi-system' indicates that hydrogen spans multiple sociotechnical systems (IEA, 2021a; Fridgen et al., 2020; Büscher et al., 2020). The success of such a transition depends on changes up and down the value chain and on numerous technical, institutional, and social processes. Achieving this requires collaboration, alignment, and coordinated efforts among diverse actors from society, government, science, and industry, each with different backgrounds and agendas (Geels, 2004; Markard et al., 2012).

While many actors in the energy domain articulate ambitious cross-system goals for hydrogen implementation, the study and understanding of complex and interwoven multi-system transition initiatives in sociotechnical transition studies remain limited. Typically, research in this field relies on case studies emphasising selected technologies in specific sociotechnical systems, such as transport or heating (as pointed out by Papachristos et al., 2013; Geels, 2018b; Schot and Kanger, 2018; McMeeking et al., 2019). This trend is reflected in hydrogen-related transition studies, which focus on emerging niches in specific sociotechnical systems, such as energy-intensive industries (Griffiths et al., 2021; Kushnir et al., 2020), the refinery system (Nurdiawati and Urban, 2022), the maritime system (Bach et al., 2020), and the transport system (van Bree et al., 2010; Suurs et al., 2009; Hacking et al., 2019). Although these single-system hydrogen studies have provided valuable insights into specific niches, a significant gap remains in understanding how niches interact and influence each other across sociotechnical systems (Andersen and Markard, 2020; Markard and Hoffmann, 2016; Sandén and Hillman, 2011).

Recently, the importance of multi-system interactions in low-carbon transitions has gained recognition, as innovations spanning multiple systems—such as hydrogen, electric vehicles, and smart grids—have become central to decarbonisation strategies.[2] The complex multi-system nature of these innovations presents distinct challenges, such as alignment of diverse actor-networks and governance institutions. While this complexity can foster synergies—such as economies of scale, technological learning, and shared infrastructure—it may also introduce competition for limited resources.[3] These dynamics are especially critical for hydrogen, given its potential to support multiple systems and the current scarcity and high cost of sustainable hydrogen production. This growing complexity has prompted an increased focus on multi-system dynamics in transition studies (Köhler et al., 2019; Andersen and Markard, 2020; Rosenbloom, 2020; Andersen and Geels, 2023; Markard, 2018; Andersen et al., 2020). Consequently, research on hydrogen implementation from a multi-system perspective is emerging, for instance, in the German context (Löhr and Chlebna, 2023; Ohlendorf et al., 2023). However, empirical studies and conceptual frameworks for analysing multi-system innovations remain limited, underscoring the need for further research to deepen understanding of these interactions (Bakhuis et al., 2024; Rosenbloom, 2020).

This paper addresses the need for deeper exploration of multi-system dynamics by examining how hydrogen niche development across various systems interrelates and potentially contributes to a broader hydrogen transition in the Netherlands. Addressing the challenges and knowledge gap presented, the main research question of this paper is: *"How is hydrogen niche development progressing in the Netherlands, taking a multi-system sociotechnical perspective?"*

The research question raises a conceptual and methodological challenge in uncovering interactions between multiple niches that span various sociotechnical systems. To systematically examine these multi-system interactions, we employ Event Sequence Analysis (ESA), a methodology that provides tools for systematically reconstructing processes as networks of events (Boons and Spekkink, 2012; Spekkink and Boons, 2016). By adopting a process-oriented perspective that treats events as the fundamental units of analysis, this study facilitates a historical reconstruction of hydrogen niche development across four key sociotechnical systems. This approach allows us to explore how these systems interact and mutually shape a potential broader hydrogen transition in the Netherlands. Our conceptual point of departure is a multi-system framework developed in Bakhuis et al. (2024), which builds on the Multi-Level Perspective (MLP) (Smith et al., 2010; Geels et al., 2017) and Strategic Niche Management (SNM) (Schot and Geels, 2008; Turnheim and Geels, 2019).

This paper is organised into six sections. Section 2 presents the conceptual framework guiding the research. Section 3 introduces Event Sequence Analysis (ESA), detailing the data collection and analysis methods while highlighting how ESA differs from earlier event analysis in transition studies. Section 4 presents the results of the empirical analysis. Section 5 offers a discussion of the findings, and Section 6 presents the conclusions of the research.

[2] Aside from the introduction of multi-system innovations, the interconnection between energy-demanding systems such as transport, industry and the built environment—often referred to as 'sector coupling'—can help deal with peaks that arise with increased intermittent electrification in future energy systems, (Fridgen et al., 2020; Brown et al., 2018).

[3] Developments in different systems may strengthen or weaken each other, adding another layer of complexity.

2. Theoretical background

2.1. Understanding sociotechnical transitions

2.1.1. Multi-Level perspective (MLP)

Within transition studies,[4] the Multi-Level perspective (MLP) is widely used for understanding transitions (Smith et al., 2010; Geels and Schot, 2010; Geels, 2002). The MLP describes transitions in terms of interactions and dynamics between three different analytical levels (Geels, 2002; Geels and Kemp, 2000; Rotmans et al., 2000).

First, the sociotechnical regime level represents established systems intended to fulfil specific societal functions, such as the fossil-based electricity system. Within the regime, there is often resistance to innovation due to vested interests, institutions, and actor networks that uphold existing rules, methods, and practices (Geels, 2004, 2014). Second, the niche level refers to protected spaces where unconventional practices and radical innovations—such as hydrogen technologies—can develop without pressures from the harsh selection processes associated with established regimes (Kemp et al., 1998; Hoogma et al., 2002; Smith and Raven, 2012; Schot and Geels, 2008). These innovations are supported by the heterogeneity of the selection environment, including prices, preferences, and standards. Third, the sociotechnical landscape encompasses external factors shaped by broader trends and developments (e.g., political, cultural, or macroeconomic) that usually evolve slowly but influence regimes and niches. However, sudden developments or systemic shocks like pandemics (e.g., Covid-19), international agreements (e.g., the Paris Climate Agreement), or wars (e.g., the Russian invasion of Ukraine) can also be considered landscape factors (Smith et al., 2010).

Central to the MLP is the interdependence among its three analytical levels, which collectively shape the introduction and success of innovations (Rotmans et al., 2001; Geels, 2018a; Loorbach et al., 2017). Transitions can take various forms but always result from interactions among processes at all three levels, each influencing the other (Geels and Schot, 2007; Geels et al., 2017). Within the traditional conceptualisation, transitions involve the gradual emergence and further development of a niche that disrupts or replaces an existing regime over several decades (e.g., Geels, 2002), defined as the substitution pathway. However, alternative pathways are also possible (Geels and Schot, 2007).

2.1.2. Strategic niche management (SNM)

The Strategic Niche Management (SNM) concept complements the MLP by providing a framework for analysing internal niche dynamics (Raven, 2005; Schot and Geels, 2008; Markard et al., 2012; Kamp and Vanheule, 2015; Turnheim and Geels, 2019). This framework highlights three crucial 'internal niche processes' for successful niche development: visioning and expectations, network formation, and learning. These processes are useful for assessing niche dynamics and determining a niche's progress (Schot et al., 1996; Kemp et al., 1998).

The internal niche processes and their assessment criteria entail the following. First, through niche experimentation, visions and expectations can become more supported by actors (robustness), more specific and clear (focus), and more substantiated by growing evidence (high-quality) (van der Laak et al., 2007). Second, actor-network formation facilitates the expansion of collaborative ties among participants in niche experimentation, helping them align more closely over time and enhance their collective impact as various actors support the expectations (van der Laak et al., 2007; Hoogma, 2000). Third, learning processes are categorised into 'first-order learning,' which involves more incremental learning processes (e.g., data-based process optimisation, and learning on selected KPIs), and 'second-order learning', which entails critical reflection on the fundamental assumptions of the innovation (e.g., reimagining individual vehicles as car-sharing) (Hoogma et al., 2002). Both types of learning are typically essential for a robust learning process (Schot and Geels, 2008).

Central to this framework is the interconnectedness of these internal niche processes, forming a feedback loop that drives 'innovation journeys' (Mourik and Raven, 2006; Raven et al., 2010). For instance, positive expectations can motivate actors to invest in experiments, which facilitates learning and refines expectations, ultimately attracting more participants to the network.[5]

2.2. A sociotechnical multi-system perspective on transitions[6]

Transition studies have traditionally mainly adopted a single-system perspective (Geels, 2018a; Markard et al., 2016). While earlier work began exploring multi-system interactions (Raven, 2007; Konrad et al., 2008; Raven and Verbong, 2007; Geels, 2007; Papachristos et al., 2013), research in this topic has surged since 2015 (see Fig. 4 in Bakhuis et al., 2024). Drawing from this work, a recent literature review highlights three key aspects to consider when adopting a multi-system perspective (Bakhuis et al., 2024).

[4] This study is grounded in the transition studies literature, which adopts a sociotechnical perspective to understand the profound reconfigurations required for transformative change in complex, non-linear transition processes (Rip & Kemp, 1998; Geels, 2002).

[5] In recent years, scholars have addressed criticisms regarding the broadness of the internal niche processes by validating and elaborating on the SNM framework (Heiskanen et al., 2015; Smith & Raven, 2012; Kamp & Vanheule, 2015). For example, Kamp & Vanheule (2015) added diversity to the origin of stakeholder expectations (i.e., internal, external, endogenous, exogenous). Naber et al. (2017) differentiated between local and global occurrences, making it possible to consider 'unplanned occurrences.' More recently, Turnheim and Geels (2019) discerned three pattern deviations: (i) Incumbent actors from adjacent regimes can play a principal role in advancing radical alternatives; (ii) the timing of voicing expectations can significantly influence the transition pathway; and (iii) critical projects can have a stimulating effect on the advancement of innovation.

[6] This section is adapted from Bakhuis et al. (2024).

First, studies show the added value of explicitly examining system configurations. This involves clearly identifying and characterising the sociotechnical systems involved and assessing adjacent innovations. Early multi-system research revealed common interactions between regimes—which can be complementary (mutually supportive), symbiotic (interdependent), or competitive (resource competition)—and showed how these interactions evolve (Geels, 2007; Raven and Verbong, 2007; Konrad et al., 2008; Erlinghagen and Markard, 2012). Later studies focused on value chain interactions (Bergek et al., 2015; McMeekin et al., 2019; Mäkitie et al., 2018), emphasising the importance of defining an innovation's "sectoral configuration," which includes the number and types of systems linked to its value chain (Stephan et al., 2017; Malhotra et al., 2019). Research also demonstrated how technologies can intersect or connect multiple systems, resulting in "technology-induced" multi-system interactions (Geels, 2007; Papachristos et al., 2013; Dolata, 2009; Markard et al., 2016; Sutherland et al., 2015). This highlights the importance of studying adjacent innovations that may either compete with or complement the focal innovation (also termed "complementarities") (Markard and Truffer, 2008; Wirth and Markard, 2011; Markard and Hoffmann, 2016; Sandén and Hillman, 2011).

Second, research highlights the relevance of understanding the phase of each system's transition. Different systems often progress at varying speeds due to factors such as timing, duration, and acceleration (Geels et al., 2017; Löhr and Chlebna, 2023). For instance, the transition of the electricity system to low-carbon technologies is more advanced than that of the transport system in many European countries (Mitchell, 2016; IEA, 2021b). These differing phases impact actors, institutions, and technologies. Some researchers break down transitions into distinct phases to better understand their timing and drivers (Geels, 2005; Geels et al., 2017; Markard, 2018; Kanger, 2021).

Third, studies underscore the importance of assessing the overarching directionality of all relevant systems, which involves identifying their shared trajectories and mutual influences. Recently, this concept has been explored through the study of "deep transitions" (Kanger and Schot, 2019; Schot and Kanger, 2018; van der Vleuten, 2019). These studies investigate long-term economic cycles of 40 to 60 years,[7] which are driven by a "meta-regime"—an overarching ruleset that coordinates interactions across multiple regimes. Such a meta-regime provides a common context for multi-system interactions. Overarching directionality may exert influence through various channels, including regulatory policies, research and development efforts, industry investments, and rising consumer awareness.

Building on these key aspects, Bakhuis et al. (2024) propose an integrative framework for multi-system analysis (Fig. 1). Inspired by the MLP, the framework includes three levels and incorporates the key aspects as follows: First, it allows for explicit system configuration, depicting the focal systems under study and categorising adjacent innovations by system. Second, it accounts for different system phases by positioning system-specific boxes within the niche level at varying heights, reflecting each system's transition stage. More developed system transitions can be placed closer to the Regime level. Third, it represents overarching directionality with a dashed box surrounding the regime-level of all focal systems.

3. Framework and methodology

3.1. Application of the multi-system framework

For this study, we use the framework proposed by Bakhuis et al. (2024) to guide our analysis. This framework provides a foundation for conceptualising hydrogen niche formation in the Netherlands, accounting for relevant sociotechnical systems, while we draw on the MLP and SNM concepts to inform our analysis. Fig. 2 illustrates how this framework is applied to the hydrogen case study. Below, we discuss how the three key aspects outlined in Section 2.2 are integrated.

First, regarding system configuration, we delineate four focal sociotechnical systems where hydrogen can contribute to decarbonisation: industry, electricity, transport, and the built environment. Hydrogen serves distinct roles in each system: in *industry*, it can support raw material processing, high-temperature heat, and sustainable gas plants; in *electricity*, it can enhance system integration, flexibility, and energy storage; in *transport*, it can offer sustainable mobility solutions; and in the *built environment*, it can facilitate sustainable heating and cooling. This translates into various hydrogen-related niches, such as steel production (industry), grid balancing (electricity), fuel cell electric vehicles (transport), and heating (built environment). These niches utilise various underlying technologies, including electrolysers and fuel cells, which are often shared across systems. The framework also highlights adjacent innovations along the hydrogen value chain, such as carbon capture and storage (CCS), renewable energy technologies, district heating, and battery electric vehicles.

Second, acknowledging that each system is at a different stage of its low-carbon transition, we positioned the system-specific niche boxes at varying heights relative to the regime level. While it is challenging to quantify progress, this visual representation offers a relative comparison. The electricity system has advanced the furthest, driven by renewable electricity targets and supportive policies (IEA, 2020b; IEA, 2021b). The built environment has also made significant strides, supported by energy performance standards and sustainable building practices, though it faces challenges related to the long lifespans of buildings and infrastructure (IEA, 2021b). The transport system has actively promoted sustainable transportation, most notably through battery electric vehicles, but struggles with decarbonising heavy-duty transportation and developing alternative fuels (Mitchell, 2016; IEA, 2020a, 2021b). The industry system faces the most significant challenges and lags behind in its low-carbon transition, particularly in energy-intensive industries like steel and chemicals (IEA, 2020b; IEA, 2021b). However, efforts have begun with the development of decarbonisation roadmaps and

[7] These studies investigate shifts akin to Techno-Economic Paradigm (TEP) changes, which involve long-term economic cycles of 40 to 60 years (Freeman and Perez, 1988; Mathews, 2013; Perez, 1983, 2003).

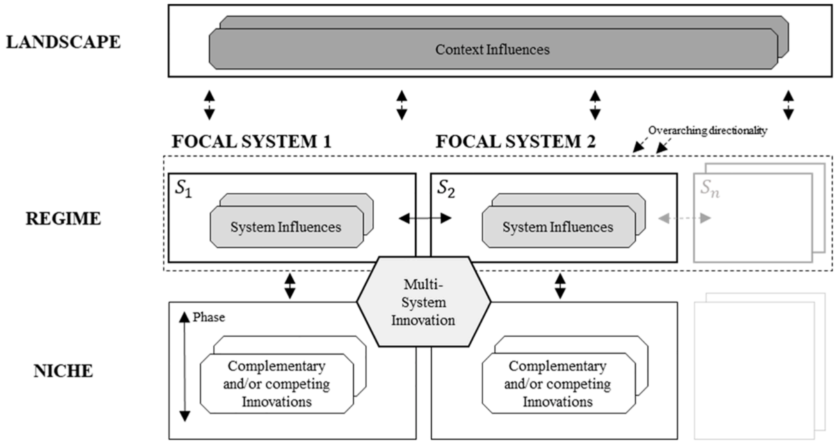

Fig. 1. Multi-system innovation framework (Bakhuis et al., 2024).

pathways towards 2050 (European Commission, 2023; E3G, 2023).

Third, regarding overarching directionality, the global shift towards sustainability and decarbonisation serves as the dominant influence in this case. Notable trends include increased electrification and the adoption of low-carbon energy carriers, both of which are essential steps toward achieving climate goals.

3.2. Research methodology

This study employs Event Sequence Analysis (ESA), a methodology that allows for systematically conducting longitudinal research (Boons and Spekkink, 2012; Spekkink, 2015). ESA takes a process perspective to provide narrative explanations in terms of patterns that result from interactions (Abbott, 1988, 1990, 2001; Abell, 1984, 1987; Poole et al., 2000). Processes are understood as complex sequences of events, which describe how phenomena emerge, develop, and possibly disappear over time. Here, 'complex' means that sequences of events are characterised by multiple progressions that may occur in parallel, or diverge and converge over time (cf. van de Ven, 1992). ESA captures this complexity by modelling processes as networks of events, where nodes represent the events and edges represent the linkages between events (e.g., events 'leading into' one another).

By adopting this process-based approach, this study responds to the call for a broader methodological scope in transition studies, particularly methods that accommodate the complexity of multi-system interactions (Köhler et al., 2019; Svensson and Nikoleris, 2018).[8] Compared to similar approaches, such as 'Historical Event Analysis'—which has been applied in some TIS studies (Suurs and Hekkert, 2009; Negro et al., 2007; Huang et al., 2016; Tziva et al., 2020; Reike et al., 2023)—ESA takes a more relational approach, emphasising relationships between events rather than, for example, tracking the number of occurrences of particular types of events over time. This focus on relationships between events makes ESA fit to study the interactions of niche processes in multiple systems. Fig. 3 illustrates the steps for applying ESA.

3.2.1. Research delineation: central subject, events, and linkages

In ESA, the first critical step is to define the central subject around which the process unfolds, as well as the types of events that this subject experiences or causes (Poole et al., 2000). The central subject can represent any entity, such as an individual, group, or system (Spekkink, 2013, based on Hull, 1975). Since ESA focuses on understanding how phenomena change over time, the central subject is not static—it can evolve as events unfold. In this study, the central subject is the development of low-carbon hydrogen niches in the Netherlands—encompassing the four sociotechnical systems depicted in Fig. 2—with a focus on blue hydrogen (from fossil fuels with CCS) and green hydrogen (from renewable energy via electrolysis), while excluding other production methods.

Within ESA, events are key occurrences that the central subject undergoes or triggers. These events, being theoretical constructs, must be defined by researchers based on existing theoretical knowledge. Depending on how well-developed the theory is, researchers may start with a tentative topology of event types, which can be refined and expanded throughout the analysis, similar to qualitative coding methods (cf. Boeije, 2014). In our study, we classify events according to the three levels of the Multi-Level Perspective (MLP)—landscape, regime, and niche—while focusing on niche-level processes analysed through SNM concepts—expectations, network formation, and learning—as discussed in Section 2.1.

[8] While process-oriented approaches fit well with transition studies, which describes transitions as 'change processes' with complex and unpredictable dynamics and diverse actor networks within divergent contexts (Geels & Schot, 2007, 2010), they are limitedly applied and could provide additional insights (Köhler et al., 2019). Moreover, with the increasing complexity of multi-system energy transitions, transition studies research may significantly benefit from incorporating methodological process approaches and interpretations beyond constructing persuasive process narratives (Köhler et al., 2019; Svensson & Nikoleris, 2018).

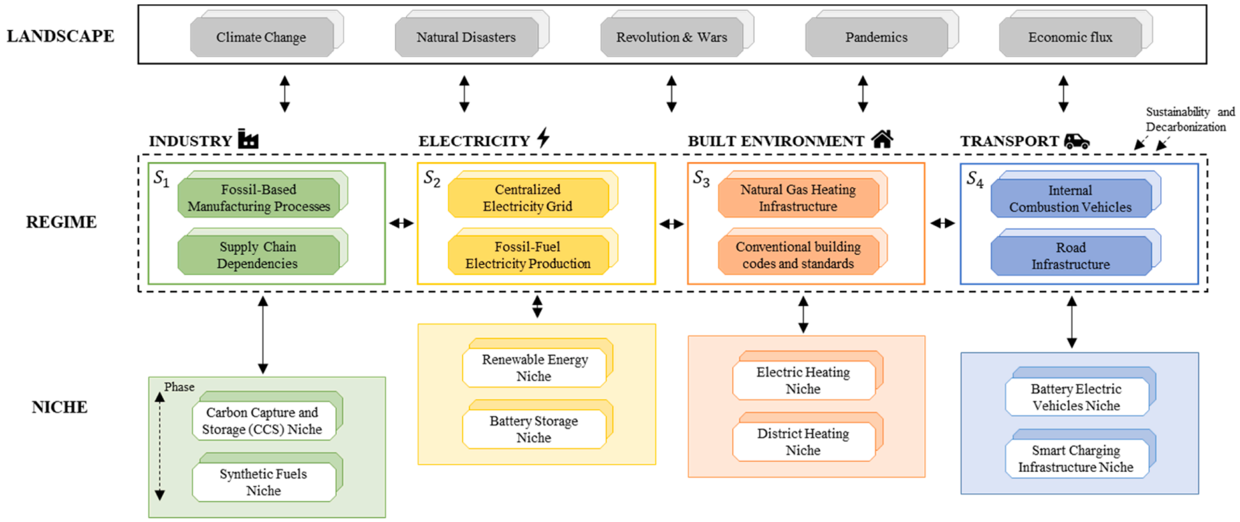

Fig. 2. Multi-system innovation framework applied to the hydrogen energy carrier in The Netherlands. This framework—adapted from Bakhuis et al. (2024)—evaluates multi-system innovations through three key aspects: system configuration, system phases, and overarching directionality. It highlights that multiple hydrogen niches interact and influence each other across systems.

ESA conceptualises processes as ‘networks of events,’ meaning that in addition to identifying event types (as nodes), researchers must also establish the types of linkages between events (as edges) (Spekkink, 2013; Boons et al., 2014). Our analysis primarily focused on how events led to subsequent events. Initially, we identified linkages based on the chronological sequence of events within each sociotechnical system. We then conducted a deeper analysis of the underlying event data to identify explicit evidence for linkages between events occurring within a single system and those spanning multiple systems.

Three main criteria were used to establish these linkages: (i) explicit references to earlier projects or events, or cases of mutual inspiration; (ii) events linked by shared partnerships, subsidy schemes, or larger initiatives (e.g., EU-funded projects); and (iii) the involvement of the same actors or networks of actors in successive events. For the third criterion, all actors involved in each event were coded. This data was then used to perform a network analysis, resulting in a network plot that provided valuable insights for the analysis.

3.2.2. Data collection and processing

After defining the central subject, relevant event types, and linkages, the longitudinal data collection process began. The collected data were recorded as “incidents” in a chronologically ordered event sequence dataset (Poole et al., 2000). Each incident is a brief, empirical description of a significant occurrence in the process under study, including the date of occurrence, involved actors, actions taken, and the information source (cf. van de Ven and Poole 1990; Poole et al., 2000).

For this case study, data on incidents were gathered from news items, documents, and web pages through an internet search using Google, with a focus on news-related websites[9] such as *Energeia* and *WaterstofNet* and government initiative websites such as *Topsector Energy* and the *National Hydrogen Programme*, which report on and track hydrogen developments. Despite differences in how information was presented across sources, enough overlap existed to ensure data triangulation. To ensure transparency, an electronic logbook was maintained to track the data collection process, documenting search engines, websites, and search terms[10] used.

After an intensive data collection period of approximately 3.5 months (from Feb 1st to May 15th, 2020), the final dataset comprised 151 chronologically ordered events, supported by multiple web pages, documents, and news articles. These incidents span from 2001 to 2020, reflecting the increasing global and national focus on hydrogen as a sustainable alternative to fossil fuels. Earlier grey hydrogen developments—while positioning the Netherlands as Europe’s second-largest grey hydrogen producer (from fossil fuels) (TNO and CBS, 2020)—fall outside the scope of this study.[11]

[9] These news-related websites often cite original documents such as project plans or reports. To minimize bias from the news outlet, we referred directly to these sources whenever possible. Additionally, we consulted multiple news-related websites reporting on the same events, enabling cross-validation of findings and ensuring that no significant events were overlooked.

[10] Search terms included “Hydrogen *AND sociotechnical system*,” replacing “sociotechnical system” with the four focal systems (or synonyms), and “Hydrogen AND *sociotechnical aspect*,” substituting “sociotechnical aspect” with elements such as technology, institutions, actors (or synonyms), or specific examples (e.g., ‘fuel cells’ for technology or ‘Shell’ for actors).

[11] An initial screening identified a surge in hydrogen development post-1970, following the oil crisis. However, from 1970 to 2001, the focus predominantly revolved around unsustainable grey hydrogen. This study considers these earlier developments as distinct from more recent blue and green hydrogen developments. Brief investigation indicated that sporadic grassroots initiatives advocating for blue or green hydrogen struggled to gain traction during this time, indicating their nascent stage and often leading to their dismissal by stakeholders.

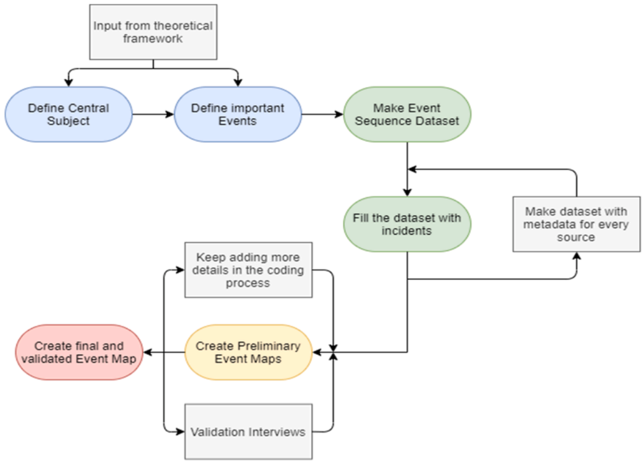

Fig. 3. Steps when applying the ESA methodology, inspired by Spekkink (2013).

Once the dataset was finalised, the incidents were coded according to different event types using a specialised software suite (developed by Wouter Spekkink[12]). This coding process involved carefully reviewing the underlying incident data and assigning labels based on the MLP and SNM concepts discussed in Section 2.1. The underlying data also provided evidence of how one event led to another. This coding process formed the foundation for reconstructing and visualising temporally ordered event sequences in an "event graph" using the software (see Figures S.1 and Figure S.2 in the Supplementary Materials for examples of output graphs). Events were further categorised by MLP level and the focal system in which they occurred. This categorisation was color-coded in the final event graph,[13] with a legend describing each event. The event graph visually demonstrates the links between events based on the researcher's interpretation, showing how activities such as articulating expectations, or conducting feasibility studies influenced subsequent developments. To validate the findings, three expert interviews were conducted.

3.2.3. Analytical approach

Once the coding process was completed, the event graph was used in conjunction with MLP and SNM concepts to analyse blue and green hydrogen niche development in the Netherlands between 2001 and 2020, focusing on the four focal sociotechnical systems. To capture distinct trends over time, the period was divided into two sub-periods: (i) the search for independence from the Organisation of the Petroleum Exporting Countries (OPEC) from 2001 to 2013, and (ii) a phase marked by growing climate change awareness from 2013 to 2020. The latter reflects the growing association of hydrogen with climate change mitigation efforts. These sub-periods were identified based on observable changes in the density of events.

The process analysis results in an analytical narrative, supported by the event graph, which charts the development of hydrogen niches over time. A key component of this research is the examination of multi-system niche interactions, where we investigate how various niches interact and influence each other's development across sociotechnical systems. This analysis includes a focus on the impacts across the three levels of the MLP and the role of the three internal niche processes as outlined by SNM. The analysis draws on insights from the event graph, supported by underlying data from various sources such as research reports, annual reports, news articles, and interviews.

4. Results

The final event graph, along with an event legend, is depicted in Figs. 4 and 5, respectively. Each event in the graph is marked by a specific code that corresponds to its listing in the legend, with dates indicating when the event began. Throughout this section, in-text references to events follow this coding structure: landscape events (e.g., L1.1), regime events (e.g., R1.1), and niche events, which are further categorised by sociotechnical system: industry (e.g., NI1.1), electricity (e.g., NE1.1), built environment (e.g., NB1.1), and transport (e.g., NT1.1). The results are organised by sub-period and examine the findings across different levels of the MLP.

4.1. Initial development: search for independence from OPEC (2001 - 2012)

4.1.1. Landscape, regime, and adjacent niche developments (2001 – 2012)

Regarding landscape developments, the start of the first period is marked by the 9/11 attacks in 2001, which initiated a movement

[12] The ESA software is not yet publicly available.

[13] Due to the comprehensive nature of the transition, the final Event Graph is not exhaustive. Furthermore, associated with the non-linear overarching effects of landscape events on the subsequent regime and niche events, linkages are not drawn.

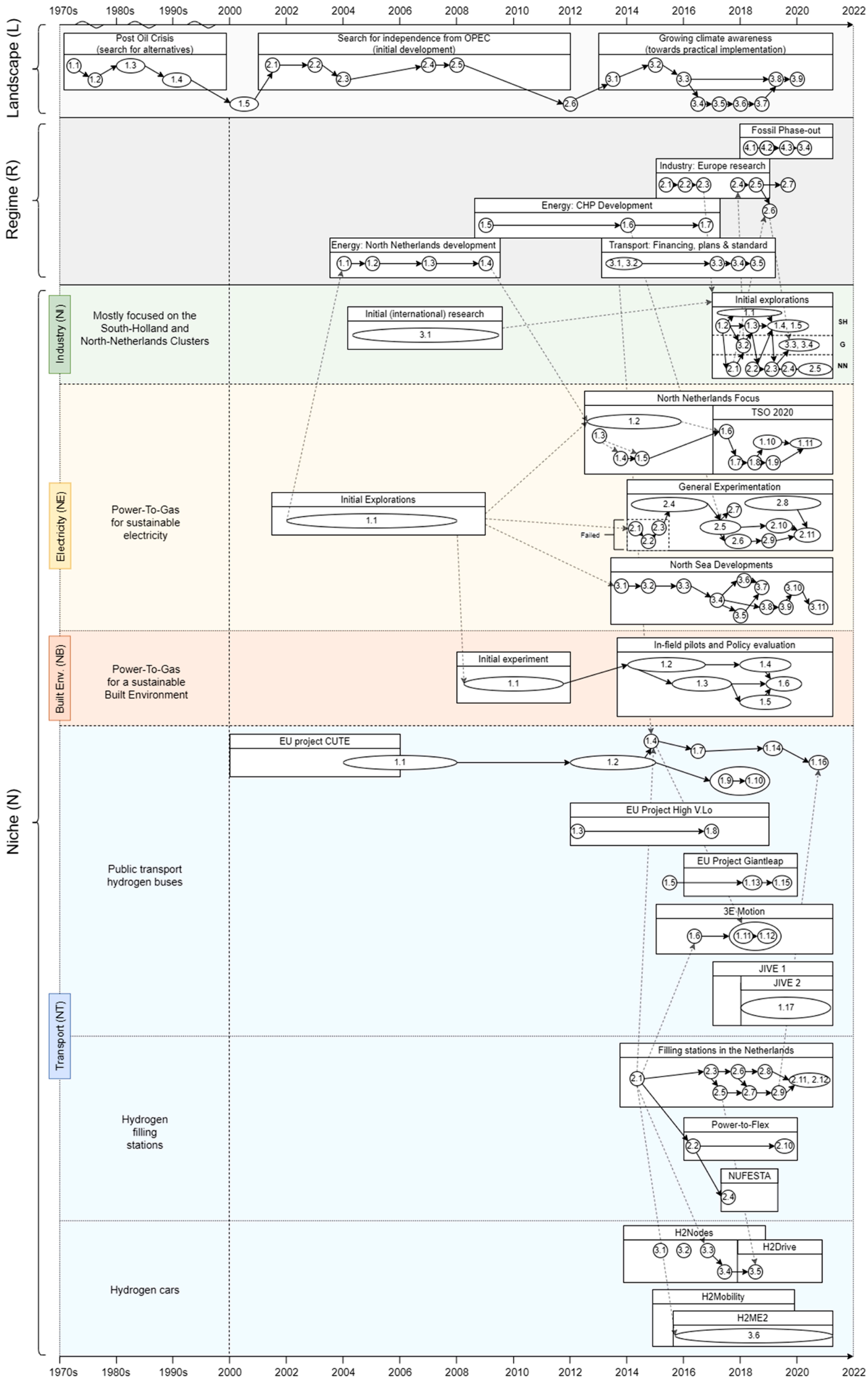

Fig. 4. Event Graph of hydrogen niche development in the Netherlands organised along the different levels of the MLP. The niche-level is differentiated per analysed system.

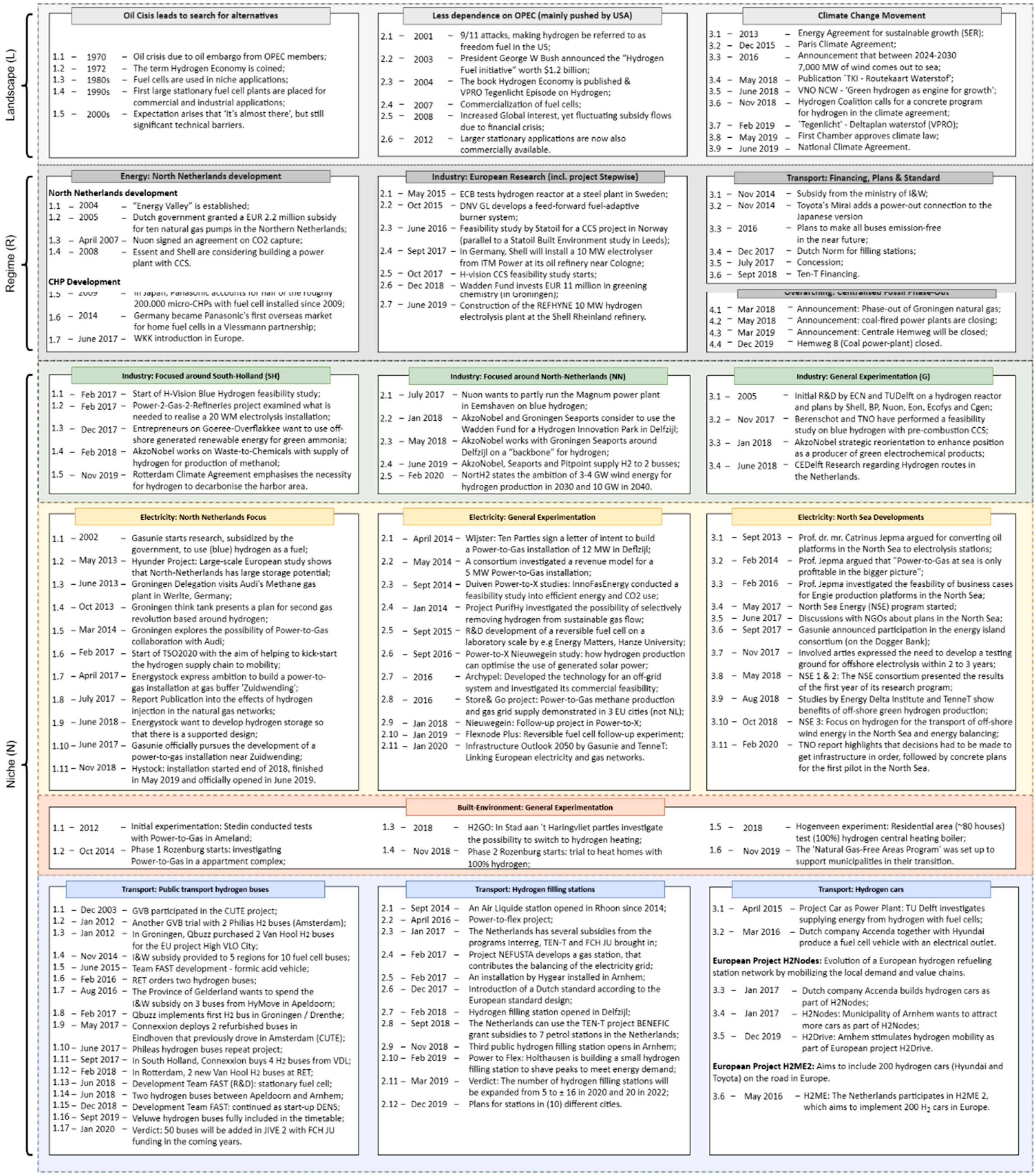

Fig. 5. Legend associated with the event graph of relevant hydrogen events in the Netherlands.

towards reducing dependence on OPEC as an energy supplier. As a consequence of the rising positive expectations towards hydrogen between 1970 and 2000 (culminating in *Event L1.5*), the landscape shift that the 9/11 attacks sparked, led the United States and Europe to quickly invest in hydrogen. Coined as 'freedom fuel' in 2003 by the President of the United States, it was considered one of the most promising alternative energy carriers (*Events L2.1, L2.2*). Between 2001 and 2007, the expectation seemed to arise that "it is almost there," implying that the energy carrier could soon break through to become an integral part of the global energy mix (exemplified by *Event L2.3*). However, developments took longer than expected, the lifespan of materials remained too short, and the costs too high. Subsequently, the financial crisis of 2008 caused a decrease in social and political interest towards hydrogen, resulting in fluctuating subsidy flows (*Event L2.5*). In the Netherlands, this led to the cessation of almost all activities related to research and development of hydrogen technology in (semi) public institutions between 2008 and 2012. For example, at the Energy Research Centre of the Netherlands (ECN), research into hydrogen technology was discontinued in early 2009 due to budget cuts.

Several regime and adjacent niche developments significantly influenced the hydrogen niche. A notable stream of regime developments occurred primarily in the Northern Netherlands region. These developments mainly opened windows of opportunity for blue hydrogen development. An early initiative in this region was the establishment of the 'Energy Valley' platform in 2004 (*Event R1.1*), reflecting a commitment to becoming a hub for sustainable gas. Moreover, the region's expertise regarding storage and transport of gaseous energy carriers facilitated the promotion of natural gas technology as a transition pathway towards (blue) hydrogen mobility (*Event R1.2*). Additionally, government and industrial support for CCS—a complementary niche—further bolstered the early inclination towards blue hydrogen, evidenced by significant investments in 2007 (*Events R1.3, R1.4*). Alongside these developments that presented opportunities for hydrogen, a significant competitive niche emerged in this period: battery electric vehicles. Their endorsement by the Dutch government around 2006 (Bakker, 2010; Government of the Netherlands, 2021) significantly eroded stakeholders' confidence in the future of hydrogen within the transport system, ultimately contributing to its partial discontinuation in 2009.

4.1.2. Hydrogen niche developments (2001 – 2012)

The ESA shows that the newly-gained interest from the EU regarding hydrogen, following the 9/11 attacks in 2001, quite quickly translated into Dutch initiatives. Notably, the first practical experiment emerged in 2003 within the *transport system* (project CUTE), with the Netherlands as one of nine European countries involved in the first large-scale volume-production test worldwide (*Event NT1.1*). Within this project, a pilot with hydrogen fuel cell buses was organised in Amsterdam (2003–2008). Despite the costs of the buses compared to electric and internal combustion alternatives, as well as the technical issues associated with the fuel cells' low lifespan, this project seemingly raised expectations for hydrogen technology due to positive feedback provided by end users and bus drivers. Furthermore, project partners reported being encouraged when faced with the challenge of addressing what they perceived as relatively simple technical constraints. Because of the higher technology readiness level, there was an explicit priority towards the practical applicability of hydrogen in mobility in Europe (European Commission, 2003a, 2003b).

Sporadic events also emerged across the other analysed systems. The events in the *electricity* and *industry* systems mainly involved research and development over a ten-year span (2005 – 2015), reflecting the technological infancy at this time (*Event NI3.1*). As noted above, particularly blue hydrogen studies gained traction (*Event NE1.1*), driven by regime developments such as government support of CCS. In the *built environment*, a key event was a four-year study conducted in Ameland between 2008 and 2012. This study explored the effects of blending green hydrogen produced from solar energy into the natural gas network (*Event NB1.1*). It became the first pilot project of its scale in Europe, supplying fourteen homes in an apartment complex with natural gas mixed with up to 20 % green hydrogen (TKI Gas and RVO, 2016). Key energy distribution partners—such as Joulz, GasTerra, and Stedin—collaborated on the project, fostering continued experimentation and strengthening network interactions in the following years.

4.1.3. Multi-System niche interactions (2001 – 2012)

During this period, hydrogen development progressed at a rather slow pace—primarily limited to a few experiments along with research studies and plans. From these limited experiments and the associated communication, we can draw some initial observations. While most experiments remained confined to individual systems, some well-performing niche processes began to exert multi-system influences, modestly contributing to laying the groundwork for future developments. Three key observations stand out.

First, despite practical experimentation revealing infrastructure, technical, and economic challenges, stakeholders generally reported these initial pilots and studies as successful. This was largely due to their perceived potential for future utility and the sense that improvements were attainable (*Events NT1.1, NB1.1*). Notably, practical experiments in the transport and built environment systems led to larger follow-up projects that incorporated lessons learned, addressing many technical deficiencies (i.e., indicating first-order learning) (*Event NT1.2*). Although the experiments were system-specific, success stories sparked rising expectations that fuelled increased hydrogen research across multiple systems, especially for technologies like hydrogen fuel cells, which could be applied in multiple sociotechnical systems.

Second, key stakeholders from each system became involved in hydrogen niches through research and collaboration (e.g., *Events NT1.1, NE1.1, NI3.1*). Early strategic partnerships and consortia formed along the hydrogen value chain, bringing together diverse actors such as government bodies, utilities, energy suppliers, and research institutes (e.g., *Events NE2.1, NI1.3, NT2.1*). Encouraged by positive experimental results (*Events NB1.1, NT1.1*), these partners continued to collaborate on subsequent projects. Alongside system-specific experimentation, key cross-system partnerships and lateral information sharing began to emerge, strengthened by actors participating in multiple projects across different systems (e.g., *Events NI3.1, NI2.2, NE2.2*). Network interactions were further supported by consortia that brought together actors from various sociotechnical systems (*Events NE2.2, NI1.1, NE3.6, NT3.6*).

Third, rising expectations led to growing consideration of hydrogen in future energy scenarios, emphasising its potential uptake across sociotechnical systems, with particular attention to blue hydrogen (*Events R2.3, R2.5, NE3.2*). Increasingly, actors stressed the importance of involving the entire value chain and multiple systems, promoting hydrogen as an "enabler"; it would be able to facilitate and create opportunities for other developments, such as long-term storage for electricity. Towards the end of the period, interest in green hydrogen—produced through electrolysis—gained traction as a solution for integrating intermittent renewable energy. Some viewed hydrogen as a "universal energy vector" with the versatility to support a broad range of applications across different scales (e.g., *Event NE1.2*).

4.2. Towards practical implementation: growing climate awareness (2013 – 2020)

4.2.1. Landscape, regime and adjacent niche developments (2013 – 2020)

Landscape shifts related to 'Growing Climate Awareness' trace back to the 1960′s, with several key agreements signed during this time, including the 1997 Kyoto Protocol.[14] However, explicit support for hydrogen in the Netherlands emerged with the signing of the Dutch Energy Agreement for Sustainable Growth (SER agreement) in 2013 (*Event L3.1*). This agreement underlined the willingness of many to commit themselves to the sustainability of the Netherlands' society and economy. Additional landscape shifts in this period included the Paris Climate Agreement in 2015 (*Event L3.2*) and the approval of the Dutch Climate Law in 2019 (*Event L3.8*), both emphasising the necessity of renewable energy to decarbonise the energy mix. The National Climate Agreement—also signed in 2019 (*Event L3.9*)—notably positioned hydrogen as a key sustainable energy carrier, mentioning it over 180 times. As depicted in Fig. 4, there was a marked increase in hydrogen-related events during this period (2013 – 2020).

Several noteworthy developments occurred within the regime and adjacent niches. After 2013, largely due to landscape shifts exerting pressure on the fossil fuel energy regime, intermittent renewable electricity became a key component in the vision for the hydrogen transition (*Events NE1.2, NE1.4, NE1.2.2*). This reflects a broader trend (i.e., overarching directionality) towards a growing consensus that electrification is a primary pathway to mitigate climate change. A major catalyst for this shift was the significant reduction in the cost of renewable energy sources like solar and wind, which boosted the potential for green hydrogen. As a result, actors started focusing more on hydrogen's potential role as large-scale storage to deal with the intermittency of renewables (*Events NE3.2, NE1.7, NI1.3*). Studies increasingly pointed to 'Power-to-Gas' (P2G) through electrolysis as a critical success factor for low-carbon transitions. Consequently, major incumbent actors became more involved in the hydrogen niche, each driven by their own agendas.

More specifically, this period saw several regime developments that created windows of opportunity for further niche formation. These included the (potential) closure of multiple coal-fired powerplants (*Events R4.2, R4.3, R4.4*), the proposed phase-out of natural gas in the Groningen region (*Event 4.1*), the anticipated introduction of a CO_2 price (increasing costs for companies that rely on fossil fuels), and the European Green Deal (e.g., pushing for CO_2 neutral ports by 2050). Significant adjacent niche developments arose in response to the prevailing emphasis on electrification. As a complementary niche, the national government strongly endorsed offshore wind energy, which led to hydrogen plans designed to address the congestion of transporting offshore electricity to the grid (*Events L3.3, NI2.1, NI2.4*). Concurrently, significant advancements have been made in competing niches, such as rapid development of battery electric vehicles and the expansion of charging infrastructure (CBS, 2021), alongside increased support for electric heating in buildings (CE Delft, 2023). Conversely, support for CCS declined due to growing scepticism about its technological and economic feasibility, as well as shifting public sentiment concerning safety and environmental impacts (Roggenkamp, 2020).

4.2.2. Hydrogen niche developments (2013 – 2020)

Building on the developments of the previous period, practical experimentation remained mainly concentrated in the *transport system*. This period saw a moderate increase in 'in the field' mobility projects, with around 100 to 200 hydrogen fuel cell electric vehicles (compared to around 200,000 battery electric vehicles (CBS, 2021)), ten public transport buses (with fifty more planned), dozens of garbage trucks, one train, five inland vessels, and five filling stations built. Particularly, experiments with public transport hydrogen buses were influential. The analysis indicates four notable developments. First, most experiments were part of larger European Union (EU) funded projects and thus received subsidies from the EU in addition to national government funding. Second, learning processes were carried across projects. For example, a direct follow-up to the 'CUTE' project resolved most technical deficiencies (*Event NT1.2*). Notably, the same buses were later introduced and used in a different project (*Event NT1.9*). Third, the limited hydrogen filling infrastructure was considered a major bottleneck for both bus and passenger vehicle projects, with only a handful built during this period (e.g., *Event NT2.1*). Finally, shared ambitions (*Event R3.3*) and (European) standards were important to stimulate progress and resolve barriers (*Event NT2.6*).

Within the *electricity system*, further development is observed in the Northern Netherlands region, building on progress from the previous phase. The region became a hub for Power-to-Gas, as most electricity system tests and demonstration projects took place there. Notably, the Europe-wide 'Hyunder' study showed a considerable hydrogen storage potential in that area (*Event NE1.2*). Consequently, in 2017 the most substantial funding up to that point was awarded by the European project 'TSO 2020' towards the Northern Netherlands region to support the development of a hydrogen supply chain for mobility (example of multi-system experimentation) (*Event NE1.6*). In this project, the first (1 MW) electrolyser, Hystock, was built and opened in June 2019 (*Event NE1.11*). Hystock was seen as a necessary first step to learn and garner positive expectations for the hydrogen transition across systems. This led to a subsequent increase in announced plans for large electrolysers (>100 MW) (*Event NI2.5*).

Developments in the *industry system* initially lagged behind those in the transport and electricity systems. However, following the Paris Climate Agreement (end of 2015) (*Event L3.2*), research and feasibility studies accelerated, leading to ambitious plans for practical experimentation (*Events NI1.2, NI2.1, NE3.4*). These initiatives were primarily driven by prominent industry incumbents

[14] The Kyoto Agreement does not explicitly address hydrogen as a form of energy.

(such as Shell and Air Liquide) and were concentrated in large industrial clusters[15] in the Northern Netherlands (Eemshaven and Delfzijl) and South Holland (Port of Rotterdam). The initial plans shared similarities, including overlapping actors and a focus on the "blue route" (*Event NI3.4*). This route aimed to develop blue hydrogen first to build demand and infrastructure for green hydrogen once it became economically viable (*Events NI1.1, NI1.2, NI3.2*). Projects reported common challenges, including substantial investments and unprofitable margins, which (incumbent) project partners preferably saw covered by government subsidies like the SDE++ feed-in premium scheme. The national government's announced subsidy budget in 2019 was considered inadequate, leading to heated discussions between industrial stakeholders and the government (*Event L3.9*). By 2020, numerous large-scale blue and green hydrogen plans were announced, but most remained in the feasibility phase, pending investment decisions.

In the *built environment*, experimentation remained limited, despite some positive early developments. This was mainly due to a discussion regarding high infrastructural costs, particularly when compared to cheaper alternatives (e.g., district heating or electric heat pumps). This led to decreasing support from the EU and the Dutch Government, resulting in dwindling expectations for the future of hydrogen in the built environment. Nevertheless, actors did see a necessity to experiment; hence they pushed for a subsidy from the bottom-up, which they received from the Dutch government as part of the 'Top Sector Energy Subsidy' of the Ministry of Economic Affairs, leading to several pilot projects (*Events NB1.2, NB1.3, NB1.5*).

4.2.3. Multi-System niche interactions (2013 – 2020)

During the 2013–2020 period, there was an increase in events compared to the previous period, reflecting growing attention to hydrogen niche development. However, relative to the overall increase in activity, practical experimentation saw only limited growth, constrained by a lack of significant investments. Despite this moderate progress, three key observations emerged regarding the multi-system interactions in hydrogen niche development during this time.

First, many experiments were linked through "bridging organisations," which played a crucial role in connecting different sociotechnical systems and facilitating multi-system learning. These organisations participated in successive events, transferring lessons learned both within and across systems (*Events NB1.1, NB1.2, NE1.1, NE1.10*). The network plot (Fig. 6) highlights key bridging organisations, including gas and electricity system operators (e.g., A47 and A113); car manufacturers (e.g., A71 and A104); knowledge organisations (e.g., A134 and A33); oil and gas incumbents (e.g., A110 and A6); and government agencies (e.g., A81). Over time, these organisations helped foster a more cohesive network, promoting transparent knowledge sharing across projects and systems. This attracted a growing and diverse set of actors to the hydrogen niches, which in turn led to complementary partnerships (*Events NE3.6, NE2.11, NI2.4, NE4.3*). As a result, knowledge began to accumulate across seemingly unrelated projects, driven by the active participation of bridging organisations. Additionally, shared ambitions and converging expectations among actors from different systems promoted project development and facilitated collaboration (*Events L3.1, L3.2, L3.9, R4.1, R4.2*). Despite limited practical experimentation, positive expectations—fuelled by some success stories—played a crucial role in advancing hydrogen niche development and attracting key actors across multiple systems (*Events NB1.2, NB1.4, NE3.6, NI2.1*).

Second, regional embedding of hydrogen projects was notable, particularly around large industrial clusters. These clusters facilitated synergies by aggregating demand across multiple systems, enabling more efficient use of produced hydrogen. Industrial clusters provided economic advantages, such as the efficient utilisation of waste streams, and supported network building and multi-system experimentation (*Events NI2.2, NT1.8, NE1.5, NI2.4*). Studies from 2013 to 2020 emphasised that at this niche development stage, a profitable hydrogen business case relied on sufficient demand across sociotechnical systems and throughout the supply chain. Examples of this multi-system interconnectivity included industry-system hydrogen production projects linked to hydrogen filling stations for mobility (*Events NT2.1, NI2.4*). These developments were crucial for advancing the hydrogen niche, as infrastructure proved critical for successful experimentation. For instance, the lack of hydrogen filling stations reportedly created a significant bottleneck for hydrogen vehicle deployment (*Events NT2.1, NT1.6, NT2.7, NT1.16*). This challenge united stakeholders across the supply chain, leading to collaborative efforts that ultimately resulted in plans for a hydrogen pipeline infrastructure, or "backbone," in the Northern Netherlands, with each partner contributing specific expertise (*Event NI2.3*).

Third, international collaboration—especially through EU-funded projects—played a pivotal role in advancing hydrogen developments. Nearly all practical experiments involved international partners or were part of EU projects co-funded by the European Commission, often supplemented by Dutch government subsidies. The ESA highlights how European standards facilitated experimentation by simplifying collaboration and opening opportunities for international funding (*Events NT1.4, NT1.7, NT2.8*). For instance, this was evident in the construction of the first large-scale electrolyser (NE1.11). From a multi-system perspective, the EU's involvement was pivotal. Beginning in 2018, the EU placed significant emphasis on fostering multi-system collaboration and implementation to meet its ambitious climate targets and accelerate the hydrogen transition[16] (European Parliament, 2018; European

[15] These industrial clusters refer to a group of interconnected production, storage, distribution and end-use facilities close to each other. The Netherlands has five major industrial clusters, which can be categorised as follows: North-Netherlands cluster (around Eemshaven and Delfzijl), North-Holland Cluster (around Port of Amsterdam), South-Holland Cluster (around Rijnmond / Port of Rotterdam), Zeeland Cluster (around Terneuzen), and Limburg Cluster (around Chemelot).

[16] Notably, the EU promoted 'Sector Coupling' to drive cost-efficient decarbonization by harnessing synergies between energy-demanding systems like electricity and transport, aligning with its hydrogen strategy and directives (European Parliament, 2018; European Commission, 2020). The EU distinguishes two types of sector coupling: end-use sector coupling and cross-vector integration. End-use sector coupling involves electrifying energy demand while reinforcing the interaction between electricity supply and end-use. Cross-vector coupling involves integrating various energy infrastructures and vectors, particularly electricity, heat and gas, on the supply side.

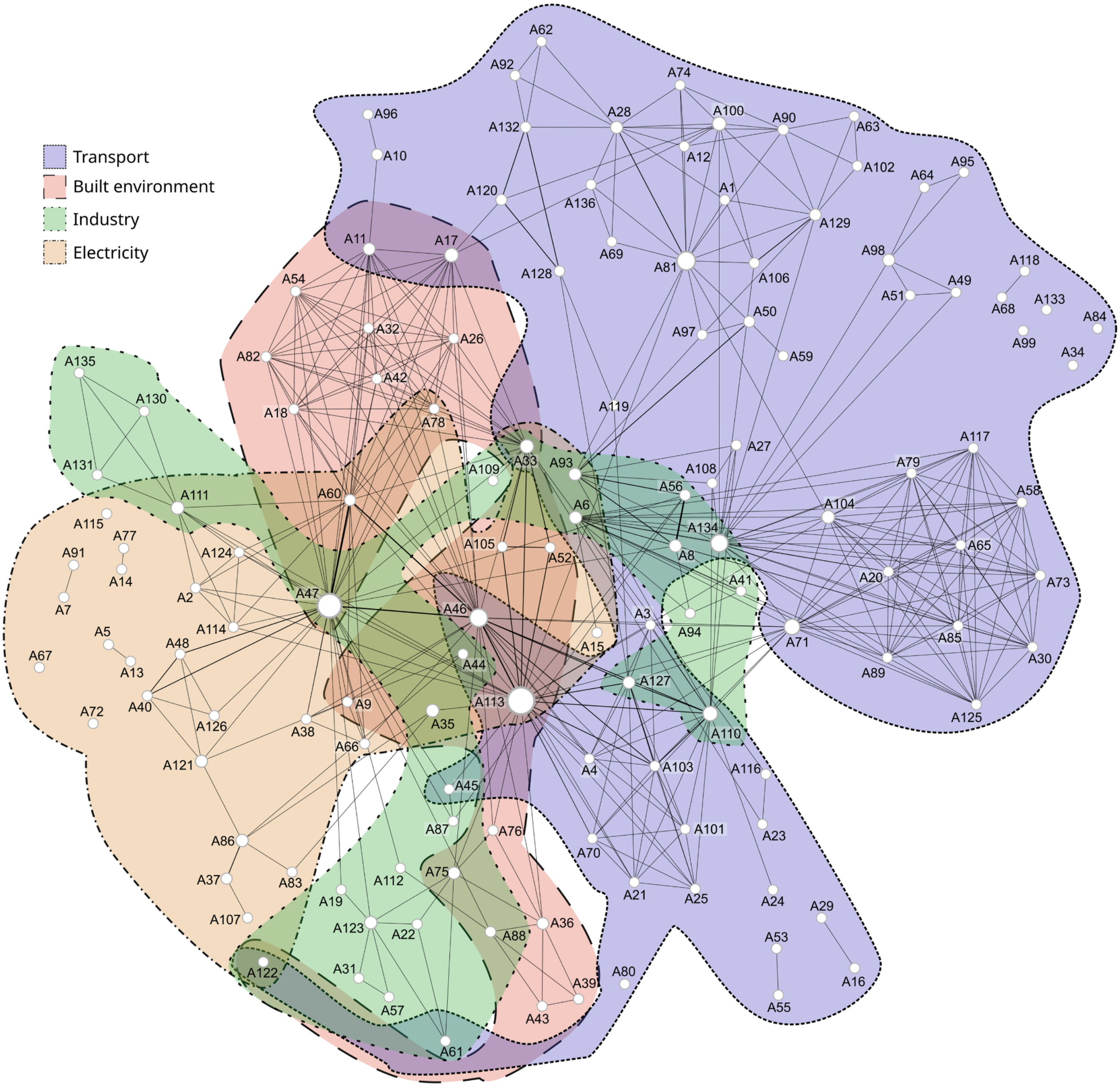

Fig. 6. This network plot visualises the ties between actors based on their co-participation in events, highlighting interactions both within and across different systems. It illustrates how key actors connect developments across sociotechnical systems. Node size represents “betweenness centrality,” a measure of how central an actor is to information flow. Refer to Table S.1 in the Supplementary Materials for a complete list of actors.

Commission, 2020).

5. Discussion

5.1. Reflections on hydrogen niche development in the Netherlands

Our findings offer a detailed analysis of the hydrogen niche developments in the Netherlands between 2001 and 2020 from a multi-system sociotechnical perspective. The initial phase (2001–2012) was marked by a wave of optimism, which was followed by a sharp decline in activity between 2009 and 2012. A resurgence of hydrogen-related initiatives occurred after 2013, driven by the momentum of low-carbon transitions. However, despite positive discourse and ambitious plans, tangible investments and practical applications remained limited up to 2020. Consequently, while carbon-free alternatives are crucial for achieving climate goals—particularly in hard-to-decarbonise industries—it remains uncertain whether hydrogen will play a significant role, or experience another cycle of optimism followed by decline. This section identifies several key factors explaining the current progression of hydrogen niche development.

5.1.1. Internal niche dynamics

From an internal niche perspective, the analysis shows that expectations have become more robust and specific, supported by evidence from early studies and experiments. The network composition has also expanded over time, attracting relevant actors, and interactions within the network have intensified. Additionally, there are signs of first-order learning—both technical and regulatory—taking place.

However, critical challenges remain. The apparent lack of second-order learning reflects the early stage of experimentation.[17] Another major challenge is the misalignment between industry and government actors regarding subsidies. Industry stakeholders consider the available subsidies insufficient to offset the unprofitable margins of hydrogen projects, leading to ongoing debates and delays in investment decisions (e.g., *Events NI1.1, NI2.1*). While this may partly reflect a strategic effort to secure additional funding, the analysis suggests that current conditions are not yet conducive to large-scale investments. These challenges have hindered the organisation of experiments and the execution of ambitious plans (e.g., *Events NI1.1, NI2.1, NI2.5, NI3.2*).

Several factors exacerbate these challenges. First, most hydrogen technologies remain at a low technology readiness level, particularly when compared to alternatives, and often require substantial infrastructure overhauls (e.g., *Events NE1.11, NE2.8, NE3.6, NE3.11, NB1.3, NI2.1, NI2.5*). This makes them capital-intensive and raises concerns about lock-in effects.[18] Second, there is the pervasive "chicken and egg" problem, where the lack of both supply and demand creates a self-reinforcing barrier to progress (e.g., *Events NE1.11, NT2.1, NT3.4, NT2.7, NI2.3*). This includes the lack of adequate infrastructure, such as refuelling stations and distribution pipelines. Third, there has been increasing scepticism towards the niche, driven by the frequent announcement of ambitious plans that are subsequently delayed or abandoned. This scepticism varies by domain; it appears to be less pronounced in areas where electric alternatives are not yet available (such as steel manufacturing).

5.1.2. Inter-niche dynamics: adjacent innovations

Adjacent innovations, both competitive and complementary, significantly impact hydrogen adoption. While there are adjacent innovations along the hydrogen value chain, our focus is on adjacent innovations in end-use.

In terms of competition, hydrogen innovation is challenged by more mature and cost-effective alternatives. For example, in the *built environment*, district heating and electric heat pumps are more established and receive stronger political and financial backing, making hydrogen's role in decarbonising this system contentious. In *transport*, battery electric vehicles dominate the sustainable personal transport market in the Netherlands, supported by robust infrastructure. However, hydrogen shows greater potential in heavy-duty applications, such as aviation and freight where electric alternatives are less developed.[19]

Complementary innovations also play a key role. In the *electricity* system, intermittent renewable energy sources complement hydrogen, since it can serve as storage to balance supply and demand, easing grid congestion as wind and solar power expand across Europe (Markard, 2018; Geels, 2019). The growth of renewables also supports green hydrogen production. In the *industry* system, CCS complements hydrogen by facilitating blue hydrogen production. Additionally, synthetic fuels—such as biofuels and ammonia—are emerging as both competitors and complementary innovations.

5.1.3. Multi-System dynamics

In this sub-section we explore the influence of key multi-system factors—as outlined in Section 2.2—considering system composition, the varying system transition phases, and overarching directionality.

System composition plays a significant role in hydrogen implementation, with two key areas illustrating its impact. First, the attitudes of actors vary widely across systems. For example, industry actors tend to be more conservative about decarbonisation and innovation compared to those in the transport system—a trend supported by previous studies (Löhr and Chlebna, 2023). Second, the structure and scale of a system shape its approach to hydrogen. For instance, industry system experiments are typically large-scale, capital-intensive, and require substantial investments, longer development cycles, and extensive collaboration.[20] Consequently, industry actors often expect—or even demand—greater government support, reinforced by the government's strategic interest in maintaining industrial capabilities due to their economic importance (Government of the Netherlands, 2020b). In contrast, hydrogen initiatives in the built environment and transport systems are generally smaller in scale.

When examining varying system transition phases, we observe two key influences. First, the stage of transition affects the degree of flexibility in shaping the narrative around hydrogen. For example, in the less advanced low-carbon transition of the industry system, actors had more freedom to lobby for hydrogen over electrification to align with their existing business models, particularly through the "blue route" (e.g., *Events NI1.1, NI2.1, NI3.2*). Second, more advanced transition phases are often accompanied by more developed

[17] While second-order learning may have occurred during earlier solutioning or preparatory phases of hydrogen niche development, our analysis found no significant evidence of this. The niche experimentation phase typically fosters higher-order learning, where participants gain insights into both specific technologies and the broader sociotechnical system (Schot and Geels, 2008).

[18] Compared to alternatives (e.g., battery storage), hydrogen requires expensive asset and infrastructure investments (usually with a long lifespan). Once investments are made, it may be challenging to switch to alternatives without incurring significant costs and disruptions.

[19] Some studies suggest hydrogen will play a limited role in sustainable road transport due to the success of electric vehicles (Plötz, 2022).

[20] While industry system projects are usually large-scale, similar challenges could apply to implementations in the other systems, e.g., when it relates to the large infrastructural overhauls or more challenging innovations (e.g., freight or aviation).

adjacent innovations, which create path dependencies and lock-ins, such as with battery electric vehicles and district heating.

Overarching directionality imposes its influence by two key factors. The momentum toward decarbonisation and sustainability—driven by financial, political, and social pressures (e.g., *Events L3.1, L3.2, R3.3, R4.1*)—has accelerated hydrogen activities and increased involvement from incumbent players and bridging organisations, especially during the second period. Additionally, the broader trend toward electrification has positioned hydrogen primarily as a storage solution through Power-to-Gas, while simultaneously creating strong competition from electricity-based innovations, such as battery electric vehicles.

Overall, while hydrogen's future role remains uncertain, steep competition from (electric) alternatives in the *transport* and *built environment* systems suggests that its greatest potential lies in the *electricity* (e.g., for grid balancing) and *industry* systems (e.g., for hard-to-decarbonise industries). Given the scarcity and cost of green and blue hydrogen—amid resource competition across systems—strategic prioritisation will be crucial in its early development stages.

5.1.4. Recent developments (2020 – 2024)

To extend the ESA analysis, which concluded mid-2020, we conducted a complementary analysis of hydrogen developments in the Netherlands from mid-2020 to 2024. Although this period was not examined in-depth using the ESA method, the findings confirm the main observations and conclusions of this study. An extended summary of the developments and key events is provided in the Supplementary Materials (incl. Tables S.2 to S.7).

The period from 2020 to 2024 reflects a clear continuation of earlier trends. Hydrogen remains central to Dutch decarbonisation strategies, with the Netherlands doubling its electrolysis ambitions to 6–8 GW by 2030, in alignment with the European Renewable Energy Directive III (see Table S.4). While the European Green Deal emphasises green hydrogen as the sole sustainable option, the Netherlands maintains that blue hydrogen will act as a transitional solution until 2050. During this period, numerous ambitious plans for green and blue hydrogen production projects were announced, alongside continued studies and collaborations regarding existing initiatives (see Table S.2). These efforts generally involved incumbent actors and maintained a strong geographical focus on the Netherlands' five industrial clusters. However, despite some funding provided through several Dutch and EU programmes (see Table S.3), most investment decisions remain pending, and overall hydrogen investments continue to fall well short of what is needed to meet 2030 targets (see Table S.7). Industry actors continue to criticise existing subsidy schemes as inadequate, leading to intensified debates over funding.

Regarding specific developments, the focus between 2020 and 2024 shifted even more sharply toward hydrogen applications in *industry* and *electricity* systems, aligning with our findings that these systems offer the greatest potential for hydrogen. This shift effectively sidelined applications in *transport* and the *built environment*—partly driven by the Dutch government's adoption of the "hydrogen ladder" framework, which prioritises subsidies for projects with the highest decarbonisation potential (an early sign of second-order learning). As a result, most hydrogen-related activities were concentrated in the *electricity* and *industry* systems, with a particular focus on announced or ongoing green and blue hydrogen production projects[21] (see Table S.2). In *transport*, battery electric vehicles continued to dominate both personal and heavy road transport,[22] although hydrogen gained some traction in shipping and aviation through newly proposed plans (see Table S.5). In the *built environment*, hydrogen heating remained confined to small pilot projects, while large-scale deployment remains constrained by high costs, regulatory uncertainties, and a preference for alternatives such as electrification and district heating (see Table S.6).

In sum, while hydrogen niches have continued to develop with increased prioritisation on the electricity and industry systems, progress remains hampered by lacking investments that fall far short of targets. Ultimately, the high costs, regulatory challenges, and slow progress raise serious doubts about whether the Netherlands can achieve its 2030 targets for green and blue hydrogen production and usage.

5.2. Reflections on multi-system niche interactions

This section reflects on the broader implications of the findings regarding the development of niches that span across multiple sociotechnical systems.

First, internal niche processes within one system can significantly influence developments in other systems. For example, positive expectations in one system often shape expectations in another. During the first phase (2001 – 2012)—when developments were more isolated within specific systems—expectations, learning, and network building in one system greatly influenced progress in other systems (refer to Section 4.1.3). This highlights the importance of considering internal niche processes in multi-system transition studies.

Second, actors or organisations can play a crucial role in facilitating multi-system interactions and translating internal niche processes across systems by acting as "bridging organisations" (or intermediaries). For instance, these entities may promote multi-system learning, where lessons from experiments in one system inform developments in others. In our case, they also raised awareness, generated demand, and attracted investment, while supporting the development of multi-system innovation testing beds. This underscores the crucial role of actors in disseminating knowledge across systems and advancing multi-system niche development. Our study suggests that incumbents are particularly well-positioned to act as bridging organisations, consistent with findings from

[21] The most notable projects remain NorthH2, targeting 10GW electrolysis capacity, and H-vision, targeting 700 kt blue hydrogen per year.

[22] By 2023, there were 613 hydrogen fuel cell vehicles (FCEVs) compared to 404,838 BEVs passenger cars, 64 FCEVs versus 1,450 BEVs buses, and 30 FCEVs compared to 966 BEVs heavy trucks, supported by 14 public hydrogen filling stations.

Turnheim and Geels (2019) and Löhr and Chlebna (2023). However, their role should not be taken for granted, as incumbents may have vested interests and motivations that diverge from their stated intentions. Some may use this position strategically, for instance, to delay the transition or keep their options open (Lamb et al., 2020). Therefore, it is crucial to critically assess their participation.

Third, building on the previous point, incumbents have played a significant role in shaping hydrogen developments, particularly during the second period (2013–2020) as decarbonisation pressures intensified. Contrary to their typical resistance to change (Hess, 2014; Smink et al., 2015), many adopted a proactive approach. While further research is needed to better understand their motivations, some incumbents likely sought to protect their business models. For instance, natural gas incumbents may view hydrogen as an opportunity to complement their operations, which explains their strong support for the "blue route." Some may also support low-carbon targets for reputational benefits, while simultaneously aiming to delay progress (Lamb et al., 2020; Ohlendorf et al., 2023). In our case, several incumbent actors are participating in numerous projects and experiments; however, their implementation record remains limited. Recent studies confirm that incumbents can adopt varied strategies—including serving as intermediaries—and significantly influence the pace and direction of low-carbon transitions (Bergek et al., 2013; Berggren et al., 2015; van Mossel et al., 2018; Erlinghagen and Markard, 2012; Mäkitie et al., 2018).

Fourth, industrial clusters appear to be key geographical locations for multi-system interactions, as we observe regional embedding in these areas. These clusters have been instrumental in overcoming early-stage barriers, such as limited demand and inadequate infrastructure—significant challenges to hydrogen implementation. The concentration of resources, actors, and infrastructure within these clusters facilitates overcoming early-stage barriers and serves as catalysts for multi-system innovation, accelerating progress across multiple systems. This observation underscores the importance of geographical proximity and spatial context for fostering multi-system innovations (Coenen et al., 2012; Hansen and Coenen, 2015; Truffer and Coenen, 2012).[23]

Fifth, we observe the importance of a clear development direction for innovations spanning multiple systems. This includes establishing international standards and regulatory frameworks that ensure cohesion and guidance across various systems. Given the diverse options for hydrogen implementation across varying system contexts and the involvement of numerous actors with differing agendas, such guidance can help prevent fragmentation and streamline collaboration among stakeholders from different systems. The Dutch government and the EU's promotion of multi-system interactions and "sector coupling" are positive steps, as they align projects with international, EU-funded initiatives—a critical factor for large-scale hydrogen experimentation. This approach resembles mission-oriented innovation systems, where government plays a pivotal role in tackling grand challenges and ensuring system-government alignment (Weber and Rohracher, 2012; Mazzucato, 2018).[24]

Sixth, analysing innovations that span multiple systems requires a multi-system perspective, as it reveals crucial insights that might otherwise be overlooked. As discussed in Section 5.1, our applied framework based on Bakhuis et al. (2024) highlights key factors influencing hydrogen niche development in the Netherlands.

5.3. *Methodological reflection*

From a methodological perspective, ESA has proven particularly valuable for studying multi-system interactions. Its advantages can be summarised in two main points. First, ESA's focus on linkages, coupled with its visualisation tools, allows for a systematic, longitudinal investigation of developments and activities across various sociotechnical systems. The tools provided by ESA make connections between events explicit, facilitating the tracking of niche development across different systems. Second, ESA enriches transition studies by framing transitions as dynamic "streams of events," emphasising the timing and context of events (Boons et al., 2014; Spekkink, 2015; Turnheim and Geels, 2019; Naber et al., 2017). Unlike traditional methods that often focus on planned, orderly processes (Farla et al., 2012), ESA incorporates "unplanned events," offering a more comprehensive view of transitions and illustrating how developments in one system can be influenced by experiments in another.

6. Conclusion

In this paper, we set out to answer the following research question: *"How is hydrogen niche development progressing in the Netherlands, taking a multi-system sociotechnical perspective?"* To address this, we employed the process-method Event Sequence Analysis (ESA), combined with a sociotechnical multi-system framework influenced by Multi-Level Perspective (MLP) and Strategic Niche Management (SNM) concepts. This approach enabled us to examine hydrogen niche development in four sociotechnical systems: industry, electricity, transport, and the built environment.

Our analysis of the period from 2001 to 2020 shows that while hydrogen niches have gradually continued to develop—with increasing prioritisation in the electricity and industry systems—investments and practical applications remained limited across all systems, despite positive discourse and ambitious plans. Consequently, the future role of hydrogen in the Netherlands remains uncertain, with significant challenges ahead. From an internal niche perspective, while some promising developments have emerged—such as more robust expectations, initial learning, and an expanding social network—two key challenges persist. First, second-order learning remains limited, reflecting the early stage of experimentation. Second, misalignments between government and

[23] Similar to how agricultural innovations are more effectively implemented in rural areas, hydrogen development benefits from the proximity and collaborative potential found within industrial clusters (Coenen et al., 2012).

[24] It is crucial to balance system-government alignment with public acceptance and responsible innovation, as highlighted by past issues such as the downplaying of earthquake risks from gas extraction (Grin et al., 2010).

industry actors regarding appropriate subsidies hinders progress. Industry projects are typically large-scale, capital-intensive, and have low technology readiness, making them a financial risk. Furthermore, while some incumbents drive innovation, others strategically support hydrogen for a competitive edge without significant investment, further delaying progress—whether deliberately or not.

Reflecting on the adopted multi-system framework, we identified several influential factors related to the three key aspects—overarching directionality, transition phases, and system composition (including adjacent niches). First, the overarching directionality toward decarbonisation intensified pressure across all four systems, driving increased hydrogen activity after 2013. Second, varying system transition phases affected how actors shaped the hydrogen narrative; for example, industry actors had more influence due to slower decarbonisation progress in their system. Third, system composition also played a role. Regarding structure, the industry system's reliance on larger-scale projects made implementation challenging and prone to delays. Moreover, attitudes towards hydrogen were shaped by the presence of adjacent niches. For instance, in the built environment and transport systems, actors prioritised electric heating and battery electric vehicles—aligned with overarching directionality toward electrification—limiting opportunities for hydrogen due to path dependence and lock-in effects. Consequently, hydrogen is expected to have most potential in the industry (e.g., for hard-to-decarbonise industries) and electricity systems (e.g., for grid balancing).

In examining hydrogen multi-system niche interactions, we observe six key points. First, internal niche processes—such as expectations, network building, and learning—within one system can significantly impact developments in others. Second, “bridging organisations” (or intermediaries) are crucial for fostering multi-system interactions, particularly for knowledge transfer. Third, incumbents have played a proactive role in shaping hydrogen developments and they are well-positioned to serve as bridging organisations. However, their involvement should be critically assessed, as they often have vested interests. Fourth, industrial clusters have been pivotal, offering economic advantages such as utilising waste streams and facilitating collaborations. This highlights the importance of geography in multi-system innovations. Fifth, a clear development direction is essential, as it supports the establishment of robust regulatory frameworks and international standards. Such directionality fosters a shared vision, enhances stakeholder coordination, and facilitates access to (international) funding—key factors for the success of large-scale hydrogen projects. Sixth, adopting a multi-system perspective when analysing innovations that span multiple systems reveals valuable insights that might otherwise be overlooked.

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CRediT authorship contribution statement

Jerico Bakhuis: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jaco Quist:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Wouter Spekkink:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Conceptualization. **Thomas Hoppe:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Kornelis Blok:** Writing – review & editing, Supervision.

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.

Supplementary materials

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Data availability

Data will be made available on request.

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