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The lack of systems thinking and interdisciplinarity is killing the hydrogen economy

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Hydrogen's promise as a transformative energy solution has been consistently unfulfilled. This perspective article suggests that the primary barrier is not necessarily technological, but a systemic failure to apply holistic systems thinking and genuine interdisciplinary collaboration. Through historical analysis and contemporary case studies, we argue that only by integrating technical, economic, policy, and social expertise within a holistic systems framework across the entire value chain can hydrogen overcome its boom-and-bust cycles and become a foundational component of the low-carbon energy future.

KEYWORDS

hydrogen, systems thinking (ST), interdiscipinarity, hydrogen economy, multidisciplinarity

Introduction

Hydrogen has been heralded as a transformative energy solution for over 50 years; however, despite recurring waves of interest, it remains perpetually "on the horizon" (IRENA, 2022; Oliveira et al., 2021; Yap and McLellan, 2023). The promise of a "hydrogen economy" first gained traction in the 1970s, when electrochemist John Bockris coined the term in response to mounting concerns about the environmental and geopolitical vulnerabilities of fossil-fuel-based energy system (Yap and McLellan, 2023). This is a system we describe today as a fossil fuel sociotechnical regime (Rip and Kemp, 1998). Around the same time, Professor Lawrence Jones of the University of Michigan articulated a visionary "liquid hydrogen fuel economy," proposing it as a long-term solution to reduce reliance on fossil fuels in transportation and improve energy efficiency (Jones, 1970).

Despite these early ambitions and decades of continuous investment, including hundreds of EU-funded R&D projects since the 1980s (Sgobbi et al., 2016), hydrogen technologies have struggled to achieve meaningful penetration in global energy systems. The most recent wave of optimism, catalyzed by the 2016 Paris Agreement and subsequent net-zero pledges, had once again positioned hydrogen as a critical tool for decarbonizing hard-to-abate sectors such as heavy industry and aviation (Yap and McLellan, 2023; Zhu and Wei, 2022). Yet nearly a decade later, the landscape is still marked by skepticism, as up to 20% of announced projects have been cancelled or delayed (Westwood Global Energy Group, 2024). This pattern echoes the boom-and-bust cycles that have characterized hydrogen's history.

This perspective article argues that hydrogen's recurrent failures stem not from technological shortcomings *per se*, but from a deeper systemic blind spot: the persistent lack of embedded systems thinking and genuine interdisciplinary collaboration across the hydrogen value chain. Where past efforts have been focused on the discrete technical or economic challenges in isolation, it is argued that realizing hydrogen's potential demands a holistic approach, one that simultaneously addresses engineering constraints, policy frameworks, economic incentives, and social acceptance. By analysing historical missteps and contemporary case studies, pathways are identified to break this cycle and reposition hydrogen as a viable pillar of the low-carbon energy future.

Hydrogen's recurrent failures: a systems thinking deficit

The origins of the modern hydrogen economy can be traced to the oil crises of the 1970s, when energy security concerns sparked renewed interest in alternative fuels (Yap and McLellan, 2023). Aviation became a particular focus, with NASA's technical reports from that era highlighting hydrogen's potential for aircraft propulsion (Adler and Martins, 2023). Despite certain perceived environmental and performance advantages, hydrogen failed to achieve widespread market penetration. This failure reflects not only the presence of unresolved techno-economic barriers, particularly beyond hydrogen production, but also deeper challenges in the process of technological adoption. The failure may partially also be attributed to resistance from an entrenched sociotechnical regime (Geels, 2005) and declining fossil fuel prices in the 1980s (Gately, 1986). Yet, Thomas Hughes' foundational work on technological systems offers a deeper insight (Hughes, 1983).

Hughes (1983) demonstrated through exhaustive historical analysis that successful technologies never emerge in isolation; rather, they require seamless webs of technical, economic, social and political elements working together in harmony. His classic example was Thomas Edison's electric lighting system, which succeeded precisely because Edison understood he was not just inventing a light bulb, but needed to create an entire associated technological system including power generation, voltage regulation, wiring standards, metering, and consumer education. Edison also cultivated political connections, engaged in lobbying through associates like Grosvenor Lowrey, and secured government support and contracts. This systems approach contrasted sharply with earlier inventors who focused solely on the lamp technology itself.

When applying Hughes' framework to hydrogen's trajectory since the 1970s, systemic gaps become immediately evident. While Edison balanced technical innovation with business models and end-user needs, hydrogen development became narrowly focused on production, especially via nuclear-powered electrolysis, seen as a way to convert nuclear energy into a transportable fuel. At the time, nuclear electricity was expected to be cheap and abundant, making hydrogen production appear techno-economically viable (Wallace and Ward, 1983; Yap and McLellan, 2023). However, little attention was paid to storage, infrastructure or user integration, which may have rendered the overall techno-economics unfavourable. This violated Hughes' principle that technologies evolve as integrated systems. Dominated by engineers and physical scientists, hydrogen efforts lacked economists to model full system costs, policymakers to guide regulation, and social scientists to gauge public attitudes.

These blind spots had real-world consequences. After the Chernobyl disaster, hydrogen's close association with nuclear energy, framed largely by technical communities without wider input, became a political and public burden (Blix, 1986; Yap and McLellan, 2023). With oil prices falling and nuclear power losing favor, hydrogen was probably abandoned not for lack of technical promise but for lack of systemic embedding. It had not been positioned as an independent energy solution but as a technological offshoot, which made it vulnerable to broader socio-political shifts. As Geels (2005) also argues, niche innovations can only penetrate existing regimes if they are embedded in broader networks of support, something which hydrogen never achieved.

Without a robust, integrated system, hydrogen remained a promising but ultimately unviable solution (Rogner, 1998). These historical failures of systems thinking (and also interdisciplinary collaboration as discussed in upcoming sections) continue to haunt contemporary hydrogen initiatives, as the next sections will explore through case studies and current strategies.

Breaking silos: why interdisciplinary integration is non-negotiable

Despite Thomas Edison's groundbreaking role in the electrification of the western world in the late 19th century and his recognition as a champion of systems thinking, his work was eventually overshadowed by the advancements made by Westinghouse and Tesla (Hughes, 1983). Edison's early success with the DC filament bulb stemmed from his holistic approach, where he not only invented a lightbulb but also developed and marketed an entire system. However, his later inability to adapt illustrates another key limitation in technological adoption: the absence of interdisciplinary collaboration.

Interdisciplinarity refers to the integration of knowledge, data, theories, and methods from multiple disciplines to solve complex, real-world problems that cannot be addressed within the boundaries of a single field (Sakao and Brambila-Macias, 2018). This process involves interaction among engineers, scientists, social scientists, economists, and policymakers to co-develop robust, scalable solutions. Once again, we turn to Hughes to understand the limits of systems thinking without interdisciplinarity.

In his later work, Hughes introduces the concept of "heterogeneous engineering," describing how technological, scientific, economic, and social elements become interwoven through mutual shaping. Successful technologies, he argued, are not just technical artefacts but the result of coordinated efforts by diverse actors (Hughes, 1986). Had Edison embraced a more interdisciplinary approach, i.e., being open to innovations and ideas beyond electrical engineering, he might have anticipated the potential rise of alternating current (AC) and formed alliances with external inventors and financiers. This failure illustrates how even sophisticated systems thinking can fall short without input from complementary disciplines. Building on this example, we propose the following hypothesis to guide the discussion in this section: Successful and sustainable systems are rooted in interdisciplinary collaboration.

The relevance of this hypothesis is increasingly apparent in the context of today's sustainability challenges. Scholars such as Holm et al. (2013) and Stock and Burton (2011) emphasize that issues like climate change cannot be understood or solved by any one field alone. Instead, they require the integration of knowledge from various fields to develop innovative and sustainable solutions. An interdisciplinary approach can help bridge the gap between knowledge and action, incorporating diverse perspectives to inform policy decisions effectively.

To ground these conceptual arguments, this paper uses a set of illustrative contemporary case studies from the hydrogen sector. These examples are not exhaustive, but are selected to reflect the different contexts in which interdisciplinarity and systems thinking, or their absence, have shaped successful or unsuccessful outcomes.

A modern example that highlights the risks of insufficient interdisciplinarity is the case of hydrogen for heating in the United Kingdom. Initially, the proposal to use hydrogen as a decarbonization pathway for residential heating seemed promising. The vision encompassed the entire value chain, from production to end use, and capitalized on existing natural gas infrastructure to minimize transition costs (UK Department for Energy Security and Net Zero, 2023). However, the early techno-economic assessments were narrowly framed, evaluating hydrogen under present-day conditions without accounting for evolving energy system dynamics, changing electricity prices, or social acceptance. As more comprehensive analyses emerged, which incorporated future scenarios and broader system impacts, it became clear that hydrogen consistently underperformed compared to alternatives like heat pumps and district heating (Rosenow, 2022; 2024).

These problems became evident to all when the UK's National Infrastructure Commission concluded that "there is no public policy case for hydrogen to be used to heat individual buildings" and advised the government to focus exclusively on electrified heat. Despite this recommendation, the government signalled its intent to continue pursuing hydrogen for home heating, citing the gas network's ongoing relevance to the UK's energy system. Industry actors have also remained invested in the idea, revealing a disconnect between institutional momentum and evolving evidence (The Guardian, 2023). This persistence, despite clear techno-economic disadvantages and also social unacceptance, reflects the powerful influence of existing socio-technical regimes, in this case the gas industry.

As Unruh (2000) warns, poor technological investments can lead to "technological lock-ins," where suboptimal systems persist due to path dependence. In the case of hydrogen, such lock-ins may not only waste resources but also hinder the deployment of genuinely promising applications, such as green hydrogen in steelmaking or shipping (Fossilfritt Sverige, 2020). An interdisciplinary framework would have provided a more balanced evaluation, safeguarding both the public interest and the long-term viability of hydrogen technologies.

From theory to practice: applying systems thinking in hydrogen deployment

Adopting a systems perspective is no longer a theoretical ideal but a practical necessity in the rollout of hydrogen technologies. While interdisciplinary research lays the foundation by integrating insights across fields, it is the application of systems thinking that ensures these insights are translated into coherent, real-world strategies. A systems perspective requires more than just technical optimization; it demands an understanding of how each part of the hydrogen value chain, from production and storage to distribution and end use, interacts within a broader socio-technical and economic context.

Northern Sweden offers an effective example of why this matters. Attracted by abundant renewable electricity and historically low electricity prices, several companies have launched hydrogen initiatives in the region (Fossilfritt Sverige, 2020; Marnate and Grönkvist, 2024). However, without coordinated planning for electricity expansion, large-scale hydrogen production via electrolysis could raise local electricity prices and strain grid capacity, undermining the very economic conditions that made these projects attractive. This pattern is reflected in global trends, as Westwood Global Energy Group (2024) reports that one-third of abandoned hydrogen projects cite higher-than-anticipated costs as a key reason, often rooted in systemic oversights rather than flaws in the technology itself.

In this context, the systems approach becomes a tool for risk mitigation and strategic foresight. For example, projects like Stegra (Stegra, 2022) and Fertiberia (Grupo Fertiberia, 2021) aim to produce hydrogen for steel and ammonia, respectively, yet neither has adequately planned for hydrogen storage. Without storage, hydrogen must be produced continuously, even during periods of peak electricity prices, which may increase operational costs and compromise economic viability (Marnate and Grönkvist, 2024).

In contrast, the HYBRIT project in the same region has successfully pilot-tested geological hydrogen storage, a strategy that could lower hydrogen production costs by up to 40% (HYBRIT, 2025). This integration of storage illustrates how systems thinking, by accounting for interdependencies between components, can enhance project resilience and long-term competitiveness.

Beyond Europe, the Saudi Arabian NEOM initiative provides another illustrative example of systems thinking applied at scale. In many ways, it resembles a modern-day strategy adopted by Edison, designed as a fully integrated hydrogen value chain. This chain begins with dedicated solar and wind power generation, proceeds through large-scale hydrogen production, and is followed by conversion to ammonia for storage and transportation. The initiative also takes into consideration the potential end-users for this hydrogen, as well as the parallel development of the ships for hydrogen export in the form of ammonia (NEOM Green Hydrogen Company, 2025).

The importance of systems-thinking can also be seen in Ørsted's cancelled e-methanol plant, where the anticipated cost of renewable methanol could not compete with fossil alternatives (S&P Global, 2024). Studies like Marnate and Grönkvist (2025) and Recolons (2024), which employed systems-level analyses, had already predicted these challenges. These examples reinforce a key lesson: the success or failure of hydrogen technologies often hinges not on individual components but on how well the entire system is conceived and coordinated. While a systems approach can introduce complexity and higher initial costs, along with the need for coordinating a wider range of stakeholders, these challenges may ultimately be outweighed by its ability to foster long-term resilience and mitigate the risk of systemic failure.

Interdisciplinary institutes with systems thinking: one small step for man, one giant leap for hydrogen

With the need for interdisciplinarity and systems thinking in hydrogen research now recognized, the next step is to not only understand how these approaches can be effectively operationalized, but also to clarify who bears the responsibility for doing so. Holm et al. (2013) offered an early and influential call to action, arguing that interdisciplinary collaboration must be central to global change research. They advocated a bottom-up strategy, led by researchers and academic institutions, while also urging funding agencies to prioritize and institutionalize interdisciplinarity within research centres. A decade later, however, much of the research landscape remains fragmented, which highlights the deeper need for institutional restructuring that embeds systems thinking across all aspects of hydrogen innovation. While academic researchers and research centres play a central role, the responsibility to apply an interdisciplinary framework does not lie with academia alone. Policymakers, funding agencies, and industry stakeholders must also commit to systemic and integrative approaches when designing strategies, regulations, and investment priorities for hydrogen.

Some initiatives are beginning to demonstrate what such structures might look like. One particularly compelling example of interdisciplinary systems thinking in practice is the EU-funded JIVE and JIVE2 projects. Rather than simply testing hydrogen fuel cell buses in isolation, JIVE approached the decarbonisation of the transport sector as a whole-system challenge. The project deployed over 290 buses across 16 countries while simultaneously investing in refuelling infrastructure and research and development to support technical learning. It integrated knowledge from engineers, researchers, environmentalists, city planners, policymakers, and industrial actors, while creating a feedback loop that accelerated learning, improved powertrain efficiencies, and reduced both capital and operational costs. For example, buses were operated under diverse terrain and climate conditions, helping to identify technical and logistical barriers to large-scale deployment. According to project representatives, this success was only possible due to the project's explicitly interdisciplinary structure, which enabled not only knowledge sharing but also genuine knowledge creation. JIVE thus provides a model for how a technical concept, long considered viable, can achieve techno-economic feasibility when embedded within a broader system that is collaboratively designed and governed (Hydrogen Europe, 2025).

Another EU-funded project that explicitly embraced interdisciplinarity is Elegancy, which combined technical, economic, legal, and sociological perspectives to assess hydrogen and CCS value chains (Benrath et al., 2019). This effort highlights how cross-disciplinary collaboration may produce more robust and context-sensitive outcomes. Similarly, the Swedish research institute Energiforsk, through its hydrogen storage project (Frost et al., 2025), exemplifies the value and challenge of this approach. Although its primary mandate is technological, the project has effectively incorporated systems principles by linking technical storage options to regulatory frameworks (such as the limitations safety standards impose on cavern development), identifying knowledge gaps through consultation with industry stakeholders, and situating Swedish hydrogen infrastructure within broader international contexts like the UK and Norway. While not always explicitly framed as systems thinking, this kind of work shows how interdisciplinary methods can be embedded in practice.

The Swedish research program PUSH (Production, Use, and Storage of Hydrogen) exemplifies another important dimension of systemic thinking (KTH, 2025). Its research structure spans the entire hydrogen value chain: from production using electrolysis, to storage, to end-use in sectors such as transport and industry, and includes a sub-project that aims to integrate these elements through a systems perspective. This structural focus reflects an understanding that hydrogen technologies do not operate in isolation, but as part of larger interdependent systems. However, PUSH, like many other technology-oriented initiatives, operates primarily through a multidisciplinary model, where distinct fields contribute in parallel, as shown in Figure 1.

This distinction is crucial: while a systems approach emphasizes interactions across technical components and value chains, interdisciplinarity goes further by integrating insights from diverse fields—technical, economic, political, and social—into the research process itself. What is ultimately needed is a combination of both: the structural systems perspective that programs like PUSH exemplify, and the integrative knowledge development seen in projects like *Elegancy*. Rather than disciplinary work followed by *post hoc* synthesis, the goal should be real-time integration, where research questions, methods, and outcomes are shaped jointly across the technical, social, and political domains. Such an approach is essential for anticipating implementation barriers, avoiding lock-ins, and ensuring hydrogen technologies contribute meaningfully to sustainable energy transitions. The successful implementation of hydrogen technologies therefore depends not only on how research is conducted, but also on how knowledge is mobilised and acted upon by governments, regulators, and industry.

Conclusions and future outlook

The hydrogen economy's recurring cycles of promise and stagnation reveal a fundamental truth: technological potential alone cannot drive energy transitions. As this analysis suggests, drawing on both historical cases and contemporary projects, the future of hydrogen may well depend on institutionalising systems thinking and interdisciplinarity, not as parallel efforts but as integrated practices. Moving beyond multidisciplinary collaborations, where disciplines merely operate side by side, hydrogen research and deployment must adopt truly interdisciplinary models that treat technical, economic, and social dimensions as co-evolving parts of a single system.

This requires a strategic shift where all stakeholders actively work toward a common goal. Policymakers and regulators should implement integrated policies that explicitly link production to infrastructure and end-use, while prioritizing funding for genuinely interdisciplinary research. At the same time, industry leaders and investors must embrace a full value-chain approach, moving beyond component-level optimization to build projects that are resilient and economically viable. The EU-funded JIVE project and Saudi Arabian NEOM initiative offer rare examples of this, where an explicit systems-thinking approach enabled

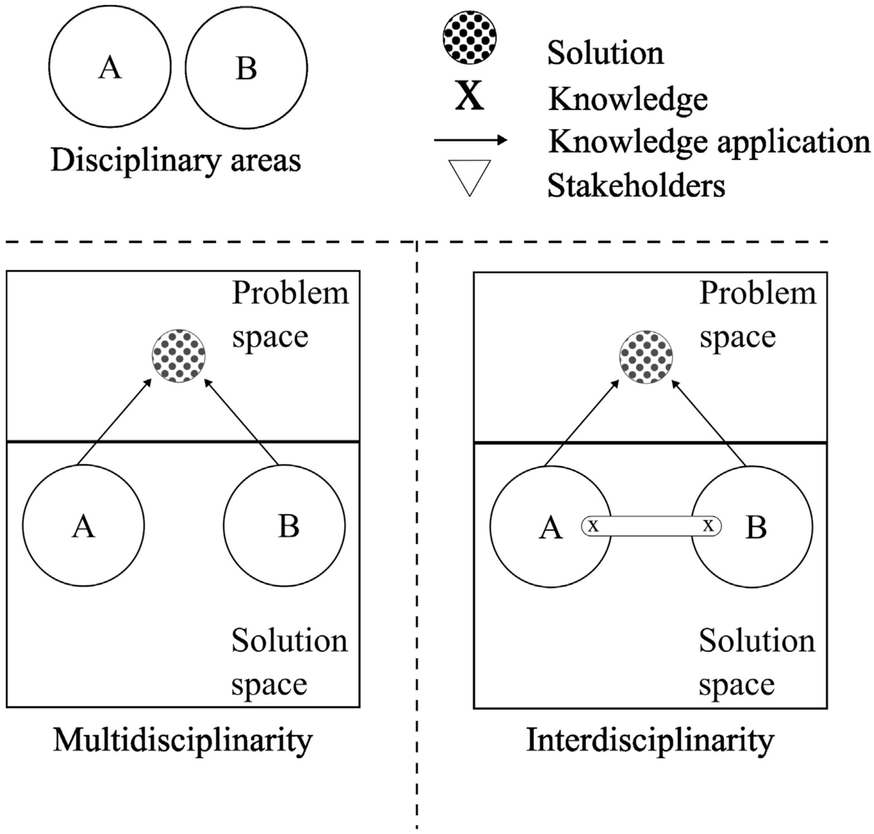

FIGURE 1
Schematic of multidisciplinarity and interdisciplinarity, adapted from Sakao and Brambila-Macias (2018).

successful implementation at scale. While many large-scale projects already reflect aspects of systems thinking in practice, these are often not made explicit or formally embedded in project governance. Ultimately, researchers must shift their focus from individual components to full-system analyses, framing research questions that directly address implementation barriers and engage with policymakers and industry from the outset. While promising developments are underway in places like Sweden, where initiatives like Energiforsk and PUSH are beginning to integrate technical, social, and economic factors, these efforts remain foundational rather than sufficient. They must also focus on developing shared research questions that evaluate system viability across socio-technical dimensions, and creating funding and institutional incentives that reward integrative outcomes.

Addressing the remaining challenges may also require moving toward transdisciplinarity, where communities and stakeholders are involved not merely as research subjects but as co-designers of hydrogen systems. While academia plays a central role in shaping research agendas and proposing integrative frameworks, it is ultimately policymakers, regulators, and private actors who carry out large-scale implementation. As highlighted in two recent studies by Gómez and Rehage (2024) and Rehage and Gómez (2024), transdisciplinary collaboration helps bridge the gap between conceptual innovation and practical deployment by aligning technical advances with governance structures, stakeholder needs, and local contexts. This approach also opens the door to a more equitable distribution of benefits, which remains largely absent in today's hydrogen discourse.

The choice ahead is clear: continue along the fragmented path and risk killing the hydrogen economy in its cradle, or commit to building the collaborative frameworks necessary to unlock its full potential. This requires that policymakers, planners, regulators, and industry leaders adopt systems thinking as a guiding principle, not only to support individual projects but to coordinate action across regions and sectors.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KM: Conceptualization, Investigation, Writing – original draft, Writing – review and editing, Formal Analysis.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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