BREAKING BARRIERS

Research Studies to Accelerate Transitions

Breaking Barriers: Research Studies to Accelerate Transitions
Full papers and abstracts from the scientific conference of the New Energy Forum 2026

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Preface

Wim Elving

It is an honor to present the first edition of *Breaking Barriers: Accelerating Transitions*, a collection of full papers and abstracts based on contributions to the Conference on Energy, Livestock, and Mobility Transitions, held on June 17th as part of the broader New Energy Forum in Groningen. This inaugural volume marks the beginning of what we intend to develop into a continuing series, documenting both the evolving state of the energy transition and the growing body of practice-oriented research in this field and its related domains.

Entrance, the Centre of Expertise Energy at Hanze University of Applied Sciences in Groningen, has been active for more than two decades. What began modestly, with a small number of containers inaugurated by the then Crown Prince (now King), has developed into a leading knowledge institute dedicated to accelerating the energy transition under the guiding principle "People in Power." Over the years, Entrance has grown from a handful of researchers into a community of more than 100 researchers and 10 professors, with an annual turnover approaching €10 million. The original site has evolved into a field laboratory featuring a range of unique facilities for testing future energy systems. These include the Renewable Molecules (REMO) laboratory for scaling up fermentation processes to produce green gas, as well as installations for electrolysis, and infrastructures for the transport of heat, hydrogen, and green gas. This integrated field lab is not only unique within the Netherlands, but also rare in the European context, offering researchers, companies, and students the opportunity to experiment with and advance the integration of future energy systems.

Applied research at Universities of Applied Sciences (hogescholen) is still relatively young. The first professorships were established in 2003, less than 25 years ago. In contrast to traditional research universities, where research has long been central and often dominant, education remains the primary focus within Universities of Applied Sciences. However, as societal challenges grow increasingly complex, monodisciplinary approaches, while still valuable, are no longer sufficient on their own. Multidisciplinary research has emerged as a crucial driver of sustainable economic development. Increased investment in applied research has enabled institutions to address complex transitions such as those in energy, materials, and mobility.

From its early stages, Entrance has recognized that the energy transition is not solely an engineering challenge, but a fundamentally multidisciplinary one. Engineers are essential for developing new sustainable gases, storage technologies, and energy systems, but equally important are insights from economics to design viable business models, legal expertise to facilitate systemic change, and behavioral sciences to understand and influence sustainable lifestyles. Communication and branding also play a vital role in disseminating knowledge, fostering dialogue, and supporting new sustainable initiatives. Over the past 20 years, Entrance has successfully integrated these diverse areas of expertise into a strong and collaborative centre of excellence.

Within applied research, the focus is not only on generating new knowledge, but primarily on applying that knowledge to develop innovations that address societal transitions. Compared to traditional academic researchers, applied researchers may publish less frequently, as their work is often oriented toward practical impact. With the introduction of this book series, we aim to encourage applied researchers to share their findings more widely through academic publication. While traditional academic environments are often guided by the principle “publish or perish,” applied research has historically prioritized societal impact. Although there is increasing overlap between these domains, this distinction remains relevant. By creating additional opportunities for publication, we hope to further strengthen the visibility and professionalization of applied research.

For this first edition, we have compiled contributions based on submitted papers, without implementing a full peer-review system. For this reason, this volume is presented as conference proceedings. Following an evaluation of this initial process, we intend to introduce a formal peer-review system for future editions, enabling subsequent volumes to be recognized as fully peer-reviewed publications. We are aware that this will have implications for submission timelines and will require the continued commitment of reviewers. Nevertheless, we hope that this inaugural volume will inspire our colleagues at Entrance and at other Universities of Applied Sciences to take further steps in advancing and professionalizing applied research.

New Energy Forum

Wim Elving

During the COVID-19 pandemic in 2021, together with the New Energy Coalition and Hive.Mobility, we launched the New Energy Forum. The first edition was primarily online due to public health restrictions, although 150 participants were able to attend in person. The livestream attracted more than 300 additional participants. Since then, the event has continued to grow steadily, increasing from 500 visitors in 2022 to more than 1,700 attendees in the 2025 edition.

For the 2026 edition, several changes were introduced. In previous years, all activities took place within a single afternoon, creating an energetic but sometimes hectic festival atmosphere. This year, the program was redesigned to create more space and a smoother experience for visitors. The scientific conference, first introduced in 2025, featured authors presenting abstracts and papers in parallel sessions. While successful, the format proved challenging to manage within the main event schedule. Therefore, in 2026 the scientific conference was organized on the day before the main event. This publication is one of the outcomes of that conference.

The New Energy Forum is designed for current and future professionals in the energy and mobility sectors. It connects practice with research and provides an ideal platform for partners and stakeholders to exchange knowledge, share insights, and strengthen professional networks. The number of partners involved in the event continues to grow each year.

Entrance Professional Award

In 2026, the Entrance Professional Award will be presented for the fifth time. This prestigious innovation prize recognizes pioneers who accelerate the energy transition through bold ideas and innovative solutions. The winning organization receives a prize valued at €100,000, consisting of both financial support and in-kind contributions.

Year	Winner	Description
2022	BioBTX	Develops technology for a circular economy by producing BTX from biomass and plastic waste.
2023	New Born Rubber	Develops innovative recycling processes for rubber products.
2024	Saluqi Motors	Develops advanced electric motor solutions.
2025	Saltes	Develops industrial heat systems without the use of fossil fuels.

The jury for the 2026 Entrance Professional Award consists of Marcel Koenis (Entrance), Dick Pouwels (Chair of Hanze), Ruud Koornstra (National Energy Commissioner), Jörg Gigler (TKI Nieuw Gas), Koen Kok (TU Eindhoven), and Eelkje Oldenburger (Entrepreneur).

Entrance Student Awards

During the New Energy Forum, the winners of the Entrance Student Awards are also announced. These awards recognize students from vocational (mbo), higher professional (hbo), and research university (wo) institutions in the Northern Netherlands who completed impactful projects related to the energy and raw materials transition during the 2025–2026 academic year.

For the first three years, the award was named after the late Frits Dröge, who played an important role in establishing the Energy Masters programs at Entrance, particularly the Energy for Society (E4S) program.

Year	Winner(s)	Program	Project
2021	Pieter van Hoeken & Denise Lee	E4S	Projects on hydrogen scaling value models and energy dashboard adoption.
2022	Saskia Glink	SESYM	Development of a valuation tool for industrial decarbonization projects.
2023	Hanna Kreuger & Sinja Albert	E4S / MIC	Research on energy poverty and female talent in renewable energy.
2024	Valeria Santos Cilento	EMRE	Assessment of offshore wind and hydrogen technology integration.
2025	Lars van der Schuur, Joren Benes, Farshad Saderi & Daan Vedder	Alfa College Groningen	Development of a power unit within the H2 Train and Learn Hub.

E4S: Energy for Society Master; SESYM: Sustainable Energy System Management; EMRE: European Master in Renewable Energy; MIC: Master International Communication.

Introducing the 2026 Research Award

For the first time in 2026, the Entrance Research Award will be presented. Authors who submitted full papers for the scientific conference are eligible for this award, and their contributions are included in this publication.

The jury consists of Frans Tillema (HAN University of Applied Sciences), Lorenzo Squintani (University of Groningen), and Marcel Koenis, Marten van der Laan, Wytze van der Gaast and Wim Elving (Entrance, Hanze).

Both the Research Award and the Student Award include prizes of €1,500 for first place, €1,000 for second place, and €500 for third place.

Together, these elements contribute to the distinctive and collaborative atmosphere that makes the New Energy Forum a unique platform for innovation, research, and connection in the energy transition.

New Energy Coalition

Charles van Santvoord

The North of the Netherlands boasts a strong energy cluster, situated at the heart of the European energy market. For over 20 years, New Energy Coalition has been the leading network organization connecting companies, knowledge institutions, and governments to work together on new energy for a powerful region. Working on knowledge and innovation we contribute to 80+ energy transition projects. Focused on a modern and future-proof energy system where sustainable solutions for green electricity, green gas, and hydrogen converge. New Energy Coalition accelerates this transition by providing a unique platform for knowledge sharing, agenda setting, and supply chain management to create a positive investment climate for new research, education, innovation, and entrepreneurship.

We are "Drivers of Change".

In this context, energy serves as a means for a powerful region. Therefore, the focus is not solely on the expansion of the energy sector, but specifically on the role of energy as an 'enabler' for other sectors and societal developments. Economic development and sustainability go hand in hand in this regard (green growth). To make this possible, a transition to a future-proof, reliable, and affordable energy system is necessary.

Important elements within the region are a historically strong energy region (from peat, oil, and gas to sustainable energy) with a unique business and knowledge cluster, a strategic location on the North Sea (offshore wind, ports), and at a crossroads of European energy infrastructure.

As a foundation, we bring the triple helix together to arrive at a shared approach and implement it collaboratively. To 'speak with one voice' and work together on new energy for a powerful region.

New Energy Forum

Organizing corporate events is an important way to foster knowledge (sharing) and connection, where partners and energy professionals from the triple helix come together to network and share knowledge. Goals: connection, agenda setting, regional economy, working towards a future-proof, reliable, and affordable energy system. The focus remains on knowledge and connection, but with the new strategy of the New Energy Coalition, the emphasis also lies on positioning the region (Dr/Gr).

The 2026 edition focuses on mindset, (behavioral) change, and the individual.

We organize New Energy Forum with two important partners: Hanze/Entrance and Hive.Mobility together with an important circle of partners giving input. Check www.newenergyforum.nl for more information.

New Energy Forum was founded on the conviction that the transition to a sustainable future is only possible if existing patterns, structures, and interests are broken within the energy and mobility sector. It is no coincidence that the subtitle is: Breaking Barriers! The goal is to bring together people, organizations, and ideas that can jointly build a new value chain and solutions for a sustainable future in the north of the Netherlands. In doing so, New Energy Forum contributes to economic development and broad prosperity in the region.

We want to create an atmosphere where we surprise people, where we connect people, and where we stimulate and accelerate the transition to a sustainable future. A valuable part of our New Energy Forum is the applied scientific research event. This research event brings together researchers from various disciplines around themes such as sustainable mobility, regional energy systems, participation, and innovation in the energy transition. The results can be found in this book. Without research, no innovation! We wish you enjoyable reading and we hope that the studies in this book will help you in your endeavour to speed up the energy transition.

Hive.Mobility

Caroline Nauta & Jasper van der Velde

The world of mobility is changing at a rapid pace. We can travel in an increasing number of ways, thanks to new forms of transport, digitalization, and innovative (vehicle) technologies. As a result, mobility is becoming increasingly greener and smarter. Consider, for example, self-driving cars and trains, or intelligent traffic lights that can communicate with traffic. Innovations in the field of smart and green mobility have great potential to further develop the Northern Netherlands region and to realize ambitions regarding nature and climate.

At Hive.Mobility, there is a buzz of activity, and innovations come to life. Hive.Mobility is a leading innovation network focused on promoting smart and green mobility solutions through close collaboration between governments, knowledge institutions, and companies — a unique and proven partnership.

Through a strong focus on collaboration, knowledge sharing, and innovation, Hive.Mobility strives to accelerate the transition to sustainable mobility and has a positive impact on the environment and society. Technological and societal innovations create numerous opportunities to transport people and goods smarter, faster, and more sustainably. Therefore, the challenge is to bridge the gap between ideas and pilots and to ensure that pilots are further developed into sustainable innovations or applications.

It is therefore not only important to try out innovations, but to also have a long-term vision and to organize entrepreneurship. In addition, it is important to develop the policy in parallel. Knowledge and collaboration can be further enriched by, for example, developing continuous learning pathways, internships, and learning communities. In this way, the labor market and knowledge institutions can also be better aligned.

Before the founding of Hive.Mobility, there was a fragmented landscape of initiatives in the field of smart and green mobility. As a result, it was more difficult for the various organizations to connect with each other and form collaborations. Since the founding of Hive.Mobility in 2019, hard work has been done to build a close-knit network. Through pooling organizations and expertise, progress has been made on the five main themes of Hive.Mobility:

- Smart logistics,
- Autonomous transport,
- Sustainability,
- Data and digitalization,
- Open and connected (mobility) networks.

Talent, knowledge and expertise

The Northern Netherlands has a strong interest in the mobility transition, particularly in areas experiencing an aging population and population decline. At the same time, the region is characterized by urban and inner-city areas with many young people and amenities, where traffic flow and environmental nuisance pose challenges. Add to this the region's ambition to work towards zero-emission mobility and infrastructure, more space for greenery, less environmental nuisance, and to become more autonomous, cooperative, and inclusive, and to enable multimodal mobility systems. Consequently, it is important to look beyond traditional mobility solutions.

The existing ecosystem of the Northern Netherlands forms the perfect basis for further shaping and driving this mobility transition. The keys to this is a culture of open innovation and collaboration. Collaboration among companies themselves, but also between the business community, education, and science. Talent, knowledge, and expertise are readily available, and in this dynamic playing field, ample opportunities arise for innovation — such as 6G, hydrogen, the Internet of Things, sensor technologies, autonomous transport, hubs, and shared mobility—but also innovations in the field of societal issues such as behavior.

The many partnerships in the Northern Netherlands between government, companies, education and science, and many other parties create a perfect climate for innovation and entrepreneurship. Groningen, as the City of Talent, is bursting with startups and scaleups, including in the field of sustainable mobility. The three northern provinces have been united for years in the Northern Netherlands Cooperation Association (SNN). Together, they have built a strong reputation in Brussels, The Hague, and Germany.

Government, knowledge institutions, and entrepreneurs collaborate intensively in the areas of lobbying, program development, and project financing.

A key strength of the North, and Hive.Mobility, has proven to be its inter- and multidisciplinary character. Additionally, within the field of mobility, there are various partnerships with sectors such as energy, the economy, and industry. The Northern Netherlands region holds the key to making cities (even) more accessible and cleaner, improving connectivity in shrinking regions, and enabling more efficient travel to work and school, including for individuals with age-related and illness-related limitations. In short, this contributes to improving the economic and social well-being of the region.

Northern Netherlands as a living lab

The Northern Netherlands is an exemplary region for the Netherlands as a whole; it has both metropolitan and rural areas. All modalities are represented, including the connection between land and water. This offers an excellent ecosystem for experimenting, piloting, and innovating.

The North offers a quiet and safe environment to develop and test concepts in both urban and rural areas. New techniques and concepts must be extensively tested so that they can later be safely put into use on public roads in similar situations. The Northern Netherlands supports the ambition of the Ministry of Infrastructure and Water Management (IenW) to position the Netherlands internationally and to further increase the opportunities for this international position.

Due to administrative simplicity, short lines of communication, a collaboration-oriented culture combined with a strong IT economy and financial and innovative strength, the Northern Netherlands is the ideal location for a leading international test region.

Innovation through collaboration

Hive.Mobility is a nationally and internationally leading innovation network of partners (consisting of knowledge institutions, government bodies, and companies) in the Northern Netherlands, within which collaboration takes place on the transition to more sustainable and smarter mobility of goods and people.

Hive.Mobility thereby plays a central role within this network, giving it a unique position to promote innovation. By creating efficient lines of communication between the various organizations, an ecosystem has emerged that can respond flexibly to (external) opportunities and possibilities. In other words, Hive.Mobility is a means/instrument to achieve and promote innovation.

Mission

We believe in the power of collaboration between companies, knowledge institutions, and governments. By bringing these parties together and stimulating them, we create an ecosystem in which innovations can be successful and the transition to sustainable mobility is accelerated.

Our door is always open. Everyone committed to smarter, cleaner mobility is welcome to work with us. By inspiring and challenging each other, we are working towards a future in which mobility is not only efficient and reliable, but also good for the environment and society as a whole (and in particular that of the Northern Netherlands and its residents).

Vision

Our vision embraces a world where smart, green mobility is the standard, where innovation leads and contributes to a more sustainable future. We strive for a world where innovation is deployed as a powerful tool for positive change, and where innovation is encouraged through collaboration and transparency.

At Hive.Mobility, we aim to be a leading force and an innovation center in the mobility transition. By connecting, strengthening, and stimulating, we are taking a significant step towards more sustainable, safer, and intelligent mobility for both goods and people. We strive for a situation in which all involved parties, including the Northern Netherlands as a region, benefit from the joint efforts being made. In this way, we strengthen the northern region and demonstrate that we are leading the way in the Netherlands and Europe in the field of smart and sustainable mobility.

Lead by example

To achieve these ambitions, governments, the business community, and knowledge institutions within Hive.Mobility will work together to explore, develop, and apply innovations into practice.

The unique aspect of this collaboration is the combination of the wealth of knowledge and expertise available among all parties, and the opportunity to utilize this knowledge and learn from one another. It also offers the chance to structure and provide an overview of the initiatives in the Northern Netherlands and to promote them. Hive.Mobility will drive, strengthen, and connect innovations, primarily within the five promising innovation themes to bridge the gap between ideas and pilots and ensure that pilots are further developed into sustainable innovations or applications.

Theme: Smart logistics

Logistical expectations have increased (i.e. being able to get everything anywhere, anytime, or direct home delivery of internet orders), while the nuisance of supply traffic is tolerated less and less (i.e. congestion, safety, emissions, liveability). Because of urbanization there is an increasing battle for the available space, how it is used and by whom and when. This also puts pressure on the logistics system.

Therefore, a new form of (city) logistics must be found, which is aimed at doing more with fewer logistical movements and with fewer emissions. This must be done by organizing logistics differently and smarter.

> *Example project: Noorderpoort Elective module - Sustainable Urban Logistics*
> No emissions, fewer transport movements, and less traffic noise in the city center. That is also Groningen's ambition. To achieve this, at the very least, well-trained logistics employees are needed who know how to organize urban transport in a sustainable manner. The development of the MBO elective 'Sustainable Urban Logistics' aims to contribute to this knowledge among (future) professionals. Together with Bidfood, Noorderpoort is taking up the challenge to perfect this elective and train the professionals of the future.

Theme: Autonomous transport
The Northern Netherlands is the European front runner when it comes to testing autonomous transport. It is the only region where road, rail, air, water and tube (hyperloop) tests are conducted using autonomous transport. Autonomous transport must, among other things, ensure better accessibility and quality of life in both urban and rural areas and reduce emissions and fuel consumption.

> *Example project: Five field labs for autonomous transport:*
> The aim of these field labs is to work towards both certification and broad use of autonomous transport in daily practice through testing and scaling up. Training and research are also linked to the field labs to sustainably safeguard and pass on knowledge and to develop sufficient talent. The field labs are practice-oriented test locations, where various parties (governments, companies and knowledge institutions) develop, exchange knowledge and test together.

Theme: Sustainability
The Northern Netherlands has the ambition to bring its mobility to zero emission and all infrastructure to a minimum of energy neutral by 2035. Sustainability can be achieved by investing in alternative fuels and (hydrogen) electric propulsion.

> *Example project: Regional Approach to Charging Infrastructure North (RAL)*
> The Netherlands is switching to sustainable transport: by 2050, all transport must be emission-free. Due to the current problems with grid congestion, it is a huge challenge to meet the charging

needs. The National Charging Infrastructure Agenda (NAL) is working to achieve this task by ensuring that the development of charging infrastructure is in line with the rollout of electric vehicles. Within the framework of the NAL, the provinces of Groningen, Drenthe and Fryslân form the RAL-North cooperation region.

RAL-North will support municipalities in the rollout of charging infrastructure. They do this by sharing knowledge and skills, helping municipalities to draw up an integrated charging vision and installation policy for the public charging infrastructure. This collaboration runs at a regional level because bundling and coordination between the private and public charging network is one of the biggest challenges.

Theme: Data and Digitalization

Communication between vehicles, the roadside and within the network, in combination with data sharing in smart information transport systems such as 5G and sensors, can contribute to making the mobility sector more sustainable and traveling from A to B much smarter.

Example project: Mobisitie

Under the leadership of Hanze University of Applied Sciences, the Mobisitie project has been carried out. Within Mobisitie, the involved partners worked in a co-creative manner on a Policy Decision Support System (PDSS) for civil servants with questions or issues regarding support and participation in the sustainable mobility transition.

The transition to a sustainable mobility system is extra challenging for rural municipalities, because these regions must also remain liveable and accessible, while also having less personnel (compared to larger urban municipalities) to tackle topics like mobility- and energy transition.

Formulating good policy is therefore complex, for example because relevant information is difficult to find. In addition, it requires specialist knowledge to stimulate communication with and participation by residents. Ultimately, the project should deliver a digital tool that helps civil servants by collecting specific and relevant information and provides methods to involve their residents in the transition.

This PDSS will deliver capacity savings by automating a lot of research and design work, serving selected themes, such as shared mobility and modal shift from the car to the bicycle. The design of a PDSS meets the professional needs of civil servants and contributes to knowledge about engagement processes, digitalization, communication, participation and their embedding in higher professional education.

Theme: Open and connected (mobility) networks

Exchange between freight and passenger transport parties, bundling deliveries and sharing storage and transport capacity offer opportunities for more efficient and sustainable logistics and mobility. In open and connected logistics networks, tasks, resources, data, space and responsibilities can be shared for a more efficient chain.

> *Example project: Deel'M*
>
> To improve mobility in rural areas, the provinces of Groningen, Drenthe, and Friesland are collaborating in the Deel'M project. This project aims to develop sustainable and accessible shared mobility solutions that meet the needs of residents and reduce the negative impact of car usage. Deel'M strives to increase awareness and create social and economic opportunities for shared mobility. The ultimate goal is to enhance overall well-being and the accessibility of shared mobility in rural areas.

Hive.Mobility x New Energy Forum

As the mobility and energy transition is one of the biggest challenges of our time, the collaboration between governments, knowledge institutions, and companies in these challenges is of the upmost importance. In Groningen, where the transition from fossil fuels to sustainable energy has been a central focus for years, New Energy Forum emerged as a response to the urgent need for collaboration and innovation. This event, initiated by Hive.Mobility, New Energy Coalition, Hanze University of Applied Sciences, and ENTRANCE, brings together knowledge, technology, and ambition to shape the future of energy.

For Hive.Mobility, New Energy Forum is not only a platform to share our vision on smart, sustainable mobility solutions, but also an opportunity to emphasize the power of collaboration and networking, and to invite heard and unheard voices in the industry to share their stories and solutions.

Sharing information and training talent are essential for the success of the transition. The New Energy Forum is therefore not just an event, but a movement that shapes the future of energy in Groningen – and beyond.

And this year, just one question remains: what are YOU doing to accelerate the future?

Entrance: From Two Containers to Thought Leader

Marcel Koenis (Entrance)
Tijske Kingma (Entrance)
Wim Elving (Entrance)

Entrance, the Centre of Expertise Energy at Hanze University of Applied Sciences Groningen, has developed from a modest experimental initiative into one of the most prominent applied research hubs in the Dutch energy and material transition. We shortly describe these developments and situate Entrance within broader debates on innovation systems, knowledge co-creation, and societal transitions. It explores how Entrance integrates interdisciplinary research, education, and practice through learning communities and how its thematic structure, lectorate system, and project portfolio contribute to impact.

Specifically, key projects and facilities include Groningen Stroomt Door, the REMO lab, the HydroHub Test Center, Hydrogen Valley Campus Europe (HVCE), Symphonie, and HyperBRIDGE, which illustrate our innovative and transdisciplinary approach. This chapter further examines the role of co-creation, our motto "People in Power", and the importance of engaging citizens and companies in shaping transitions. Finally, it identifies the strategic challenges and opportunities for Entrance, particularly in relation to knowledge dissemination, digital knowledge infrastructures, artificial intelligence, and emerging research lines such as nuclear energy. The analysis concludes that Entrance is well positioned to evolve into a thought leader, provided it succeeds in institutionalising its knowledge practices and strengthening its role in shaping transition narratives.

1. Introduction

The development of Entrance can be read as a microcosm of the broader transformation of innovation systems in the twenty-first century. It all began as a small experimental initiative with only two containers at what is now Entrance's living lab. No one really knew what Entrance was, but when the word got out that the Dutch crown prince, now King Willem-Alexander, was attending the opening of the facility, both the mayor of Groningen as well as the chairmen of Hanze's Board of Governance decided to be present as well. Their reasoning must have been: "if it's important enough for the crown prince, it must be something valuable."

Those two containers evolved into a complex, interconnected, and influential knowledge ecosystem. This trajectory is not merely one of growth in scale, but of qualitative transformation. Entrance has moved from a focus on technological experimentation toward an integrated model in which research, education, innovation, and societal engagement are intertwined. In doing so, it reflects a shift from linear models of innovation toward systemic, networked, and transdisciplinary approaches that are increasingly required to address complex societal challenges such as the energy and material transition.

The ambition of Entrance is not limited to contributing to these transitions through individual projects or technological innovations. Rather, it seeks to play a more fundamental role in shaping how these transitions unfold. This ambition implies a move toward thought leadership, understood here as the capacity to influence agendas, frame problems, develop methodologies, and guide collective action across sectors. Thought leadership in this context is not simply a matter of visibility or reputation, but of the ability to integrate knowledge, actors, and practices into coherent and impactful strategies.

Today, our stakeholders increasingly expect Entrance to play an active and forward-looking role in addressing the challenges of the energy transition, particularly the shift from fossil energy and materials to renewable sources. In this contribution, we outline how Entrance has systematically built the foundations needed to fulfil this role, positioning itself as a trusted partner in navigating the complexities of a more sustainable future.

2. Entrance as a Knowledge Community

At the core of Entrance's approach lies the concept of a knowledge community that is constantly learning and developing. This concept captures a distinctive way of organising research and innovation that goes beyond traditional institutional boundaries. Entrance is not merely a research centre or an educational institution; it is a dynamic network in which students, researchers, companies, governments, and citizens continually interact to develop knowledge, solutions, and competencies, pointed at new collective perspectives on renewable solutions. This interaction is both inward and outward oriented (and vice versa), linking the internal processes of the Hanze with the evolving needs and opportunities of the external environment, governments, institutions, organisations, SME's etcetera.

This dual orientation is essential for achieving societal impact. New knowledge and innovations emerge from practice-oriented research and are subsequently integrated into educational programmes, where they contribute to the development of future professionals and actual professionals. At the same time, these professionals bring new perspectives and skills back into practice, creating a continuous cycle of learning and innovation. The effectiveness of this cycle depends on the intensity and quality of the interactions within the knowledge community. Entrance therefore places strong emphasis on building and maintaining relationships with a wide range of partners, including companies, public authorities, and societal organisations.

The scale of these interactions is considerable. Entrance operates with an internal budget that is relatively modest in comparison to the size of its overall project portfolio, which is significantly larger due to external funding, partnerships, and cooperations. This leverage effect reflects the organisation's ability to mobilise resources and actors around shared goals. It also illustrates the importance of trust and reputation in sustaining long-term collaborations. Entrance is perceived as a reliable and competent partner, capable of translating complex societal challenges into actionable research and innovation projects.

3. Interdisciplinarity and the Role of Professorships

A defining feature of Entrance is its interdisciplinary character. The energy and material transition encompasses technical, economic, social, legal, and cultural dimensions, and cannot be addressed effectively within the confines of a single discipline. Entrance responds to this complexity by organising its research through a system of six professorships, each led by a professor (in Dutch: lector) with a specific domain of expertise (see Table 1 for an overview). These professorships form the intellectual backbone of the organisation and provide the base for its interdisciplinary collaborations.

As seen in the table, Entrance's professorships cover a broad range of fields. Together, they enable the integration of technical and social perspectives, which is essential for understanding not only how technologies function, but also how they are adopted, regulated, and experienced in practice. Professors and their research groups play a central role in connecting research, education, and external partners. They are responsible for developing research agendas, supervising projects, and ensuring that knowledge is translated into educational programmes and practical applications.

Table 1. Overview of Entrance's professorships and current and recent professors

Name lectoraat (research group)	Professors	Expertise	Retired
Energy Transition	Jan-jaap Aué	Hydrogen applications	
	Marten van der Laan	System integration	
	Martien Visser[1]	Energy transition	2025
Life Sciences and Renewable Energy	Zohre Kurt	Life sciences and renewable energy	
	Jan Peter Nap	Life sciences and renewable energy	2024
Communication, Behaviour & Sustainable Society	Carina Wiekens	Sustainable behaviour	
	Wim Elving	Sustainable communication	
Wind Energy	Gerard Schepers	Wind energy	
Sustainable Gases and Fuels	Joàn Teerling	Sustainable gases	
Legal and Economic Aspects of the Energy Transition	Wytze van der Gaast	Economic aspects of the energy transition	
	Daisy Tempelman	Legal aspects of the energy transition	
	Bert de Jonge[1]	Legal aspects of the Energy transition	2025

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[1] Both Martien and Bert had appointments for 1 day a week, besides their regular jobs.

This structure also facilitates the involvement of students in research and innovation processes. Students are not merely recipients of knowledge, but active participants in projects that address real-world challenges. This approach enhances their learning experience and contributes to the development of competencies that are directly relevant to the labour market. At the same time, it strengthens the connection between education and research, ensuring that both are aligned with societal needs.

A wide variety of Hanze's bachelor programmes is linked to Entrance, including technical programmes such as engineering as well as studies in social, legal and business fields. Moreover, Entrance offers three so-called Energy Masters: European Master in Renewable Energy (EMRE), Sustainable Energy System Management (SeSym) and Energy for Society (E4S). On top of that, Entrance offers various PhD projects and the recently introduced Professional Doctorate (PD). A PD is like a PhD project, but focusses on applied research, working together with partners from the field. The PD is currently in its pilot phase and addresses the need for highly qualified professionals who can research and implement complex innovations in practice.

A special mention needs to go to the University of Groningen regarding PhD projects. Since our professors of applied sciences do not have rights to be promotor, University of Groningen offers a special arrangement for PhD students from Hanze. Several PhD students of Entrance have made use of this arrangement.

4. Thematic Integration: From Fragmentation to Coherence

In order to organise its interdisciplinary activities, Entrance has developed a thematic structure that brings together different professorships around shared challenges. The five themes—sustainable mobility, renewable fuels and sustainable gases, industrial transformation, local and regional energy strategies, and system integration—provide a framework for aligning research, education, and innovation activities. This structure enables Entrance to move beyond fragmented project portfolios and to develop more coherent and strategic programmes.

Sustainable mobility addresses the transformation of transport systems, integrating technological innovation with behavioural change and system-level considerations. Renewable fuels and sustainable gases focus on the development of alternative energy carriers, particularly hydrogen and biomethane, and the infrastructures and markets required to support them. Industrial transformation examines the decarbonisation of energy-intensive sectors, emphasising system optimisation and the development of sustainable industrial ecosystems. Local and regional energy strategies highlight the importance of governance, participation, and equity in implementing the energy transition. System integration serves as an overarching theme, addressing the interactions between different energy carriers, sectors, and infrastructures.

These themes are not isolated domains but are deeply interconnected. For example, the integration of renewable gases into industrial processes requires not only technological solutions but also regulatory frameworks, market mechanisms, and societal acceptance. Similarly, sustainable mobility depends on the integration of energy systems, infrastructure development, and behavioural change. By organising its activities around these themes, Entrance is able to address the energy transition in a holistic manner.

5. Innovation in Practice: Flagship Projects

The practical relevance of Entrance's approach is demonstrated through its project portfolio, which includes a wide range of initiatives that address different aspects of the energy and material transition. These projects are characterised by their innovative nature, their interdisciplinary composition, and their emphasis on co-creation.

The project Groningen Stroomt Door (Groningen transitions) focuses on addressing grid congestion, a critical bottleneck in the energy transition. As the share of renewable energy increases, existing infrastructure struggles to accommodate fluctuations in supply and demand. This project develops solutions that combine technical innovation with data analysis and organisational change, enabling companies to optimise their energy use and reduce pressure on the grid. It exemplifies how Entrance integrates engineering, data science, and behavioural insights to address complex challenges.

The REMO lab (Renewable Molecules lab), is an excellent example of applied research at Entrance, focusing on the conversion of carbon dioxide and hydrogen into methane. This process, often referred to as Power-to-Gas, offers a way to store renewable energy and to close carbon cycles. The facilities operate at a scale that bridges laboratory research and industrial application, making them a crucial step in the development of sustainable energy systems. The project brings together expertise in chemistry, engineering, and system integration, as well as partners from industry and government.

Hydrogen Valley Campus Europe (HVCE) programmes: H2 Train & Learn Hub and the H2 Knowledge & Innovation Hub. Both programmes focus on human capital solutions. The first on all kinds of learning activities and the second on physical and technical facilities for education, testing and research. Both programmes are executed in close cooperation with businesses and vocational, applied and academic institutions.

The HydroHub Test Centre (HHTC), also located at our field lab, provides a unique environment for testing mid-large-scale electrolysis systems. It enables experimentation under realistic conditions and supports the development of hydrogen technologies that are essential for the energy transition. The facility also functions as a learning environment, involving students and professionals in hands-on experimentation and training.

The Symphonie project focuses on system integration and the optimisation of energy systems through digital technologies. It addresses the increasing complexity of energy systems by developing solutions that integrate data, infrastructure, and user behaviour. This project highlights the growing importance of digitalisation in the energy transition and positions Entrance at the forefront of smart energy systems research.

The HyperBRIDGE project extends Entrance's activities into the domain of advanced mobility technologies. It aims to strengthen the hyperloop ecosystem in the Dutch-German border region by connecting small and medium-sized enterprises, research institutions, and innovation networks. The project leverages test facilities in Veendam (European Hyperloop Center) and Emden (goTube at Emden Leer University of Applied Sciences) to develop and test new technologies, while also creating digital tools such as interactive digital twins and serious games. It involves at least twenty companies and emphasises cross-border collaboration, knowledge dissemination, and the development of new business models.

These projects illustrate the breadth and depth of Entrance's activities, as well as its ability to integrate different domains and actors into coherent and impactful initiatives.

6. Co-creation and the Principle of "People in Power"

A central element of Entrance's methodology is its emphasis on co-creation and participation. The energy transition is not only a technical challenge but also a social process that requires the involvement of a wide range of stakeholders. Entrance recognises this by actively involving companies, governments, and citizens in the design and implementation of its projects.

The motto "People in Power" encapsulates this approach. It reflects the belief that transitions are most effective when they are driven by the people who are directly affected by them. This requires creating spaces for dialogue, experimentation, and learning, where different perspectives can be brought together and translated into action.

Co-creation takes many forms within Entrance's activities. It includes living labs, participatory design processes, and learning communities, as well as more informal interactions facilitated by events such as the New Energy Forum, our monthly Barn Talks and various workshops and seminars. These interactions are not merely supplementary to research and innovation; they are integral to the process, shaping the questions that are addressed and the solutions that are developed.

Significant investments have been made in human capital within the energy transition sector. Various programmes, supported by both European and national funding, have been established to train professionals. These initiatives create space for innovation. Entrance has developed substantial experience in both innovation and learning, which has led to the establishment of a dedicated "Learning & Innovation" division.

This reflects a dual focus: learning within an innovative sector, and learning how to learn differently—that is, innovating the learning process itself. As part of this approach, learning communities have been developed and implemented, alongside flexible, time- and location-independent forms of education that utilise multimedia, virtual reality (VR), and simulations. In contexts where practical training is costly or potentially unsafe, simulation-based learning offers a valuable alternative.

While these characteristics are typical for the sector, they also reveal a broader and transferable principle for lifelong learning (LLL). LLL provides the space to develop new forms of professional learning outside the constraints of initial education, in a more flexible environment. These innovations can later be integrated into formal, initial education programmes.

7. Toward Thought Leadership: Opportunities and Challenges

While Entrance has established a strong position within the regional and national innovation landscape, the transition to thought leadership requires further development. One of the key challenges is the need for more systematic knowledge dissemination. Although projects generate valuable insights and tools, these are not always effectively shared or integrated into broader knowledge systems. Developing digital knowledge platforms that enable the storage, analysis, and dissemination of knowledge is therefore essential.

Artificial intelligence offers significant opportunities in this regard. AI can support the organisation and analysis of large amounts of data, facilitate the development of digital twins and simulation models, and enhance learning processes through personalised education. By integrating AI into its activities, Entrance can strengthen its capacity to generate and disseminate knowledge, as well as to develop innovative solutions.

Another important challenge is the need to move from project-based to programmatic approaches. While individual projects can generate significant impact, long-term change requires coordinated programmes that address multiple aspects of a problem and involve a wide range of actors. Developing such programmes requires strong governance structures and the ability to align different interests and perspectives.

Finally, Entrance must continue to adapt its research agenda to emerging developments. One example is the potential inclusion of nuclear energy as a new research line. If government investments in nuclear energy increase, there will be a growing need for knowledge and skills in this area. Entrance is already exploring the development of a learning community focused on nuclear energy, which would contribute to addressing this need and to expanding its thematic scope.

8. Future

Entrance's journey from a small experimental initiative to a central actor in the energy and material transition demonstrates the importance of interdisciplinary collaboration, ecosystem thinking, and practice-oriented research. Its approach, based on a knowledge community and a strong emphasis on co-creation, provides a solid foundation for further development.

The transition to thought leadership requires building on this foundation by strengthening knowledge dissemination, developing digital infrastructures, and integrating emerging technologies such as artificial intelligence. It also requires maintaining the organisation's openness and flexibility while developing more structured and strategic approaches to collaboration and governance.

If Entrance succeeds in addressing these challenges, it will not only contribute to the energy transition but also play a leading role in shaping its direction, demonstrating how applied research institutions can drive societal change in an increasingly complex and interconnected world.

Featured Research

Making Subjectivity Visible: Entrepreneurial Mind-sets of Micro-firm Owner-managers in the Transition towards Zero-emission Mobility

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In this contribution, we argue that making subjectivity visible is essential for advancing the current transition towards zero-emission mobility. We focus on a large yet often overlooked stakeholder group: owner-managers of micro-firms. In the Arnhem–Nijmegen region alone, approximately 15.000 micro-companies (less than 10 employees) were registered in 2022. Many of these firms are directly affected by the introduction of zero-emission zones in urban areas, either because they are located within such zones or because they provide services there. Their frequent dependence on vans makes this transition particularly impactful for their daily operations. Moreover, adoption rates of zero-emission solutions among a large part of this group are slow.

Insights from multiple recent data sources—including KBI data (2025), panel data from VNO-NCW Midden (2025), and in-depth studies from KvK and RVO (2025)—consistently highlight both the structural importance and the diversity of this group. These sources also point to their reliance on informal, trust-based networks in decision-making. To complement these insights, we adopted Q- methodology as an approach specifically designed to investigate subjectivity as shared patterns of meaning rather than individual attitudes. Through q-sort interviews (n = 30) with owner-managers in the Arnhem region, currently in the midst of implementing a zero-emission zone, we systematically elicited how they prioritize, interpret, and relate to statements concerning this transition.

The desk-research and preliminary q-sort analysis reveals three distinct clusters of shared perspectives. These clusters do not represent types of people or objective categories, but rather coherent and interpretable configurations of meaning: entrepreneurial mind-sets that capture how owner-managers position themselves in relation to the transition. We label these mind-sets as (1) a causation-oriented logic, (2) a lifestyle-oriented logic, and (3) an effectual logic. Each reflects a different way of engaging with uncertainty, constraints, and opportunities the transition to zero- emission brings. Additionally, we used the COM-B framework to analyze in depth which factors (Capability, Opportunity, or Motivation) drive behavior and behavioral change, serving as stepping stones for future interventions.

These results will be discussed in the full paper into more depth, including how they may inform public (e.g. local governments) and private stakeholders (e.g. value chain partners) in their efforts to accelerate the transition towards zero emission transport.

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1. Introduction

In this contribution, we argue that making subjectivity visible is essential for advancing the current transition towards zero-emission mobility. We focus on a large yet often overlooked stakeholder group: owner-managers of micro-firms. In the Arnhem–Nijmegen region alone, approximately 15.000 micro-companies (less than 10 employees) were registered in 2022. Many of these firms are directly affected by the introduction of zero-emission zones in urban areas, either because they are located within such zones or because they provide services there. Their frequent dependence on fossil fueled vans or other equipment makes this transition particularly impactful for their daily operations.

However, adoption rates of zero-emission solutions among a large part of this group are slow (De Groene Koers, 2025). For example, at the time of the introduction of zero-emission zones in at least 30 cities on January 1, 2025, only 3.3% of light commercial vehicles were electric (RVO, 2024). Existing, mostly 'grey literature' on the transition toward emission-free business practices in SMEs emphasizes different barriers that hinder investment decisions. Financial and economic constraints are among the most frequently mentioned obstacles (De Groene Koers, 2025). For instance, the high upfront costs of zero-emission vehicles or machinery discourages many owner-managers from investing. This may further be reinforced by uncertainty regarding the return on investment and the future resale value of such equipment. Moreover, many SMEs report that they feel that clients are unwilling to fully compensate for the additional costs associated with emission-free operations, forcing firms to absorb these costs themselves and potentially reducing already narrow profit margins (Van Teeffelen & Dolsma, 2025). For smaller firms especially, limited financial capacity may simply prevent investments of this scale altogether.

In addition to financial barriers, infrastructural limitations also complicate the transition toward emission-free operations. Even when firms are willing to invest, practical implementation may be constrained by a shortage of charging facilities, insufficient electricity infrastructure at work sites, and broader issues of grid congestion. As a result, SMEs often face uncertainty not only about the financial viability of transition investments but also about their practical feasibility. Political and regulatory conditions further contribute to this uncertainty. SMEs frequently point to inconsistent government policies, changing regulations, and the absence of a stable long-term policy vision as reasons for postponing investments (Right Marktonderzoek, 2025).

Finally, barriers also emerge at the level of market demand and information provision. Many SMEs indicate that they do not invest in emission-free solutions because customers or supply chain partners are not yet explicitly demanding them (De Groene Koers, 2025). At the same time, substantial knowledge gaps remain. Many owner-managers lack a clear understanding of how relevant regulations operate in practice, while others are unaware of available subsidies or perceive subsidy application procedures as overly complex (Van Teeffelen & Dolsma, 2025). This suggests that the transition challenge is not solely financial or technical in nature, but also informational.

Taken together, these barriers highlight that the transition toward emission-free solutions make up a fundamentally uncertain and complex decision-making context for SMEs. It is rarely a straightforward "replacement investment" in which existing equipment or technologies are simply substituted with newer alternatives. While existing studies provide important insights into technical, financial, market, informational or infrastructural barriers shaping SME transition behavior, they pay less attention to how owner-managers themselves interpret, evaluate, and navigate such uncertainty (KvK, 2020).

It is within this context that the entrepreneurial mindset becomes particularly salient. Rather than framing transition decisions as rational cost–benefit calculations, an entrepreneurial mindset perspective highlights how owner-managers interpret uncertainty, identify opportunities, and mobilize knowledge and networks in deciding whether (or not) to act. The ability to navigate such uncertainty is not confined to the start-up phase, but constitutes an ongoing, dynamic capability that enables SMEs to respond and adapt to challenging and evolving environments (Mousavi and Kirkels, 2025).

Understanding such differences may also provide a basis for the need for developing additional tailored, demand-side policy approaches aimed at promoting and facilitating the uptake of emission-free technologies among SMEs. From this viewpoint, the transition toward emission-free business practices cannot be stimulated solely through generic financial incentives or regulatory pressure, as such interventions primarily target motivation through economic incentives and formal authority. As argued above, SMEs may also face constraints related to limited (internal) capability and (external) opportunity, such as restricted access to specialized knowledge, uncertainty regarding the feasibility and desirability of transition investments or infrastructural developments. Consequently, SMEs may benefit more from tailored forms of support.

Against this background, the present study focuses on the entrepreneurial mindset of owner-managers as a key mechanism shaping how small firms perceive, interpret, and respond to the transition toward emission-free business practices. This leads to the following research question:

> *What characterises entrepreneurial mindsets of small business owners in the context of the transition to emission-free solutions?*

2. Theoretical framework

2.1. An entrepreneurial mindset perspective

A vast body of research shows that an entrepreneurial mindset may be present in individuals, but does not manifest itself automatically (Shepherd et al., 2021). Rather, it is enacted and further developed through a process in which individuals move from ignorance and doubt toward recognizing and evaluating opportunities, and ultimately translating them into action (Pidduck et al., 2023). In other words, the entrepreneurial mindset serves as a crucial link between sensing that something should be addressed and actually “taking the plunge.”

According to Pidduck et al. (2023), the entrepreneurial mindset comprises both dispositional elements and situation-specific opportunity beliefs. Dispositional beliefs include proactiveness, innovativeness, and risk-taking. More in detail, these concern the belief in the importance of being a “first mover” (proactiveness), a tendency to experiment with new technologies and engage in creative problem-solving (innovativeness), and the belief that taking chances and making investments with uncertain outcomes is normal (risk-taking). The dispositional side of the entrepreneurial mindset can thus be understood as a more general entrepreneurial orientation or proclivity that owner-managers possess to varying degrees.

The situation-specific side, by contrast, concerns the cognitive processes and triggers that lead to action in particular contexts. According to McMullen and Shepherd (2006), entrepreneurial action results from the interaction between knowledge and motivation. Knowledge shapes the perceived level of uncertainty, while motivation determines whether the owner-manager is willing to act despite that uncertainty. This perspective highlights that opportunities are not only objectively present, but are also subjectively constructed.

Moreover, McMullen and Shepherd (2006) further refine this situation-specific dimension of the entrepreneurial mindset by proposing a two-phase model. The first phase is closely related to the previously discussed dispositional factors, such as proactiveness, but additionally emphasizes the importance of prior knowledge, which determines whether a technological change (e.g., emission-free equipment) is even recognized as a potential opportunity. In the subsequent phase, the key question becomes: “Is this also an opportunity for me?” This phase relates directly to situation-specific beliefs. Even when owner-managers recognize an opportunity in general, they may decide not to act because they perceive the feasibility or desirability for their own firm as too uncertain.

This perspective adds depth to our understanding of the entrepreneurial mindset in the context of the energy transition. Moving from recognizing an opportunity to acting upon it requires not only entrepreneurial proclivity and motivation, but also sufficient knowledge and capability to reduce uncertainty to an acceptable level. If uncertainty remains too high even highly motivated owner-managers may refrain from acting. Altogether, differences in entrepreneurial mindsets among small business owner-managers may help explain why firms operating in the same sector or market arrive at very different decisions regarding the adoption of emission-free equipment—their opportunity beliefs differ fundamentally.

Taken together, the literature suggests that the adoption of emission-free solutions in SMEs cannot be understood solely in terms of financial or technological barriers. Rather, transition decisions are also shaped by the entrepreneurial mindsets of owner-managers, including their entrepreneurial dispositions, subjective opportunity beliefs, prior knowledge, and the social networks through which they interpret uncertainty and evaluate possible courses of action. Differences in these dimensions may therefore explain why owner-managers facing similar external conditions nevertheless arrive at very different transition decisions.

2.2. Methods

This study applies Q-methodology to systematically examine subjective perspectives among owner-managers regarding transitions. Q-methodology is particularly suited to exploring "wicked problems" characterized by diverse and contested viewpoints, as it identifies shared patterns of thought rather than explaining individual attitudes (Minkman & Molenveld, 2020). One of the main strengths of Q-methodology is that it combines the depth of qualitative research with the rigor of quantitative analysis. It allows researchers to identify areas of agreement and disagreement efficiently, even with relatively small samples. At the same time, it has limitations: it is primarily descriptive rather than explanatory, meaning it reveals what perspectives exist but not why individuals hold them. Additionally, it requires considerable effort from researchers to accurately map the debate and construct a representative set of statements.

2.2.1. Instrument development

The research followed a structured multi-step approach, including testing prototypes in three rounds with small-business owner-managers. A first concourse was developed by mapping relevant concepts and debates based on literature, expert input (e.g., regional SME support organizations), and insights from the target population. Second, a Q-set of statements was constructed, consisting of a balanced and representative selection of items designed to be thought-provoking and interpretable, while covering the full conceptual domain. The initial set consisted of 32 statements which was discussed with experts and users. To improve this first prototype, data were collected and analysed from multiple sources. Additional literature was reviewed to conceptualize the entrepreneurial mindset as a combination of cognitions, emotions, and behaviors, while also incorporating insights from sector reports and existing entrepreneur interviews. Second, interviews were conducted with four local small-business owners and five experts resulting in a refined set of 26 statements that formed the second prototype. The 26 Q-sort statements used represented the full spectrum of the entrepreneurial mindset (thinking, doing, and feeling). This new prototype was again tested in a workshop with owner-managers. This led to again to several improvements, including clearer instructions, minor adjustments to the tool, and the addition of blank cards to capture missing statements. Participants indicated that the tool helped them reflect on their position, set priorities, and engage in meaningful discussions.

2.2.2. Respondents and analysis

The final set of 26 Q-sort statements was used in this study 16 small business owner-managers that were confronted with the introduction of the zero-emission zone in Arnhem in June 2026 were interviewed using the developed Q-sort method. The sample included small firms in retail and hospitality. Interviews took about 1 hour to complete the Q-sorting task by ranking statements along a quasi-normal distribution from “most agree” to “most disagree,” following clear instructions. Post-sort interviews were conducted to explore the reasoning behind participants’ rankings and to enrich interpretation. The Q-sort data were analysed using factor analysis to identify clusters of respondents with similar sorting patterns. Finally, these factors were interpreted as distinct narratives or perspectives, based on distinguishing and consensus statements.

3. Results

The interviews with the small-business owner-managers show that the transition to emissive free solutions evokes a wide range of reactions. The respondents clearly show differences in how they experience and evaluate these developments. Based on the factor analysis on the 26 statements and the post-sort interviews, three dominant narratives which we labeled as different mind-sets can be distinguished (see figure 1).

The first factor comprises statements that articulate the opportunities that emission free solutions may bring. Owner-managers scoring high on these statements strongly believe in the necessity of zero-emission urban logistics. They view the current city-centre logistics situation as unsustainable, particularly due to congestion, pollution, and the high number of delivery vans. This is reflected in post-sort interview statements such as:

> *“All those annoying DHL and DPD vans stopping here sometimes four times a day and blocking everything. Then I think: just one hub for the city centre.” (Respondent 3)*

Figure 1. Average (Z-scores) per top 5 highest and lowest statements per factor

FACTOR 1 DESCRIPTION

HIGHEST RATED STATEMENTS

#	Info	ID	Statement	Z
1	☆	18	Ik wil er graag aan bijdragen.	1.86
2	☆	4	Ik doe het graag samen met anderen.	1.80
3	☆	3	Ik zie het als een kans.	1.39
4	☆	11	Ik word er enthousiast van.	1.00
5	☆	10	Ik ben afhankelijk van derden.	0.92

LOWEST RATED STATEMENTS

#	Info	ID	Statement	Z
1	☆	8	Ik doe het omdat anderen het doen.	-2.16
2	☆	26	Ik ben er geïrriteerd over.	-1.50
3	👥	16	Ik word er onzeker van.	-1.01
4	☆	14	Ik vind het risicovol.	-0.99
5	☆	17	Ik wacht het wel af.	-0.91

FACTOR 2 DESCRIPTION

HIGHEST RATED STATEMENTS

#	Info	ID	Statement	Z
1	☆	18	Ik wil er graag aan bijdragen.	2.49
2	☆	14	Ik vind het risicovol.	1.53
3	☆	15	Ik ben er nieuwsgierig naar.	1.29
4	☆	3	Ik zie het als een kans.	1.16
5	☆	17	Ik wacht het wel af.	0.95

LOWEST RATED STATEMENTS

#	Info	ID	Statement	Z
1	☆	24	Ik vind mijn onderneming er te klein voor.	-1.56
2	☆	6	Ik kan het niet financieren.	-1.21
3	👥	19	Ik heb er geen zin in.	-1.18
4	☆	11	Ik word er enthousiast van.	-1.14
5	👥	13	Ik krijg er stress van.	-1.01

FACTOR 3 DESCRIPTION

HIGHEST RATED STATEMENTS

#	Info	ID	Statement	Z
1	☆	26	Ik ben er geïrriteerd over.	2.32
2	☆	9	Ik word beperkt door de regels.	1.51
3	☆	10	Ik ben afhankelijk van derden.	1.35
4	☆	24	Ik vind mijn onderneming er te klein voor.	1.35
5	☆	25	Ik vind het veel tegelijk.	1.19

LOWEST RATED STATEMENTS

#	Info	ID	Statement	Z
1	☆	11	Ik word er enthousiast van.	-2.15
2	☆	2	Ik weet er te weinig van af.	-1.34
3	👥	13	Ik krijg er stress van.	-1.18
4	☆	3	Ik zie het als een kans.	-1.18
5	👥	19	Ik heb er geen zin in.	-0.86

Another owner-manager emphasized:

> *"I'm just done with the pollution in the city centre." (Respondent 13)*

At the same time, there is a clear feeling of dependence on others, like suppliers and logistics partners. Although these owner-managers are motivated to contribute, they also recognize that they cannot manage the transition alone. They experience dependency on suppliers and logistics partners:

> *"Yes, definitely." (Respondent 2, responding to the statement 'I am dependent on others')*
>
> *"I am somewhat dependent on third parties." (Respondent 3)*

Their motivation is strongly driven by collaboration and collective action.

> *"I like doing it together with others." (Respondent 2)*
>
> *"I would like to see everyone in the [Fashion Quarter] doing this together." (Respondent 3)*
>
> *"I have a lot of contact with nearby entrepreneurs and want to think along about central hub locations." (Respondent 4)*

Overall, Factor 1 comprises a mind-set of optimism and solution-oriented, but also relying heavily on cooperation and coordinated action from other stakeholders.

The narrative of Factor 2 is generally in support of the idea of zero-emission solutions the importance of sustainability. However, the concerns about practical feasibility and financial implications for their own businesses.

As one of the respondents explained in the post-sort interview:

> *"I understand why zero-emission policies are being introduced and I think it's good, but things are being prohibited without alternatives." (Respondent 6)*

Their concerns mainly revolve around uncertainty regarding investments, operational impact, and unclear regulations. As a result, they adopt a wait-and-see attitude:

The owner-managers simply want proof that the transition will work in practice and that investments are worthwhile. As the respondent stated in the post-sort interviews:

> *"If it later turns out that electric driving saves costs, I'm willing to listen, but right now I see it as a huge investment." (Respondent 7)*
> *"You need to tell a positive story, a good-feel story." (Respondent 11)*
> *"If they show hard figures and what the benefits are… then I find it interesting." (Respondent 10)*

Altogether the mind-set represented in Factor 2 is not one of resistance, but more about cautious and conditional in terms of willingness to act.

A clear third factor is predominantly negative attitudes towards the transition to zero-emission solutions. They experience the transition as an additional burden on top of already difficult business conditions and feel insufficiently heard by policymakers. Their concerns are dominated by stress, lack of time, and financial pressure. Owner-managers describe the transition as simply "too much at once":

> *"We go from one misery to another: pandemic, staffing crisis, gas crisis, inflation." (Respondent 1)*
> *"I don't have time to figure this all out." (Respondent 1)*
> *"I can't earn it back; an electric van does not fit my work." (Respondent 12)*

Factor 3 represents a mind-set which is predominantly negative towards the transition. They mainly experience constraints due to regulations, feel dependent on others, and perceive the transition as coming all at once. Feelings of irritation and the sense that their business is too small to make a meaningful contribution play an important role. They see fewer opportunities and are not enthusiastic about the change. Overall, this mind-set experiences the transition primarily as a burden rather than an opportunity.

From mindsets to interventions and follow up research

We started the paper from the notion that the adoption of emission-free solutions in SMEs cannot be understood solely in terms of financial or technological barriers. Rather, transition decisions are also shaped by the entrepreneurial mindsets of owner-managers, including their entrepreneurial dispositions and subjective opportunity beliefs through which they interpret uncertainty and evaluate possible courses of action. Differences in these dimensions may explain why small firms facing similar external conditions nevertheless arrive at very different transition decisions. As such we started this paper with the question: *what characterizes entrepreneurial mindsets of small business owners in the context of the transition to emission-free solutions?*

In line with recent research on the entrepreneurial mindset, our results also suggest differences in mindsets (Hattenberg et al. 2024). This diversity can be understood through differences in both willingness (e.g. perceiving it as the right thing to do, or feeling irritated by it) and capability (e.g. not knowing what to do, feeling overwhelmed) to act under uncertainty. Mindsets characterized by neither willingness nor capability tend to ignore the transition entirely due to a lack of awareness. The most prominent axe in our study relates to motivation. Mindsets that are willing first of all have strong motivation: they recognize the benefits of change for their business. They perceive the opportunity as desirable. For mindsets that are not willing, the potential benefits do not outweigh the effort or risks to their current, stable situation. For example, a mindset with a strong "passion for impact" experiences an automatic positive motivation to act sustainably, without always preceding this with a conscious cost–benefit analysis. By contrast, feelings of irritation leads to an automatic, impulsive blockage when a change feels complex. The fact that the motivation axe was so prominent in our mind-sets might be due to the fact that the 26 statements were skewed towards more motivational and emotional statements, rather than capability statements. On the other hand, transitions like emission free solutions typically tap into what could be described as the psychological "underlayer" (including values, drivers, and personality traits) from which more motivational responses (including emotions) may arise automatically.

In addition, our analysis highlights the importance of social orientation (together versus alone). The explanation for this is that small-business owner-managers rely strongly on their "warm network" (i.e. fellow entrepreneurs, accountants, and suppliers) when shaping their mindset and dealing with uncertainty (Lans et al., 2008). These strong ties may act as a reliability filter: if peers have not yet adopted emission-free technologies, owners may assume these are not mature or viable. The network may also serve as an application filter by translating abstract trends into concrete, actionable practices, which aligns with their focus on continuity and efficiency. However, this reliance can also have drawbacks. Missing knowledge within the network (e.g. about specific subsidies) may remain unnoticed, reinforcing misconceptions (e.g., being "too small" for adopting certain solutions). Additionally, collaborating on emission-free solutions requires interpersonal skills such as communication, empathy, and effective language use.

The difference in mind-sets also provide stepping stones for different tailored interventions. One avenue for this comes from the work on entrepreneurial learning and entrepreneurship education. From this perspective different entrepreneurial mind-sets represent different starting points for learning and development. One relatively new way to look at this learning and development question is scaffolding (Hattenberg et al., 2022). Rooted in Vygotsky's sociocultural theory of the zone of proximal development, scaffolding in this particular context refers to targeted supports provided to small business owners as they develop and refine their emission-free practices. Scaffolding in the small-business environment typically occurs through interactions with peers, advisors, and professional networks. These actors may provide targeted guidance that helps owner-managers to navigate challenges slightly beyond their current motivation and capabilities. Typical scaffolding practices include mentorship and coaching, constructive feedback from customers and stakeholders, observational learning through role models, simulation or role-playing of business scenarios, and structured reflection on experience. The central premise of scaffolding is that such support is dynamic and temporary. As small business owners gain experience, confidence, and skills, these supports are gradually reduced, enabling greater autonomy and strengthening self-efficacy in decision-making and opportunity recognition.

A second promising avenue, including further research, comes from the realm of more generic behavioral research, in particular the vast amount of work around the COM-B model (Michie et al., 2011). The use of this model also leads to considering other types of interventions, rather than those that primarily or solely targeting motivation through economic incentives and formal authority. While all three COM-B components, Capability, Motivation, and Opportunity, were represented in the 26-statement Q-sort instrument, the set could be further enriched. Several sub-domains in the current Q-sort set-up remain less explored: within capability, statements addressing understanding of transition rationales, interpersonal skills, and cognitive processing are largely absent; within Motivation, the alignment between emission-free practices and owner-manager self-identity is not explicitly addressed; within Opportunity, physical accessibility receives limited attention. Including such elements may help to increase our understanding of the 'social orientation' dimension. For instance what are primary sources of knowledge, who is admired and chosen as role models and what is actually the level of interpersonal skills needed to benefit from these contacts (such as communication, empathy, listening and use of appropriate language). How this is leveraged can then lead to very different intervention designs. Altogether, expanding the statement across more COM-B domains could yield richer profiles and even more stepping-stones for tailored (policy) interventions.

Finally, what is important to keep in mind is that the study focused on small retailers and hospitality. Their mindsets with regard to emission-free solutions may be quite different from for instance small firms in construction work, service providers as these sectors are confronted with different clients, possibly having different views on sustainability and impact on services and products.

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Disinformation as a Barrier to Public Acceptance of Onshore Wind Energy in the Netherlands: A Qualitative Case Study of Vattenfall

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The Netherlands has set ambitious targets for expanding onshore wind capacity as part of its broader energy transition. Yet in practice, projects face persistent local opposition that delays or prevents deployment, even where general public support for renewable energy remains high. This study examines how mis- and disinformation undermines public acceptance of onshore wind turbines by distorting the three key psychological constructs identified by Huijts, Molin, and Steg (2012): trust, fairness, and knowledge. Using a qualitative case study design centered on Vattenfall's onshore wind operations in the Netherlands, the research draws on 14 semi-structured expert interviews and two years of social media monitoring (August 2023 – July 2025) conducted via Meltwater. Findings reveal that mis- and disinformation is the single most influential factor across all three constructs, co-occurring with trust (n = 142), fairness (n = 103), and knowledge (n = 212) sub-codes at frequencies that substantially exceed all other underlying factors. Misleading narratives like concerning health effects, noise, chemical hazards, and procedural manipulation circulate through organized anti-wind networks and social media platforms, particularly X, Facebook, and WhatsApp, creating a structurally resistant information environment. The study argues that disinformation should be understood not as a peripheral communication problem but as a structural barrier to the energy transition, requiring systematic, proactive, and locally embedded communication responses.

Keywords: Public acceptance, Wind energy, Disinformation, Misinformation, Trust, Fairness, Knowledge, Netherlands, Vattenfall, Social media, Energy transition

02

1. Introduction

Onshore wind energy is central to the Netherlands' ambition to reduce carbon emissions by 49% by 2030 and to reach climate neutrality by 2050 (International Energy Agency, 2020). As countries seek to decarbonize electricity systems, wind power has become a vital component of the global energy transition (Quitzow, 2021). The Netherlands offers highly suitable conditions for wind energy generation due to its flat terrain and proximity to the North Sea, contributing meaningfully to Europe's overall wind potential (Enevoldsen et al., 2019).

Vattenfall, one of Europe's largest energy companies and a major investor in Dutch wind development, operates multiple onshore wind projects across the country and is directly implicated in the social and communicative challenges that accompany local deployment. Despite widespread national support for renewable energy, consistently above 80% in public surveys, individual wind projects routinely encounter organized opposition that extends development timelines, increases costs, and, in some cases, results in project cancellation (Planbureau voor de Leefomgeving, 2019; Wolsink, 2007).

This paradox, often described in the literature as the "social gap" (Wüstenhagen et al., 2007; Wolsink, 2018) between aggregate societal support and local project resistance, has been attributed to a range of factors including NIMBY attitudes, perceived health and noise risks, visual and landscape concerns, and inequitable distribution of costs and benefits (Devine-Wright, 2005; Bell et al., 2013; Klok et al., 2023). However, an emerging body of evidence suggests that these factors are increasingly mediated and often amplified by a more fundamental problem: the systematic spread of mis- and disinformation through digital communication channels (Hameleers, 2023; Crichton et al., 2014; Chapman et al., 2013).

Wind energy resistance is no longer primarily a product of uninformed publics or parochial self-interest. Organized anti-wind groups, active across the Netherlands and coordinated at national and international levels, produce and distribute misleading narratives with sophistication and strategic intent (Bechstein, 2025). Claims about infrasound causing cardiac failure, turbine blades releasing toxic chemicals, or planning processes being pre-approved by government-developer coalitions circulate through Facebook groups, WhatsApp chains, and local media long before factual communication reaches affected communities. Once established, these narratives prove highly resistant to correction.

This study examines how disinformation influences public acceptance of onshore wind turbines, with Vattenfall as the focal case. It focuses on how misleading narratives shape the three psychological constructs identified by Huijts, Molin, and Steg (2012) as central to acceptance: trust in developers and institutions, perceptions of procedural and distributive fairness, and knowledge about wind energy and its effects. The following research questions guide the study:

RQ1: *How does disinformation influence public acceptance of onshore wind turbines in the Netherlands through trust, fairness, and knowledge?*
RQ2: *What is the role of social media platforms in shaping mis- and disinformation about onshore wind turbines in the Netherlands?*

The research employs a qualitative case study design combining 14 semi-structured expert interviews with Vattenfall staff, wind industry professionals, and Dutch energy policy advisors, with two years of social media monitoring using Meltwater. Triangulation across these two data sources enables an empirically grounded account of how disinformation operates as a structural barrier to the energy transition, and what this implies for communication practice.

2. Theoretical Background

This section presents the theoretical foundation of the study, introducing the three-construct public acceptance framework that structures the empirical analysis, and developing the conceptual framing of disinformation as a cross-cutting disruptive mechanism across all three constructs.

2.1 Public Acceptance of Wind Energy

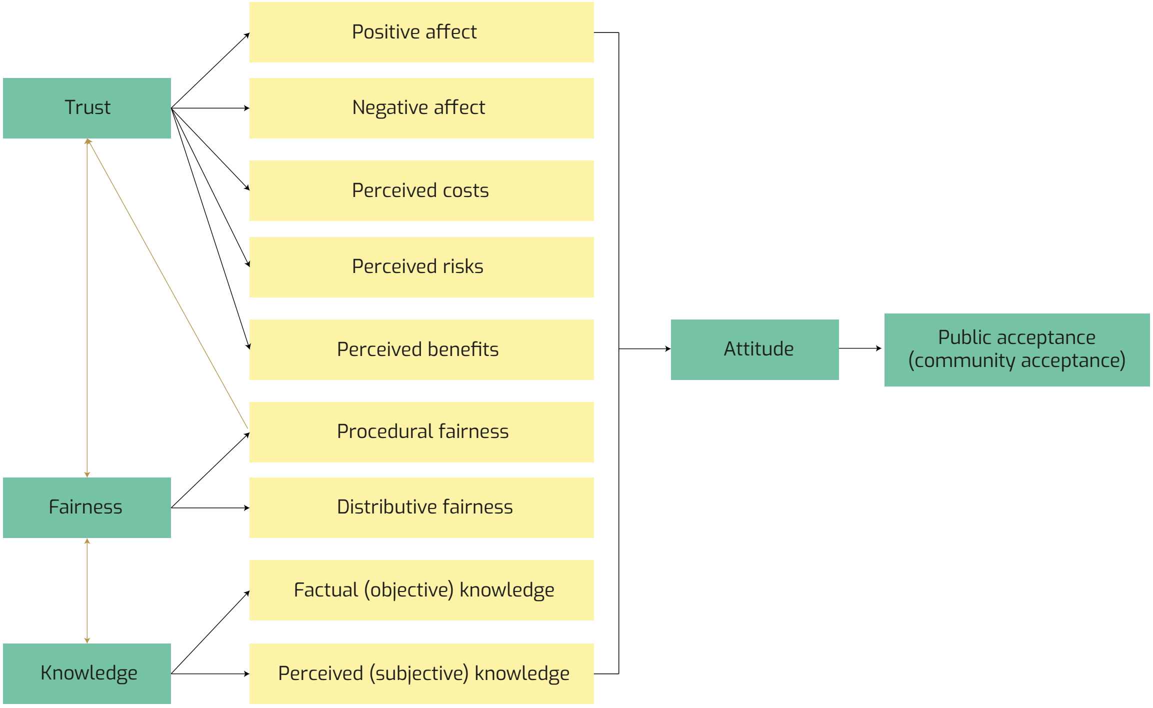
Public acceptance is a multi-dimensional concept operating at different scales and through different mechanisms. Wüstenhagen, Wolsink, and Bürer (2007) distinguish three forms: socio-political acceptance, the broad legitimacy granted to renewable energy by society and institutions; market acceptance, the willingness of consumers and investors to engage with renewable energy products; and community acceptance, the degree to which local residents and authorities support or oppose a specific project. For onshore wind, community acceptance is the most critical dimension because opposition most often emerges locally, where projects can be delayed or blocked (Wolsink, 2018; Petrova, 2013).

The integrated framework of Huijts, Molin, and Steg (2012) identifies three key psychological constructs shaping responses to energy technologies. Trust refers to residents' confidence that developers and public authorities act transparently, responsibly, and in public interest (Devine-Wright, 2011; Aitken, 2010). It includes both social trust, confidence in institutions, developers, authorities, and experts, and system trust, confidence in the technology, its regulation, and safety measures (Huijts et al., 2012). Trust also has a competence-based dimension, belief in technical capability, and an integrity-based dimension, belief in honesty and good intentions (Terwel et al., 2009).

Fairness includes both procedural fairness, whether community members feel genuinely heard in planning and decision-making, and distributive fairness, whether costs and benefits are perceived as shared equitably (Wolsink, 2005; Gross, 2007; Lind & Van den Bos, 2002). Earle and Siegrist (2008) note that trust and fairness reinforce each other, though trust more often shapes fairness perceptions. Knowledge refers both to factual understanding of wind energy and its effects, and to residents' confidence in their own understanding (Bidwell, 2013; House et al., 2004).

Previous research confirms that all three constructs are subject to influence by social and communicative processes well beyond the physical characteristics of individual projects (Milani et al., 2024; Wolsink, 2018). The present study focuses on a specific communicative process that has received comparatively limited systematic attention: the role of mis- and disinformation in shaping these constructs.

Figure 1. A schematic representation of the public acceptance framework (Huijts et al., 2012)



2.2 Information Disorder: Mis-, Dis-, and Malinformation

The theoretical framework for understanding misleading information is provided by Wardle and Derakhshan's (2017) Information Disorder model, which distinguishes three forms of problematic content. Disinformation refers to false content deliberately created to harm a person, group, organization, or country. Misinformation refers to false content shared without deliberate intent to harm, typically a product of error, misunderstanding, or motivated reasoning. Malinformation refers to factually grounded content deployed with intent to cause harm, such as the selective use of real wind noise recordings from industrial settings to misrepresent normal turbine operation.

Figure 2. How mis-, dis-, and malinformation intersect around falseness and harm (Wardle & Derakhshan, 2017)

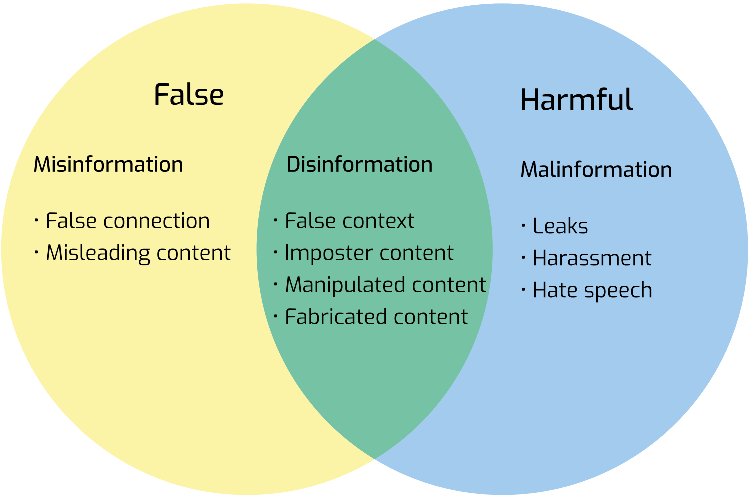
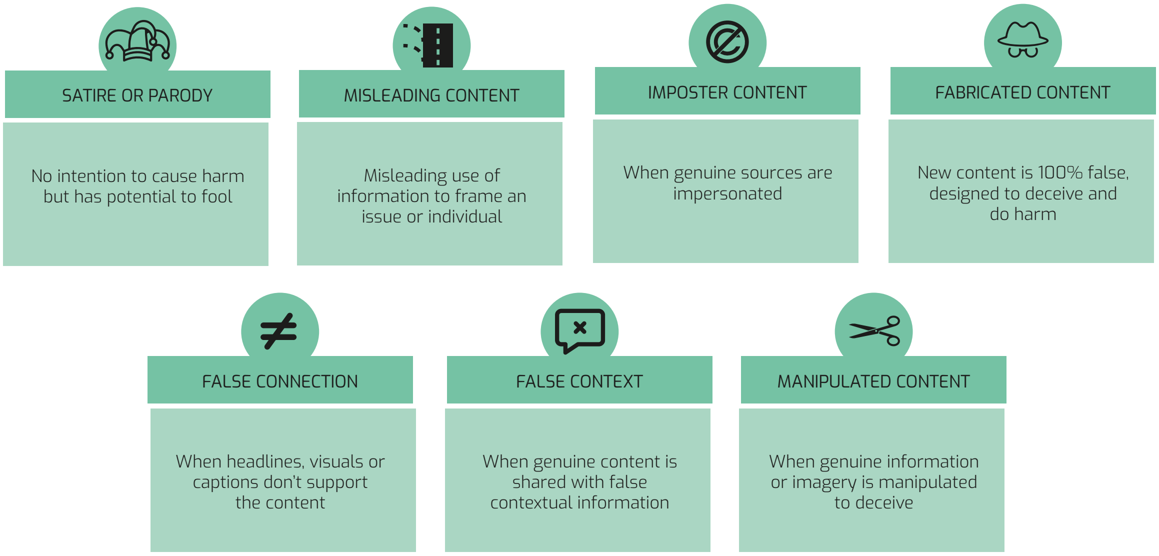


Figure 3. Seven types of mis- and disinformation (Wardle & Derakhshan, 2017)



SATIRE OR PARODY	No intention to cause harm but has potential to fool
MISLEADING CONTENT	Misleading use of information to frame an issue or individual
IMPOSTER CONTENT	When genuine sources are impersonated
FABRICATED CONTENT	New content is 100% false, designed to deceive and do harm
FALSE CONNECTION	When headlines, visuals or captions don't support the content
FALSE CONTEXT	When genuine content is shared with false contextual information
MANIPULATED CONTENT	When genuine information or imagery is manipulated to deceive

Wardle and Derakhshan (2017) organize the broader ecosystem of problematic content into seven types, ranging from satire and parody. This typology is particularly relevant for wind energy discourse, which draws on multiple types simultaneously: exaggerated health claims (fabricated content), context-manipulated images of turbine size or industrial smoke (false context), and satirical anti-wind content that circulates without its ironic framing. The framework further identifies three structural elements of information disorder — the Agent, the Message, and the Interpreter — interacting across three developmental phases of creation, production, and distribution, through which misleading narratives propagate into public discourse.

Figure 4. The three elements of information disorder (Wardle & Derakhshan, 2017)

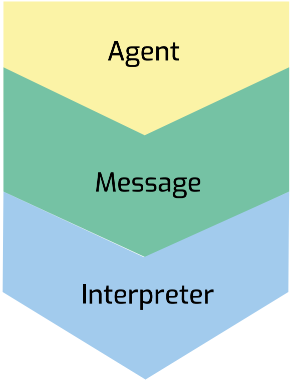
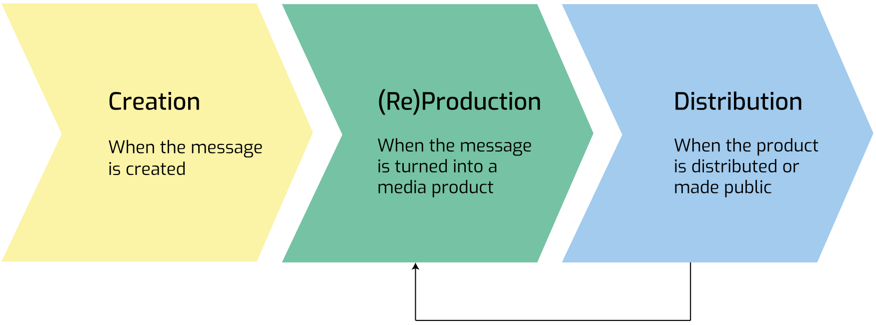


Figure 5. The three phases of information disorder (Wardle & Derakhshan, 2017)



2.3 Disinformation as a Cross-Cutting Acceptance Barrier

Applied to onshore wind, the Information Disorder framework reveals a structural communication problem that extends beyond factual inaccuracy. As Bechstein (2025) shows for the Dutch context, misleading narratives about noise, health effects, and visual impact are not simply spontaneous expressions of community concern. They are actively produced, strategically packaged, and systematically distributed through organized anti-wind networks and social media ecosystems with material and ideological interests in obstructing the energy transition.

The central argument of this study is that disinformation does not simply add another grievance to the list of acceptance barriers. It functions as a meta-factor that distorts the cognitive and emotional environment in which all other acceptance-relevant information is received. When false narratives occupy the emotional frame first, trust becomes harder to build, fairness harder to demonstrate, and knowledge harder to convey, regardless of the quality or quantity of factual communication. This conceptualization, disinformation as a structural acceptance barrier rather than a peripheral communication challenge, is the study's key theoretical contribution.

This framing aligns with Coombs' (2023) argument that misinformation thrives under conditions of low institutional trust, ambiguous risk, and weak alignment between institutional interests and community welfare, all of which are structurally present in the Dutch onshore wind context. As Hameleers (2023) argues, disinformation is not an isolated pathology of individual bad actors, but a context-bound phenomenon shaped by the broader informational ecosystem in which audiences receive and interpret content.

3. Methodology

3.1 Research Design

This study employs a qualitative case study design (Pearse, 2019), centered on Vattenfall's onshore wind operations in the Netherlands. The case study approach is appropriate when the research question concerns a complex contemporary phenomenon that cannot be meaningfully separated from its real-world context (Treadwell & Davis, 2019). The study follows a primarily deductive approach, grounded in the theoretical frameworks of Wüstenhagen et al. (2007) and Huijts et al. (2012), while allowing for inductive emergence of additional themes not anticipated in existing literature (Eriksson et al., 2006). Data was collected through two complementary methods, expert interviews and social media monitoring, analyzed using qualitative content analysis. Triangulation across these sources allows cross-validation of findings across practitioner perspectives and publicly circulating narrative data.

3.2 Expert Interviews

Semi-structured interviews were conducted with 14 professionals drawn from wind energy development, stakeholder management, corporate communication, and energy policy. Participants were selected using purposive and convenience sampling to ensure coverage of both multinational corporate perspectives (Vattenfall, Wind Europe) and local organizational perspectives (Ned Zero, Entrance, Province of Groningen). Table 1 presents the participant overview.

Table 1. Participant overview

No.	Role	Organization	Scope
1	Wind developer	Vattenfall	Multinational
2	Stakeholder manager	Vattenfall	Multinational
3	Head of communications	Wind Europe	Multinational
4	Wind communication advisor	Ned Zero	Local
5	Wind energy specialist	Ned Zero	Local
6	Wind developer	Vattenfall	Multinational
7	Wind energy specialist	Entrance	Multinational
8	Stakeholder manager	Vattenfall	Multinational
9	Policy advisor, energy transition	Province of Groningen	Local
10	Policy advisor, noise & environment	Province of Groningen	Local
11	Stakeholder manager	Vattenfall	Multinational
12	Stakeholder manager	Vattenfall	Multinational
13	Wind developer	Vattenfall	Multinational
14	Communication advisor	Wind Europe	Multinational

Interviews were conducted online via Microsoft Teams, recorded with participants' informed consent, and transcribed using intelligent verbatim. Analysis was conducted in Atlas.ti using a deductive and inductive coding scheme structured around the three core constructs (trust, fairness, knowledge) and their established underlying factors. Additional codes were added inductively as new patterns emerged in the data.

3.3 Social Media Monitoring

Social media monitoring was conducted using Meltwater, a media intelligence platform that aggregates data from X (formerly Twitter), Facebook, LinkedIn, online news sources, and public forums. The analysis covered August 2023 to July 2025, divided into two consecutive 12-month periods to enable trend comparison. To identify relevant content, the study drew on 10 recurring mis- and disinformation themes identified by Bechstein (2025) in prior research on the Dutch wind energy context, operationalized as Boolean search queries. A qualitative content analysis was then applied to identify dominant narrative patterns, sentiment profiles, message framing, key actors, and platform-specific circulation patterns.

4. Results

Results are organized around the three core constructs — trust, fairness, and knowledge — with particular focus on the role of mis- and disinformation, which emerged as the single most influential underlying factor across all three. Six additional factors that emerged inductively are presented first, as they provide essential context for interpreting the disinformation findings.

4.1 Emerging Underlying Factors

Beyond the established factors from the prior literature, six additional underlying factors shaping acceptance dynamics emerged from the qualitative analysis.

Figure 6. All established and emerging underlying factors influencing trust, fairness, and knowledge

Emerging factors

- Institional and process trust
- Procedural fairness and inclusion
- Local credibility and messengers
- Emotional and cognitive dynamics of opposition
- Perceived reciprocity and responsiveness
- Distribution of benefits and burdens

Established factors

- Mis/disinformation
- NIMBY attitutes
- Visual or landscape intrusion
- Noise pollution
- Local economic benefits and ownership models
- Perceived risks

Institutional and Process Trust

Participants described a generalized climate of distrust toward both government and large corporate actors that shapes communities' initial orientation toward wind projects before any project-specific communication occurs. Low baseline institutional trust increases susceptibility to misinformation, because as Coombs (2023) notes, people fill information gaps with speculation when they distrust official sources. Vattenfall, as a multinational, was particularly vulnerable to this dynamic:

> *"People say Vattenfall is a foreign company, extracting all the good stuff while locals stay empty-handed." (Interviewee 1)*

Procedural Fairness and Inclusion

Participants consistently emphasized that the timing and quality of community involvement critically shape resistance. When participation is perceived as late, symbolic, or performative, resistance escalates. This aligns with Grunig's (1992) concept of two-way symmetrical communication and Lund and Refshauge's (2024) argument that communication must be situationally anchored in genuine stakeholder engagement:

> *"The earlier you are, the more chances you have to make a difference." (Interviewee 3)*

Local Credibility and Messengers

Information from local organizations, neighbors, or community representatives is trusted significantly more than equivalent content from national bodies or large energy companies. This aligns with

Cornelissen's (2020) argument that communication is most persuasive when the messenger is perceived as socially and emotionally aligned with the audience:

> *"Local energy corporations usually have higher trust; people know them personally or see them in the streets." (Interviewee 6)*

Emotional and Cognitive Dynamics of Opposition

Opposition to wind projects is primarily emotional in origin. Negative emotional responses precede the search for justifying arguments, leading people toward readily available misinformation narratives. As Coombs (2023) describes, emotions precede facts: once an emotional stance is formed, audiences selectively seek out confirming information:

> *"They dislike it first, and then look for reasons — noise, cows, plastics, anything." (Interviewee 2)*
>
> *"The first problem is change — people withdraw and fear any type of change in their landscape and view, then they start finding arguments to justify it." (Interviewee 8)*

Perceived Reciprocity and Responsiveness

Participants noted that small, tangible gestures of responsiveness such as adjusting turbine lighting or temporarily pausing operations can significantly improve community relationships. This aligns with Lund and Refshauge's (2024) emphasis on authentic, ongoing dialogue as a foundation for stakeholder legitimacy:

> *"Just changing the radar lights at night made people feel heard." (Interviewee 9)*

Distribution of Benefits and Burdens

A widely expressed concern was the perceived inequity in how costs and benefits are distributed. Residents near turbines frequently feel they absorb the negative externalities while financial gains accrue to the developer or distant consumers, a dynamic that several participants described as fertile ground for misinformation narratives about corporate exploitation:

> *"Farmers whose land hosts turbines get the most money — people nearby say they're in it for the profits." (Interviewee 11)*

4.2 Mis- and Disinformation: Influence on Trust, Fairness, and Knowledge

Across all three constructs, mis- and disinformation emerged as the single most influential underlying factor by a substantial margin. The Atlas.ti co-occurrence analysis showed misinformation co-occurring with trust sub-codes 142 times, fairness sub-codes 103 times, and knowledge sub-codes 212 times, consistently outpacing all other factors.

4.2.1 Influence on Trust

Trust is the most directly and rapidly damaged by misinformation. Nearly all participants described a dynamic in which false or emotionally charged narratives, particularly around health, noise, and chemical exposure, erode residents' confidence in Vattenfall's transparency and integrity, often before any direct communication occurs. Trust was consistently described as fragile and asymmetric, built slowly but lost rapidly, as one participant captured in a telling expression: "Trust arrives on foot and leaves on horseback." As another noted:

> *"People's trust in developers and institutions depends on transparency, perceived honesty, and the credibility of information sources. Lack of unclear communication fuels skepticism." (Interviewee 1)*

Once misinformation takes hold, factual corrections lose persuasive power. Emotional fear becomes the dominant cognitive frame, rendering informational interventions largely ineffective unless delivered by trusted local messengers. Participants also noted that large companies begin from a structurally disadvantaged position: *"As a big company, you are immediately one–zero behind" (Interviewee 3).* This means misinformation does not only create resistance, it locks communities into mistrust, making subsequent dialogue substantially harder.

Table 2. Co-occurrence Frequency Between Trust and Key Influencing Factors

Influencing Factor	Description	Co-occurrence (n)
Mis-/Disinformation	False or misleading narratives shaping perceptions of health, noise, or fairness of wind projects	142
Institutional and Process Trust	Confidence in government, corporations, and procedural transparency	74
Perceived Risks	Concerns about health effects, property value, or environmental impacts	47
Procedural Fairness and Inclusion	The extent to which locals feel included and represented in decision-making	44

4.2.2 Influence on Fairness

Misinformation shapes fairness perceptions by constructing narratives of procedural manipulation and inequitable outcomes. False claims that permits were pre-approved, that local concerns were ignored, that companies collude with provincial authorities reframe technically legitimate planning processes as corrupt or exclusionary:

> *“When people see the landscape change but don’t see what they get in return, it feels like something is being taken away from them.” (Interviewee 7)*

Table 3. Co-occurrence Frequency Between Fairness and Key Influencing Factors

Influencing Factor	Description	Co-occurrence (n)
Mis-/Disinformation	False or misleading narratives about unequal treatment or hidden agendas in benefit-sharing and local inclusion	103
Local Economic Benefits and Ownership	Opportunities for locals to share profits or gain ownership, fostering perceived fairness	63
Distribution of Benefits and Burdens	Perceived balance between who gains and who bears environmental or visual costs of wind projects	56
Procedural Fairness and Inclusion	The extent to which locals feel included and treated equitably in decision-making	55

4.2.3 Influence on Knowledge

The relationship between misinformation and knowledge is the most empirically pronounced in the data (n = 212). The central mechanism is information displacement: misleading narratives circulating through social media and local networks fill knowledge gaps before factual explanations can reach audiences. Once false claims are established as the dominant reference point, accurate information must compete against already-formed emotional frameworks:

> *“People don’t just base their opinion on facts; they base it on what feels true to them.” (Interviewee 5)*

Table 4. Co-occurrence Frequency Between Knowledge and Key Influencing Factors

Influencing Factor	Description	Co-occurrence (n)
Mis-/Disinformation	False or misleading claims shaping public understanding of health, noise, or environmental effects of wind turbines	212
Emotional and Cognitive Dynamics	Emotional reactions and mental shortcuts influencing how information is interpreted or rejected	89
Noise Pollution	Concerns or misconceptions about turbine sound, low-frequency noise, and health implications	46
Perceived Risks	The level of concern or misunderstanding about personal, environmental, or property-related hazards	46

4.3 Nature, Types, and Sources of Mis- and Disinformation Narratives

4.3.1 Dominant Narrative Categories

Participants identified three dominant thematic categories of wind energy misinformation: health-related (low-frequency noise, infrasound, cardiac effects), environmental-related (chemical release from blade materials), and economic-related (profit extraction by foreign developers, unfair land deals). These narratives are structurally repetitive, participants noted that the same claims resurface across different regions and project stages, suggesting that misinformation operates as a stable, organized discourse rather than spontaneous local concern:

> *"Whenever we do any kind of wind development, 'Tegenwind' pop up... and they all come up with the same arguments all the time: health effects, noise pollution, all that sort of stuff." (Interviewee 3)*

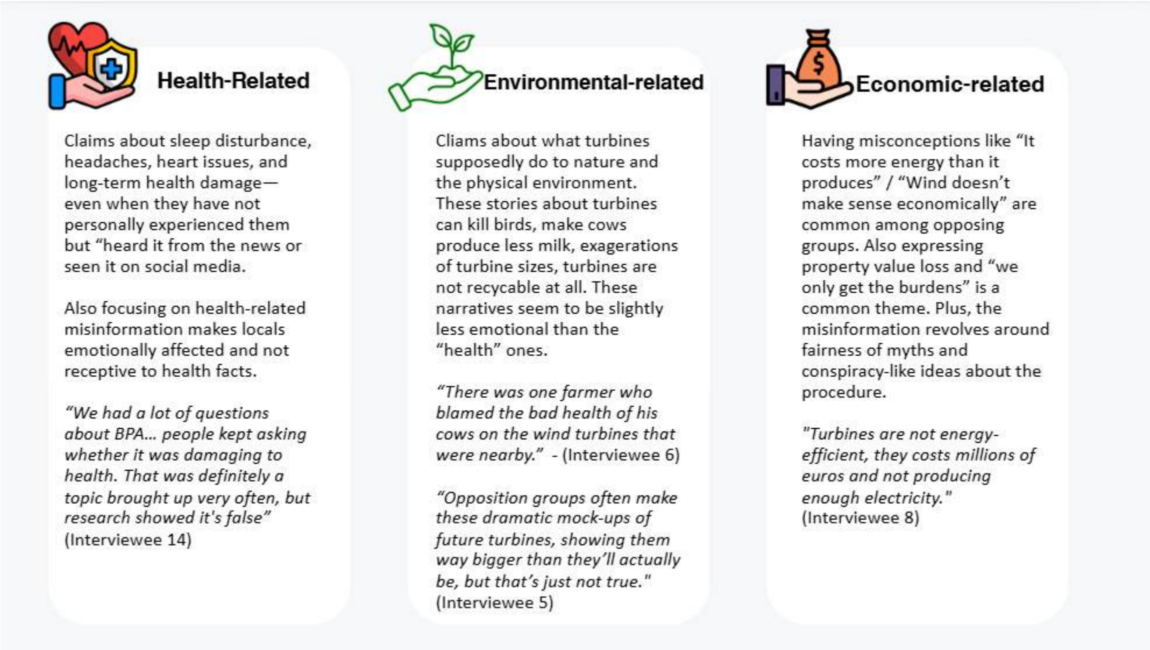
4.3.2 Sources and Channels

Participants described mis- and disinformation as spreading through a self-reinforcing ecosystem of digital platforms and organized groups. Social media platforms — particularly Facebook, X, WhatsApp, and YouTube — serve as primary vectors, with algorithm-driven amplification accelerating reach. Organized anti-wind groups (NLVOW, Tegenwind, WindAlarm, WindWiki, Clintel, Bindalarm) were mentioned by nearly all respondents as persistent, coordinated producers of recurring narratives.

4.3.3 Target Audiences and Emotional Appeal

Misinformation achieves greatest traction among communities that already feel vulnerable, excluded,

Figure 7. Nature and categories of wind energy mis- and disinformation narratives.



Health-Related

Claims about sleep disturbance, headaches, heart issues, and long-term health damage—even when they have not personally experienced them but "heard it from the news or seen it on social media.

Also focusing on health-related misinformation makes locals emotionally affected and not receptive to health facts.

"We had a lot of questions about BPA... people kept asking whether it was damaging to health. That was definitely a topic brought up very often, but research showed it's false" (Interviewee 14)

Environmental-related

Cliams about what turbines supposedly do to nature and the physical environment. These stories about turbines can kill birds, make cows produce less milk, exagerations of turbine sizes, turbines are not recyclable at all. These narratives seem to be slightly less emotional than the "health" ones.

"There was one farmer who blamed the bad health of his cows on the wind turbines that were nearby." - (Interviewee 6)

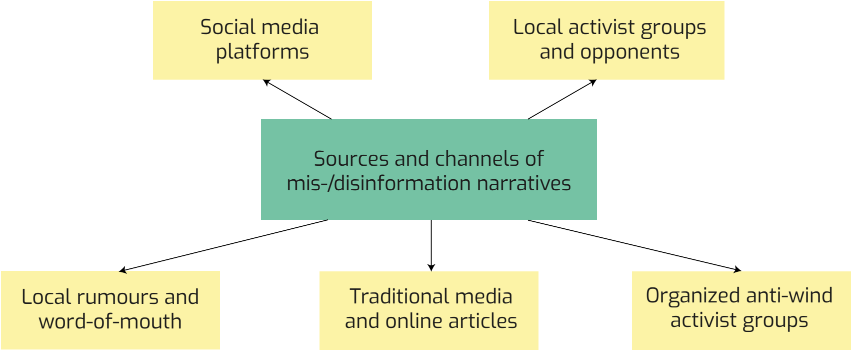
"Opposition groups often make these dramatic mock-ups of future turbines, showing them way bigger than they'll actually be, but that's just not true." (Interviewee 5)

Economic-related

Having misconceptions like "It costs more energy than it produces" / "Wind doesn't make sense economically" are common among opposing groups. Also expressing property value loss and "we only get the burdens" is a common theme. Plus, the misinformation revolves around fairness of myths and conspiracy-like ideas about the procedure.

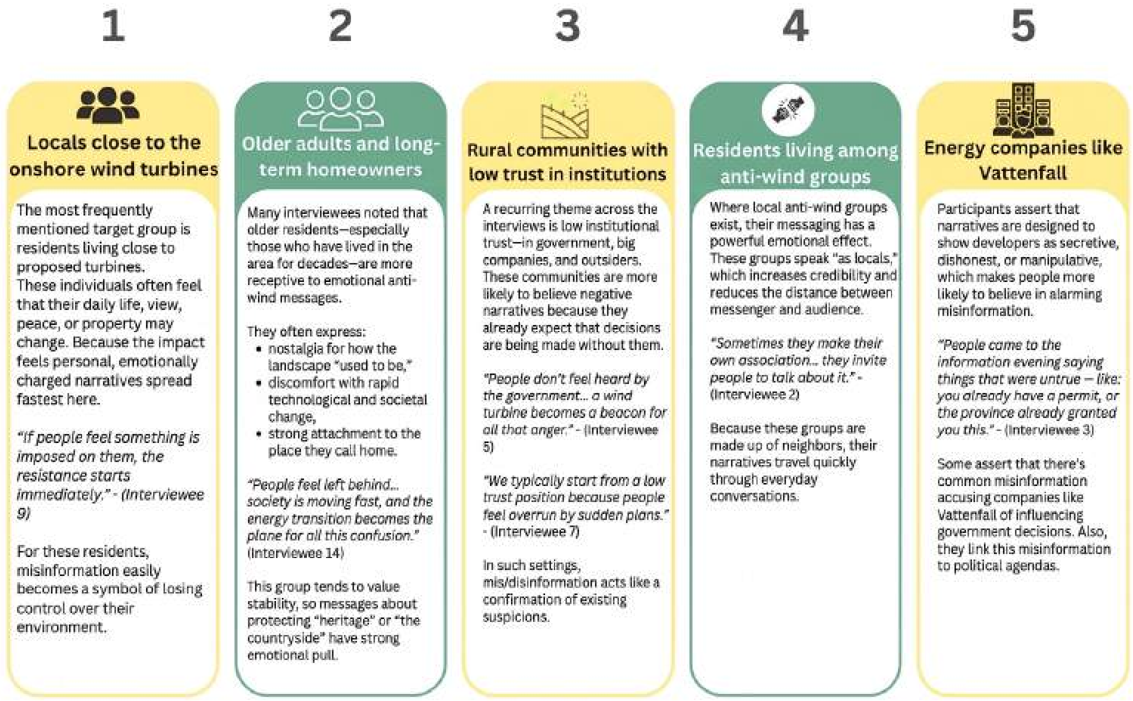
"Turbines are not energy-efficient, they costs millions of euros and not producing enough electricity." (Interviewee 8)

Figure 8. Sources and channels of mis- and disinformation narratives in the Dutch onshore wind context



or distrustful of institutions. Emotionally resonant framing, fear of health harms for children or elderly relatives, anger at perceived inequity, grief over landscape loss, makes misleading narratives highly persuasive for these groups. Emotional activation precedes information processing, meaning that once fear is triggered, factual rebuttals are less effective than empathetic engagement.

Figure 9. Target audiences, most susceptible to wind energy misinformation



1

Locals close to the onshore wind turbines

The most frequently mentioned target group is residents living close to proposed turbines.
These individuals often feel that their daily life, view, peace, or property may change. Because the impact feels personal, emotionally charged narratives spread fastest here.

"If people feel something is imposed on them, the resistance starts immediately." - (Interviewee 9)

For these residents, misinformation easily becomes a symbol of losing control over their environment.

2

Older adults and long-term homeowners

Many interviewees noted that older residents—especially those who have lived in the area for decades—are more receptive to emotional anti-wind messages.

They often express:
- nostalgia for how the landscape "used to be,"
- discomfort with rapid technological and societal change,
- strong attachment to the place they call home.

"People feel left behind... society is moving fast, and the energy transition becomes the plane for all this confusion." (Interviewee 14)

This group tends to value stability, so messages about protecting "heritage" or "the countryside" have strong emotional pull.

3

Rural communities with low trust in institutions

A recurring theme across the interviews is low institutional trust—in government, big companies, and outsiders. These communities are more likely to believe negative narratives because they already expect that decisions are being made without them.

"People don't feel heard by the government... a wind turbine becomes a beacon for all that anger." - (Interviewee 5)

"We typically start from a low trust position because people feel overrun by sudden plans." - (Interviewee 7)

In such settings, mis/disinformation acts like a confirmation of existing suspicions.

4

Residents living among anti-wind groups

Where local anti-wind groups exist, their messaging has a powerful emotional effect. These groups speak "as locals," which increases credibility and reduces the distance between messenger and audience.

"Sometimes they make their own association... they invite people to talk about it." - (Interviewee 2)

Because these groups are made up of neighbors, their narratives travel quickly through everyday conversations.

5

Energy companies like Vattenfall

Participants assert that narratives are designed to show developers as secretive, dishonest, or manipulative, which makes people more likely to believe in alarming misinformation.

"People came to the information evening saying things that were untrue – like: you already have a permit, or the province already granted you this." - (Interviewee 3)

Some assert that there's common misinformation accusing companies like Vattenfall of influencing government decisions. Also, they link this misinformation to political agendas.

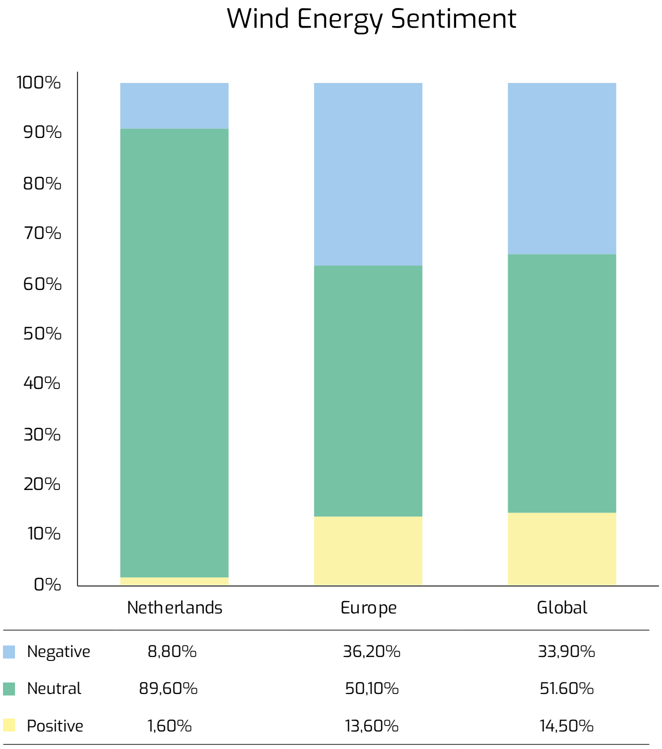
4.4 Social Media Monitoring Results (Meltwater, August 2023 – July 2025)

The social media analysis provides a platform-level view of how misinformation narratives circulate and evolve across the two-year monitoring period.

Sentiment analysis across Dutch, European, and global contexts shows that wind energy discussion in the Netherlands is notably more negative than at other geographic scales — suggesting that the local political and informational environment produces a distinctly resistant discourse climate.

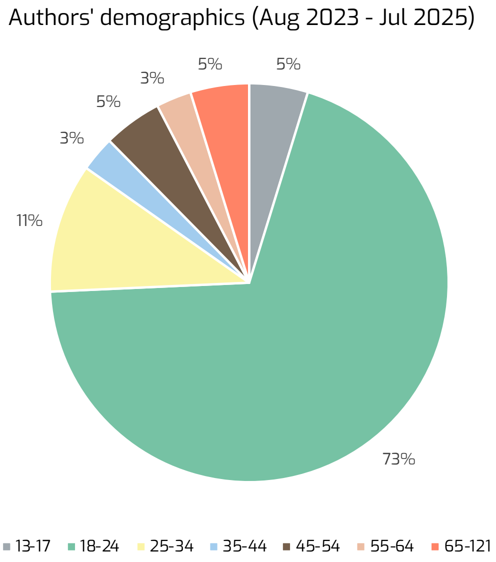
Demographic analysis reveals that over 80% of authors posting about wind energy in the Netherlands are aged 18–34, with older demographic groups significantly underrepresented despite evidence that communities closest to wind sites, often older rural populations, are most directly affected by local opposition. This age skew indicates that social media data captures a demographically partial slice of public opinion.

Figure 10. Share of voice by sentiment across geographic contexts (Meltwater, Aug 2023 – Jul 2025)



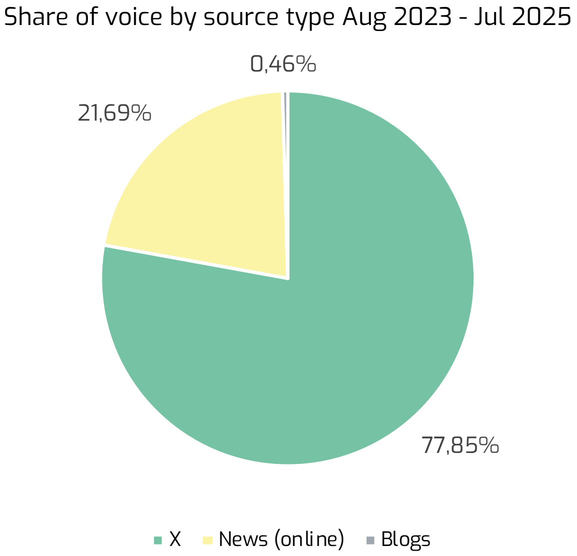
	Netherlands	Europe	Global
🟦 Negative	8,80%	36,20%	33,90%
🟩 Neutral	89,60%	50,10%	51.60%
🟨 Positive	1,60%	13,60%	14,50%

Figure 11. Demographic profile of authors posting about wind energy in the Netherlands (Meltwater, Aug 2023 – Jul 2025)



X dominates as the platform with the highest volume of wind energy mentions across all sentiment categories. Online news and blogs represent secondary channels with distinct narrative profiles. This pattern confirms that high-reach content reinforces conflict and risk framing rather than factual explanation, consistent with the negativity bias described in the academic literature (Hameleers, 2023).

Figure 12. Share of voice by source type (Meltwater, Aug 2023 – Jul 2025)



Comparing the two monitoring periods reveals meaningful shifts in narrative prominence. Between August 2023 and July 2024, dominant misinformation topics included low-frequency noise, mental health, cardiac effects, and visual/landscape intrusion. In the subsequent year (August 2024 – July 2025), mental health and low-frequency noise retained prominence, while concerns around harmful chemicals increased significantly.

Platform-specific analysis shows distinct narrative profiles across channels. On X, harmful chemicals and low-frequency noise dominate, consistent with the platform's tendency toward brief, emotionally charged claims. In news media, low-frequency noise and visual intrusion receive most attention. Blogs disproportionately feature cardiac and health-related claims.

Figure 13. Share of voice by mention trend, August 2023 – July 2024 (Meltwater)

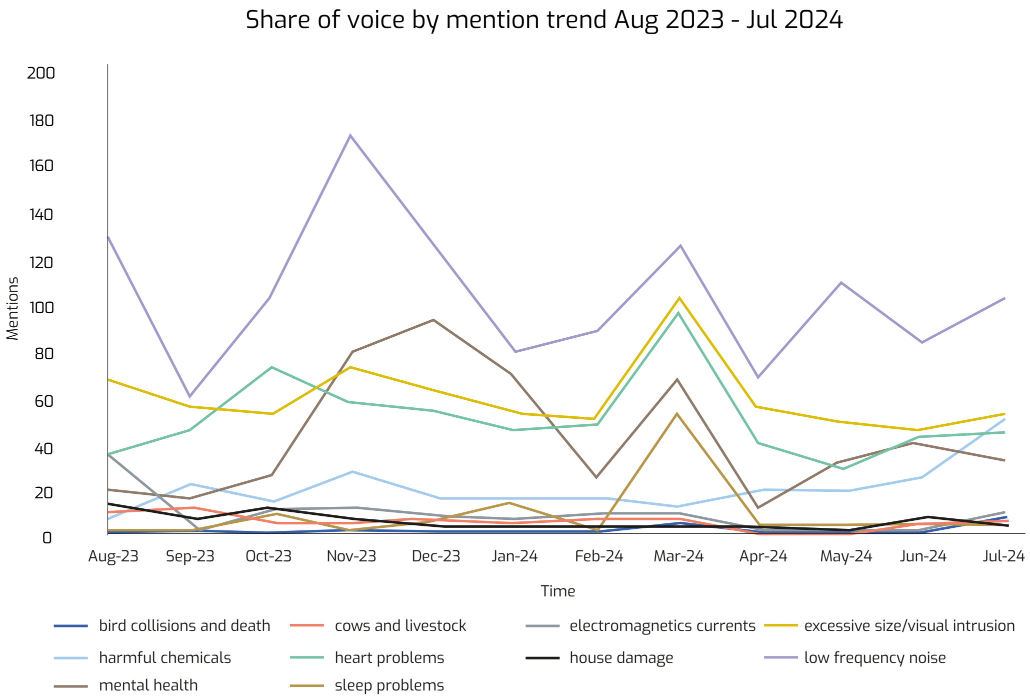


Figure 14. Share of voice by mention trend, August 2024 – July 2025 (Meltwater)

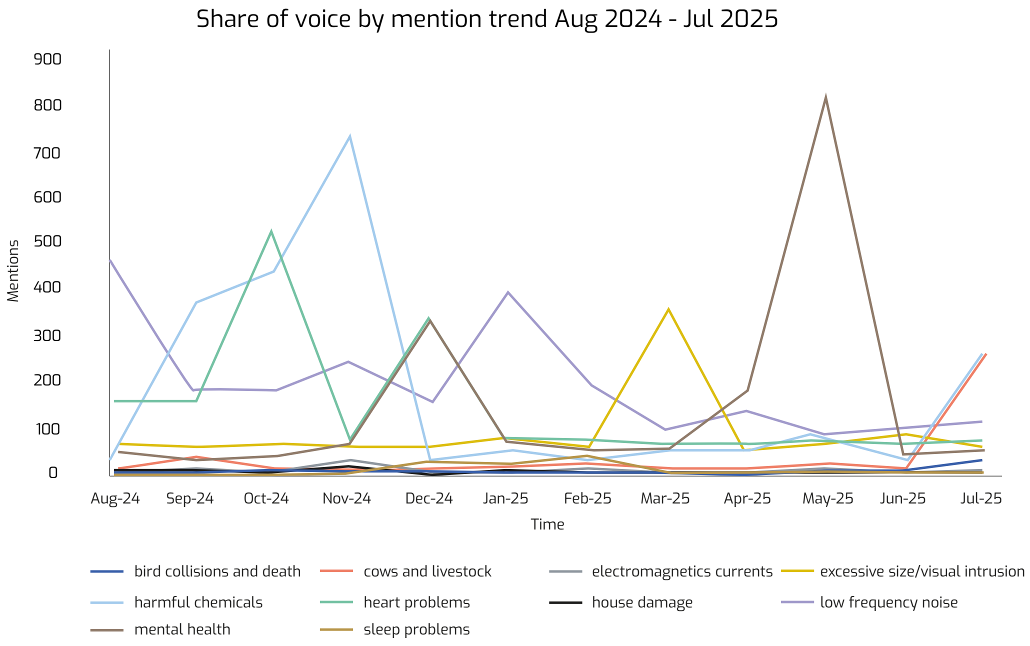
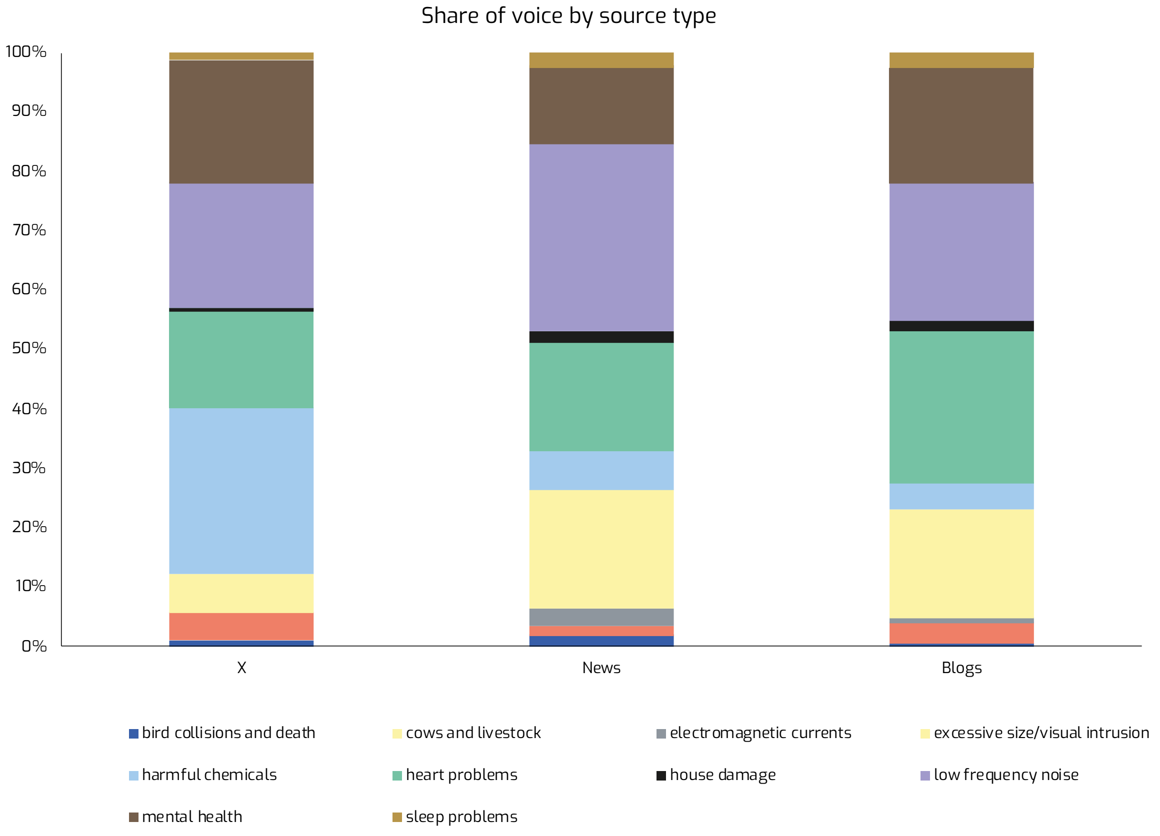


Figure 15. Share of voice by source type and narrative topic (Meltwater, Aug 2023 – Jul 2025)



5. Discussion

The findings reveal a consistent empirical pattern: public acceptance of onshore wind energy in the Netherlands is not primarily determined by the technical characteristics of turbines or the legal quality of planning processes. It is shaped by the social and communicative environment in which communities encounter and interpret information about these projects. Across trust, fairness, and knowledge, disinformation operates as the dominant disruptive force not an isolated communication problem, but a structural feature of the information landscape in which wind developers operate.

5.1 Disinformation as a Structural Acceptance Barrier

The finding that mis- and disinformation co-occurs with trust (n = 142), fairness (n = 103), and knowledge (n = 212) sub-codes at frequencies that substantially exceed all other underlying factors points to a fundamental reframing of how wind energy communication should be understood. Previous literature has tended to treat misinformation as one factor among many, alongside NIMBY attitudes, perceived risks, and local economic concerns (Petrova, 2013; Bell et al., 2013). The present findings suggest it is more accurately understood as a meta-factor: one that amplifies and distorts the influence of every other underlying factor simultaneously.

When false narratives about noise, health effects, or procedural manipulation circulate in a community, they do not merely add a grievance to an existing list. They fundamentally alter the cognitive and emotional context within which all subsequent information including factually accurate developer communication is received. Once residents operate within a misinformation-saturated information environment, trust becomes harder to build, fairness harder to demonstrate, and knowledge harder to convey, regardless of the quality or volume of factual information provided.

5.2 Social Media as Amplification Infrastructure

The social media monitoring data substantiate the interview findings at a systemic level. The dominance of X as the platform with the highest volume of wind energy mentions across all sentiment categories reflects its role as the primary public arena for wind energy debate in the Netherlands. The prominence of conflict-framed and safety-incident content in the most widely circulated material reflects the negativity bias in social media amplification: emotionally arousing and conflict-framed content circulates more widely than informational content (Hameleers, 2023).

The platform-specific narrative profiles have direct implications for communication strategy. The prominence of harmful chemicals on X, low-frequency noise in news media, and cardiac claims on blogs suggest that different misinformation narratives find their most receptive audiences in different channels and therefore require channel-specific interventions. Crucially, the repetition of the same core narratives across both monitoring periods demonstrates that wind energy misinformation is not a temporary phenomenon. It is a persistent, structurally maintained discourse produced and sustained by organized actors with material interests in obstructing the energy transition.

5.3 The Primacy of Emotional Dynamics

A consistent finding across both data sources is that opposition to wind projects is primarily emotional in origin, and that misinformation succeeds because it provides emotionally satisfying explanations for pre-existing discomfort. Participants described a sequence in which residents develop negative feelings such as anxiety about landscape change, distrust of institutions, fear of health effects, and subsequently seek out confirming information. This creates a dynamic in which the first narrative to occupy the emotional space becomes the dominant reference point, regardless of its accuracy.

This finding has a direct implication for communication practice: factual rebuttal alone is insufficient, because it does not address the emotional foundation of opposition. As Cornelissen (2020) and Lund and Refshauge (2024) emphasize, effective communication must engage with the affective dimensions of resistance, acknowledging concerns genuinely, demonstrating responsiveness, and working through locally trusted messengers, before factual information can be received and processed.

5.4 Theoretical Contribution

The primary theoretical contribution of this study is the conceptualization of disinformation as a structural barrier to renewable energy acceptance, rather than a peripheral communication problem to be managed reactively. The study demonstrates empirically through triangulation of expert interview analysis and longitudinal social media monitoring that disinformation operates across all three constructs of the Huijts et al. (2012) acceptance framework simultaneously and with greater magnitude than any other single factor. This suggests that future theoretical and empirical work on wind energy acceptance should treat the disinformation environment as a foundational context not an additional variable within which acceptance processes unfold. The study also demonstrates the value of combining qualitative expert insight with longitudinal social media monitoring in acceptance research, each data source illuminating dimensions invisible to the other.

5.5 Limitations

Several limitations should be acknowledged. The interview sample consisted exclusively of wind energy professionals, leaving out local residents, anti-wind activists, and elderly community members near turbine sites. The Meltwater analysis skews toward younger demographics (over 80% aged 18–34), underrepresenting older residents who are often most directly affected. The study's focus on trust, fairness, and knowledge also leaves aside other relevant dimensions such as place attachment (Devine-Wright, 2011), and the qualitative coding process carries inherent interpretive subjectivity that multi-coder reliability checks would help address in future research.

6. Conclusion

This study examined how disinformation influences public acceptance of onshore wind turbines in the Netherlands, with Vattenfall as the focal case. The findings lead to an empirically grounded conclusion: mis- and disinformation, amplified through social media platforms, anti-wind networks, and emotionally charged local narratives, is the dominant barrier to acceptance, and addressing it must be the central priority of any evidence-based communication strategy.

The research demonstrates that trust, fairness, and knowledge are not simply weakened by a lack of information. They are actively damaged by the presence of misleading information that pre-occupies the cognitive and emotional space that accurate communication would otherwise fill. Trust erodes when false narratives cast developers as extractive foreign companies indifferent to local concerns. Fairness perceptions collapse when communities believe that permits are pre-approved and public participation is performative. Knowledge is displaced when fear-based explanations for health risks, noise effects, and environmental harms circulate faster and more persuasively than factual alternatives.

The broader implications extend beyond wind energy. Technologies like solar farms, hydrogen infrastructure, and battery storage face structurally similar communication environments: early-mover misinformation narratives, low baseline institutional trust, and social media ecosystems that amplify emotional content. The pattern identified in this study, disinformation as a structural driver of resistance requiring proactive and systematic communication responses, is likely to recur as each new technology moves from policy agenda to local planning reality. The energy transition is, in this sense, fundamentally a communication challenge as much as a technical or regulatory one.

Future research should test the effectiveness of prebunking, proactively inoculating audiences against specific misleading narratives before they encounter them, in the energy communication context. The identification of platform-specific narrative profiles in this study provides a starting point for designing such targeted interventions. Longitudinal community-level studies triangulating practitioner insight with resident experience would further strengthen the empirical foundation for evidence-based energy communication strategy.

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A Modelling Framework for Multisectoral Energy Collaboration in Multi-Voltage Networks: Enhancing System Performance Through Shared Storage and Energy Exchange

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Local energy systems have recently gained significant attention in the Netherlands as a response to the grid congestion challenges, promoting more efficient utilisation of existing electrical infrastructure.

Conducted within the REFORMERS project, this study assesses how energy exchange and a shared battery between a low-voltage residential network and a medium-voltage industrial park affect system-level performance, leveraging both empirical and synthesised data on network topology, demand profiles, and renewable generation. Results show modest gains from direct energy exchange yielding 0,71% for self-sufficiency, 1,36% to self-consumption, and reducing the annual community costs 0,89%. While the shared BESS integration shows significantly higher improvements increasing 6,99% in self-sufficiency, 14,17% in self-consumption, while contributing to the reduction of the community's annual costs in 9,38%. However, strong seasonal PV intermittency and the host company's grid-connection capacity limited further improvements, while preventing the accomplishment of 75% self-consumption target and annual positive energy balance, underscoring the need for long-term storage solutions or complementary renewable sources.

The study highlights both performance and economic gains, proposing a practical model where industrial and residential sectors enhance the renewable generation's use and share storage, while locating BESS in industrial zones within urban energy systems.

Keywords: Multisectoral collaboration, Shared Battery, Renewable energy, Residential network, Industrial network, System-level performance.

03

1. Introduction

In response to climate change and in pursuit of the goals set by the Paris Climate Agreement, distributed energy resources have emerged as a solution to involve citizens in local renewable energy production (Facchini, 2017). However, the rapid electrification of industries, transportation, and households has outpaced the capacity of existing distribution networks, creating severe grid congestion across the Netherlands (- International Energy Agency, 2025), resulting in approximately 10,000 large consumers and 7,500 renewable generation projects grid connection approvals in waiting list in 2024, due to insufficient network capacity (- International Energy Agency, 2025). The issue, first evident in 2018 (Pató, 2024), now representing a major barrier to the energy transition in the electrical sector (Hammingh et al., 2023). To overcome this challenges, national policies emphasise the need to optimise the use of the existing grid capacity through smarter coordination among government, industry, and local communities (- International Energy Agency, 2025). Complementary measures include the creation of shared grid connections and compensations to promote Energy hubs (Pató, 2024). These are as local decentralised networks integrating renewable generation and storage systems to enhance the consumption of the locally produced energy, reducing grid dependency, called Local Energy Systems (LES)(Belmar et al., 2023). However, their effectiveness highly depends on factors such as the consumers' typology (Victoria Gasca et al., 2025), that can be measured by four key performance indicators (KPIs): self-sufficiency, self-consumption, community costs (Belmar et al., 2023) and Net Annual Energy Balance (NAEB) (Gabaldón et al., 2021).

1.1. Multisectoral Energy Collaboration

The concept of multisectoral energy collaboration emerged as a strategy to enhance LES efficiency, flexibility, the integration of renewable, coordinating the energy exchange between consumers of different typologies, such as residential and industrial users, within the LES (Valkering Lina Silva Rodriguez et al., 2024). Studies show that by coupling these diverse demand profiles, multisectoral LES can achieve complementary consumption patterns that reduce overall grid dependency and energy waste (Belmar et al., 2023)(Victoria Gasca et al., 2025), therefore, significantly improving system-level performance. However, diversity in consumption patterns, beyond community size, plays a crucial role in system balance and efficiency (Belmar et al., 2023)(Victoria Gasca et al., 2025).

1.2. Battery Energy Storage Systems

A key enabler of grid flexibility in LES is the use of Battery Energy Storage System (BESS), which can operate at multiple scales, such as the grid and local level, providing services such as peak shaving, load balancing, and congestion management (Seward et al., 2021). Despite significant cost reductions in recent years, BESS remain relatively expensive making their integration and control strategies remain critical to maximising both technical and economic benefits (Seward et al., 2021). Additionally, research have consistently shown that centralised BESS deployments outperform decentralised storage in terms of collective benefits and cost savings (Zakeri et al., 2021), as individually managed storage provides limited collective impact (Qiao & Yang, 2017).

1.3. Research Gap and Proposed Study

Despite the technological maturity of local energy systems, the implementation of multisector LES integrating shared BESS remain underexplored in current research. Most existing studies focus on collaboration among users of similar typology (Albouys-Perrois et al., 2022) or rely on individual BESS use (Victoria Gasca et al., 2025), often overlooking practical validation and operational constraints that occur in practical applications.

This research addresses these gaps by modelling and assessing a multisectoral energy collaboration between a low-voltage (LV) residential area composed of 50 households and a medium-voltage (MV) industrial park comprising 4 companies in Heiloo, Netherlands. Developed in collaboration with the New Energy Coalition under the REFORMERS project, this study explores the technical benefits of direct energy exchange and the integration of a shared BESS between the two regions.

The objectives of this research are listed as follows:

1. Quantify the annual total energy exchanged and its impact on the system performance from the multisectoral energy collaboration.
2. Quantify the impact on collective performance and potential grid congestion relief from the shared BESS integration.
3. Assess the feasibility and compare the amount of generation and storage assets required to meet 75% self-consumption and a positive NAEB, for both split and interconnected configurations
4. Quantify the impacts on the annual total electricity costs from the multisectoral energy exchange and shared BESS integration.

And ultimately answer the following research question:

> *How does the collaboration between low-voltage residential and medium-voltage industrial networks and the use of a shared battery affect the overall system performance and the planning of a local energy system?*

By demonstrating the feasibility and performance outcomes from the multisector energy collaboration, this work offers a replicable model for urban–industrial cooperations in future LES.

2. Methodology

This study employs a simulation-based modelling approach to assess the performance of a multisectoral Local Energy System (LES) under four different configurations. The methodology comprises three key components: (i) data collection, (ii) model development and simulation analysis, and (iii) a simplified economic evaluation. Annual quasi-dynamic simulations were conducted in DIgSILENT PowerFactory, performing 15-minute resolution annual quasi-dynamic simulations. The system incorporates a centralised Energy Management System (EMS) designed to minimise grid imports and maximise local renewable energy utilization, in line with the project's objectives.

2.1 Data collection

The MV industrial network comprises four companies, of which two integrate rooftop PV, totalling 514 kWp. Additionally, an electric truck was integrated into the company later integrating a 466 kWh shared BESS, which provided measured 15-minute demand and PV generation data from the year 2023. For the remaining companies, 15-minute demand profiles were constructed using standard normalised sector-specific load curves from the Liander Open Data platform (Liander, 2025), scaled to the contracted power levels, known from internal project data. For the second prosumer, an MV-connected retail store, the PV generation was estimated using the measured profile from the packaging company and scaled to the installed PV capacity, assuming similar installation setups.

The LV residential network includes 50 households, of which 10 integrate an individual BESS and an EV, referred to within the project as smart houses. In the absence of measured data, demand and PV generation profiles were reconstructed using postcode-level annual imports/exports from the DEGO database (Vereniging van Nederlandse Gemeenten (VNG), 2024), a standard Dutch residential load curve based on the annual demand from HET NORMO (Het Normo, 2022), and a normalised PV production curve generated using PVGIS tool (EU Science Hub, n.d.), assuming optimal values of 37º tilt facing south (Van Aken et al., 2021). An iterative scaling process ensured that the reconstructed profiles matched the aggregated annual values reported by DEGO (Vereniging van Nederlandse Gemeenten (VNG), 2024).

The distribution networks were represented using typical Dutch transformer capacities (Bhattacharyya et al., 2008) and cable types (Bhattacharyya et al., 2008) (Jiménez-Ruiz et al., 2024), while MV lines and companies' grid-connection limits were obtained from internal project data. Since the full grid couldn't be modelled, infrastructure constraints focus on the connection points where new assets are integrated, ensuring a technically credible representation. Details from the data applied are shown in Appendix 1.

2.2 Simulation models and research stages

The analysis follows four sequential research stages, each answering a part of the research question and building upon the previous configuration. The Research stage 1 (RS1) focuses on the two separate networks, modelled to reflect current conditions. This stage establishes the annual energy demand, grid exchanges at each point of connection (PoC), and reference values for the KPIs expressed in Equations (1), (2) and (3).

$$Self - sufficiency = \frac{Consumption_{local}\ (kWh)}{Consumption_{total}\ (kWh)} * 100 \ \ (1)$$

$$Self - consumption = \frac{Consumption_{local}(kWh)}{Production_{local}(kWh)} * 100 \ \ (2)$$

$$\text{NAEB}\ (kWh) = Surplus_{to\ grid} - demand_{from\ grid} \ \ (3)$$

Where $Consumption_{local}$ is the annual consumption of total annual locally generated energy $Consumption_{total}$, and $Production_{local}$ is the total annual energy demanded from the system's loads. The NAEB is found by the difference between grid exports, from PV surpluses, ($Surplus_{to\ grid}$) and grid imports ($demand_{from\ grid}$).

The Research Stage 2 (RS2) introduces an MV link between the two networks, allowing bidirectional energy exchange, and connecting all network elements to a single grid PoC. The comparison of the outcomes with those from RS1 highlights the impact of the energy exchange on KPIs and the reduction in external grid dependency, thereby addressing the first research objective. Research Stage 3 (RS3) integrates a centrally controlled shared BESS at the packaging company, considering the host grid connection capacity. The storage charges are exclusively from the local PV surplus and discharges to support industrial and residential loads, while prioritising the industrial loads. This stage evaluates improvements in KPIs under shared storage, and contributions to grid congestion relief and annual peak export/import values. Additional analysing assessed the performance improvements sensitivity to the storage capacity, and the influence of BESS location. The second research objective is addressed by comparing the results from RS2 and RS3, showing the additional performance benefits from the shared BESS integration. The final Research Stage 4 (RS4) investigates whether the system can meet the defined performance goals, under realistic technical and spatial constraints. This stage finds additional storage and PV required, and the role of multisectoral collaboration in infrastructure needs.

2.3 Economic Assessment

A simplified economic assessment quantifies the benefits of each stage relative to the baseline scenario. Community energy bills are calculated using the average 2023 Dutch electricity tariffs (CBS Statistics Netherlands, n.d.). Investment costs for the shared BESS are derived from internal project data, indicated in Appendix 1, and PV panels on the module (Solar Panel Canadian Solar CS6P-260P, n.d.). Finally, a simplified payback period is estimated by dividing the total cost of additional energy assets by their contribution to the community costs reduction.

3. Results

This section presents the main outcomes of the four research stages, progressively analysing the impact of the energy exchange, shared BESS integration, and PV and BESS expansion, on the KPIs and annual grid interactions.

3.1. Research Stage 1 – Baseline Assessment

RS1 established the reference performance of the split networks, with each network operating independently. Results showed partial temporal complementarity between the load profiles, illustrated in Appendix 2. Industrial loads demand peaked at late morning and night, due to the EV truck charge, while households demand peaked in the early morning and evening period, aggravated by the residential EVs charge. This profile's diversity indicated potential for mutually beneficial energy exchange once interconnection was allowed. However, limited by the exhibited high seasonal intermittency of solar PV generation, driven by the study's site northern latitude. The baseline KPIs demonstrated a collective self-sufficiency (CSS) of 27,24%, collective self-consumption (CSC) of 56,20% and a NAEB of -681,4 MWh.

3.2. Research Stage 2 – Enabled Energy Exchange

In RS2, the enabled multisector energy exchange increases local energy consumption in 8,35 MWh (2,41%). Shown in Figure 1 and Figure 2, the seasonal analysis of the energy exchange showed higher residential contributions in winter, during industrial operating hours, while industrial contributions were most significant in summer, supported by their larger PV capacity, which primarily supplied the residential network during evening demand peaks.

As reflected in the hourly distribution of the annual total energy exchanged, illustrated in Figure 3, the highest energy savings are found at 17:00, totalling 1,51 MWh, corresponding to 18,13% of the annual savings.

Under enabled energy exchange, the model shows modest improvements, increasing CSS by 0,71%, CSC by 1,36%, and NAEB by 0,35%. The grids interactions showed a 1,13% reduction in the annual grid imports. However, the simultaneity of imports and exports across the networks prevented the reduction of the annual peak power values. This configuration found a reduction in the community costs of 2435,23€

(0,89%), showing that even without additional assets, multisector collaboration provides benefits to the system performance.

Figure 1. Hourly Distribution of Total Networks Energy Exchanged During Winter

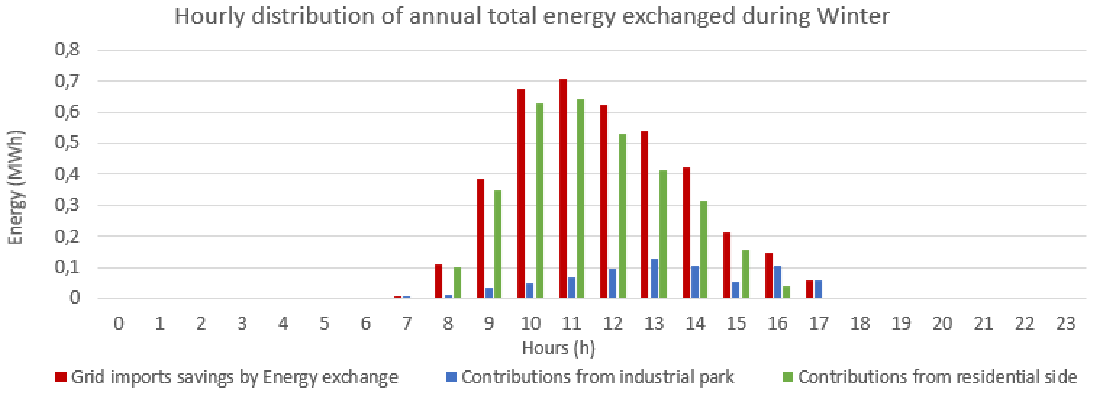


Figure 2. Hourly Distribution of Total Networks Energy Exchanged During Summer

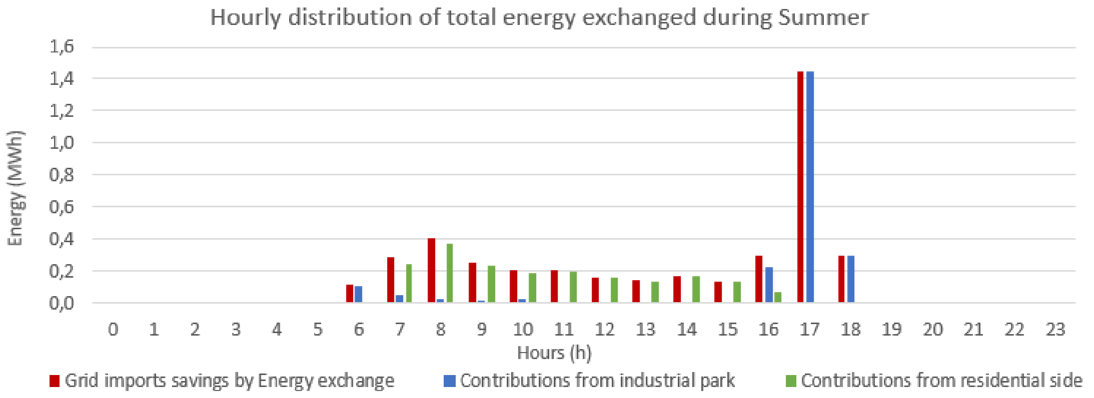
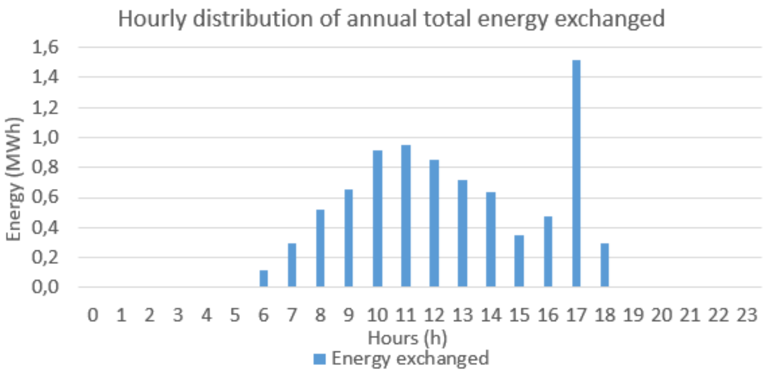


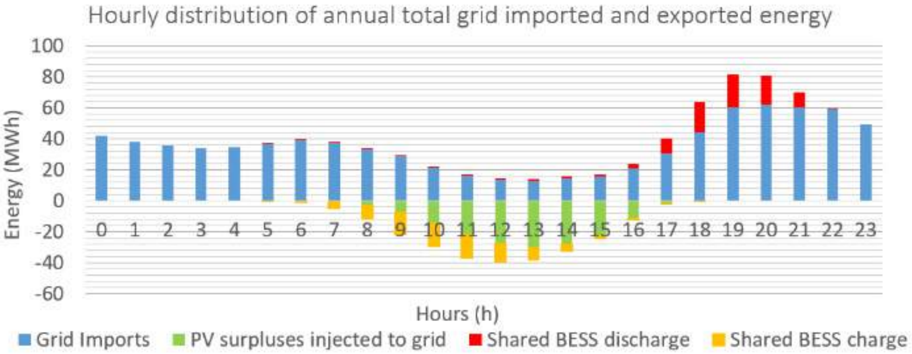
Figure 3. Hourly Distribution of Annual Total Energy



3.3. Research Stage 3 – Integration of Shared BESS

RS3 introduced the shared BESS at the industrial park, enabling coordinated energy storage and discharge across the sectors. However, the BESS's operation was constrained by the host company's grid connection capacity, limiting its maximum rated power to 120 kW. Nevertheless, the BESS significantly enhanced system performance, contributing with 89,3 MWh annually. Results showed notable reductions in PV surpluses and grid imports, particularly during the evening consumption triggered by EVs' charge, reducing annual consumption during peak by 25% the consumption, shown in Figure 4.

Figure 4. Hourly Distribution of Annual Total Grid and Shared BESS Interactions

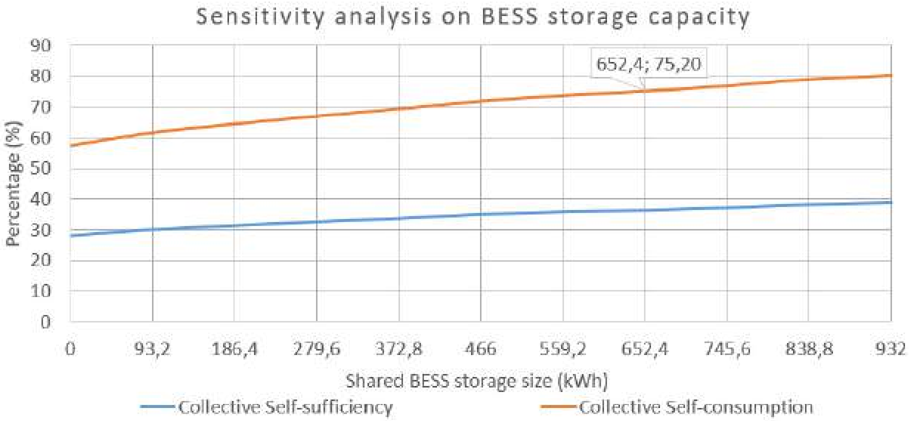


This stage achieved substantial KPI improvements, with a CSS of 71,72% and a CSC of 34,94%, where the BESS contributed to an increase in CSS by 6,99% and CSC by 14,17%. The NAEB remained unchanged, reflecting the nature of the BESS operation under the assumed ideal storage conditions, which does not directly affect NAEB, since stored energy equally offsets both imports and exports. Although the model shows an annual grid import reduction of 11,00%, no impact was found on the annual peak import and export values, respectively, due to the BESS constraint to charge exclusively from PV surpluses and the absence of a BESS charge control system.

RS3 finds a reduction in 28.013,02€ (10,23%) on the community costs, of which 9,38% resulted from the shared BESS contributions, yielding a BESS payback period of 6,7 years. The shared operation proved particularly efficient when residential users participated, as their higher electricity tariffs enhanced cost savings per unit of stored energy. A comparative analysis between the total household BESS and the shared BESS showed that the shared BESS would reduce the community in 1,81%, while the combined individual BESS would only reduce 1,32%.

Expanding BESS capacity beyond 466 kWh showed diminishing returns, thus extending the BESS payback time. However, a storage capacity over 652,4 kWh was found to meet the CSC performance target of over 75%.

Figure 5. Sensitivity Analysis on Shared BESS Storage Capacity



The analysis of BESS location and associated grid connection power constraints revealed only a slight increase in annual energy savings, while primarily affecting the energy distribution between sectors, where unconstrained configurations favoured residential users.

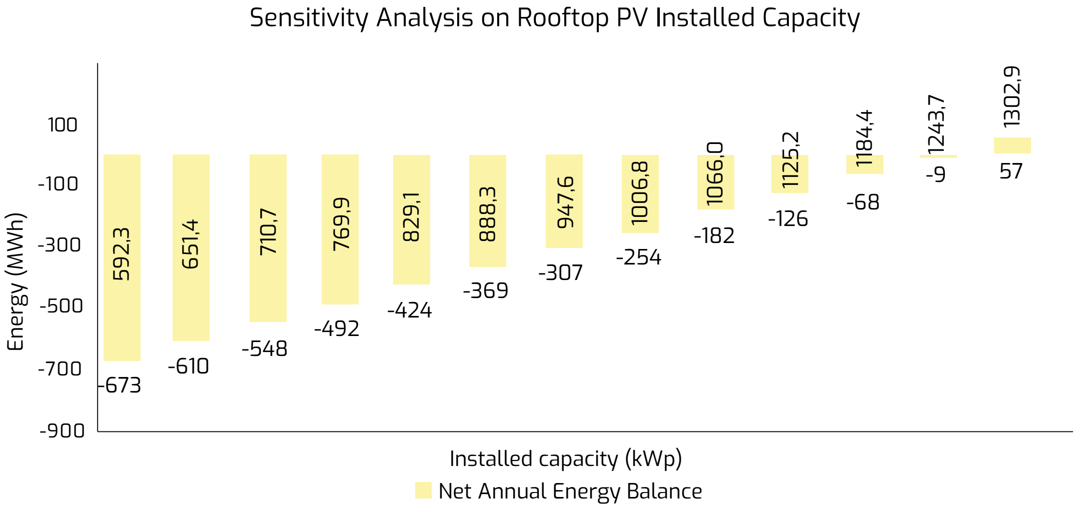
Table 1. Share BESS location's impact on Annual Contributions and Shares of usage

BESS Power Constraint	Lower Grid Connection Capacity (71 kW)	Current Grid Connection (120 kW)	No Power Constraint (200 kW)
Annual Contributions from Shared BESS	83,413	89,296	91,504
BESS Discharge to Residential Side	8,166	20,416	38,645
BESS Discharge to Industrial Side	75,247	68,880	52,860

3.4. Research Stage 4 – REFORMERS KPIs Fulfilment

RS4 begins with the analysis under interconnected networks, where a sensitivity analysis on the installed PV capacity, illustrated in Figure 6, indicated that the positive NAEB could theoretically be achieved with approximately 1,3 MWp of PV capacity.

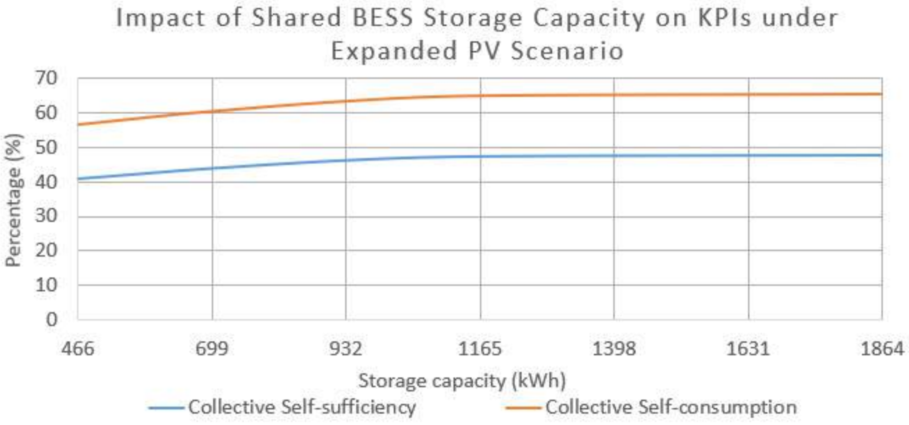
Figure 6. Sensitivity Analysis on PV installed Capacity impact on NAEB



However, this configuration was found to be technically unfeasible under the existing companies' grid-connection capacities; therefore, concluding that such performance couldn't also be achieved under the split-network setup, based on the findings from RS2. Considering these limitations, the best NAEB achieving configuration corresponded to a total PV installed capacity of 888,1 kWp (+295,88 kWp), resulting in a NAEB reduction of 46,24%. Under expanded PV configuration, analysis on the shared BESS storage capacity showed that CSC values saturate at 67% beyond 1,165 MWh, due to the shared BESS power constraint, which limited the BESS's ability to efficiently store the additional PV surpluses, as illustrated in Figure 7.

Under the expanded PV and 1,165 MWh shared BESS configuration, the model exhibited notable performance improvements, particularly in CSS and NAEB, which increased by 21,02 % and 46,24%, respectively, due to the increased renewable generation. In contrast, CSC improved by 9,92 % relative to the CSC found in RS1, indicating a reduced gain compared to RS3. This reduced improvement results from the 50,61% increase in total PV generation, and the 15,90% increase in PV surpluses unable to be stored by the shared BESS, thereby constraining the CSC enhancement.

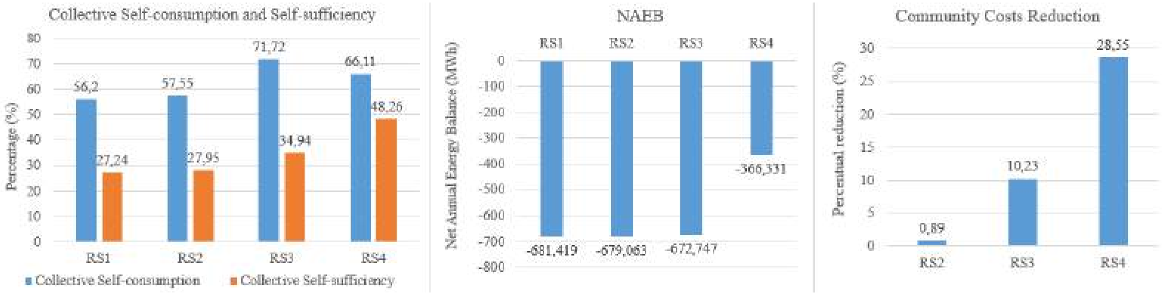
Figure 7. Sensitivity Analysis on Shared BESS Storage Capacity Impact in KPIs Under Expanded PV



This configuration required to calculate the community savings, while considering both increased direct PV self-consumption, the additional contributions from the households' BESS and increased energy exchange. The analysis on the contributions to the system energy savings revealed that the shared BESS contributed with 201,95 MWh, resulting in a contribution to the community costs reduction of 57.493,69€. While the PV contributed to 15.860,03€, from the increased self-consumption and energy exchange. This configuration would require an investment for the shared BESS of 438.335€, and 108.110€ for the additional PVs. Resulting in a payback period of 7,6 years for the BESS, and 6,8 years for the PVs.

This study demonstrates the benefits in collective performance from multisector energy collaboration and outlines key insights for future LES. The main results from each research stage are in summarised the Figure 8.

Figure 8. Summary of main findings from each research stage



4. Discussion

Under the multisectoral energy collaboration and integrating shared BESS, the system showed enhanced performance. Despite not fully meeting the ambitious KPI targets, this study validates literature insights and highlights new considerations for future LES.

4.1. Multisectoral energy exchange

Results from RS2 address the research objective 1 by demonstrating the potential of multisectoral energy exchange and delivering measurable, though modest, performance improvements relative to the reference values. The largest grid import savings are found at 17:00, hour associated with probable grid congestion, providing a beneficial contribution also to the grid. The results support the findings of prior studies (Belmar et al., 2023)(Victoria Gasca et al., 2025) on mixed-use energy communities, which identified that higher diversity in demand profiles can smooth collective demand, reducing the grid's dependence. However, the magnitude of the improvement here was limited by local solar intermittency and the system's large demand mainly from industrial loads. RS2 addresses research objective 4, as improved performance reduces grid imports by 1,13%, thereby reducing community costs by 0,89%.

4.2. Impact of Shared BESS Integration

Research objective 2 is addressed by comparing the results from RS3 with those obtained in RS2. Results from the shared BESS integration indicate significant performance improvements, although limited by the BESS power constraint and solar intermittency. Findings show a substantial reduction in annual grid imports, especially during peak consumption hours, contributing substantially to the grid congestion. The stored surpluses also significantly reduce grid feed-in, while improved BESS charge management could shift these savings toward peak export hours, providing even greater support in mitigating grid congestion and reducing the annual peak export power. The reduction of annual peak demand was also constrained by the BESS's exclusive charge from PV surpluses, reducing its effectiveness during winter months.

Addressing the research objective 4, shared BESS yielded a 9,38% reduction in the community energy bill, outperforming the individual BESS in normalised savings, supporting the findings from (Zakeri et al., 2021),(Qiao & Yang, 2017). Overall, these results show the strategic value of shared BESS for LES's flexibility, while highlighting the importance of optimised BESS control strategies.

4.3. Achieving REFORMERS' Energy Targets

RS4 aimed to meet the REFORMERS targets; however, findings showed that due to strong seasonal solar intermittency, achieving a positive NAEB would largely depend on the summer PV generation, rather than on a consistent decrease in grid dependence throughout the year, resulting in an unfeasible required PV capacity. Under the maximum feasible PV expansion, the increase in the BESS storage capacity shows uncapable to achieve the targeted CSC. This limitation is caused by the limited BESS rated power, making the BESS unable to efficiently store the increased PV generation.

As a result, Research Objective 3 could not be fully addressed. Nevertheless, the increased performance demonstrated in the RS2 supports the conclusion that multisectoral collaboration can reduce the need for additional energy infrastructure investments.

A proposed configuration includes the shared BESS integration at the MV-connected retail store, whose higher grid-connection capacity, could allow full BESS utilisation, and overcome the existing power constraint. This highlights the strategic value of collaborating with such consumers, due to the large contributions from the PV generation, but also its capacity for an efficient shared BESS deployment.

4.4. Model Limitations and Future Work

This section outlines key model limitations and proposes improvements to enhance result accuracy and guide future research. A primary constraint was the PowerFactory license, which limited the number of nodes that could be modelled, thereby reducing network details and associated losses. Additionally, both EVs and BESS were modelled using ideal models, which do not fully capture real-world load behaviour and efficiency losses. Economic considerations were simplified, considering only PV and BESS assets costs and using static electricity tariffs. Incorporating dynamic pricing mechanisms and a broader cost structure could significantly influence the economic outcomes, particularly the estimated payback period. Future research should focus on advancing EMS capabilities and system integration strategies to further enhance the performance and scalability of LES. Priority should be given to integrating dynamic pricing into BESS control to enable price arbitrage, thus improving economic returns and increasing storage utilisation, mainly during the winter. Additionally, integrating complementary renewable sources, such as wind energy, could mitigate PV intermittency and enhancing BESS annual contributions. Finally, the centralised coordination of distributed BESS, linking residential and industrial storage assets, offers a pathway to address power constraints and explore economic compensation mechanisms. Together, these directions can significantly strengthen the resilience and efficiency of LES.

5. Conclusions

This study assessed the potential of multisectoral collaboration between MV and LV distribution networks, combined with the integration of a shared BESS, to enhance LES performance achieving up to a 71,72% CSC and a 34,94% CSS. While the system did not meet the target KPIs, results show significant system performance improvements and contributions to the grid under real technical and meteorological constraints. The multisector complementary loads and energy exchange enabled a more efficient utilisation of locally generated energy, leading to an increased CSC and CSS by 1,36% and 0,71%, respectively, while reducing the community costs by 0,89%, confirming its contribution to enhanced system performance. Under the integration of the shared BESS, the system showed further enhanced performance, increasing CSC by 14,17% and CSS by 6,99%, and reducing community costs by 9,38%; while significantly contributing during critical hours for the grid congestion. Although the system did not meet the targeted performance goals, the study underscores the challenges of achieving high energy autonomy in solar-dependent LES. Finally, multisectoral energy collaboration presents a strategic opportunity to enhance performance and offers a practical model where industrial and residential sectors jointly optimize the use of renewable generation and shared BESS, while locating BESS in industrial zones within urban energy systems.

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Pathways for EU-MENA Hydrogen and Derivative Trade: An Energy-system Optimisation Perspective

Lucas Christopher Mandl-Ehmann (Hanze)[1]

Decarbonising the European energy system is likely to require large-scale imports of renewable hydrogen and synthetic fuels, for which the Middle East and North Africa (MENA) region represents a primary candidate supplier owing to its exceptional renewable resources and proximity to European demand centres. This paper presents a techno-economic assessment of hydrogen and synfuel trade between the European Union and MENA over 2030–2050, using an extended brownfield REMix energy-system optimisation model that couples both regions via existing and expandable electricity and gas networks alongside a broad portfolio of hydrogen and synfuel pathways. Five scenarios are evaluated: a baseline with uniform financing and unconstrained infrastructure; a no-trade autarky case; two hydrogen-transport variants; and a case with country-specific costs of capital in MENA. Under uniform financing and unconstrained infrastructure, the cost-optimal configuration is strongly MENA-centred,

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[1] Supplementary materials, the the techno-economic input parameters used across all scenarios, and the methodology for modelling cross-regional land and maritime transport, and additional results that complement the figures and discussion in the main text, organised by scenario can be obtained with the author: lucas.mandl.ehmann@gmail.com

with most renewable generation, electrolysis, and synfuel conversion located south of the Mediterranean and Europe remaining structurally import-dependent. The resulting architecture is carrier-specialised: methane saturates a few near-congested legacy pipeline corridors, hydrogen provides medium-haul redistribution to European demand centres, and Fischer-Tropsch fuels carry the longest-distance flows, with Central Europe the common import sink. Infrastructure constraints reduce trade volumes and shift the carrier mix without eliminating the rationale for cross-regional exchange. Differentiated financing costs in MENA suppress capital-intensive export projects, concentrate activity in lower-risk producing countries, and re-shore parts of the supply chain to Europe, yielding the highest total system cost among all scenarios. Across all variants, Fischer-Tropsch fuels emerge as the most robust long-distance carrier, while liquefied hydrogen does not achieve competitiveness in any scenario examined.

Keywords: Renewable hydrogen, Synthetic fuels, MENA region, EU-MENA energy trade, energy-system optimisation.

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1. Introduction

Global warming is unequivocally anthropogenic in origin and poses extensive risks to both societies and ecosystems, making climate-change mitigation a central policy priority for the foreseeable future (European Commission, 2018; Lee et al., 2023). The European Union has positioned itself as a frontrunner in this effort, committing to climate neutrality by 2050 (Béres et al., 2024). Achieving this objective requires the deep decarbonisation of hard-to-abate sectors containing aviation, maritime shipping, high-temperature industry; that collectively account for a substantial share of energy-related greenhouse-gas emissions (Curmi et al., 2024). Renewable hydrogen and renewable fuels of non-biological origin (hereafter synfuels) are widely regarded as promising energy carriers for these end-use segments (Johnson et al., 2025).

Domestic production of renewable hydrogen and synfuels in Europe currently faces significant barriers such as high electricity costs, limited surplus renewable generation capacity and immature conversion technologies (Johnson et al., 2025). Importing hydrogen and synfuels from regions with superior renewable energy resources, which may outweigh transportation cost and losses, is a strategically plausible and economically attractive complement to domestic supply build-up. The European Commission explicitly recognises the importance of imports in its hydrogen strategy, envisaging significant cross-border hydrogen and derivative flows until 2030 (European Commission, 2020).

Long-term sourcing strategies remain, however, contested. Published estimates of Europe's import dependency by 2050 span a wide range: some studies anticipate only marginal import requirements (Lux et al., 2024), while others project dependencies exceeding 50% of final hydrogen and synfuel demand (Nuñez-Jimenez & Blasio, 2022). Synfuel import is commonly cited as the most likely import candidate, based on the lower relative transport cost share (Wietschel et al., 2024).

This spread in outcomes can frequently be traced to simplifying assumptions along three dimensions: (i) a narrow carrier portfolio or stylised transport chains that omit competing options; (ii) greenfield infrastructure assumptions that ignore the value of legacy networks; and (iii) uniform or absent treatment of country-specific financing risk, even though risk-adjusted costs of capital can raise delivered supply costs by multiples relative to a risk-free benchmark (Egli et al., 2019; Terrapon-Pfaff et al., 2025).

The Middle East and North Africa (MENA) region is consistently identified as a prime candidate trade partner, combining exceptional solar irradiation and wind resources with geographic proximity to key European grid entry points (Fattahi et al., 2024). To the authors' knowledge, however, no prior study jointly combines a brownfield network representation, a broad hydrogen and synfuel carrier portfolio, and regionally differentiated costs of capital for an integrated EU-MENA energy system. The present study addresses this gap by extending an existing intra-European optimisation model to include the MENA region, expanding the technology portfolio with additional synfuel supply chains and by systematically exploring how infrastructure and financing constraints shape the optimal trade architecture between 2030 and 2050.

2. Methodology and Modelling Framework

The integrated EU-MENA system in this study is modelled within the energy-system optimisation framework REMix, developed at the German Aerospace Center (DLR) (Wetzel et al., 2024). REMix translates a user-defined energy system into a linear programming problem that minimises total system cost (TSC) subject to technical, physical and regulatory constraints. This study employs the existing intra-European REMix instance from Wetzel et al. (2026) and extends it to include the MENA region as well as additional hydrogen and synfuel supply chains to form the integrated EU-MENA system.

The model is configured as a perfect-foresight optimisation across the target years 2030, 2040 and 2050, with each model year resolved at three-hour temporal resolution (2,920 time slices) to preserve diurnal and seasonal variability. Capital expenditures are annuitised using a uniform weighted average cost of capital (WACC) of 8% in all scenarios except the dedicated financing-risk variant, and discounted to the base year using a socio-economic discount rate of 2% (Wetzel et al., 2026). TSC aggregates investment costs, fixed and variable operation and maintenance costs, fuel costs, CO_2 costs (net of carbon capture credits), water costs and loss-of-load penalties. The following chapters highlight additions and changes made to the existing model, with detailed model descriptions, parameter tables and the full mathematical formulation provided in the supplementary material.

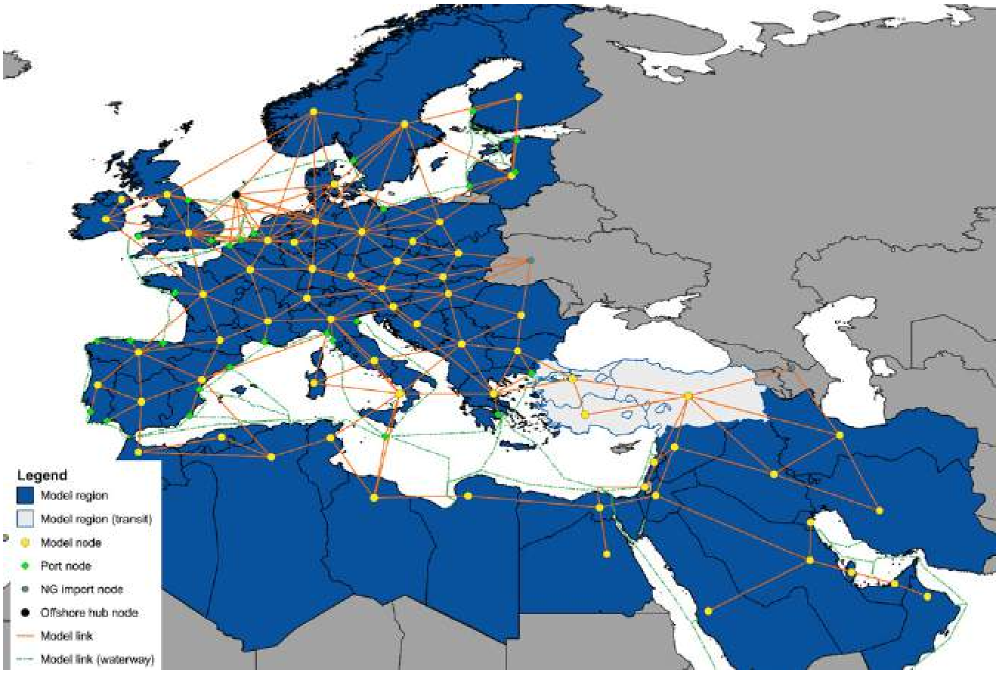
2.1 System Boundaries and Network

Geographically, the model covers all EU member states as well as the United Kingdom, Norway, Switzerland and the Balkans. The MENA region covers the sixteen countries shown in Figure 1, with Turkey included as a transit node bridging the interconnected EU grid with MENA networks. Each country is mapped onto one or more model regions, which aggregate domestic demand, generation and storage. Smaller countries may be grouped together to limit model complexity, while larger countries may be subdivided to capture regional networks more accurately. The model regions are assigned to network nodes connected via technology-specific links. External imports across the system boundary are disallowed, except for a limited volume of natural gas (NG) from Ukraine and Azerbaijan reflecting historic import patterns (European Network of Transmission System Operator for Gas, n.d.).

Node placements and interconnections are derived from existing high-voltage electricity and natural-gas transmission networks using the grid partitioning algorithm developed by Wetzel et al. (2026), based on the SciGRID_gas (Pluta et al., 2022) and OpenStreetMap (Xiong et al., 2025) datasets. Link lengths are determined from straight-line distances between node centroids, with a minimal number of new interconnections being introduced where legacy infrastructure is insufficient to ensure full system connectivity. An offshore hub in the North Sea is added to capture future offshore hydrogen production potential as described in Wetzel et al. (2026).

Additional land and maritime transport options enable the overland and seaborne movement of synfuels and liquefied hydrogen. To remain within the linear-programming limits of the base model, these modes are represented through a business-case abstraction rather than explicit unit dispatch, with transport costs derived using a total-cost-of-ownership (TCO) approach. Maritime trade is captured through dedicated waterway links connecting 28 European port nodes with MENA port locations selected based on existing or planned LNG infrastructure; shipping distances are computed via the SeaRoute software (Gaffuri & Korhonen, 2022). Detailed assumptions on vehicle sizes, speeds, utilisation, loading times, hydrogen liquefaction and port terminal representation are documented in the supplementary material.

Figure 1. Integrated EU-MENA model — geographic country scope, representative model regions and nodes connected via model links



The model altogether comprises 65 model regions, 96 model nodes and 272 model links, shown in Figure 1.

2.2 Technology Portfolio

The modelled supply chain covers four stages: (i) renewable and conventional electricity generation; (ii) conversion to hydrogen and synfuels; (iii) transport via new and repurposed pipelines, electricity grids, land and shipping links; and (iv) exogenously specified final energy demand (Figure 2).

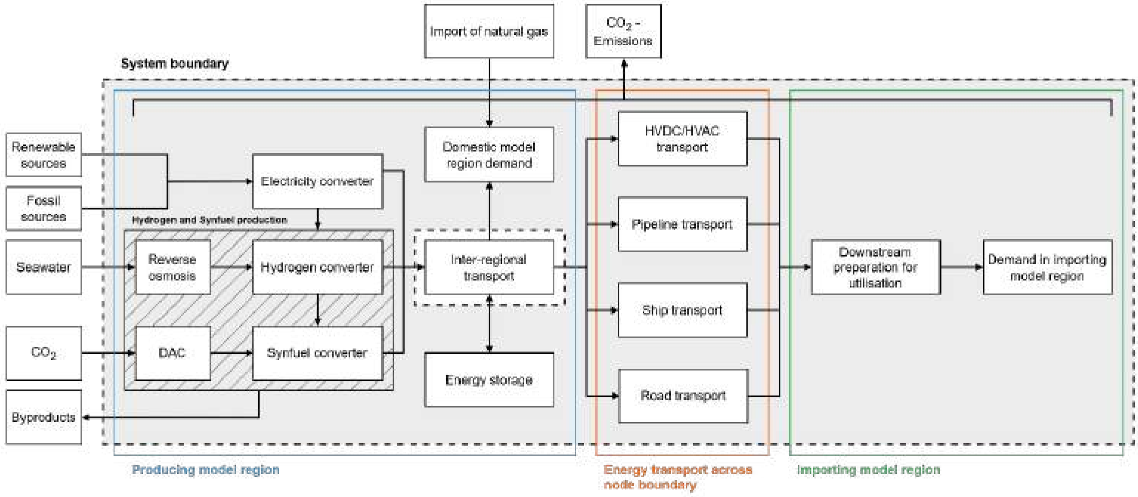
The technology portfolio includes coal- and gas-fired generators; ground-mounted solar photovoltaics, onshore wind, and concentrated solar power; three electrolysis pathways (alkaline electrolysis, AEC; proton-exchange membrane, PEM; solid-oxide, SOEC); catalytic methanation; low-temperature Fischer-Tropsch (FT) synthesis; and a methanol-to-hydrocarbon (MTH) route.

Supporting infrastructure includes direct air capture (DAC), seawater reverse-osmosis (SWRO) desalination, and dedicated storage for electricity, gases, CO_2, water and liquid hydrocarbons. All hydrogen derivatives rely on CO_2 supplied by DAC, consistent with the phase-out of fossil point sources after 2041 under EU regulation 2023/1185 (2023). Methanol and liquid organic hydrogen carriers are excluded due to inconsistent demand data and the limited competitiveness of synfuel reconversion pathways (Hampp et al., 2023).

In water-stressed regions, identified through regional baseline water stress levels in 2030 using data from Kuzma et al. (2023), SWRO is added as a dedicated feedwater process with a specific energy requirement of 3.1 MWh/tH_2O, while other regions can source water through a simple cost term of 1 €/m^3. Overall conversion efficiencies range from 32.6 to 47.5% for methanation, 28.1 to 42.4% for FT synthesis, and 30.1 to 44.0% for the MTH route, depending on year and SWRO inclusion. Maritime and land transport of liquefied hydrogen and liquid hydrocarbons are represented with specific costs of 3.33 €/GWhkm (synfuel) and 15.30 €/GWhkm (LH_2) for land, and 0.62 to 0.80 €/GWhkm (synfuel) and 0.40 to 0.45 €/GWhkm (LH_2) for seaborne transport. Detailed techno-economic parameters for all technologies are provided in the supplementary material.

Final energy demand trajectories for Europe are sourced from the Clean Planet for All P2X scenario (European Commission, 2018), which is transformed into a country-specific SYN scenario trajectories as described in Wulff et al. (2025), while MENA demand draws in the ALT2 dataset from Braun et al. (2025). Both scenarios represent high-uptake cases for hydrogen and synfuels across industry, transport, buildings and services and are treated as exogenous inputs identical across all scenarios.

Figure 2. Technological system boundary of the adapted model



Annual carrier-specific demands are disaggregated into hourly profiles preserving daily and seasonal variability following the methodology described by Wetzel et al. (2026) using weather years (2012, 2013 and 2014) taken from the REA6 reanalysis (Bollmeyer et al., 2015). All monetary values are harmonised to a 2025 base year. A common CO_2 price path, rising from 120 €/t in 2030 to 195 €/t in 2040 and 350 €/t in 2050, is applied uniformly to all combustion emissions within the model boundary in all scenarios. Natural-gas pipeline expansion is prohibited to incentivise efficient use of the legacy network, while new and retrofitted hydrogen pipelines, HVDC and HVAC capacity are each limited as shown in Table 1.

2.3 Scenario Design

Four scenarios are constructed as counterfactuals to a central reference case, isolating the influence of individual structural assumptions. All scenarios share identical demand trajectories, technology costs, resource series and network representation, and are solved under TSC minimisation with a 2% socio-economic discount rate.

The **BASE** scenario provides the reference with uniform 8% financing across all regions and technologies, full technology availability, and unconstrained network roll-out within the imposed build-rate limits (Table 1). **AUTARKY** disables all cross-regional trade in non-electric carriers between the EU and MENA while permitting electricity exchange, justified by the high perceived value of electricity trade established in prior integrated energy studies, thereby exposing the additional investment and operating costs required for European energy independence (Wetzel et al., 2026).

Table 1. Modelled scenario overview

Scenario	BASE	TRANS_delay	_no_pipeline	AUTARKY	WACC
EU-MENA trade assumptions					
EU-MENA exchange	Enabled	Enabled	Enabled	Disabled	Enabled
Exchange portfolio	All	All	Electricity, FT fuel	Electricity	All
Exchange delay	None	Until 2050	None	None	None
Build rates	CH_4: no expansion H_2, HVDC: +1 GW/year, HVAC: +0.5 GW/year				
Accounting assumptions					
Accounting objective	Total system cost (TSC) minimisation				
Discount rate	Socio-economic discount rate of 2%				
Cost of capital	8%	8%	8%	8%	Variable
CO_2 emission cost	120/200/350 €/t				

TRANS_delay enforces a delayed roll-out of new and repurposed hydrogen pipelines until 2050, forcing the system to rely on legacy methane infrastructure, shipping and land transport in the interim. **TRANS_no_pipeline** eliminates all cross-regional hydrogen pipeline capacity, both legacy and new, restricting cross-regional exchange to electricity and FT fuels only and thus exposing the role of FT fuel trade. Finally, **WACC** replaces the uniform 8% cost of capital in MENA with country-specific values from Terrapon-Pfaff et al. (2025) for renewable generation, electrolysis and synfuel investments, while retaining 8% for European projects, isolating the effect of differentiated financing conditions on spatial investment patterns, trade flows and regional cost distribution.

2.4 Scenario Evaluation and model validation

The base REMix model has been utilised for continental energy system applications in prior system studies and is treated as given (Wetzel et al., 2023, 2026). New technologies and transport abstractions are integrated following the existing modelling logic; additionally results are benchmarked against a comparable study by Krüger et al. (2025).

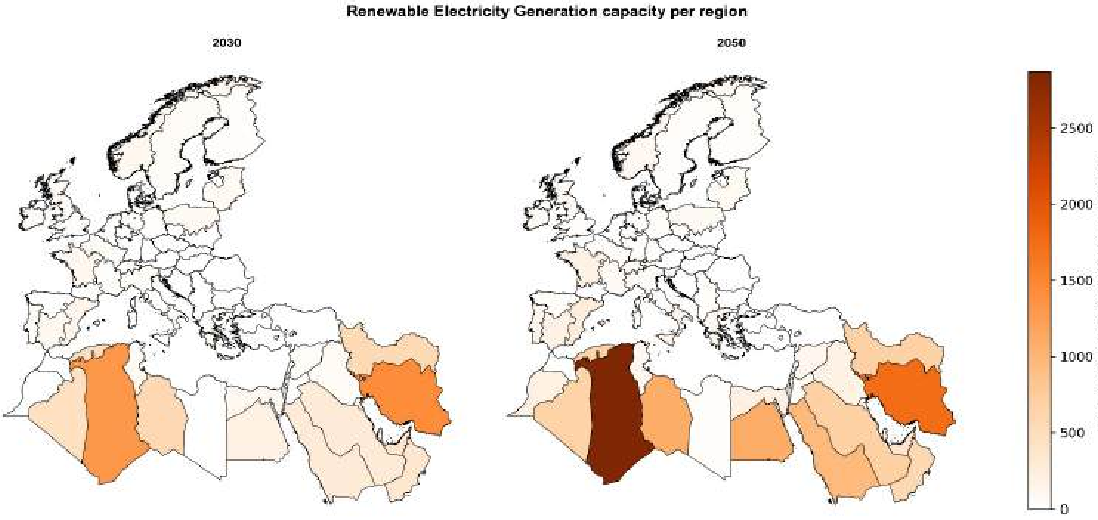
Results are interpreted through three lenses. The technical dimension covers installed capacities, annual energy flows, full-load hours, build rates and carrier-specific trade balances. The economic dimension is captured through nodal marginal prices and their cross-regional differentials, total and specific system costs decomposed by stage, and the autarky penalty as defined by Dalla Longa et al. (2024), which captures the TSC differential between a no-trade configuration and the scenario under consideration, making the cost of forgoing trade explicit. The political dimension is captured via import dependency, defined as net imports relative to regional final demand per carrier and year, allowing assessment of whether cost-optimal outcomes are compatible with energy independence concerns.

3. Results and Discussion

3.1 BASE: A MENA-Centred Architecture

Under uniform financing and unconstrained infrastructure, the optimum is decisively MENA-centred. By 2050, solar PV and onshore wind supply 96.3% of annual electricity generation, with a strong bias towards solar PV (11.8 TW installed capacity) relative to onshore wind (2.8 TW). MENA hosts 88% of total solar PV capacity and 64% of onshore wind capacity (Figure 3), eflecting MENA capacity factors 57% above European averages for PV and 23% for onshore wind. Even in wind-rich settings such as Tunisia, Algeria, or Morocco, the model systematically prefers solar-fed supply chains, consistent with prior findings on integrated EU-MENA architectures (Franzmann et al., 2023).

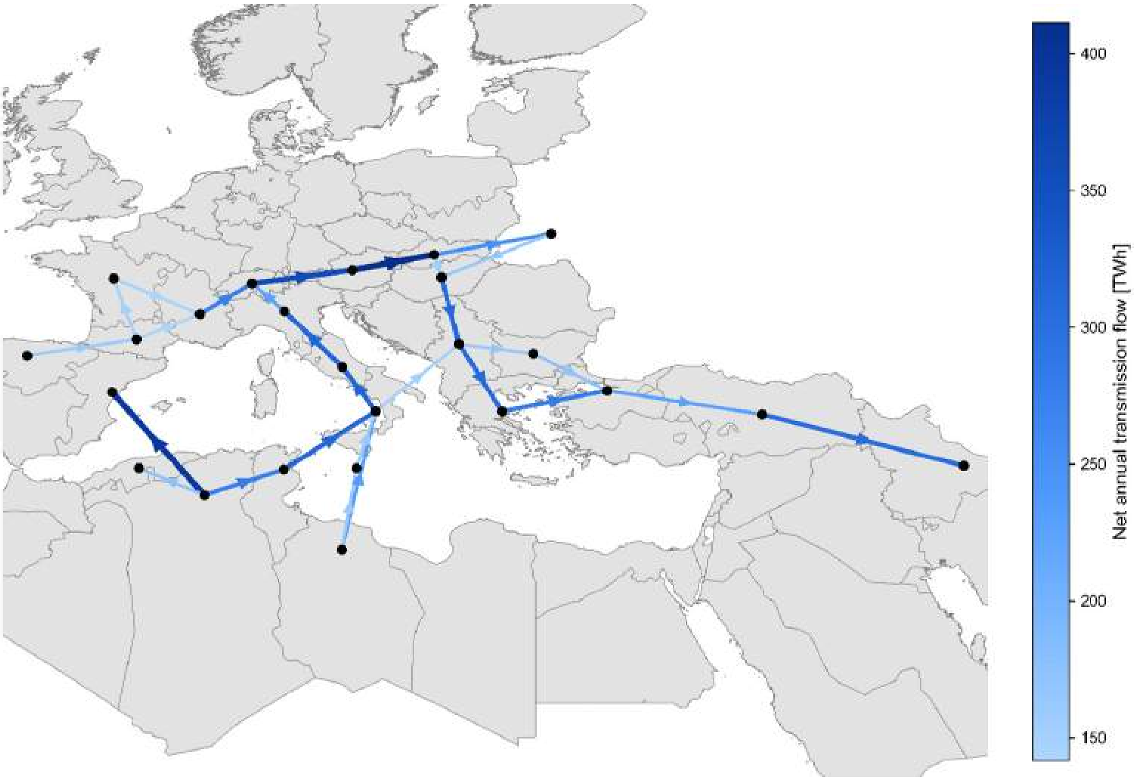
Figure 3. Total renewable electricity generation capacity in MENA and Europe, 2030 (left) and 2050 (right), BASE scenario



Electrolysis closely follows renewable generation, given its high electricity requirements. By 2050, electrolysers consume approximately 44.5% of global electricity output, with nearly all installed capacity being alkaline, reflecting the penny-switching tendency of optimisation models (Lopion et al., 2019). In MENA, electrolyser dispatch mirrors the diurnal profile of solar generation, with hydrogen rapidly being refined into synfuels at the production site (see supplementary material), aided by short-cycle hydrogen tank storage (9.0 TWh). Within Europe, a larger contribution of variable wind power yields a flatter electrolysis profile, with cavern storage (8.8 TWh) providing the primary medium-term balancing service.

The three derived carriers assume distinct functional roles. Hydrogen serves primarily as a spatial redistribution vector, moving from MENA production hubs to European demand centres via retrofitted and newly constructed pipelines. Synthetic methane uses legacy infrastructure and cavern storage for seasonal flexibility, where North Africa-Southern Europe pipelines run near saturation, while European caverns behind these links buffer approximately 205 TWh of working gas across the year. FT fuels act as long-distance carriers bypassing pipeline bottlenecks via shipping and road, with major flows from Algeria, Egypt, and Iran into European demand clusters. Iran emerges as a notable hybrid node, importing 26.6% of its methanation hydrogen from Europe while producing roughly five times its domestic FT-fuel demand for export.

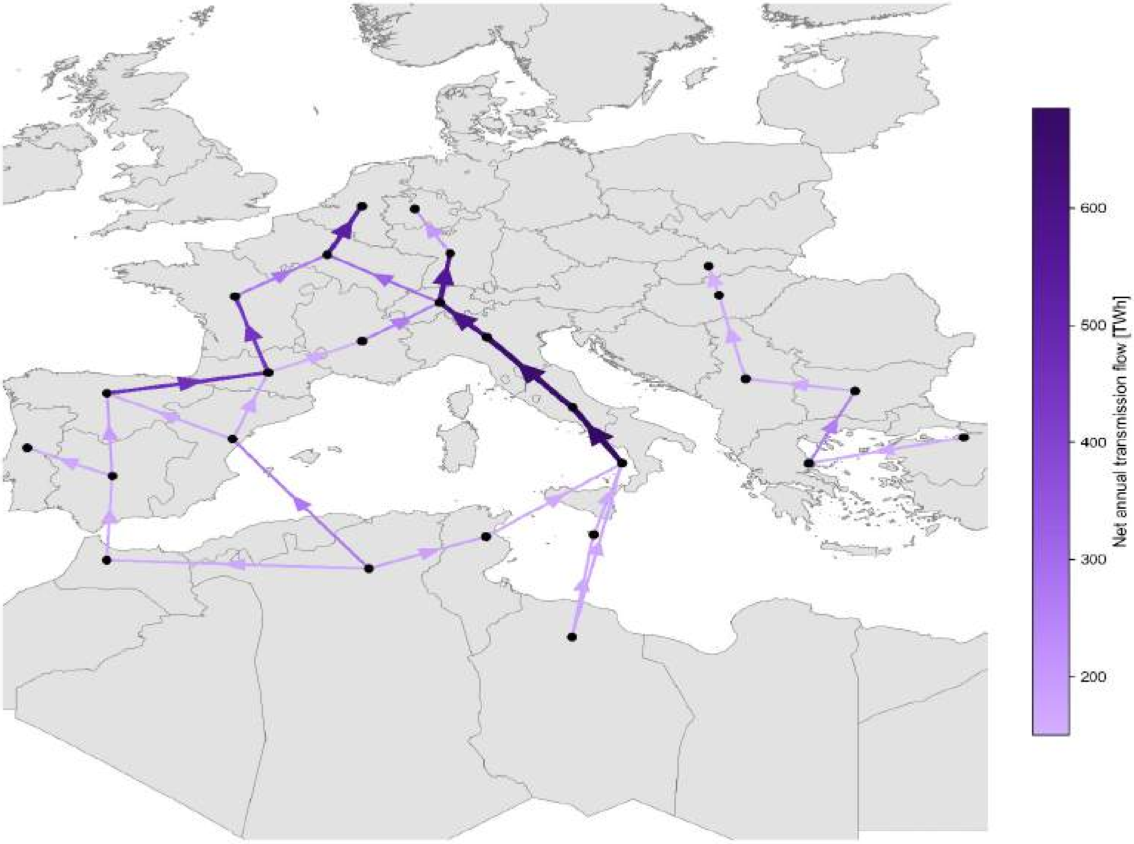
Figure 4. Net annual transmission top flows of hydrogen (top 80% of flows), BASE scenario, 2050



The spatial signature of this carrier specialisation is made explicit by the net annual transmission flows of each carrier. Hydrogen flows (Figure 4) reach up to approximately 400 TWh on the most heavily loaded links and organise into two principal corridors: a western axis carrying North African production from Algeria and Tunisia across the central Mediterranean into Italy and onward to the Central European demand cluster, and a pronounced eastern axis running through Turkey to Iran where it is used to satisfy domestic derivative demand. Hydrogen thus moves predominantly along medium-haul routes that connect MENA production hubs directly to the largest European loads.

Methane (Figure 5) exhibits the most intense individual corridors of the three carriers, with net flows of up to roughly 650 TWh concentrated on a small number of backbone links. A dominant spine runs from the Iberian Peninsula and North Africa into France and Germany, complemented by a heavy axis ascending the Italian peninsula. This concentration on few, near-saturated legacy pipelines is consistent with methane's role as the principal seasonal-flexibility carrier, aggregated and routed toward northern cavern-storage nodes behind the constrained cross-Mediterranean corridors.

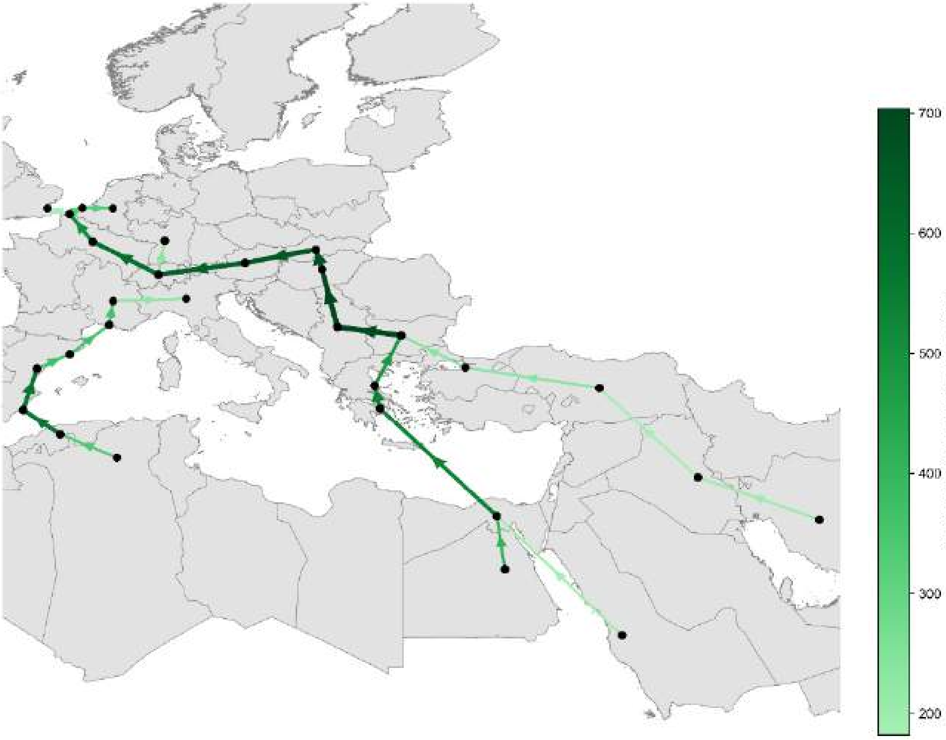
Figure 5. Net annual transmission top flows of methane (top 80% of flows), BASE scenario, 2050



Fischer-Tropsch fuel (Figure 6) is transmitted over the greatest distances and reaches the highest peak corridor magnitude, at approximately 700 TWh. Production is anchored in the eastern and southern periphery of the modelled region, including the Arabian Peninsula and Egypt, and is routed through the Eastern Mediterranean and the Balkans into Central Europe, alongside a western leg from the Iberian Peninsula and North Africa.

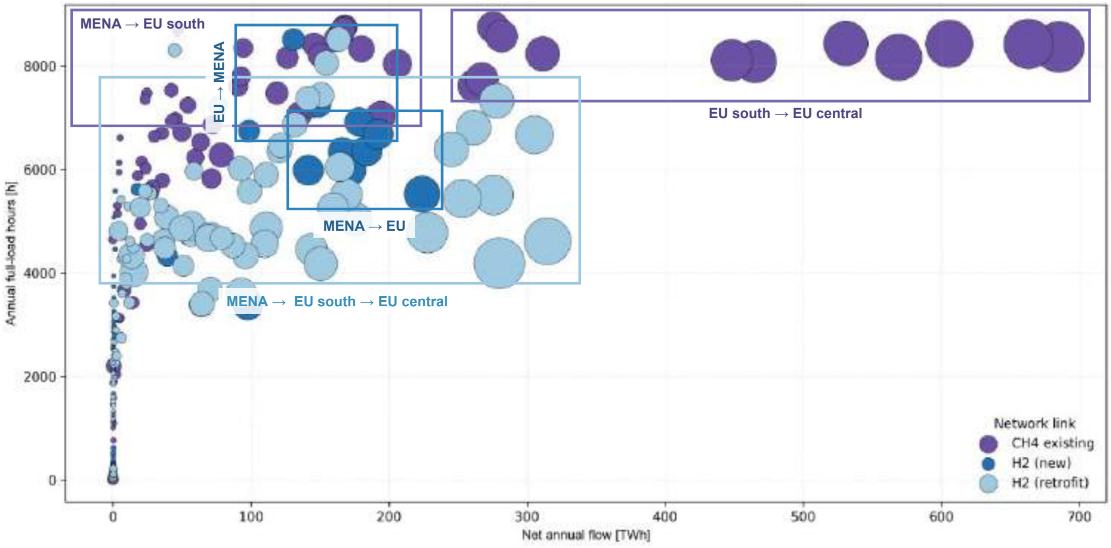
The long-haul character of these flows reflects FT fuel's pipeline independence and high energy density, which allow it to bypass the congestion that binds the methane and hydrogen networks. Taken together, the three maps confirm a clear division of labour: methane saturates the legacy backbone, hydrogen provides medium-haul redistribution, and FT fuels serve the most distant demand, with Central Europe acting as the common import sink and the Mediterranean basin as the central transit zone.

Figure 6. Net annual transmission top flows of FT-fuel (top 80% of flows), BASE scenario, 2050



The network utilisation pattern confirms this carrier specialisation (Figure 7). Cross-regional methane pipelines combine very large flows with near-full utilisation (>8,000 full-load hours), signalling congestion on legacy infrastructure that cannot be expanded under the build-rate limits. Retrofitted hydrogen pipelines form a broad mid-range cluster (4,000-7,000 FLH) as intra-European redistribution backbones, while newly built hydrogen pipelines occupy a narrower band of high utilisation but moderate absolute flows, reflecting their role as thin import spines rather than continent-wide networks.

Figure 7. Net annual network utilisation by link type, BASE scenario, 2050



Cross-regional electricity trade remains quantitatively modest: net imports from MENA into Europe in 2050 amount to only 112.5 TWh, roughly 1.7% of European final electricity demand. Long-distance exchange thus occurs overwhelmingly via molecular carriers, with electricity serving as a locally consumed backbone.

Over the full horizon, BASE total system cost amounts to 8.50 trillion EUR (approximately 425 billion EUR annually), of which MENA carries 56.8% (241 billion EUR annually). While a persistent electricity-cost advantage remains in selected MENA nodes, hydrogen production-cost spreads shrink from approximately 1 EUR/kWh in 2030 to a few cents by 2050 (Figure 8), as transport and storage investments arbitrage away most spatial rents.

Import dependence remains structurally high. Several European demand clusters cover more than 50% of their final hydrogen and synfuel demand through imports; Germany and the Benelux area reach import dependencies of approximately 95% (Figure 9). In aggregate, Europe covers 47.6% of its final energy demand through imports in 2050, only moderately below the average EU import dependency of 59.2% in 2023 (European Commission, n.d.). Decarbonisation therefore changes the origin and composition of imports, from fossil fuels to synthetic methane, hydrogen, and FT fuels, but does not eliminate structural reliance on external suppliers.

Figure 8. Marginal hydrogen production cost differential relative to lowest-cost node, 2030 vs 2050, BASE

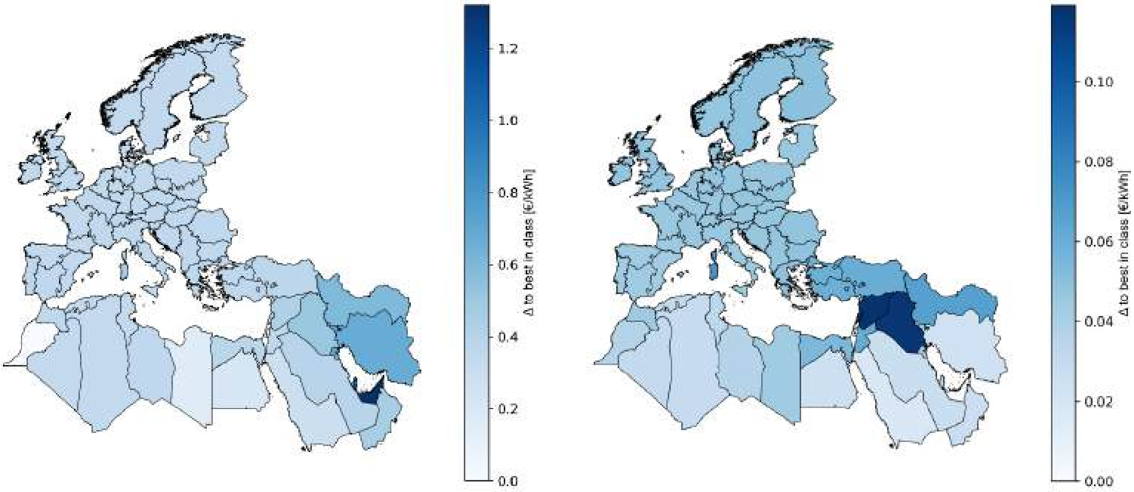
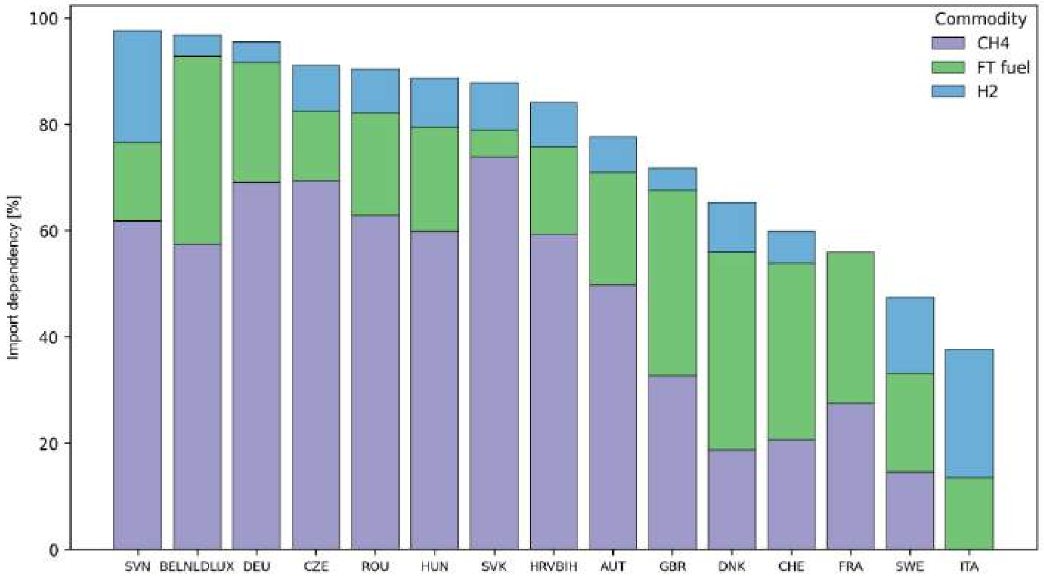


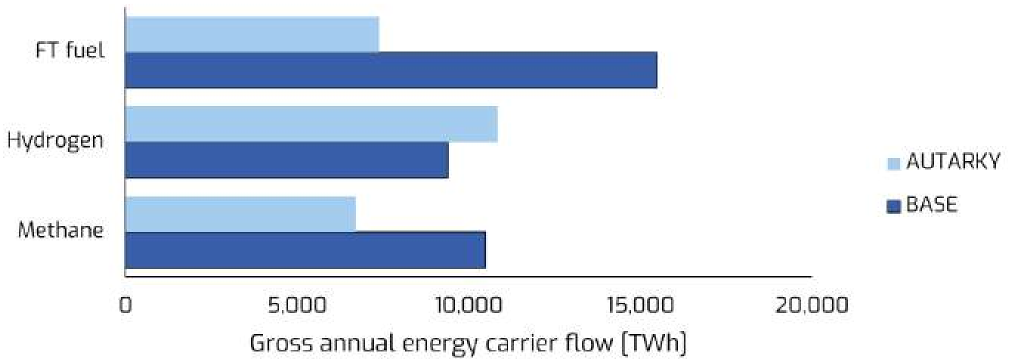
Figure 9. Import dependency by country and carrier, 2050, BASE scenario



3.2 AUTARKY: The Cost of Foregoing Molecular Trade

Prohibiting non-electric carrier trade forces a geographically more distributed pattern. Europe expands domestic renewable generation, electrolysis, and storage, with new production clusters emerging in Spain, the Balkans, and the Nordic countries (see supplementary material). Total working-gas storage volume increases to 268 TWh (+19% relative to BASE), driven by a nearly sevenfold expansion of European hydrogen cavern capacity. Hydrogen's role shifts from a spatial redistribution vector to a genuine seasonal storage medium, with pronounced annual charge–discharge cycles. Gross hydrogen flows increase by approximately 15%, while methane and FT-fuel flows decline by roughly one-third and one-half respectively, reflecting production sited closer to demand centres (Figure 10).

Figure 10. Gross annual energy carrier flows, BASE vs AUTARKY, 2050



Global TSC increases by 2.7% relative to BASE, with Europe incurring an autarky penalty of 19%, or about 698 billion EUR over the model horizon. The penalty is driven primarily by a 107% increase in European electricity generation investment and a 63% rise in storage dispatch. MENA, by contrast, sees its total system cost fall by approximately 9.7% as export-oriented capacity is displaced by a domestically focused system.

3.3 Transport Constraints: TRANS_delay and TRANS_no_pipeline

Delaying the roll-out of new hydrogen pipelines in TRANS_delay reduces hydrogen flows by approximately 47%, while methane (-15%), electricity (-11%), and FT-fuel flows (-1%) experience more moderate reductions. European electrolyser capacity rises by 36% and hydrogen cavern capacity by 184% relative to BASE, partially replacing imported hydrogen. The AUTARKY effects therefore re-emerge at smaller scale. Total system cost increases by only 1.4% relative to BASE, with the EU's autarky penalty amounting to approximately 5.2%. Legacy methane infrastructure and pipeline-independent FT-fuel trade thus absorb a substantial share of the penalties otherwise associated with full autarky, indicating that the additional benefit of early corridor expansion is real but incremental.

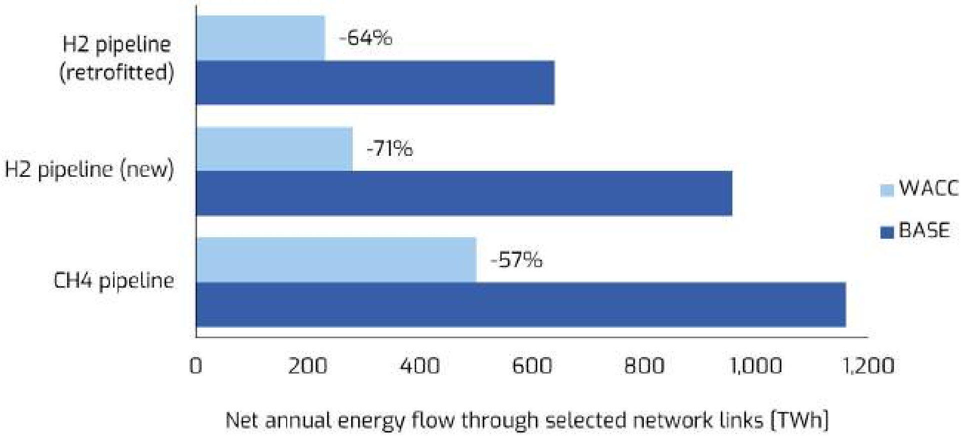
In TRANS_no_pipeline, electricity and FT fuels become the only cross-regionally tradeable carriers. The system responds by relying more heavily on existing intra-regional methane pipelines and on synfuel shipping between MENA export hubs and European ports. The cost decomposition reveals an apparent paradox: global TSC remain 1.1% below AUTARKY even though European system costs are 6.5% above it. Relative to AUTARKY, European electricity generation costs fall by 18.2% and storage costs by 28.1%, while conversion-related costs rise by 106.5% due to intensive use of methanation pathways. This is resolved by examining the location of DAC capacity: in AUTARKY, part of the DAC fleet is co-located with European emitters, so CO_2 removal credits accrue partly to the EU; in TRANS_no_pipeline, FT-fuel production and the associated DAC units are consolidated exclusively in MENA, where low-cost electricity and high CO_2 prices make DAC a net-beneficial activity. The resulting CO_2 capture rents are therefore attributed mainly to MENA, while Europe primarily bears the costs of final energy use and residual emissions.

More broadly, these results illustrate that CO_2 prices and the treatment of DAC credits are not peripheral background parameters but actively shape both total system cost and its regional distribution. Under the shared baseline CO_2 trajectory, cheap MENA renewables and high carbon prices combine to make large-scale DAC economically attractive in exporting countries. Counterintuitively, uniformly lowering CO_2 prices would likely raise total system cost by reducing the value of net-beneficial DAC deployment while simultaneously allowing more residual emissions.

3.4 WACC: Differentiated Financing and Geopolitical Risk

Country-specific costs of capital in MENA materially alter the trade architecture. Higher WACCs in exporting countries such as Algeria, Egypt, Tunisia, and Libya suppress capital-intensive export projects, with electrolyser capacity falling by 29% and methanation capacity by 32% in MENA relative to BASE. Net annual EU-MENA pipeline flows decline sharply: methane by 57%, new hydrogen pipelines by 71%, and retrofitted hydrogen pipelines by 64% (Figure 11). Saudi Arabia, where country-specific WACCs lie below the European benchmark, emerges as the dominant FT-fuel supplier, while Iran reverts to serving domestic demand only. FT fuels remain the only dominant long-distance carrier given the lower distance dependence of FT fuel, with long-distance flows actually increasing by approximately 14%. Liquefied hydrogen does not become competitive in any model run under any scenario examined.

Figure 11. Net annual energy flow through EU-MENA pipeline links, BASE vs WACC, 2050



European TSC rises by approximately 35% relative to BASE as domestic renewable generation, electrolysis, methanation, and storage capacity expand to compensate for reduced imports. MENA TSC declines by roughly 16% as fewer export corridors are built. The WACC scenario yields the highest aggregate TSC of all variants (+6% relative to BASE). Changing only the cost of capital thus fundamentally weakens the EU-MENA corridor and concentrates export activity in a few low-risk countries. Because European WACC is held constant, the results also reflect an asymmetric treatment of risk that structurally favours European reshoring whenever MENA risk premia rise.

3.5 Discussion

Across all scenarios, a consistent structural picture emerges. With uniform financing and realistic infrastructure expansion (BASE), the cost-optimal configuration is strongly MENA-centred, with most renewable generation, electrolysis, and synfuel production sited south of the Mediterranean and Europe depending on imports for a large share of its final hydrogen and synfuel demand. The AUTARKY and TRANS scenarios demonstrate that Europe can reduce this dependency by expanding domestic capacity and constraining infrastructure development, but only at the cost of considerably higher total system costs. The WACC stress test underlines that financing conditions are a first-order driver of who trades, in which carrier, and at what cost.

Several caveats merit emphasis. The results rest on harmonised techno-economic input data with uncertain long-term cost trajectories; if MENA hydrogen or synfuel costs prove higher than assumed, the southward shift weakens. Penny-switching dynamics within ESOMs systematically concentrate investment in single technologies, most visibly in the model's near-exclusive selection of alkaline electrolysis and the late-horizon switch to low-temperature FT synthesis and the absence of liquefied hydrogen in any scenario should therefore be interpreted as a result conditional on the chosen cost ranges rather than a robust technological verdict. Water and CO_2 are stylised: freshwater scarcity, competing uses, and local acceptance constraints are absorbed into a single SWRO energy term, and DAC is treated as a symmetric source of CO_2 credits at the prevailing price. Local acceptance, permitting times, and supply-chain bottlenecks are approximated only through generic build-rate limits, representing an optimistic upper bound on deployment speed.

A comparison with the integrated EU-MENA study by Krüger et al. (2025) is instructive. Both models produce a decisively MENA-centred architecture under uniform financing, identify Algeria, Egypt, and Middle Eastern countries as principal exporters, and find that cross-regional electricity trade plays a quantitatively minor role. The clearest divergence concerns financing risk: in Krüger et al., differentiated WACCs reduce Europe's import quota from 82% to near zero in the most pessimistic case, whereas in the present analysis EU-MENA trade contracts but does not collapse, and long-distance FT-fuel flows even rise by 14%. This divergence underscores that the magnitude of the financing-risk effect is highly sensitive to how risk premia are specified.

Politically, the combined evidence points to structural interdependence between the EU and MENA across most plausible futures. Decarbonisation changes the origin and composition of European energy imports, but does not automatically remove dependence on external suppliers. Financing conditions emerge as the central political lever: risk premia are endogenous to policy and depend on regulatory stability, contract enforcement, credit support, and diplomatic relations. If EU and MENA actors design risk-sharing instruments that lower the cost of capital for clean-energy investments in exporting countries, many of the benefits of a MENA-centred architecture remain accessible at lower total cost. Conversely, if perceived risks remain high, much of the cost-efficient trade potential identified here may not materialise; regardless of the underlying technical potential. The corridor architectures derived here should therefore be read as inputs into a broader political debate weighing cost efficiency against sovereignty, resilience, and equity, rather than as prescriptions.

4. Conclusion

This study presents a system-level techno-economic assessment of EU-MENA hydrogen and synfuel trade under alternative infrastructure and financing conditions over the period 2030-2050. The following principal conclusions are drawn.

First, under uniform financing and unconstrained infrastructure expansion, a MENA-centred trade architecture constitutes the cost-optimal configuration for supplying the decarbonised European energy system with hydrogen and synfuels. Superior solar and wind resources in MENA, combined with existing and expandable transmission and transport links, make it economically attractive to locate the bulk of renewable generation, electrolysis, and synfuel conversion south of the Mediterranean and to export hydrogen, synthetic methane, and FT fuels to Europe. Europe remains structurally import-dependent in this configuration.

Second, robustness tests confirm that this qualitative picture survives substantial infrastructure and financing shocks, but that the scale and structure of trade are sensitive to how these levers are set. Constraints on hydrogen pipeline expansion trigger a partial reshoring of electrolysis and storage capacity to Europe and increase total system costs, yet MENA retains its role as the principal synfuel production hub. Full autarky is technically feasible but carries a significant system-cost penalty, with Europe bearing the overwhelming share of the additional expenditure.

Third, differentiated costs of capital in MENA are a first-order driver of the trade architecture. Higher financing costs weaken export-oriented investment, reshape trade corridors, concentrate activity in a small number of low-risk producer countries, and shift investment and cost burdens back towards Europe. Fischer-Tropsch fuels are the most resilient long-distance carrier across all scenarios; liquefied hydrogen does not achieve competitiveness in any variant.

Fourth, CO_2 price trajectories and the treatment of DAC credits materially shape both the level and regional allocation of total system cost. Under high and spatially uniform carbon prices combined with low-cost MENA renewables, large-scale DAC deployment in exporting countries becomes net-beneficial, generating CO_2 capture rents that influence where FT-fuel supply chains are located and how system costs are distributed.

Methodologically, the study demonstrates the importance of combining a brownfield network representation, a broad carrier portfolio, and regionally differentiated financing assumptions within a single integrated energy-system model. Assumptions about existing infrastructure, financing risks, and carbon-price trajectories are not peripheral details but can materially alter system-optimal outcomes, particularly for long-distance hydrogen and synfuel trade. These findings point to the need for further research on how policy instruments, blended-finance mechanisms, investment guarantees, and carbon contracts for difference, can manage financing risks along prospective EU-MENA energy corridors and thereby influence the pace and geography of the energy transition.

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Active Flow Control in Low-Pressure Gas Distribution Networks to Enable Increased Biomethane Integration

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The integration of biomethane into existing gas distribution networks is a key component of the energy transition, but its implementation is often limited by local network constraints. This study investigates the impact of local pressure losses on biomethane injection capacity in a real-world low-pressure (100 mbar(g)) gas distribution network and evaluates the potential of active flow control (AFC) as a solution.

Using the simulation software IRENE Pro, a detailed model of an operational 100 mbar(g) distribution network was developed. Steady-state simulations were performed under low-demand conditions, representing a conservative scenario for injection capacity. The results show that local hydraulic bottlenecks, caused by frictional pressure losses in specific pipeline sections, can significantly limit the transport of biomethane, even when overall network capacity is sufficient.

To address this limitation, a gas blower was introduced as an AFC measure to locally increase pressure and compensate for pressure losses. This intervention increased the maximum biomethane injection capacity from 57 m^3/h to 100 m^3/h, demonstrating that targeted pressure control can unlock substantial additional capacity within existing infrastructure.

The findings highlight the importance of considering local network behavior in biomethane injection capacity assessments and demonstrate that AFC provides a flexible and effective alternative to traditional network reinforcement strategies. While the analysis is based on steady-state conditions, the results underline the significant technical potential of AFC for enhancing biomethane integration in low-pressure gas distribution networks.

This study contributes to the development of practical solutions for increasing renewable gas integration and supports the transition towards more sustainable and flexible energy systems.

Keywords: Biomethane injection, Gas distribution networks, Low-pressure networks, Active flow control, Gasblower, Energy transition, Decentral production, Distribution system operator

05

1. Introduction

Biomethane is playing an increasingly important role in the global energy transition, driven by climate targets, energy security concerns, and the need for sustainable alternatives to natural gas. International analyses indicate that the production of biomethane and other low-emission gases is expected to grow significantly in the coming decades, largely due to policy measures and national climate commitments (IEA, 2025). The European Union has taken a leading role in this development and has set an ambitious target under the REPowerEU plan to scale up biomethane production to 35 billion cubic metres (bcm) per year by 2030 (European Commission, 2022). Similar goals are being established at the national level. In the Netherlands, the Climate Agreement sets a target of approximately 2 bcm of green gas production by 2030, representing a substantial increase compared to current production levels (EBN, 2024).

To realize this growth, several policy instruments are being introduced, including a blending obligation for gas suppliers in the Netherlands. This measure is intended to increase the share of renewable gases in overall gas consumption. Such policy developments imply a strong increase in biomethane production and grid injection in the coming years, which will place additional pressure on existing gas distribution networks (Rijksoverheid, 2023).

The transition towards renewable energy systems fundamentally changes the operation of gas distribution networks. The increasing integration of decentralized renewable gases, such as biomethane, introduces new operational challenges. Traditionally, gas distribution systems have been designed as top-down infrastructures, in which gas supply follows demand. However, the emergence of decentralized injection sources requires a shift towards more flexible and adaptive operational strategies. Decentralized injection alters both pressure distributions and flow patterns within the network, which may lead to local transport constraints.

These effects are particularly pronounced in low-pressure networks, where pressure margins and flexibility are limited. At the same time, it is economically attractive for producers to inject biomethane into these networks due to lower operational costs (e.g. compression) and lower initial investment costs (e.g. connection and compression infrastructure). As a result, renewable gas production can be curtailed during periods of low demand, despite the availability of production capacity. Furthermore, many production sites are located in rural areas, while gas demand is mainly concentrated in urban areas (EBA, 2024). The connections between these regions typically consist of pipelines with relatively limited transport capacity, reflecting historically low demand and transport needs. With increasing decentralized production, however, there is now a growing need to transport gas from rural areas to urban demand centers, causing injection constraints in low-pressure networks due to limited transport capacity.

To address these challenges, research increasingly focuses on concepts such as active flow control (AFC) and passive flow control (PFC). Flow control can be defined as the manipulation of flow characteristics, such as pressure and velocity, to improve system performance. Passive flow control methods rely on inherent system properties and do not require external energy input, whereas active flow control introduces external energy input to directly influence the flow behavior (Zheng et al., 2025).

In the context of the gas network, flexibility is commonly provided through passive mechanisms, most notably linepack, which allows temporary storage of gas within pipelines and can be used to balance supply and demand mismatches. Recent studies demonstrate that linepack, in combination with the optimization of pressure setpoints and injection strategies, can significantly reduce biomethane curtailment and improve network utilization. More broadly, research on biomethane integration highlights the need for monitoring, control, and adaptive operation strategies to ensure grid stability (Ashiru et al., 2025; Cavana & Leone, 2022; Dvorkin et al., 2022). A comparable transition from passive to active operation has been widely observed in electricity distribution networks, where the increasing integration of distributed energy resources leads to bidirectional flows and requires advanced monitoring, control, and optimization strategies (Saldaña-González et al., 2025; Zhao et al., 2014).

Within this context, most existing approaches are based on adjusting operational settings, such as pressure setpoints at regulator stations and biomethane injection stations (PFC). While these methods can improve system performance, they provide only limited capability to actively influence internal pressure gradients and flow directions, particularly in low-pressure networks. In current systems, there is a lack of controllable elements that can locally increase pressure and thereby actively influence gas flows (AFC).

An alternative strategy for distribution system operators is to reinforce existing connections between demand clusters and decentralized injection locations. This typically involves replacing pipelines, which are often not yet fully depreciated, with larger diameter pipes to reduce friction losses and increase transport capacity. However, such upgrades require significant investments and are typically designed for long asset lifetimes. In contrast, biomethane producers generally do not provide long-term injection guarantees, which complicates the economic justification of such investments.

To provide an alternative to network reinforcement and enable active control of gas flows, this paper introduces a novel AFC approach by implementing an active pressure-boosting device, specifically a gas-blower, within a low-pressure gas distribution network (100 mbar(g)). Gas blowers are established technologies in industrial gas handling and renewable gas systems, where they are used for gas transport and modest pressure increases. However, their application as controllable elements within gas distribution networks, aimed at increasing biomethane injection capacity through active network control, has not yet been systematically investigated.

To evaluate this concept, this study applies a network simulation approach in which a representative low-pressure gas distribution network is modelled under a steady-state low gas demand with biomethane injection scenarios. The gas-blower is introduced as a controllable pressure-boosting element within the network, allowing for comparison between baseline operation and AFC-enabled operation. The analysis focuses on the impact on biomethane injection flow and network pressures within the network at specific nodes.

The results demonstrate that the introduction of a gas-blower enables redistribution of gas flows from injection locations towards concentrated urban areas, thereby alleviating local transport constraints. This leads to a measurable increase in the effective capacity for biomethane injection and a reduction in curtailment under high production scenarios. The findings indicate that localized active pressure control can complement existing flexibility mechanisms, such as linepack, and provide an additional degree of freedom in the operation of gas distribution networks.

Although previous studies have demonstrated the value of dynamic control strategies and passive flexibility mechanisms such as linepack, the application of localized pressure-boosting devices as active flow control elements within low-pressure gas distribution networks has not been explicitly addressed in the literature. This work therefore contributes to the emerging field of smart gas grids and the application of AFC in gas distribution systems by analyzing and evaluating a previously unexplored control strategy. It provides a new perspective on how existing gas infrastructure can be utilized more efficiently to support the integration of renewable gases without requiring large-scale network reinforcement.

2. Method

This chapter describes the modelling approach, case study, simulation model implementations, assumptions and boundary conditions, the scenario definition and scope and limitations.

2.1 Modelling approach

In this study, gas distribution networks were analysed using the commercial simulation software IRENE Pro, developed by Kiwa. IRENE Pro is a calculation and analysis tool specifically designed for gas networks and is widely used by distribution system operators for network design, operation, and asset management (KIWA, n.d.-b, n.d.-c).

The software enables steady-state simulations of gas flows in networks of varying size and complexity, ranging from small distribution grids to complete supply areas with multiple pressure levels and sub-networks. It calculates key hydraulic variables such as flow rates, gas velocities, pressure distribution, and pressure losses across the network.

Additionally, the tool allows modelling of different gas compositions, including natural gas and biomethane, making it suitable for analysing energy transition scenarios (KIWA, n.d.-a, n.d.-c).

2.2 Case study networks

The modelling approach was applied to a real-world low-pressure gas distribution network (100 mbar(g)) operated by a Dutch distribution system operators. This network was selected to represent typical regional distribution systems.

A digital network model was constructed using data provided by the system operator. This included pipeline topology, pipe diameters, lengths, material properties, and consumer demand data. The model represents the physical structure of the existing network and form the basis for the simulation scenarios.

In contrast to generic or synthetic network studies, this research is based on a real operational network, enabling a more realistic assessment of system behaviour, constraints, and practical applicability of the results.

2.3 Model implementation

The network models were implemented in IRENE Pro by importing and structuring the network data within the software environment. The tool supports integration with GIS-based datasets, allowing efficient transfer of spatial and asset information into the simulation model (KIWA, n.d.-c).

Within the model, the following elements were defined:

- Nodes representing consumers, supply points, and network junctions
- Pipelines characterised by length, diameter, and material properties
- Boundary conditions, including supply pressures and demand loads

The software solves the network equations to determine the pressure and flow distribution throughout the system, ensuring mass balance and hydraulic consistency across all nodes and pipelines.

2.4 Simulation assumptions and boundary conditions

To ensure consistency across the analyzed scenarios, a set of fixed boundary conditions was applied in the simulations.

For this network, pressure-controlled boundary conditions were implemented at the key supply locations:

- the biomethane injection point
- the gas regulator station(s)
- and, where applicable, the gas blower (AFC) outlet pressure

The regulator stations were modelled as pressure-controlled sources maintaining a constant outlet pressure representative of normal operation of low-pressure distribution networks (approximately 100 mbar(g)). The maximum allowable pressure in the low-pressure network was limited to 150 mbar(g), in accordance with typical material constraints and the presence of household regulators, which reduce the pressure to approximately 25 mbar(g) at end users.

For scenarios including an active flow control unit, the gas blower was modelled as a fixed output pressure device, enabling controlled pressure increase within the network. The suction-side pressure and resulting flows were calculated by the simulation model.

The biomethane injection point was modelled as a pressure-controlled supply node. For each scenario, the injection pressure was varied up to the maximum allowable level (150 mbar(g)), and the corresponding maximum feasible biomethane injection flow was determined based on the resulting hydraulic constraints within the network.

All simulations were performed under steady-state conditions, assuming constant demand levels. These demand levels correspond to an average ambient temperature of 18°C, representing the lowest gas demand condition in IRENE Pro. Dynamic effects such as temporal demand variations (e.g. hourly profiles), were not explicitly included.

2.5 Scenario definition

To evaluate the performance of the networks under different operating conditions, two simulation scenarios were defined:

1. Current situation (reference scenario)
2. Scenario with AFC

These scenarios focused on assessing the impact of:

- integration capacity (m^3/hour) of biomethane injection
- changes in network pressures

2.6 Scope and limitations

This study focuses on a technical network analysis based on hydraulic simulations. The results therefore represent a technical potential assessment of the analysed networks.

Non-technical aspects such as:

- economic feasibility
- regulatory constraints
- market dynamics

were not included in the modelling and are therefore outside the scope of this study. Furthermore, the results are specific to the analysed network and may not be directly generalisable to other distribution systems with different characteristics.

3. Results

The first network is shown in Figure 1. The green lines represent the 100 mbar(g) distribution network, which is connected to and supplied by the higher-pressure transport network (4 bar(g), blue lines, and 8 bar(g), pink lines) via gas regulator stations, indicated by green squares (e.g. point 3). The majority of consumers are connected to the 100 mbar(g) network and are therefore not shown in the figure.

Under normal operation, gas consumption leads to a slight pressure drop in the network, causing the gas regulator stations (e.g. point 3) to open and maintain the operating pressure at approximately 100 mbar(g). The blue dot at point 1 represents the biomethane production location, where biomethane is injected into the 100 mbar(g) distribution network.

By increasing the injection pressure at this location, the local network pressure increases, resulting in a prioritization of biomethane over natural gas supplied via the gas regulator stations. Due to gas consumption and frictional pressure losses along the pipelines, the pressure decreases further downstream and reaches an equilibrium within the network.

In the reference situation, the largest pressure drop occurs in the pipeline section between the biomethane injection point (1) and the intersection at point 2, primarily due to frictional losses. To overcome this limitation, a gas blower (AFC) was introduced in this pipeline section, approximately halfway between points 1 and 2.

In Scenario 1, the gas blower was not included, representing the current network configuration. The results of the different scenarios are summarized in Table 1.

Figure 1. Configuration of network 1

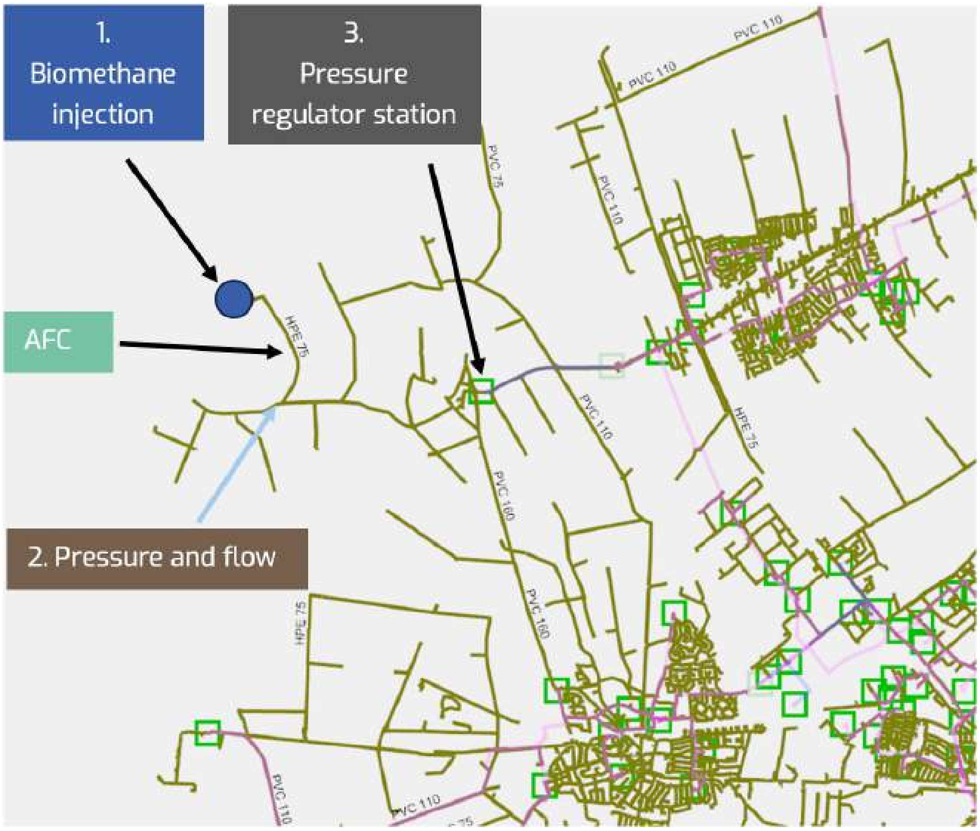

Table 1. Results of different scenarios

Scenario	Flow at 1 (m^3/hr)	Pressure at 1 (mbar)	Pressure at 2 (mbar)	Pressure at 3 (mbar)	Pressure at 4a (mbar)	Pressure at 4b (mbar)
1. Reference	57	150	102.5	100	-	-
2. AFC	100	150	110	100	70	160

The simulation results show that the introduction of the gas blower increases the maximum biomethane injection flow from 57 m^3/h to 100 m^3/h. In the reference scenario, the frictional pressure losses in the pipeline between points 1 and 2 amounted to 47.5 mbar, resulting in only a marginal overpressure of 2.5 mbar at point 2. This pressure difference was insufficient to transport additional biomethane further into the network towards the gas regulator station at point 3. Increasing the injection flow was not feasible, as this would further increase frictional losses and reduce the pressure at point 2.

By introducing the gas blower, these pressure losses are partially compensated, allowing higher biomethane injection flows to be transported through this pipeline section. In this scenario, the discharge pressure of the gas blower was set to 160 mbar, as no consumers are connected between the gas blower and point 2 and no regulators at households would experience this higher pressure level.

Due to the increased flow, the pressure drop between the biomethane injection point and the gas blower increased to 80 mbar. The gas blower subsequently increased the pressure by 90 mbar, resulting in a net pressure drop of 50 mbar between the gas blower and point 2. Consequently, the pressure at point 2 exceeds the regulator setpoint at point 3 by approximately 10 mbar, enabling further transport of biomethane towards downstream consumers.

This demonstrates that local pressure losses in low-pressure distribution networks can significantly limit injection capacity, and that targeted pressure boosting can effectively unlock additional transport capacity without major network modifications.

4. Discussion

The results demonstrate that local pressure constraints can significantly limit biomethane injection capacity in low-pressure distribution networks. In the analysed network, the main limitation was not the overall system capacity, but the presence of a local bottleneck caused by frictional pressure losses in a specific pipeline section. This resulted in insufficient pressure at downstream nodes to transport additional biomethane into the network.

The introduction of a gasblower (AFC) effectively mitigated this limitation by locally increasing the pressure and compensating for frictional losses. As a result, the maximum biomethane injection capacity increased substantially, from 57 m^3/h to 100 m^3/h. This highlights that introducing a gasblower can significantly enhance the biomethane injection capacity of existing gas distribution networks without requiring major infrastructure upgrades. These findings are particularly relevant in the context of the energy transition, where increasing volumes of decentralized biomethane are expected to be injected into existing gas grids. This increase corresponds to a relative improvement of approximately 75%, highlighting the significant impact of local pressure control.

However, practical implementation requires careful consideration of operational conditions. When biomethane injection is interrupted, conventional gas supply from the gas regulator station must be able to feed the consumers located in the pipeline section between the biomethane injection point and the gas blower. This implies that a smart gas blower configuration enabling bi-directional flow is required. Furthermore, the blower must operate reliably and adapt to changing pressure conditions within the network. In the absence of biomethane injection, the blower should not induce pressures below the minimum allowable level (40 mbar(g)).

It should be noted that the effectiveness of active flow control depends on the specific network characteristics. In this case, the absence of consumers between the gas blower and the downstream intersection enabled a relatively high discharge pressure without violating pressure constraints for end users. In networks with different configurations, such as higher consumer density or alternative topologies, the achievable benefits may be lower or require different control strategies.

Furthermore, the use of fixed pressure boundary conditions in the simulations implies that the results represent an idealized operational scenario. In practice, gas networks are subject to dynamic variations in demand and supply, which may influence the performance and control requirements of AFC systems. Future work could therefore extend this analysis by incorporating time-dependent demand profiles and operational strategies.

Finally, while this study focuses on technical feasibility, additional aspects such as economic performance, regulatory constraints, and system integration need to be considered for practical implementation. Nevertheless, the results clearly demonstrate the potential of active flow control as a novel approach to increase biomethane integration in low-pressure gas distribution networks.

5. Conclusion

This study demonstrates that biomethane injection capacity in low-pressure gas distribution networks can be significantly constrained by local hydraulic bottlenecks rather than overall network capacity. Using a real-world 100 mbar(g) distribution network, it was shown that frictional pressure losses in a critical pipeline section limit the ability to transport additional biomethane under low-demand conditions.

The application of AFC in the form of a gas blower effectively alleviated this limitation by locally increasing the pressure and compensating for pressure losses. This resulted in a substantial increase in the maximum biomethane injection capacity by approximately 75%, from 57 m^3/h to 100 m^3/h. These findings highlight that targeted pressure control can unlock additional capacity within existing infrastructure without the need for extensive and costly network reinforcements.

The results underline the importance of considering local network behaviour when assessing injection capacity for decentralized gas injection. Furthermore, they demonstrate that active flow control represents a promising and flexible solution to facilitate higher levels of biomethane integration in existing gas distribution systems.

While the analysis is based on steady-state simulations and specific network configurations, the findings provide valuable insights into the technical potential of AFC in low-pressure networks. Future research should focus on dynamic operation, practical control strategies, and the techno-economic feasibility of implementation in real-world systems.

Overall, this study contributes to the development of practical solutions for increasing renewable gas integration and supports the transition towards more sustainable and flexible energy systems.

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Value Creation for Renewable Hydrogen via Local Hydrogen Hubs

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While prominently highlighted in the National Plan Energy of the Netherlands government (2022), green hydrogen has been facing obstacles in terms of scaling up in energy markets and thus fulfilling expectations. An important reason is that production of green hydrogen has remained relatively costly, partly due to the lack of economies of scale as of yet in combination with investment dilemmas caused by market uncertainties.

The project H_2opper aims at addressing this dilemma by designing a local hydrogen hub with a governance structure, standardised contracts and a virtual trading platform. This paper explores the economic benefits for suppliers of green hydrogen when modifying their production profiles according to electricity market profiles. Assuming that a producer continues to trade the majority of its produced green hydrogen via long-term hydrogen purchase contracts, as is the default trading option for securing finance investment decisions, and supplies the remainder via short term ('spot') market trading, additional financial benefits can be realised. The paper analyses examples of green hydrogen production profiles and impacts of each profile on the levelized costs of green hydrogen.

Keywords: green hydrogen, hub, regional innovation ecosystems, energy transition; hydrogen barriers, business model

06

1. Introduction

Along a technology learning curve, new technologies first proceed through a phase of research and development (RD). Then follows a phase of demonstration (D) in pilot projects or programmes after which the technology is deployed in markets. Throughout these phases, first, mainly publicly funded research institutes are in the lead and once the technology enters the stage of market deployment, private sector actors take over to diffuse the technology in the market towards a scale of commercial viability. During this transition, technologies face so-called 'Valley of Death' risks (Ellwood, Williams, & Egan, 2022) (Siegmund, et al., 2021). Within the 'valley' promising technologies may be terminated as available public funding dries up, while commercial funding has not yet been secured, or other barriers may emerge that are related to scaling up from promising demonstration projects towards commercially diffused solutions.

An example of a potential valley of death case is that of green hydrogen deployment. At the level of the EU, green hydrogen development has been among the top priorities towards realising a net-zero emission society. By 2050, green hydrogen, i.e. hydrogen produced with renewable energy sources is scheduled to cover 10% of energy consumption in the EU, mainly in the sectors of industry and transportation (European Commission, 2026). In its National Plan Energy, the Netherlands Ministry of Economic Affairs and Climate (2022) included hydrogen as one of the four pillars of a future net-zero emission energy system. While not considered to be playing a dominant role, i.e., renewable energy-based electricity is expected to become the backbone for a Dutch CO_2-neutral energy system, approximately 10 to 20% of mid-century final energy consumption in the Netherlands is expected to be met with hydrogen, mainly in (industrial) sectors for which electrification is technically and economically complex.

Yet, green hydrogen development is frequently associated with challenges such as the relatively high costs and scarcity of materials for electrolysis options (Younus, et al., 2025) which limit large-scale production as of yet and thus prevent operators and manufacturers to realise economies of scale. As a result, green hydrogen has been facing obstacles in terms of scaling up in energy markets and thus fulfilling policy-level expectations. This creates investment dilemmas such as potential offtakers not switching to green hydrogen due to a lack of production, whereas potential producers do not invest in electrolysis without sufficient offtake perspectives.

In order to contribute to solving this dilemma, the research project H_2opper aims at designing a proof of concept for a local hydrogen grid for an industrial cluster[1]. As a case study, H_2opper targets the industrial cluster of Delfzijl in Northern Netherland to assess what a local hydrogen market hub could look like, including a governance model, a virtual market place, standardized contracts and a physical infrastructure for efficient hydrogen trade and transport. The hypothesis is that a local hydrogen hub supports matching individual offtake and producer profiles and propositions, resulting in a larger scope for short-term ('spot') market trading and economic benefits. For example, one of the hub's promises could be to offer more flexibility and use of low electricity prices during hours of the day that renewable energy sources are abundantly available.

This paper explores how a local hydrogen hub, such as explored by H_2opper, could strengthen the business case for green hydrogen production and how this could support green hydrogen in successfully getting passed the 'valley of death'.

2. Requirements for system improvement according to innovation theory

As per the European Green Deal, by 2050 European societies are to be climate-neutral (Europese Commissie, 2026), implying that for reaching the intermediate target of 55% CO_2-equivalent emission reduction (compared to 1990 levels) by 2030, an estimated annual investment of over Euro 1 trillion per year during the current decade would be needed (Andersson, Nerlich, Pasqua, & Rusinova, 2024). The importance of managing the transition towards deployment and diffusion of low-emission solutions effectively and efficiently is therefore crucial and requires next to technology innovation of innovative approaches for making systems suitable for technology uptake (Grubb, McDowall, & Drummond, 2017). Innovation is a broad term used to describe this transition, either referring to new or renewed technology options or changing or improving market system conditions to increase use of these options (Ockwell & Byrne, 2016) (Albu & Griffith, 2006). Given that the scope of this paper covers an innovative approach to accelerating the uptake of green hydrogen technologies in an industrial cluster environment, an elaboration of factors that play a key role in that acceleration is presented in the rest of this section.

Grubb, McDowall & Drummond (2017) analyse technology development by describing a technology 'journey' via invention, development and demonstration phases during which a new technology is pushed

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[1] H_2opper is funded through the Nationaal Programma Groningen and is carried out by a consortium consisting of Baringa Partners International LLP (project leader), Sinz Management, Kikkers Advies and Centre of Expertise Energy Entrance at Hanze University of Applied Sciences. The project website is: https://www.H2opper.eu.

forwards, supported by push factors such as technical knowledge development and basic and applied research and development. Further on during the 'journey', the technology is supposed to be pulled by factors such as the commercial viability of a technology (so that its implementation becomes profitable for market investors) and market actors' preference for a particular technology solution.

While the required transition from push to pull factors is in line with the 'valley of death' concept, Grubb, McDowall & Drummond (2017) add a second dimension to the analysis by identifying how requirements 'along the journey' evolve for organizations and supply chains, customers and standards, financing, market organization and regulation, and institutional and infrastructural investments. For example, during the R&D stage a small team may work on a technology idea, after which, during the stage of commercialization, the team develops into a mature company; while during R&D no clear profile may exist of potential customers, successful commercialization requires a well-defined customer profile and clear product or technology branding. Moreover, the application scale of a technology becomes larger along its journey, which requires that wider groups of stakeholders are engaged in technology decisions and that (market) systems are in place, supported by institutions (public or private) required to facilitate the process of uptake. This is in line with the perspective of technological innovation systems (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008) (Bößner, Johnson, & Taylor, 2018) which imply that the journey of a mature, deployment-ready technology option starts from the level of a successful demonstration and then proceeds along the scale to wider diffusion at the sector or country level.

3. H_2opper's contribution to green hydrogen system improvement

The objective of H_2opper is to develop a conceptual design for a local hydrogen hub, taking the industrial cluster of Delfzijl as a case study. A working hypothesis of the project is that a hub offers an increase in transaction opportunities for existing and potential suppliers and offtakers of hydrogen enabling them to take a financial investment decision on hydrogen equipment. With that, H_2opper aims at addressing Grubb, McDowall & Drummond's (2017) requirements for market and infrastructure developments along the technology journey by designing a model of industrial collaboration for green hydrogen (Baringa, 2025). Once established, such collaboration enables trading beyond conventional bilateral agreements, thereby reaping market opportunities. Examples of these opportunities are more efficient matching of demand and supply profiles of local market actors, avoiding transportation and storage costs as the hub shortens the distances between producers and offtakers, and benefitting from electricity market developments such as producing extra green hydrogen when electricity prices are relatively low. A hub's operationalisation of spot market trading supports these opportunities.

In designing a hydrogen hub-structure, H_2opper has undertaken the following steps:

1. Prioritising a governance model for a hub.
2. Identifying the functioning of a hydrogen hub market from production through delivery of hydrogen, including roles and responsibilities of market actors.
3. Developing a virtual market platform to facilitate local hydrogen trades.
4. Prioritising and virtually and physically testing a topology for hydrogen transportation within the hub.

3.1 Prioritising a governance model

The project has considered several archetypes for governing a local hub market, such as Bilateral market, Insights service, Broker and Trading exchange:

- The Bilateral market archetype has been considered as it resembles existing practice in many hydrogen transactions whereby supply and demand matching is managed between two parties. While it enables customisable, bespoke sales terms, often agreed for longer periods of time, it has limited transparency and standardisation (Baringa, 2025, p. 42).
- The model of Insights Service enables volumes and bid or ask prices[2] to be communicated via an openly accessible platform, based on which market actors can contact each other to strike a deal. While this archetype supports increase of transactions, it does not function as a trading platform and does not offer matching and negotiation support to market actors.
- The archetype of a Broker introduces third party intermediary support offering matching and negotiation support to markets. Through this, market actors are facilitated to enter direct contracts.
- A Trading exchange functions as a centralized platform from which producers and offtakers of hydrogen can acquire real-time pricing and clearing services. This model is generally used in natural gas markets. While contributing to market efficiency, this model requires high trading liquidity and participation and requires relatively strict regulatory oversight. Therefore, for the initial stages of a hydrogen hub, this model is less suitable.

Given the above considerations, thereby concluding that no single archetype meets all hub requirements, H_2opper proposes, particularly during the early stages of a hydrogen hub development, to leverage the

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[2] An 'ask' price is the price a buyer is asking for an amount of hydrogen, while a 'bid' price is the price that an offtaker is willing to pay.

archetype of Broker (Baringa, 2025, p. 48). It is concluded that this archetype "enables efficient supply and demand matching and ability to scale by managing the flow of payments and title transfer for producers and offtakers." (Baringa, 2025, p. 46)

3.2 Market processes and roles

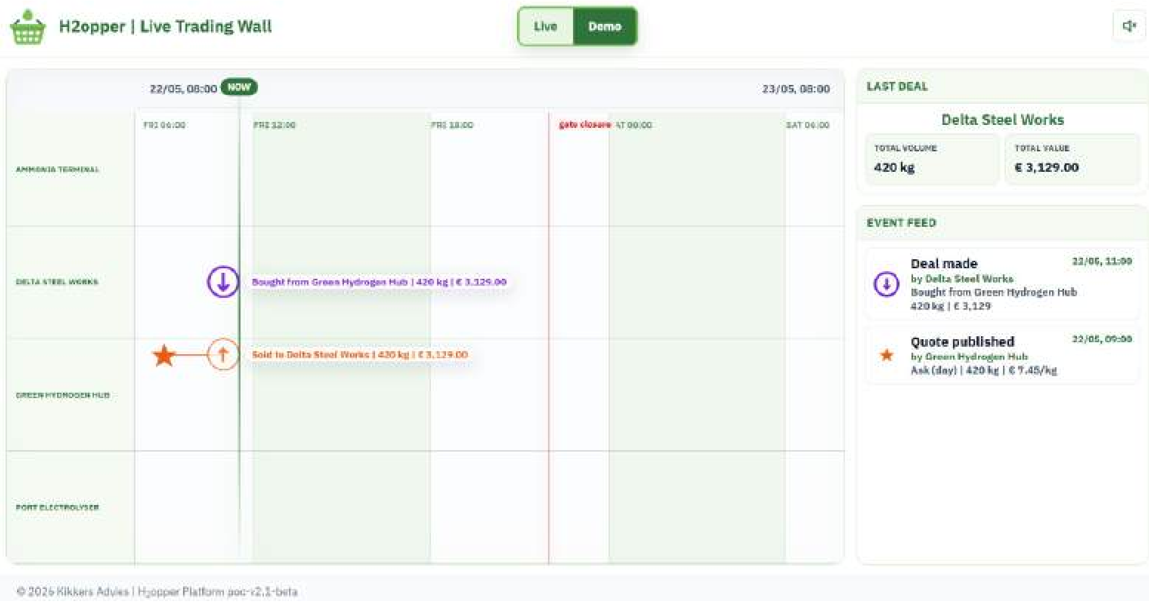
As a next step, H_2opper has reflected on the stages of a hydrogen market process that the broker model would need, to support:

1. Contracting: during this phase producers and offtakers of hydrogen agree on a volume and price to be traded. During this phase also grid transportation capacity needs to be contracted from the party that has the responsibility of grid operator of the local hub. Usually, as in natural gas markets, a shipper plays a key role in this stage, both as an intermediary to ship the commodity from producer to offtaker and arranging the required grid capacity for that within the grid.
2. Nomination: the shipper then nominates the contracted volume to the grid operator, who considers the available grid capacity and checks whether the transaction can be processed, leading to an acceptance or rejection decision.
3. Delivery: upon acceptance by the grid operator, the contracted volume is physically processed via the hub's grid, whereby the flows are metered for grid balancing and invoicing purposes.
4. Allocation: Based on nominated and agreed transactions, the grid operator officially distributes the capacity in the pipeline topology among the different market participants.
5. Settlement: Finally, upon delivery of the hydrogen and collection of data, invoices can be composed as well as settlement of grid capacity utilisation finalised.

3.3 Developing a virtual market platform to facilitate local hydrogen trades

Supporting the implementation of a market broker, H_2opper aims to deliver an online marketplace enabling producers and offtakers to communicate their 'asks' and 'bids'. These quotes contain information about volumes, colour (grey or green) and prices of hydrogen. A market actor that is interested in a transaction can check the platform and select an 'ask' or 'bid' that it considers acceptable. Upon selecting a quote, a deal is struck via the platform after which a contract is established (H_2opper also aims at delivering standardised contract formats for that service). The latter takes place during the contracting stage. The H_2opper trading platform is developed in co-creation sessions with market stakeholders to align its design with their priorities and constraints. A screenshot of a demo of the H_2opper trading wall is shown in Figure 1.

Figure 1. Screenshot H_2opper's Live Trading Wall (Note: mock screen with artificial names, not representing existing companies)



Bought from Green Hydrogen Hub | 420 kg | € 3,129.00

Sold to Delta Steel Works | 420 kg | € 3,129.00

Delta Steel Works

TOTAL VOLUME: 420 kg

TOTAL VALUE: € 3,129.00

Deal made 22/05, 11:00
by Delta Steel Works
Bought from Green Hydrogen Hub
420 kg | € 3,129

Quote published 22/05, 09:00
by Green Hydrogen Hub
Ask (day) | 420 kg | € 7.45/kg

© 2026 Kikkers Advies | H₂opper Platform poc-v2.1-beta

3.4 Prioritising and testing a topology for hydrogen transportation within the hub

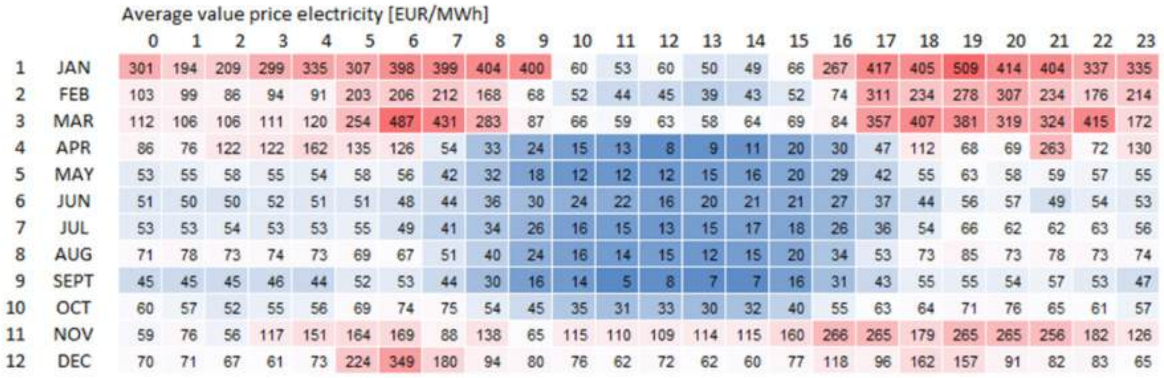
Finally, the hub model of H_2opper is simulated and physically tested at the Entrance living laboratory environment at Hanze to offer insights into potential vulnerabilities in the grid system and how to mitigate these. A detailed elaboration on the simulation can be found elsewhere in this volume.

4. Economic benefits from flexible use of electricity markets

A key assumption of establishing a local hydrogen hub is that it can help local market actors to break through the dilemma of recognizing market opportunities but not being able to operationalise these. The broker model, the market platform and physical infrastructure that together form a hub potentially remove the key obstacles to market development for renewable hydrogen. Another working hypothesis of H_2opper is that this will enable market actors to actively use electricity price fluctuations and use the hub's spot market facilities to lower the costs of renewable hydrogen. This section explores what cost savings might be achievable following this narrative.

Approximately 55-70% of production costs of green hydrogen are related to the costs of electricity use for the process of electrolysis (Energy Solutions Intelligence, 2026). Hence, for the business case of green hydrogen insight into possible electricity market developments is of key importance. As per the National Programme Energy (Ministerie van Economische Zaken en Klimaat, 2022), during the energy transition, over 70% of the Dutch energy mix is estimated to be based on renewable energy such as on- and offshore wind and ground mounted solar parks. Consequently, electricity prices will, due to the intermittent nature of renewable energy sources, become more volatile during the Winter times, early Spring and late Autumn, when electricity demand is assumed to peak due to peaking heat demand and corresponding use of heat pumps. Instead, during most daytime hours during Spring and Summer, electricity prices are expected to become relatively low, with possibly even negative prices, also on day ahead markets, due to abundant renewable energy availability. Figure 2 shows an example of a possible profile of future electricity price patterns, assuming the median scenario of the Energy Transition Model, for the year 2035 (Energy Transition Model, 2026), with red cells showing relatively high electricity prices while blue cells reflect relatively cheap electricity.

Figure 2. Heat map of projected average monthly electricity prices in 2035 (Klein, Gaast, Rotariu, & Timmer, 2026)



Average value price electricity [EUR/MWh]

		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	JAN	301	194	209	299	335	307	398	399	404	400	60	53	60	50	49	66	267	417	405	509	414	404	337	335
2	FEB	103	99	86	94	91	203	206	212	168	68	52	44	45	39	43	52	74	311	234	278	307	234	176	214
3	MAR	112	106	106	111	120	254	487	431	283	87	66	59	63	58	64	69	84	357	407	381	319	324	415	172
4	APR	86	76	122	122	162	135	126	54	33	24	15	13	8	9	11	20	30	47	112	68	69	263	72	130
5	MAY	53	55	58	55	54	58	56	42	32	18	12	12	12	15	16	20	29	42	55	63	58	59	57	55
6	JUN	51	50	50	52	51	51	48	44	36	30	24	22	16	20	21	21	27	37	44	56	57	49	54	53
7	JUL	53	53	54	53	53	55	49	41	34	26	16	15	13	15	17	18	26	36	54	66	62	62	63	56
8	AUG	71	78	73	74	73	69	67	51	40	24	16	14	15	12	15	20	34	53	73	85	73	78	73	74
9	SEPT	45	45	45	46	44	52	53	44	30	16	14	5	8	7	7	16	31	43	55	55	54	57	53	47
10	OCT	60	57	52	55	56	69	74	75	54	45	35	31	33	30	32	40	55	63	64	71	76	65	61	57
11	NOV	59	76	56	117	151	164	169	88	138	65	115	110	109	114	115	160	266	265	179	265	265	256	182	126
12	DEC	70	71	67	61	73	224	349	180	94	80	76	62	72	62	60	77	118	96	162	157	91	82	83	65

Given the large share of electricity costs in the levelised costs of green hydrogen (LCOH), business case strengthening could thus occur by producing green hydrogen during market slots with low electricity prices (blue areas) and avoiding the relatively expensive hours (red areas). This can be illustrated as follows. Table 1 shows an example of a hypothetical green hydrogen producer, with a capacity utilisation of 8000 hours per year (approximately 90% capacity utilisation). For this producer, the investment costs per kg of produced hydrogen amounts to € 0.94.

Table 1. Investment costs green hydrogen production

Continuous production H_2	8000	hours/year
Investment costs electrolyser	€ 1.500.000,00	euro/MW power
Economic lifetime electrolyser	10	years
Investment costs per year	€ 150.000,00	euro/year
Production capacity per MWh power	20	kg H_2/MWh
Annual production H_2 continuous production	160.000	kg H_2/year
Investment costs per kg produced H_2	€ 0,94	euro/kg H_2

Taking this example further by adding electricity consumption and prices, the impact of reduced electricity prices can be illustrated. Table 2 below shows how electricity costs per kg hydrogen can decrease by 45% if the producer only produces hydrogen during 50% of the hours of the year when the electricity prices are the lowest, with an average price of €55/MWh instead of €100/MWh.

However, limiting hydrogen production to the 50% of the hours with lower electricity market prices would also imply that the electrolyser will have fewer operational hours and thus lower hydrogen production. In our example, the number of production hours drops from 8000 hours to 4000 per year. This implies that the electrolyser's capital expenditures will have to covered by fewer kilograms of hydrogen produced, thereby increasing the capital expenditures (capex) per operational hour. Table 3 combines the data above and shows the impact on the LCOH, combining both the impact of reduced operational expenditures (opex) due to lower electricity prices and increased capex per unit costs due to lower annual production. As a result, the €2,25/kg cost saving is partly offset by a doubling in capex/kg expenses, resulting in a net LCOH reduction of €0.69/kgH_2.

Table 2. Electricity cost impact green hydrogen production

Annual production H_2 continuous	160.000	kg H_2
Electricity consumption/kg	50	kWh/kg H_2
Total electricity consumption	8000	MWh
Average annual electricity price	€ 100,00	€/MWh
Total electricity costs per year	€ 800.000,00	Euro
Total electricity costs per kg	€ 5,00	€/kg H_2
Average electricity price 50%	€ 55,00	€/MWh
Total electricity costs low	€ 440.000,00	Euro
Total electricity costs low / kg	€ 2,75	€/kg H_2
Electricity cost saving	€ 2,25	€/kg H_2

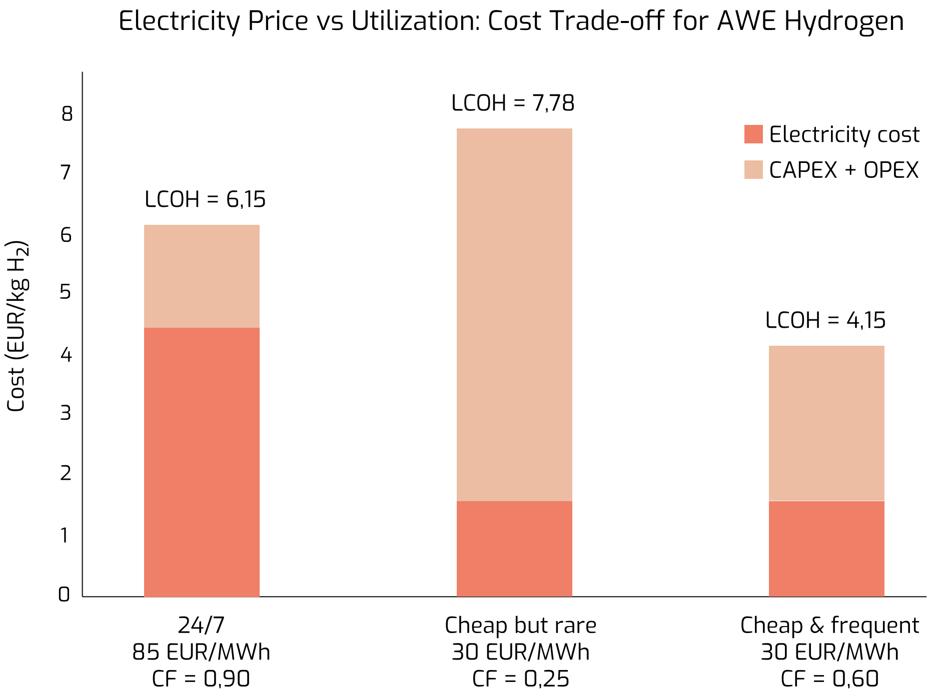
Table 3. Example of impact LCOH when modifying operating hours to power market prices

Continuous production H_2	8000	hours/year
Production H_2 at 50% lowest electricity prices	4000	hours/year
Investment costs electrolyser	€ 1.500.000,00	€/MW power
Economic lifetime	10	years
Investment costs per year	€ 150.000,00	€/year
Production capacity per MWh power	20	kg H_2/MWh
Annual production H_2 continuous production	160.000	kg H_2/year
Investment costs per kg produced H_2	€ 0,94	€/kg H_2
Annual production at 50% lowest power prices	80.000	kg H_2/year
Investment costs per kg produced H_2	€ 1,88	€/kg H_2

	OPEX	CAPEX	TOTAL
Production continuous	€ 5,00	€ 0,94	€ 5,94
Production at 50% lowest power prices	€ 2,75	€ 1,88	€ 4,63

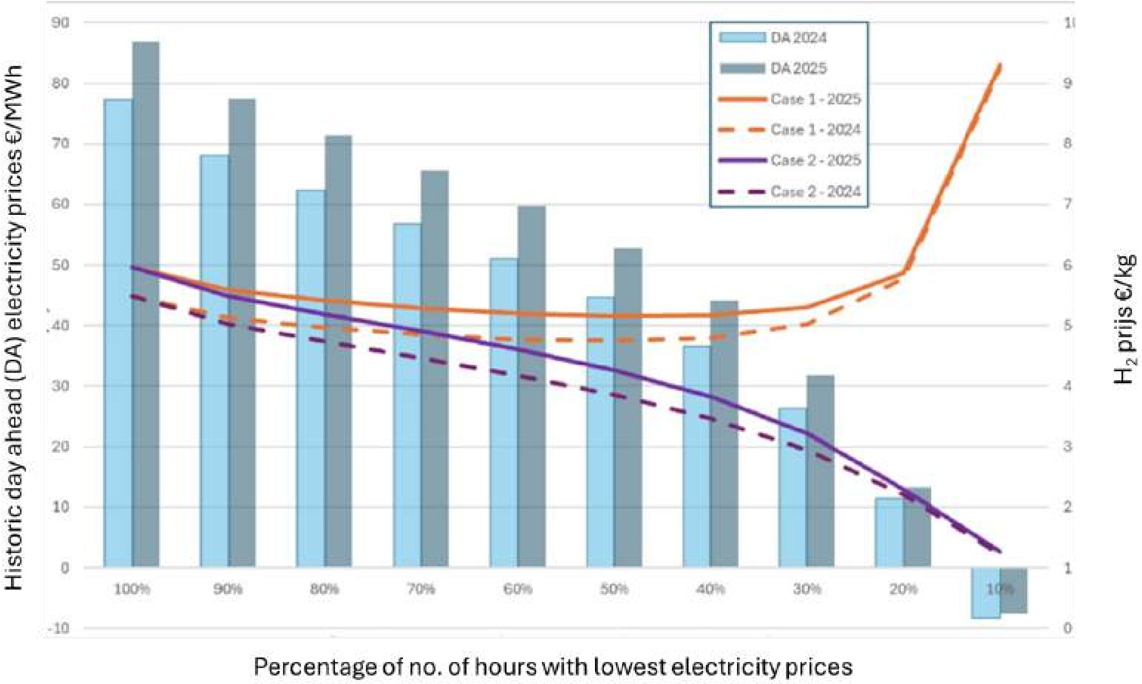
For Latvia, a study was conducted (Zemite, et al., 2026) similar to the above example, using data from the year 2024. It analysed for electrolyser options the impacts of optimising green hydrogen production after electricity market developments. The study found that a €1 reduction in electricity prices reduces the LCOH by 5.2 €cents per kgH_2. Subsequently, targeting lower-priced electricity market slots (from the annual average of €85/MWh to €30/MWh) while reducing the capacity utilisation of the electricity to 60% of the full year, the LCOH would drop from €6.15 to €4.15 per kgH_2. The study also found, in line with the above example, that if capacity utilisation (CF) would drop to 25% only, the LCOH would in fact increase to Euro 7.78/kg H_2, driven by higher per unit capex costs and despite lower per unit electricity costs.

Figure 3. Impact of electricity price and electrolyser capacity factor on LCOH (example of alkaline water electrolysis), from Zemite, et al. (2026)



The above examples make clear that tapping into the cheaper electricity market hours can be beneficial for the business case of green hydrogen production, but the capacity utilisation rate must be sufficiently high to enable sufficient coverage of capital expenditures by production hours and kilograms of hydrogen produced. Projecting these insights to the local hydrogen hub case study of H_2opper at Delfzijl results in the following insights. Figure 4 shows, based on recent Dutch electricity market prices, how lower electricity costs reduce LCOH-values. However, should the production rate drop below 50% of the capacity utilisation, the impact of higher per unit capex becomes stronger than the per unit reduction of electricity costs-based opex. This is shown by Case 1 in Figure 4. Should, instead, the producer be able to develop a portfolio with long-term and short-term contracts (e.g. 70% long term and 20% short term flexible), a high capacity utilisation of 90% (assumed as being full capacity, considering outages due to maintenance) could be achieved for the electrolyser, resulting in correspondingly lower hydrogen production costs per kg produced. This is shown by Case 2 in Figure 4.

Figure 4. LCOH development when following electricity market price development (own calculations, based on data for 2024 and 2025 (EPEX, 2025))



Finally, a hydrogen hub with short-term market facility could incentivise producers to increase hydrogen production. Should, for example, a producer decide to produce 25% extra hydrogen during 30% of the hours with the lowest electricity prices per year in the day ahead market (average price: €30/MWh), this would result in 264 ton of extra hydrogen production at marginal costs of €3/kgH_2 resulting in an extra revenue of €418,187 per year for the producer, which is an increase in annual revenue of approximately 2.5%.

5. Discussion

H_2opper aims at exploring options for the governance and trading facilities within a local hydrogen hub, taking the industrial cluster of Delfzijl as a case study. The examples of possible economic benefits serve as an illustration of the dynamics of LCOH impacts due to tapping into favourable energy market conditions and combinations of long-term contracting and short-term market transactions within a hub context. These insights contribute to addressing existing dilemmas in green hydrogen market development.

Yet, H_2opper acknowledges that the development of a local hydrogen hub around an industrial cluster such as Delfzijl will at best have to take place in stages, from an initial stage with the participation of a relatively small number of market actors, via an intermediate phase during which potential connections are made with wider hydrogen infrastructures, towards a phase with eventually liquid markets having a minimally required number of daily deals for price discovery and disclosure. H_2opper's design is made to serve such an end state.

Another point for discussion is the aspect of security of supply and offtake. In the above example, it was assumed that market actors in the hub would secure 70% of their volumes via long-term contracts and complete the remaining 30% via spot markets within the hub. However, the percentage of 70% may be considered unrealistic in most current hydrogen markets with low liquidity and insufficient security of supply. Having only 70% of its demand or supply of hydrogen secured via a long-term contract is likely to be insufficient for securing a financial investment decision. Therefore, the examples discussed in this paper are most likely to be realised during future phases of hub development.

Consequently, the insights gained from H_2opper can be seen as instrumental for shaping a future local hydrogen market. At the same time, for realising a hub, a wider set of conditions need to be met, such as infrastructure building, policy vision development and strategies for implementing this. Once these conditions have been fulfilled, H_2opper's package can be utilised for furthering green hydrogen along its technology 'journey'.

6. Conclusion

The market deployment of green hydrogen in the Netherlands is potentially risking a Valley of Death situation, since individual market actors have insufficient opportunities to accelerate market development and market infrastructure building is impeded for lack of market activities. H_2opper's objective is to demonstrate the value creation potential of a green hydrogen hub to build an infrastructure with a market model and governance structure that can unlock green hydrogen market potential within, e.g., an industrial cluster.

A specific aspect of the value creation through a local hub construct is the ability to increasingly exchange hydrogen via spot markets. Spot market trading enables producers to act more flexibly, enabling them to tap into favourable electricity market conditions. Costs of electricity form a considerable share of green hydrogen production costs, and these can be substantially reduced when electricity is consumed for electrolysis during market slots when electricity is relatively cheap. This requires producers to act more flexibly in terms of hydrogen production and delivery.

A hub enables producers to act flexibly by striking a balance between long-term contracts that are needed for financial investment decisions and short-term trading to make use of relatively low electricity market prices. This flexibility can also create an incentive to invest in extra production capacity for more flexible production and additional revenues to be delivered via the hub market space.

These insights contribute to the rationale of a hydrogen hub such as proposed by H_2opper, enabling producers to increase sales volumes by sharing data via the H_2opper trading platform and increasingly entering short term portfolio matching to optimize the sellout of produced volumes. As such, production capacity utilization can be improved because the trading platform enables offtakers to collectively generate purchasing profiles that match optimised producer profiles.

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NO more! Reducing Nitrous Oxide Emissions in Wastewater via Ammonia Electrolysis

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Ammonia is a major nitrogenous constituent of municipal wastewater and poses environmental challenges when discharged to receiving waters. Conventional biological treatment processes can be limited by operational instability, sensitivity to loading conditions, and greenhouse gas emissions, motivating the investigation of alternative treatment approaches. This thesis investigates electrochemical ammonia depletion from real municipal wastewater using a laboratory-scale alkaline electrolyzer operated under galvanostatic conditions.

Experiments were conducted using both model electrolytes and real wastewater to assess the influence of wastewater complexity on system behavior. The effects of supporting electrolyte addition, current density, membrane selection, and initial ammonia concentration were systematically evaluated. Ammonia depletion was monitored over time, alongside measurements of cell voltage and electrolyte pH, to characterize operational performance and stability.

The results show that, when supported by sufficient alkalinity, electrochemical ammonia depletion in real wastewater proceeds in a manner comparable to that observed in model electrolytes. The presence of a supporting electrolyte was found to be essential for practical operation, as experiments conducted without added KOH required substantially higher cell voltages. Increasing current density accelerated ammonia depletion but led to diminishing gains at higher values due to increased electrical demand. Across the investigated concentration range, ammonia depletion exhibited linear behavior consistent with apparent zero-order kinetics with respect to ammonia concentration over the observed operating window. Membrane selection influenced pH stability and species distribution between compartments, with anion exchange membranes providing more stable alkaline operation than cation exchange membranes.

Overall, the findings demonstrate that electrochemical ammonia depletion from real municipal wastewater is technically feasible under alkaline conditions and is primarily governed by operational parameters rather than wastewater complexity alone. The results provide a baseline understanding of system behavior and highlight key considerations for future optimization and scale-up of electrochemical ammonia treatment technologies.

07

1. Introduction

1.1. Ammonia as a Persistent Challenge in Wastewater Treatment

Ammonia is a ubiquitous nitrogenous pollutant in municipal wastewater, arising primarily from the biological breakdown of organic nitrogen during upstream treatment. Its environmental significance is well established: in aquatic environments, total ammonia nitrogen (TAN) exists as an equilibrium between molecular ammonia (NH_3) and ammonium (NH_4^+), with the toxic NH_3 form favoured at higher pH and temperature (1). The U.S. EPA identifies ammonia as capable of both acute and chronic harm to aquatic organisms at concentrations in the low mg N L-1 range (1), and the revised EU Urban Waste Water Treatment Directive has strengthened nutrient discharge limits for larger installations and ecologically sensitive receiving waters (2). As treatment standards tighten globally, ammonia management has become an increasingly pressing operational and regulatory challenge.

1.2. Limitations of Conventional Ammonia Removal Technology

The dominant treatment paradigm of biological nitrification-denitrification is effective under stable conditions but inherently fragile. The underlying microbial communities are sensitive to temperature fluctuations, loading shocks, pH swings, and dissolved oxygen availability, leading to incomplete nitrification and variable effluent quality. Streams from anaerobic digestion are particularly problematic, as their high ammonia loads and limited biodegradable carbon constrain denitrification. Critically, biological nitrogen removal generates nitrous oxide (N_2O), a greenhouse gas with a global warming potential approximately 300 times that of CO_2 (3), adding a significant climate burden to an already complex treatment challenge. Physicochemical alternatives such as air stripping, breakpoint chlorination, and ion exchange are effective in controlled settings but are generally energy-intensive, chemically demanding, or produce secondary waste streams (4).

1.3. Electrochemical Treatment of Wastewater and Ammonia Oxidation

Electrochemical treatment approaches offer a fundamentally different operating paradigm: reaction rates are controlled directly by applied current, enabling rapid response to changing conditions without dependence on microbial activity (4). For ammonia specifically, alkaline electrochemical oxidation drives the direct conversion of NH_3 to N_2 at an anode, with concurrent hydrogen production at the cathode, a dual-benefit pathway with potential integration into renewable energy systems. Studies have confirmed that ammonia oxidation is thermodynamically favorable relative to oxygen evolution in alkaline media (5), though practical performance varies considerably with catalyst material, cell configuration, and operating conditions (3, 5).

A critical gap in the existing literature is the near-exclusive reliance on idealized model electrolytes (pure ammonia in controlled alkaline solution) that do not capture the ionic complexity, buffering capacity, or matrix effects of real wastewater (3, 4). Whether and how these factors affect electrochemical ammonia removal remains poorly characterized. This study addresses that gap directly: using real municipal wastewater collected after anaerobic digestion and filtration, key operational parameters governing ammonia depletion performance are systematically evaluated, establishing a reproducible lab-scale baseline to inform the design of pilot-scale electrochemical treatment systems.

2. Theory

2.1. Ammonia Chemistry in Aqueous and Alkaline Systems

In aqueous systems, ammonia exists in equilibrium between its molecular form (NH_3) and its protonated form, ammonium (NH_4^+). The relative distribution of these two species depends primarily on pH and temperature. At 25 degrees C, the acid dissociation constant (pKa) of the NH_4^+/NH_3 equilibrium is approximately 9.25, meaning that molecular ammonia becomes the dominant species at pH values above this point (6). This pH-dependent behavior is fundamental to understanding both the environmental relevance of ammonia and its behavior in engineered treatment systems.

In municipal wastewater, ammonia is formed mainly through the degradation of nitrogen-containing organic matter during upstream biological treatment processes. As a result, ammonia is typically present together with a range of dissolved constituents, including bicarbonates, chlorides, and residual organic species, which contribute to buffering capacity and overall ionic strength (7, 8). While these components influence the overall chemical composition of the wastewater, they do not alter the underlying dependence of ammonia speciation on pH.

The distinction between NH_3 and NH_4^+ is particularly important for electrochemical treatment. Under alkaline conditions, a larger fraction of total ammonia is present as molecular NH_3, which is the electrochemically active species involved in anodic oxidation reactions. In contrast, ammonium does not undergo direct anodic oxidation under the alkaline conditions relevant to this work (9). Alkaline operation also has practical implications for electrochemical cell performance. The addition of a strong base such as potassium hydroxide increases electrolyte conductivity and reduces ohmic losses within the cell, allowing operation at lower and more stable voltages (10). When real wastewater is used as the feed, buffering species and dissolved salts remain present, but alkaline conditions ensure that ammonia speciation and electrochemical operation are governed primarily by the imposed pH rather than by variations in wastewater composition.

2.2. Principles of Electrochemical Ammonia Oxidation

Electrochemical ammonia oxidation is based on the anodic conversion of ammonia driven by an externally applied electrical current. In alkaline systems, this process is investigated as an alternative or complement to conventional biological nitrogen removal, with the aim of achieving direct ammonia depletion under controlled electrochemical conditions (8, 9). Unlike biological processes, which rely on microbial activity and are sensitive to temperature, loading, and operational disturbances, electrochemical systems respond directly to imposed electrical and chemical operating parameters such as current density and electrolyte composition (10). Current density is defined as the applied electrical current normalized by the geometric electrode area:

$$j = \frac{I}{A}$$

where j is the current density, I is the applied current, and A is the active electrode area. Normalizing current by electrode area allows electrochemical behavior to be compared across different systems and operating conditions, and provides a consistent basis for evaluating ammonia depletion behavior as a function of electrical input (10).

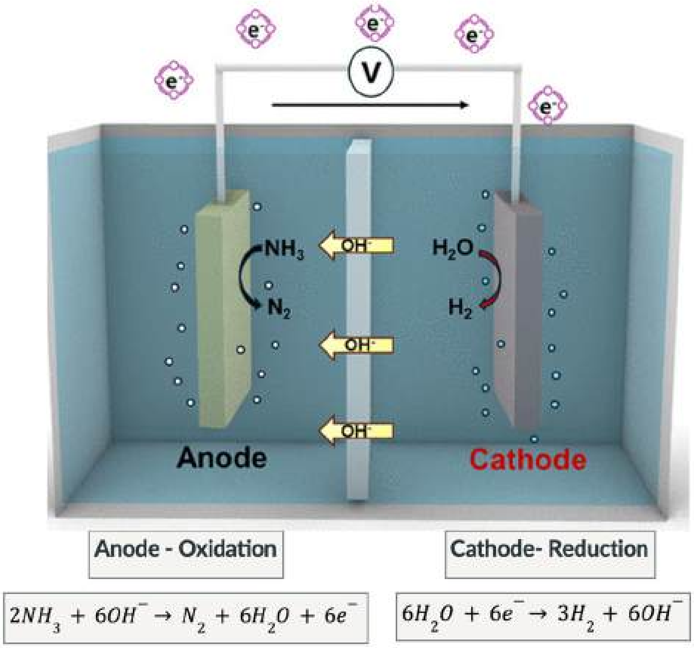
A defining characteristic of electrochemical ammonia oxidation is that ammonia oxidation does not occur in isolation. At the anode, ammonia oxidation proceeds in parallel with competing reactions, most notably oxygen evolution. The relative contribution of these reaction pathways depends on the applied current density and the resulting electrode potential. At higher current densities, increased anodic overpotentials generally promote side reactions such as oxygen evolution, thereby reducing the fraction of electrical charge utilized for ammonia conversion (3, 8, 9). The effectiveness with which supplied electrical charge contributes to ammonia oxidation is commonly described using the Faradaic efficiency:

$$FE = \frac{n * F * N_{product}}{Q}$$

where Q is the total electrical charge passed through the system, n is the number of electrons transferred per mole of product formed, F is the Faraday constant, and $N_{product}$ is the number of moles of product formed through the electrochemical reaction of interest (12). In this work, Faradaic efficiency is used as a supporting metric to aid interpretation of ammonia depletion behaviour and charge utilisation, rather than as a primary optimisation target.

Electrochemical ammonia oxidation experiments are commonly conducted under constant-current (galvanostatic) operation (10). Under these conditions, the applied current density directly controls the rate of electron transfer within the cell, while the resulting cell voltage reflects the electrochemical response of the system to this imposed load. Variations in measured voltage therefore indicate changes in internal resistance, reaction overpotentials, and transport limitations, rather than changes in the applied current itself (12).

Figure 1. Generic Alkaline Electrolyzer Schematic



2.3. Alkaline Electrolyzer Configuration and Electrochemical Reactions

Electrochemical ammonia oxidation in this work is performed in an alkaline electrolyzer, in which anodic and cathodic reactions take place in separate compartments while being electrically connected through an external circuit. Alkaline electrolyzers are commonly configured with an ion-conducting separator, such as an anion exchange membrane, which enables ionic charge transport while limiting bulk mixing between the anolyte and catholyte (5, 9, 10). Under alkaline conditions, the electrochemical half-reactions are (5, 9):

$$\text{Cathode:}\ \ 6H_2O + 6e^- \rightarrow 3H_2 + 6OH^-$$

$$\text{Anode:}\ \ 2NH_3 + 6OH^- \rightarrow N_2 + 6H_2O + 6e^-$$

$$\text{Overall:}\ \ 2NH_3 \rightarrow N_2 + 3H_2$$

The standard equilibrium potential associated with this overall reaction is approximately E^0 = -0.06 V versus the standard hydrogen electrode, which is substantially lower than that required for water oxidation (5). This indicates that, from a thermodynamic perspective, ammonia oxidation is favorable relative to oxygen evolution. In practice, however, the operating cell voltage is significantly higher than the equilibrium value due to kinetic overpotentials, internal resistance, and the concurrent occurrence of competing anodic reactions, most notably oxygen evolution (5, 9).

From the stoichiometry of the anodic reaction, the oxidation of two moles of ammonia involves the transfer of six electrons, corresponding to three moles of electrons per mole of ammonia oxidized. This relationship allows electrical charge to be related to the extent of ammonia conversion:

$$Q_{theoretical} = 3 * F * \Delta n_{NH3}$$

where F is the Faraday constant and Δn_{NH_3} is the number of moles of ammonia converted (12). The alkaline electrolyte fulfils a central role in electrolyzer operation. High hydroxide ion concentration increases ionic conductivity, thereby reducing ohmic losses and enabling operation at lower cell voltages for a given current density (9, 10). The membrane or separator further influences electrolyzer behaviour by governing ionic transport between compartments. In alkaline systems, anion-conducting membranes facilitate hydroxide ion transport while restricting convective mixing of electrolyte solutions (5, 9). Membrane properties can affect pH stability, species crossover, and the distribution of reactants between the anode and cathode compartments.

2.4. Compartmentalization and Implications for Nitrogen Species

In this work, two operational modes were used: an initial single-loop configuration, in which the anode and cathode shared a common circulating electrolyte, and a later dual-loop configuration, in which the anolyte and catholyte were circulated independently using separate pump heads operating at the same flow rate. The transition to a dual-loop configuration enabled hydraulic separation of the anode and cathode environments while maintaining ionic connectivity through the membrane. This configuration limits immediate redistribution of species generated at one electrode throughout the entire system, allowing concentration changes measured in the anolyte to be more directly associated with anodic reactions (5, 9). In contrast, under single-loop operation, measured concentration changes reflect the combined behavior of both electrodes.

Although nitrate and nitrite were initially considered as secondary species of interest, reliable quantitative analysis was not possible within the scope of this study. Nitrite, in particular, is known to be chemically unstable, and electrolyte samples were not preserved by freezing at the time of collection, which can lead to changes in concentration during storage (8). Consequently, the analysis in this study focuses on ammonia depletion behavior and associated system performance.

2.5. Performance Metrics and Evaluation Framework

Ammonia depletion is tracked through changes in ammonia concentration over time. The extent of depletion is expressed as:

$$\Delta C_{NH_3} = C_{NH_3,0} - C_{NH_3,t}$$

where $C_{NH_3,0}$ is the initial ammonia concentration and $C_{NH_3,t}$ is the concentration measured at time t. The ammonia depletion rate is defined as the slope of the concentration-time profile:

$$r_{NH_3} \approx -\frac{\Delta C_{NH_3}}{\Delta t}$$

In this work, ammonia depletion rates are obtained from linear fits to concentration-time data within the selected operating window. The linearity observed across all conditions indicates zero-order kinetic behavior with respect to bulk ammonia concentration, a key finding discussed in Section 5. Alongside depletion rates, average cell voltage and Faradaic efficiency are used as supporting metrics to characterize the electrical cost and charge utilization associated with ammonia removal under each operating condition.

3. Methodology

Electrochemical experiments were conducted using a laboratory-scale micro-flow electrochemical cell (ElectroCell, Denmark) with a geometric active area of 10 cm^2. A platinum-coated titanium electrode served as the anode and stainless steel as the cathode, selected to establish a chemically stable, reproducible reference system rather than as optimised catalysts. Experiments used either a Nafion 117 cation exchange membrane (Chemours) or a Sustainion X37-50 anion exchange membrane (Dioxide Materials) as the cell separator. Two hydraulic configurations were employed: an initial single-loop setup in which anolyte and catholyte were fully mixed, and a subsequent dual-loop configuration in which the two compartments circulated independently, enabling compartment-specific sampling. The system was operated under galvanostatic control using a programmable power supply, with continuous logging of voltage, pH, and temperature. The experimental setups are shown on the next page.

Figure 2. Single Pump Set-up

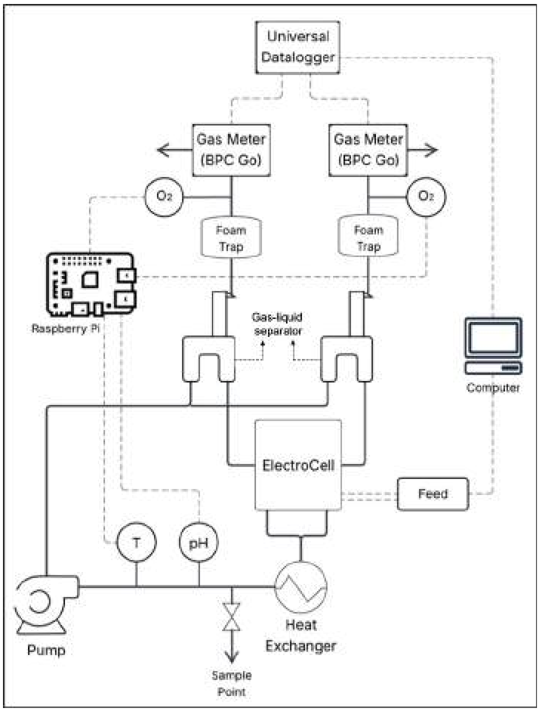
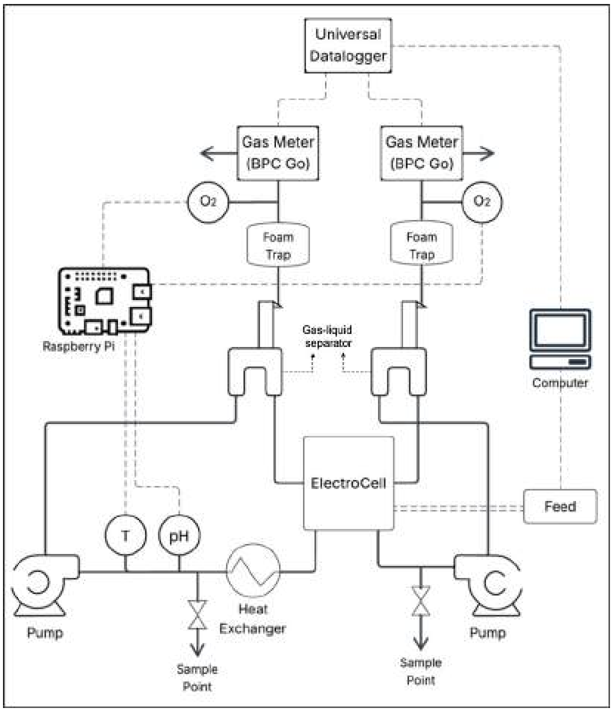


Figure 3. Double Pump Set-up



Wastewater was obtained from a municipal treatment facility at an intermediate processing stage, after anaerobic digestion and pressed filtration. The initial ammonia concentration was approximately 1.8-2.0 g L^{-1}, with a chloride content of approximately 2 g L^{-1} and high bicarbonate content. For alkaline experiments, 1 M KOH was added to the wastewater and the mixture was filtered prior to use to remove precipitated solids. Experiments were also conducted without added KOH to assess feasibility under the wastewater's intrinsic conductivity. All experiments used the same wastewater batch to ensure internal consistency.

Current densities of 50, 100, and 200 mA cm^{-2} were applied systematically, and the effect of initial ammonia concentration was investigated by comparing experiments at approximately 0.1 M and 1 M NH_3. Ammonia concentrations were determined spectrophotometrically using a calibrated test kit (NANOCOLOR Ammonium 50, Macherey-Nagel) (14). Full experimental details, including P&ID diagrams, gas handling, data processing procedures, and a worked efficiency calculation example, are provided in the Appendix.

Figure 4. Lab Set-up

4. Results

Results are organized according to the experimental objectives, beginning with baseline comparisons between model electrolyte and real wastewater, followed by evaluation of the effects of supporting electrolyte, current density, membrane type, and initial ammonia concentration. Reported results focus on measured ammonia depletion behavior, depletion rates, pH evolution, and electrical performance metrics.

4.1. Comparison of Model Electrolyte and Real Wastewater

At a current density of 200 mA cm^{-2}, ammonia depletion rates were closely matched between the model electrolyte (-0.0020 g L^{-1} min^{-1}) and real wastewater supplemented with 1 M KOH (-0.0022 g L^{-1} min^{-1}), with approximately linear concentration-time profiles observed in both cases.

Average cell voltages were similarly comparable: 5.4 V for the model electrolyte and 6.4 V for KOH-supplemented wastewater. Total gas volumes produced at the anode and cathode were also similar between the two systems (see Appendix 1).

In contrast, operation without any supporting electrolyte required a mean cell voltage of approximately 43 V. Although a comparable depletion slope of -0.0027 g L^{-1} min^{-1} was measured over a brief stable window, sustained galvanostatic operation was not feasible, as voltages increased rapidly and exceeded practical operating limits.

Figure 5. Ammonia Concentration over Time at 200 mA cm^{-2} for Varying Electrolyte

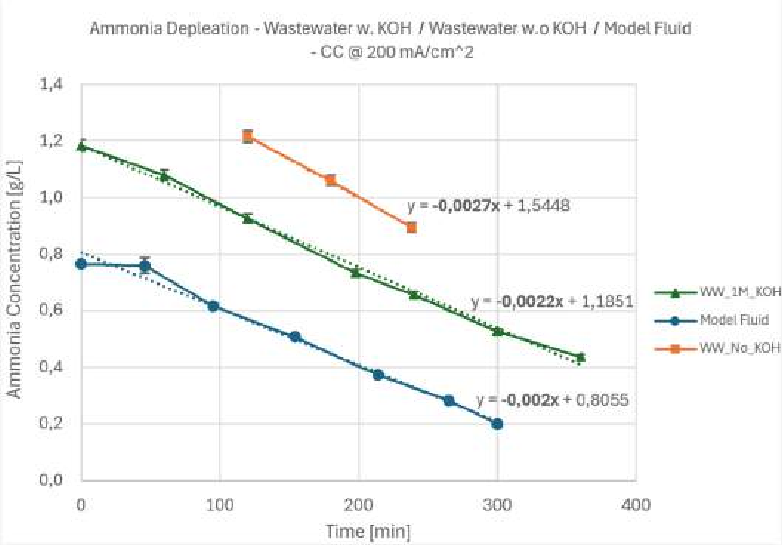
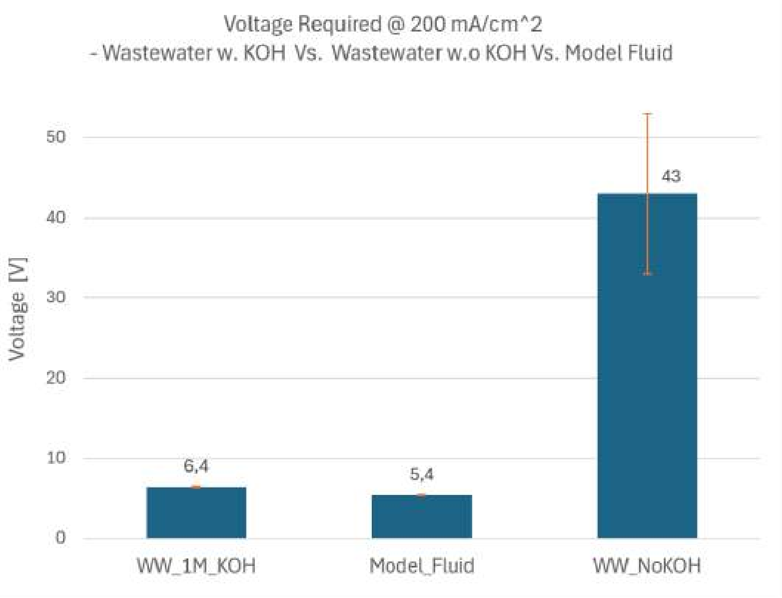


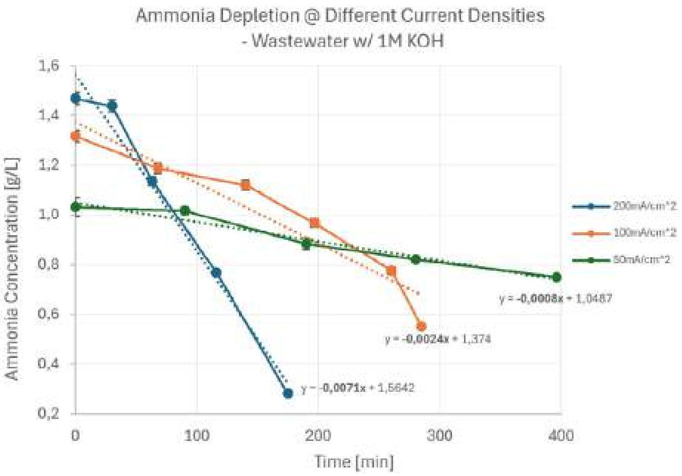
Figure 6. Average Cell Voltage at 200 mA cm^{-2} for Varying Electrolyte



4.2. Effect of Current Density on Ammonia Depletion

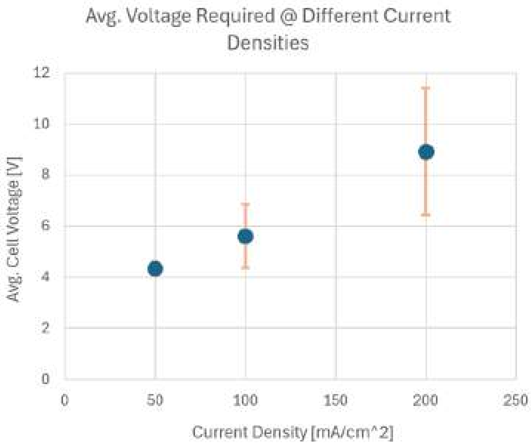
The effect of applied current density on ammonia depletion was investigated using the dual-loop configuration with municipal wastewater supplemented with 1 M KOH. At a current density of 50 mA cm^{-2}, ammonia depletion proceeded at a rate of -0.0008 g L^{-1} min^{-1}. Increasing the current density to 100 mA cm^{-2} resulted in a higher depletion rate of -0.0024 g L^{-1} min^{-1}. At 200 mA cm^{-2}, the ammonia depletion rate increased further to -0.0071 g L^{-1} min^{-1}. In all cases, ammonia concentration decreased approximately linearly over the evaluated time interval under constant-current operation (Figure 7).

Figure 7. Ammonia Depletion at Varying Current Densities



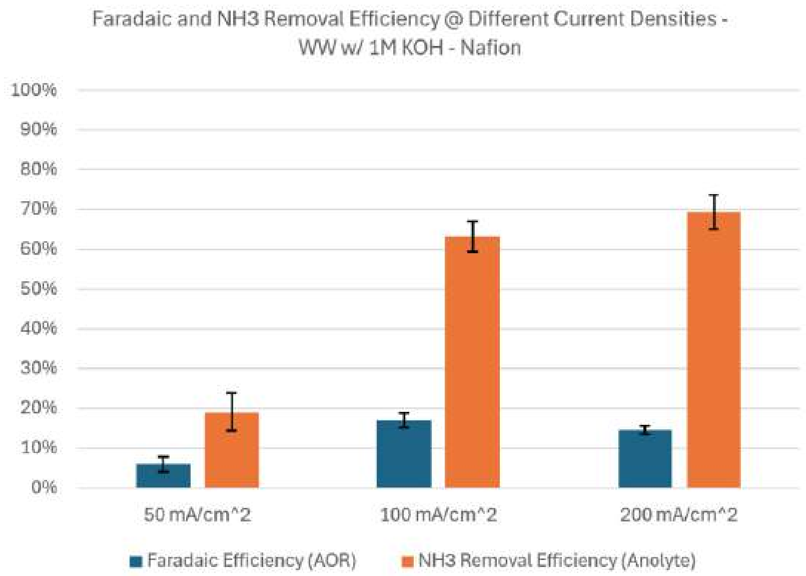
Average cell voltages rose from 4.3 V at 50 mA cm^{-2}, to 5.6 V at 100 mA cm^{-2}, to 8.9 V at 200 mA cm^{-2}. Voltage variability also increased with current density, reflecting increased sensitivity of the system to internal resistance, heat generation, and transient operating behavior at higher imposed currents.

Figure 8. Average Cell Voltage as a Function of Current Density



Both Faradaic efficiency and ammonia removal efficiency increased substantially when current density was raised from 50 to 100 mA cm^{-2}, indicating more effective utilization of electrical charge toward ammonia conversion within this range. In contrast, further increasing the current density from 100 to 200 mA cm^{-2} resulted in only minor changes in both metrics, with no proportional improvement relative to the increase in applied current. These results highlight a trade-off between maximizing ammonia removal rate and maintaining efficient use of electrical input.

Figure 9. Overview of Faradaic and Ammonia Removal Efficiencies at Varying Current Density



4.3. Comparison of Nafion and Sustainion Membranes

Both Nafion and Sustainion membranes supported comparable ammonia depletion rates at 100 mA cm^{-2}: -0.0024 g L^{-1} min^{-1} for Nafion and -0.0022 g L^{-1} min^{-1} for Sustainion. Despite similar depletion behavior, significant differences were observed in the evolution of solution pH. In the Sustainion experiment, pH remained relatively stable throughout operation, maintaining strongly alkaline conditions. In contrast, the Nafion experiment exhibited a gradual decrease in pH followed by a sharp drop at later times, suggesting insufficient hydroxide ion replenishment across the Nafion membrane under sustained current operation, leading to local acidification in the anolyte. Faradaic efficiency was higher for Nafion, while ammonia removal efficiency in the anolyte was also higher for Nafion compared to Sustainion.

Figure 10. Ammonia Depletion Under Sustainion vs. Nafion Membrane Use

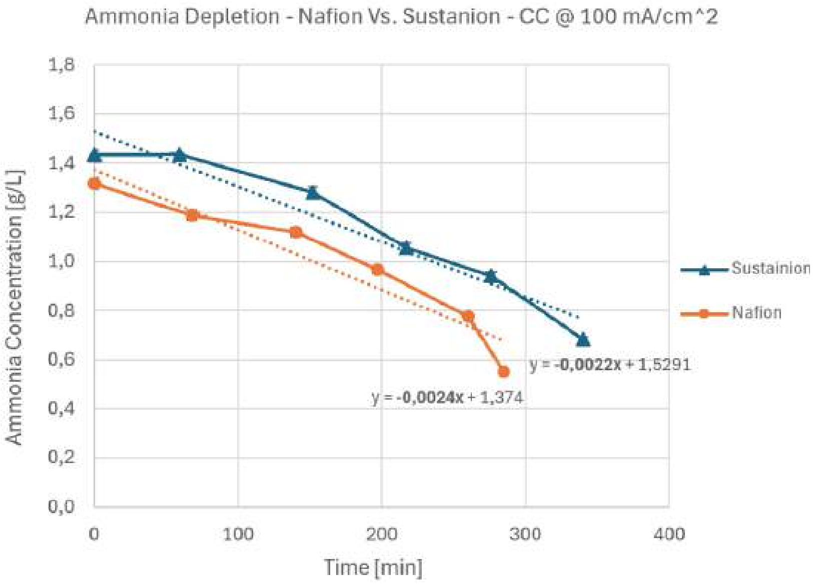
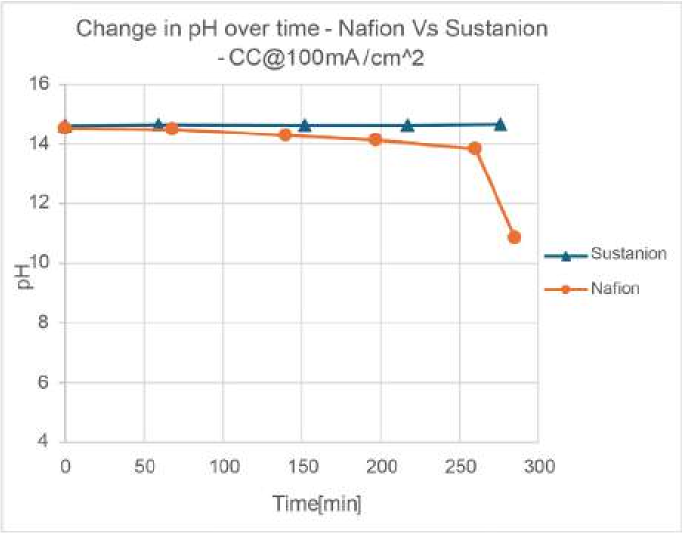


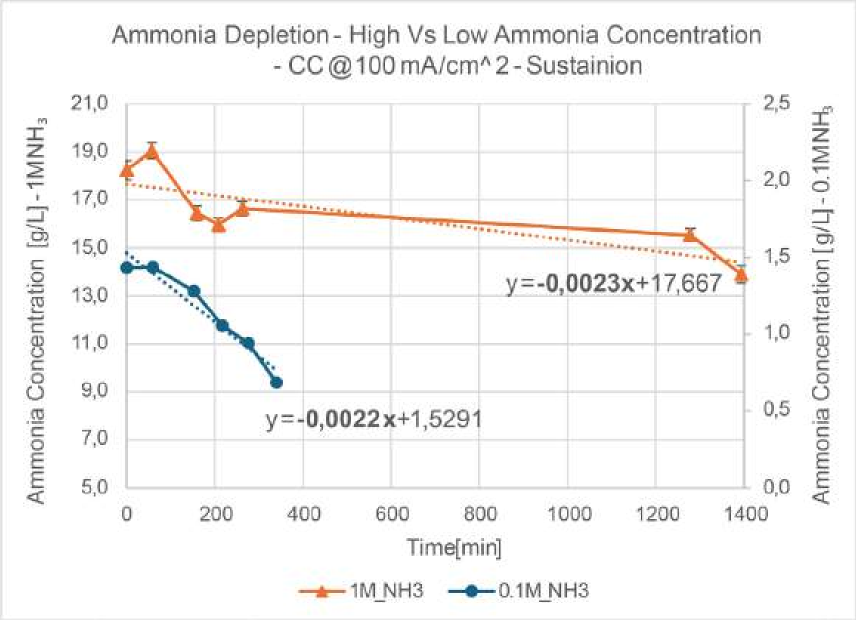
Figure 11. Difference in pH Evolution During Experiment Run - Nafion Vs. Sustainion



4.4. Effect of Initial Ammonia Concentration on Depletion Rate

Experiments conducted at low (approximately 0.1 M) and high (approximately 1 M) initial ammonia concentrations at 100 mA cm^{-2} with Sustainion yielded near-identical depletion slopes: -0.0022 g L^{-1} min^{-1} and -0.0024 g L^{-1} min^{-1} respectively. Despite a 10-fold difference in starting concentration, the rate of ammonia removal was unchanged. This concentration-independence is consistent with apparent zero-order kinetics with respect to bulk ammonia, confirming that under galvanostatic operation the depletion rate is determined by the imposed current density rather than by substrate availability over the investigated range.

Figure 12. Ammonia Depletion Rate at High vs. Low Initial Ammonia Concentration



5. Discussion

5.1. Real Wastewater Is a Viable Electrochemical Feed

A foundational concern in translating electrochemical ammonia treatment from laboratory to practice is whether the complexity of real wastewater fundamentally degrades system performance relative to idealized laboratory conditions. The results presented here provide a clear answer. Under alkaline operating conditions (1 M KOH), the ammonia depletion rate in real municipal wastewater was indistinguishable from that in a model electrolyte within experimental uncertainty, and average cell voltages differed by less than 20%. This equivalence is significant. It indicates that the dissolved constituents of post-digestion municipal wastewater, despite elevated chloride and bicarbonate content, do not introduce prohibitive electrochemical interference when conductivity and pH are controlled by alkaline electrolyte addition. The existing body of electrochemical ammonia oxidation literature, almost entirely based on synthetic solutions, can therefore be considered a reasonable foundation for predicting performance in real treatment contexts, provided that electrolyte conditions are appropriately managed.

5.2. Role of Supporting Electrolyte (KOH)

The necessity of a supporting electrolyte was unambiguous. Without KOH addition, cell voltages exceeded 40 V at 200 mA cm^{-2}, an approximately 7-fold increase over the KOH-supported case, rendering continuous operation impractical from both an energy and equipment standpoint. The root cause is insufficient ionic conductivity in the raw wastewater, which drives large ohmic losses even at moderate current densities. While a comparable depletion rate was momentarily achievable in a narrow stable window, this does not represent a viable operational strategy.

The addition of 1 M KOH provided a conductive and chemically stable electrolyte environment, resulting in far lower operating voltages and improved voltage stability over time. The presence of KOH also ensured strongly alkaline conditions, favoring ammonia over ammonium and supporting consistent electrochemical oxidation at the anode. These experiments conducted without KOH therefore serve as a feasibility boundary rather than a competing operational strategy, demonstrating that a supporting electrolyte is required for practical electrochemical ammonia depletion under the investigated conditions. Future work should explore the minimum KOH concentration required for stable operation, as well as alternative alkaline additives compatible with downstream treatment processes.

5.3. Effect of Current Density on Ammonia Depletion and Energy Demand

Current density emerged as the key operational parameter influencing both ammonia depletion behavior and electrical demand. A large improvement in system performance was observed when increasing the current density from 50 to 100 mA cm^{-2}. Within this range, ammonia depletion rates increased substantially, from 0.8 mg L^{-1} min^{-1} to 2.4 mg L^{-1} min^{-1}, while the associated increase in cell voltage remained moderate, from 4.3 V to 5.6 V. In contrast, further increasing the current density from 100 to 200 mA cm^{-2} resulted in a more pronounced voltage increase (5.6 V to 8.9 V) alongside a less-than-proportional gain in depletion rate (from 2.4 to 7.1 mg L^{-1} min^{-1}) and no meaningful improvement in Faradaic or removal efficiency. This pattern is consistent with theoretical expectations: at higher anodic potentials, oxygen evolution competes increasingly effectively with ammonia oxidation for available charge [3, 8, 9].

The observation that depletion rate scales with applied current regardless of ammonia concentration in the feed means that system throughput can be controlled directly by adjusting current density, providing a straightforward handle for real-time process control in response to varying influent loads. For treatment applications powered by intermittent renewable sources, operating at moderate current densities is likely to be the optimal strategy, delivering significant removal rates while maintaining acceptable energy efficiency.

5.4. Membrane Effects: Nafion vs. Sustainion

Both Nafion and Sustainion membranes enabled comparable ammonia depletion rates, with depletion slopes of -2.4 mg L^{-1} min^{-1} and -2.2 mg L^{-1} min^{-1} respectively under identical operating conditions. Despite similar short-term depletion behavior, distinct differences were observed in electrolyte pH stability. The Sustainion membrane maintained strongly alkaline conditions throughout extended operation, consistent with its anion exchange functionality, which facilitates hydroxide ion transport from cathode to anode. Under alkaline electrolysis, hydroxide ions are consumed at the anode during ammonia oxidation and generated at the cathode during hydrogen evolution, as described in the half-reactions in Section 2.3. Sustained operation therefore requires effective redistribution of hydroxide ions to maintain a stable alkaline environment.

In contrast, Nafion, a cation exchange membrane, does not facilitate hydroxide transport to the same extent. As a result, prolonged operation led to progressive depletion of hydroxide ions in the anolyte and a sharp pH drop at later times. It should be noted that pH is a logarithmic scale, such that changes at high pH correspond to large variations in hydroxide ion concentration. As ammonia oxidation consumes hydroxide ions at the anode, this insufficient replenishment can alter the electrochemical environment and potentially affect reaction pathways. For extended operation at pilot or full scale, the pH drift observed with Nafion could progressively degrade performance in ways not captured by short-duration laboratory experiments. Supporting efficiency metrics, including Faradaic efficiency and ammonia removal efficiency, differed between the two membranes, with Sustainion exhibiting lower Faradaic efficiency alongside higher measured ammonia crossover. These differences are interpreted as indicators of contrasting ion transport pathways rather than intrinsic differences in catalytic activity, and are treated as contextual indicators of system behavior rather than definitive measures of membrane performance.

5.5. Effect of Initial Ammonia Concentration

The similarity of depletion slopes across a 10-fold difference in initial ammonia concentration, at -2.2 mg L^{-1} min^{-1} for the low concentration and -2.3 mg L^{-1} min^{-1} for the high concentration, is consistent with apparent zero-order behavior with respect to ammonia concentration over the investigated operating window. Under galvanostatic conditions, this indicates that the rate of ammonia depletion was governed primarily by the imposed current density rather than by ammonia concentration. Increasing the initial ammonia concentration extended the duration over which depletion could be sustained but did not significantly increase the instantaneous depletion rate.

This concentration-independence has direct implications for scale-up and process design. For a given current density, treatment time scales linearly with total ammonia loading, independent of feed concentration, which simplifies the design of systems intended to treat concentrated post-digestion effluents. It is noted, however, that this zero-order interpretation applies only to the concentration range and time window examined in this study, and that deviations from this behavior may occur at extended operation or at lower ammonia concentrations approaching the detection limit.

5.6. Implications and Outlook

The results of this study position electrochemical ammonia oxidation as a technically credible component of next-generation wastewater treatment infrastructure. The modular, electrically driven nature of electrochemical systems makes them naturally compatible with intermittent renewable electricity. Unlike biological nitrogen removal, which requires continuous stable conditions, electrochemical reactors can be ramped up or down in response to electricity availability and price, a form of demand-side flexibility that could reduce the operational cost of treatment while supporting grid stabilization. The concurrent production of hydrogen at the cathode ($2NH_3 -> N_2 + 3H_2$) represents a potential value-recovery pathway, partially offsetting the electrical input required for treatment.

The zero-order kinetics observed across a wide concentration range suggest particular suitability for treating concentrated nitrogen streams, such as digestate or sludge centrate, that are difficult to handle within conventional biological treatment trains. The concentration-independence of removal rate means that high-load streams do not require proportionally longer hydraulic retention times, enabling compact system designs appropriate for integration into existing treatment plants.

Importantly, the study demonstrates that electrochemical performance in real wastewater is largely governed by operational parameters (current density, electrolyte composition, membrane type) rather than by the inherent complexity of the wastewater matrix. This operational controllability is a key advantage over biological treatment, where performance is mediated by microbial ecology that responds slowly and unpredictably to changes in influent character.

Future work should prioritize: replicated experiments to establish statistical reproducibility; complete nitrogen mass balances including nitrite, nitrate, and gas-phase ammonia; systematic optimization of KOH concentration to identify the minimum required for stable operation; investigation of electrode materials with higher intrinsic selectivity for ammonia oxidation over oxygen evolution; and long-duration experiments to characterize electrode stability and membrane degradation. Eventual pilot-scale testing should incorporate flow-through operation with continuous or semi-continuous feed, enabling evaluation of hydraulic residence time as an additional design parameter.

6. Conclusion and Future Work

This thesis investigated electrochemical ammonia depletion from real municipal wastewater using a laboratory-scale alkaline electrolyzer operated under controlled galvanostatic conditions. The study aimed to evaluate system behavior under realistic wastewater conditions, assess the influence of key operational parameters, and establish baseline performance trends relevant for future development of electrochemical ammonia treatment technologies.

Experiments comparing model electrolytes and real wastewater demonstrated that, when supported by sufficient alkalinity, ammonia depletion behavior was comparable in both systems. This indicates that wastewater complexity did not fundamentally inhibit electrochemical ammonia oxidation under the investigated conditions and supports the relevance of controlled laboratory studies for informing treatment of real streams.

The presence of a supporting electrolyte was shown to be essential for practical operation. While ammonia depletion was observed both with and without added KOH, operation without supporting electrolyte required substantially higher cell voltages, rendering such conditions impractical from an energy perspective. Systematic variation of current density revealed clear trade-offs between ammonia depletion rate and electrical demand. Increasing current density accelerated ammonia removal, but gains diminished at higher values due to increased voltage requirements and competing reactions. Across the investigated concentration range, ammonia depletion exhibited linear behavior consistent with apparent zero-order kinetics with respect to ammonia concentration over the observed time window, indicating current-limited operation.

Membrane selection influenced operational stability rather than instantaneous ammonia depletion rates. While both Nafion and Sustainion membranes enabled comparable ammonia depletion, Sustainion maintained more stable alkaline conditions during extended operation. Overall, the results demonstrate that electrochemical ammonia depletion from real wastewater is technically feasible and strongly governed by operational parameters such as current density, electrolyte composition, and membrane transport behavior. The findings provide a coherent experimental basis for future work focused on system optimization, extended operation, and improved mass balance resolution, contributing to the development of electrochemical approaches as complementary solutions for nitrogen management in wastewater treatment.

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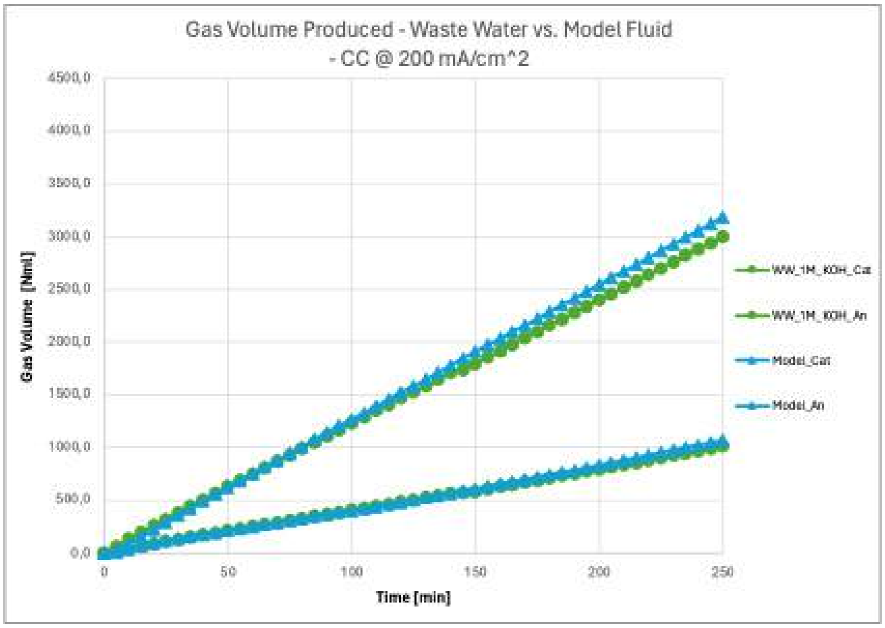
Appendices

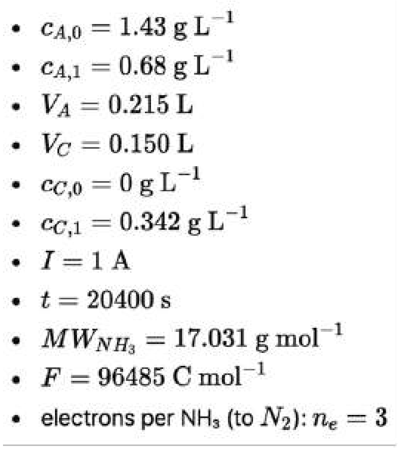
Appendix 1: This appendix shows the total gas volume produced over time at the cathode and anode during galvanostatic operation at 200 mA cm^{-2}.



Appendix 2: This annex provides a representative calculation framework illustrating how ammonia conversion, crossover, and efficiency metrics were determined.

The example shown corresponds to the experiment conducted at 100 mA cm^{-2} using a Sustainion membrane. All calculations in the main text follow the same methodology.

Input Parameters



- $c_{A,0} = 1.43\ \mathrm{g\ L^{-1}}$
- $c_{A,1} = 0.68\ \mathrm{g\ L^{-1}}$
- $V_A = 0.215\ \mathrm{L}$
- $V_C = 0.150\ \mathrm{L}$
- $c_{C,0} = 0\ \mathrm{g\ L^{-1}}$
- $c_{C,1} = 0.342\ \mathrm{g\ L^{-1}}$
- $I = 1\ \mathrm{A}$
- $t = 20400\ \mathrm{s}$
- $MW_{NH_3} = 17.031\ \mathrm{g\ mol^{-1}}$
- $F = 96485\ \mathrm{C\ mol^{-1}}$
- electrons per NH_3 (to N_2): $n_e = 3$

Anolyte moles at start

$$n_{A,0} = \frac{c_{A,0}V_A}{MW} = \frac{(1.43\,\mathrm{g\,L^{-1}})(0.215\,\mathrm{L})}{17.031\,\mathrm{g\,mol^{-1}}} = 0.01805\,\mathrm{mol}$$

Anolyte moles at end

$$n_{A,1} = \frac{c_{A,1}V_A}{MW} = \frac{(0.68\,\mathrm{g\,L^{-1}})(0.215\,\mathrm{L})}{17.031\,\mathrm{g\,mol^{-1}}} = 0.00858\,\mathrm{mol}$$

Catholyte moles at end (crossover)

$$n_{C,1} = \frac{c_{C,1}V_C}{MW} = \frac{(0.342\,\mathrm{g\,L^{-1}})(0.150\,\mathrm{L})}{17.031\,\mathrm{g\,mol^{-1}}} = 0.00301\,\mathrm{mol}$$

NH_3 removed from anolyte

$$n_{\text{removed}} = n_{A.0} - n_{A.1} = 0.01805\,\mathrm{mol} - 0.00858\,\mathrm{mol} = 0.00947\,\mathrm{mol}$$

NH_3 crossed to catholyte

$$n_{\text{crossed}} = n_{C,1} - n_{C,0} = 0.00301\,\mathrm{mol} - 0\,\mathrm{mol} = 0.00301\,\mathrm{mol}$$

NH_3 oxidized

$$n_{\text{oxidized}} = n_{\text{removed}} - n_{\text{crossed}} = 0.00947\,\mathrm{mol} - 0.00301\,\mathrm{mol} = 0.00646\,\mathrm{mol}$$

Actual charge passed

$$Q = It = (1\,\mathrm{A})(20400\,\mathrm{s}) = 20400\,\mathrm{C}$$

Theoretical charge for ammonia oxidation to N_2

$$Q_{\text{theoretical}} = n_e F n_{\text{oxidized}} = (3)(96485\,\mathrm{C\,mol^{-1}})(0.00646\,\mathrm{mol}) = 1868.69\,\mathrm{C}$$

Faradiac efficiency (AOR)

$$FE = \frac{Q_{\text{theoretical}}}{Q} = \frac{1868.69\,\mathrm{C}}{20400\,\mathrm{C}} = 0.0916 \approx 9.16\%$$

Crossover fraction of initial

$$f_{\text{cross}} = \frac{n_{\text{crossed}}}{n_{A,0}} = \frac{0.00301\,\mathrm{mol}}{0.01805\,\mathrm{mol}} = 0.1669 \approx 16.7\%$$

Oxidized fraction of initial

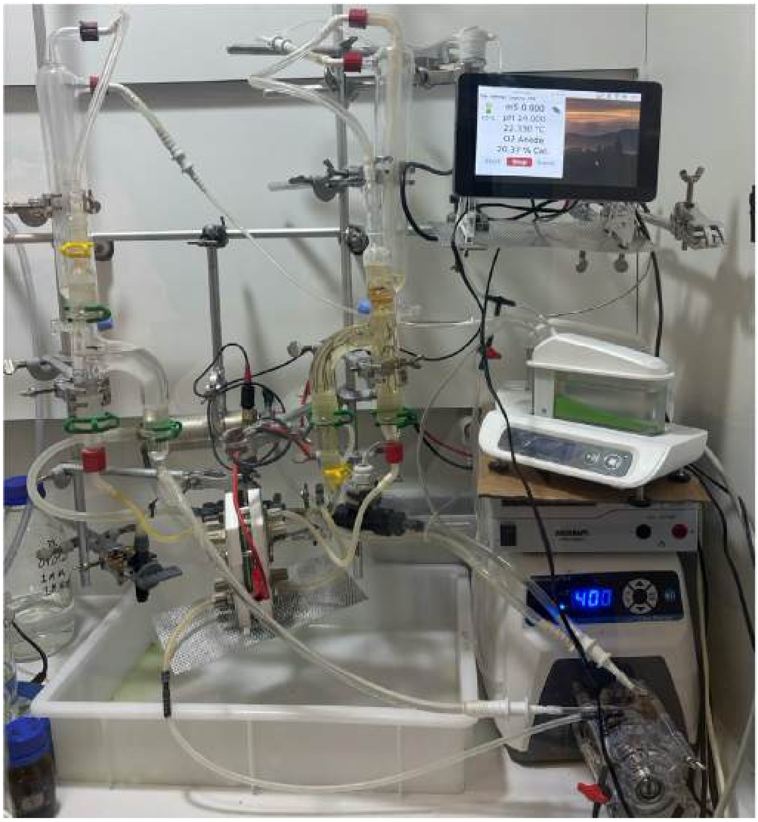
$$f_{\mathrm{ox}} = \frac{n_{\mathrm{oxidized}}}{n_{A,0}} = \frac{0.00646\,\mathrm{mol}}{0.01805\,\mathrm{mol}} = 0.3576 \approx 35.8\%$$

Result summary

- $n_{A,0} = 0.01805\ \mathrm{mol}$
- $n_{A,1} = 0.00858\ \mathrm{mol}$
- $n_{C,1} = 0.00301\ \mathrm{mol}$
- $n_{\mathrm{removed}} = 0.00947\ \mathrm{mol}$
- $n_{\mathrm{crossed}} = 0.00301\ \mathrm{mol}$
- $n_{\mathrm{oxidized}} = 0.00646\ \mathrm{mol}$
- $Q = 20400\ \mathrm{C}$
- $Q_{\mathrm{theoretical}} = 1868.69\ \mathrm{C}$
- **FE (AOR) = 9.16%**
- **Crossover fraction = 16.7%**
- **Oxidized fraction = 35.8%**

Appendix 3: This annex depicts the real system set up for the single pump head configuration

Appendix 4: This appendix depicts the real system set up for the double pump head configuration



Greener Farms, Smarter Energy: Exploring Biogas Utilization Pathways

Saeed Alavi (Entrance)
Sander Dijk (Entrance)
Zohre Kurt (Entrance)

This study compares three farm-scale biogas utilization pathways—combined heat and power (CHP), biogas upgrading, and bio-methanation—using process simulation and life cycle assessment to identify the most suitable option for on-farm application. Bio-methanation showed the highest practical energy efficiency, while CHP exhibited the lowest overall environmental burdens. Freshwater eutrophication and climate change were the dominant impact categories across all pathways, largely due to digestate and manure management. The findings highlight the need to jointly consider energy performance and environmental impacts when selecting farm-scale biogas utilization strategies.

08

1. Introduction

Excessive reliance on fossil fuels to meet global energy demands has created numerous problems for today's societies. On the one hand, this reliance leads to several environmental issues due to increased concentrations of carbon dioxide and methane in the atmosphere, which in turn drive global warming (Chu et al., 2024). On the other hand, it also causes economic instability because of the inherently volatile nature of fossil fuel prices (International Energy Agency, 2025). The numerous challenges arising from the use of fossil fuels have led many countries around the world, especially in Europe, to move towards producing energy from renewable sources (Meyer et al., 2018). This shift has also been legally and politically mandated through various international frameworks, such as the Paris Agreement and the European Green Deal.

Among various renewable energy sources such as wind, solar, and hydropower, biogas produced through Anaerobic Digestion (AD) of organic residues is attracting increasing attention as it offers several advantages (Aworanti et al., 2023). This energy carrier not only utilizes agricultural waste — particularly animal manure, a major source of greenhouse gas emissions — as feedstock but also yields a gaseous fuel that can be readily stored or injected into existing gas grids (Savickis et al., 2020). Additionally, as a by-product of the AD process, digestate sludge is produced, which can be used as a biofertilizer. The significance of biogas production in European Union (EU) countries is reinforced by legislative measures such as RED II and RED III which establish an ambitious target of 35 billion cubic meters of sustainable biomethane per year by 2030.

Driven by the multiple environmental, economic, and regulatory benefits associated with biogas systems, several sectors are actively expanding their biogas production capacity (International Energy Agency, 2023). In particular, the agricultural sector has gained increasing attention due to its direct and continuous access to large volumes of organic residues, including manure and crop waste, making it highly suitable for decentralized biogas production (O'Connor et al., 2021). Farms, therefore, represent a strategic opportunity for implementing small-scale anaerobic digesters that can process feedstocks on-site, reducing the need for transportation and improving resource efficiency. In response to supportive policy frameworks and sustainability targets, many European countries have increasingly promoted the deployment of farm-scale biogas systems. For instance, as of 2024, approximately 80% of biogas digesters in Germany and 76% in France are located on farms, highlighting the strong integration of biogas technologies within the agricultural sector (Gustafsson et al., 2024).

Biogas produced at the farm scale can be utilized through several pathways, depending on the technical configuration, energy demand, and economic objectives of the operation. The first and perhaps most established option is its use in a combined heat and power (CHP) unit, where biogas is converted into electricity and heat for on-site use or export (Sidek et al., 2022). Another increasingly important route is the upgrading of biogas through carbon dioxide removal to produce biomethane, a higher-value renewable gas that can be injected into the natural gas grid or used as a transport fuel (Ahmed et al., 2021). A further emerging option is bio-methanation, in which additional methane is generated by converting the carbon dioxide fraction of biogas with renewable hydrogen, thereby increasing methane yield from the same feedstock (Rusmanis et al., 2019).

As farm-scale biogas production and its on-farm utilization continue to expand, it is essential to identify options that deliver the highest energy efficiency while simultaneously minimizing environmental burdens. From an energy security perspective, priority should be given to utilization pathways that maximize energy efficiency and resource recovery. Furthermore, in line with carbon neutrality objectives, it is critical to comprehensively evaluate how biogas production and its various on-farm applications impact the environment. This includes identifying the most affected environmental impact categories to enable evidence-based and context-specific recommendations. Despite its importance, the existing literature provides limited insight into these integrated considerations, and this study seeks to address this gap.

2. Methodology

In order to assess the energy efficiency and environmental implications of three feasible farm-scale biogas utilization pathways — CHP, biogas upgrading, and biological methanation — a hypothetical dairy farm housing 250 cows was defined as the reference case. The farm was assumed to be equipped with an anaerobic digestion (AD) system producing 29.6 m^3 of biogas , with a composition of 60% methane and 40% carbon dioxide, following desulfurization and dehumidification. This biogas output was estimated from the manure produced by the herd and the biogas yield of dairy manure reported in the literature. Furthermore, the farm was assumed to operate a wind turbine capable of generating sufficient electricity to meet the energy demand of the evaluated process options.

2.1. Technical Modelling

Aspen Plus version 14 was employed to calculate the energy content of the input and output streams based on their higher heating values (HHVs). This approach enabled a consistent evaluation of the energy flows across the different process configurations and provided the basis for comparing their overall energy performance.

The simulated process model of the CHP configuration is presented in Figure 1. In this process, biogas and air are fed into a combustion chamber, where the biogas is combusted to produce a high-temperature gas stream. This hot stream is subsequently expanded through a turbine to generate electricity. The remaining thermal energy is then recovered through heat exchangers, enabling the utilization of waste heat and improving the overall energy efficiency of the system (Furtado Amaral et al., 2020).

Figure 1. Simulation model of the CHP pathway in Aspen Plus

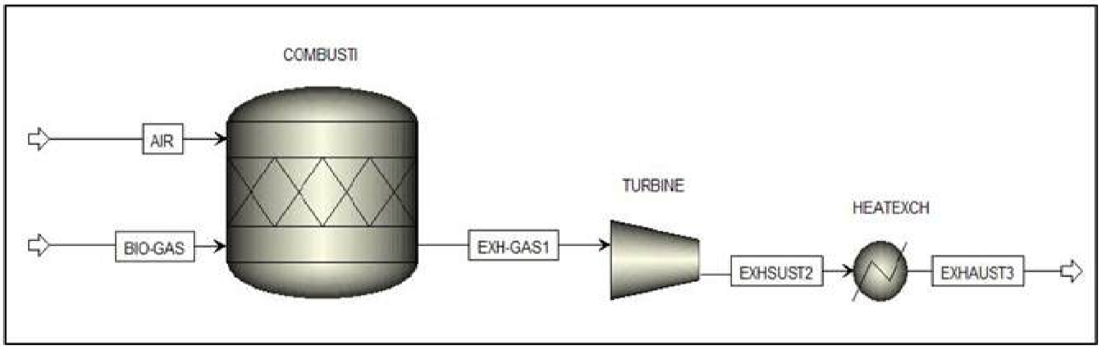
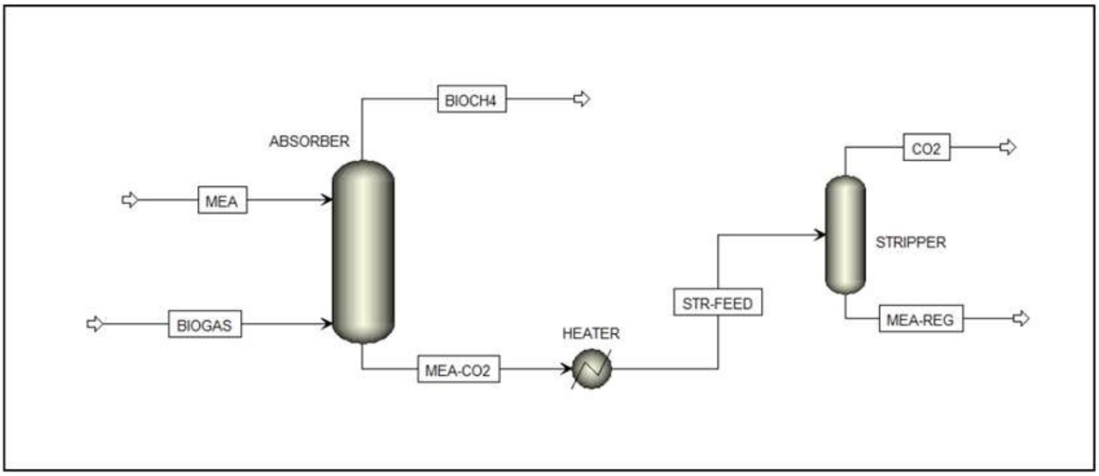


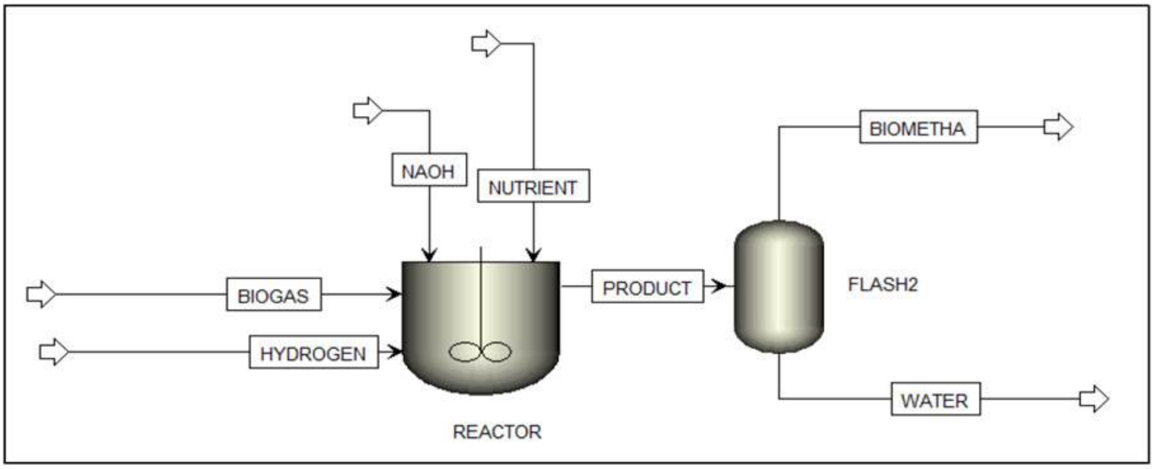
Figure 2 presents the simulated configuration of the biogas upgrading pathway. In this process, biogas and monoethanolamine (MEA) are introduced into an absorption unit, where MEA selectively captures carbon dioxide from the biogas stream. As a result, an upgraded gas stream with a high methane content is produced, while the CO_2-rich MEA solution is directed to a regeneration unit for solvent recovery. In the regeneration step, the absorbed carbon dioxide is released, allowing the MEA to be recycled back into the process and improving the overall efficiency of the upgrading system.

Figure 2. Simulation model of the upgrading pathway in Aspen Plus



The simulated configuration of the bio-methanation pathway is presented in Figure 3. In this process, biogas and hydrogen are supplied to the reactor at a stoichiometric ratio of 1:4, while nutrients and NaOH are added to support microbial activity, including cell maintenance and enzyme synthesis, and to maintain a suitable pH for biological conversion. Through microbial action, carbon dioxide and hydrogen are converted into methane and water based on Sabatier reaction, thereby increasing the methane content of the product gas (Feickert Fenske et al., 2023).

Figure 3. Simulation model of the bio-methanation pathway in Aspen Plus



The developed Aspen Plus models, shown in Figures 1-3, were executed to simulate the three biogas utilization pathways and to determine the energy content of all input and output streams. For all pathways, stream energy content was calculated based on the higher heating value (HHV). However, for the bio-methanation process, the energy content of the input streams was evaluated using two different methods: one based on the HHV and the other based on the energy demand associated with hydrogen production. This additional assessment was included because hydrogen supply plays a critical role in the overall energy performance of the bio-methanation route. Consequently, the energy efficiency of the processes was calculated according to the following equation:

$$\text{Energy efficiency} = \frac{\text{net output energy}}{\text{total input energy}}$$

2.2. Environmental Modelling

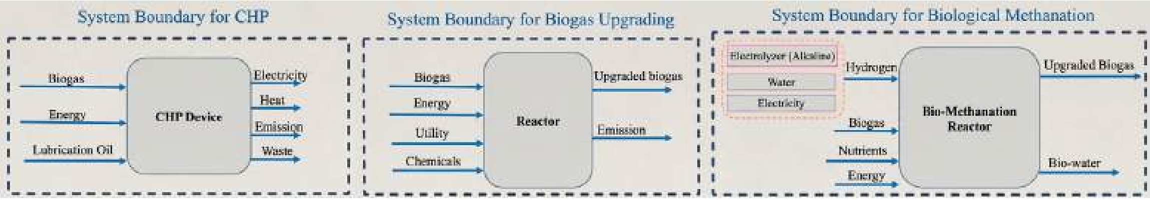
To assess the environmental footprint of the three selected biogas utilization pathways, a Life Cycle Assessment (LCA) was conducted using openLCA software in combination with the ecoinvent 3.11 APOS Unit Processes database. This framework enabled a systematic evaluation of the environmental impacts associated with each process configuration across its relevant life cycle stages. In accordance with ISO 14040/14044, the LCA was structured following the four standard phases (Esteves et al., 2019; Starr et al., 2012):

2.2.1. Goal and Scope Definition

The goal of this study is to evaluate the environmental footprint of three farm-scale biogas utilization pathways: direct use in a CHP unit, upgrading to biomethane, and conversion through a bio-methanation pathway. By comparing these alternatives, the study aims to identify their relative environmental performance and provide insights into the sustainability of farm-scale biogas utilization.

- **A functional unit** of 1 m^3 of biogas processed was adopted for all three pathways in order to ensure a consistent and comparable assessment of their environmental impacts. This common basis facilitates a direct comparison between the assessed processes at the farm scale.
- **System boundary:** The system boundaries for the three scenarios are presented in Figure 4. They were defined to reflect the relative simplicity of farm-scale biogas utilization systems, while excluding the more complex infrastructure and auxiliary processes typically associated with industrial-scale installations. This boundary selection ensures that the assessment remains focused on process configurations that are technically relevant and realistically applicable at the on-farm level.

Figure 4. The system boundary of the modelled pathways
(left: CHP, middle: upgrading, right: bio-methanation)



2.2.2. Life Cycle Inventory

As the next stage of the LCA, the life cycle inventory (LCI) for the selected scenarios was developed using process data obtained from Aspen Plus, background data from the ecoinvent database, and supplementary information from relevant literature sources. This combined approach ensured a comprehensive and consistent inventory for all assessed pathways. The resulting LCI data for the three scenarios are provided in Tables A1–A3 in the Appendix.

2.2.3. Life Cycle Impact Assessment

As the next step, the constructed product systems of the three utilization pathways were modelled and executed in openLCA using the Environmental Footprint impact assessment method, version 3.1 (EF v3.1), as recommended by the European Commission. The resulting environmental impacts were then normalized and weighted using EF v3.1 (Global Reference 2010) in accordance with the European Commission's guidelines (Crenna et al., 2017). This procedure enables impact categories expressed in different units to be compared on a common basis and facilitates the identification and ranking of the most significant environmental burdens associated with each scenario.

2.2.4. Interpretation

Based on the results obtained in the previous step, the three impact categories with the highest environmental burdens were selected for further interpretation.

3. Results and Discussions

3.1. Energy Efficiency

The results of the energy efficiency assessment for the three processes, as described in the methodology, are shown in Table 1.

Table 1. Energy efficiency results of the three utilization options

CHP	84.20%
Biogas Upgrading	87.00%
Bio-methanation (Based on HHV of Hydrogen)	94.32%
Bio-methanation (Based on energy required for H_2 production)	83.90%

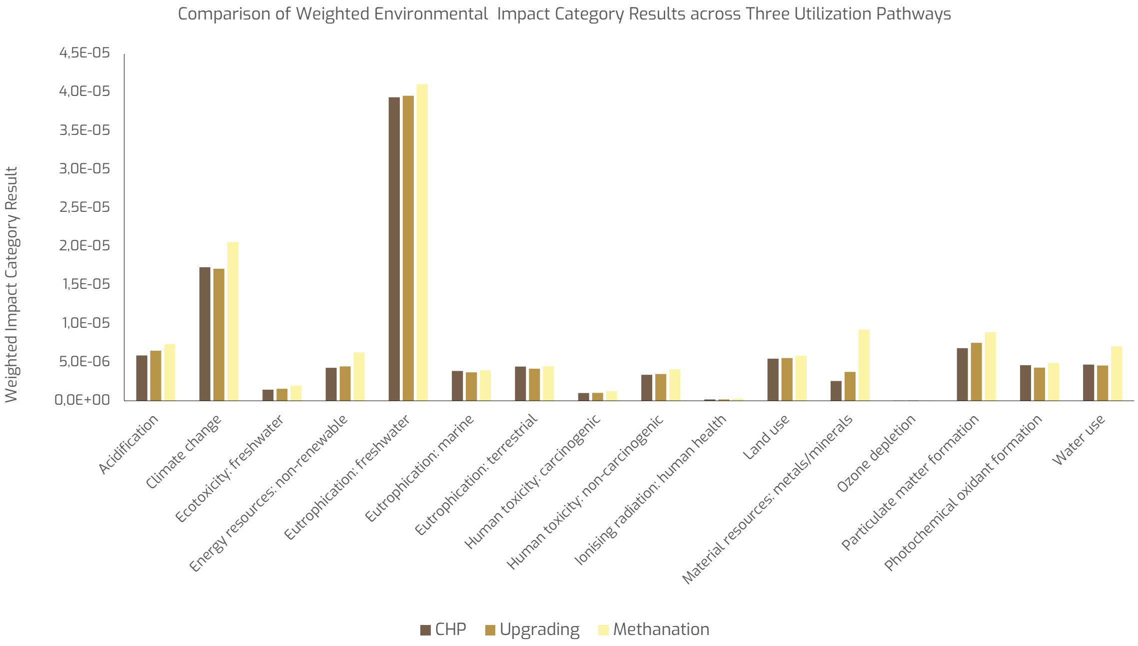
As shown in Table 1, when the energy content of hydrogen is evaluated on the basis of its higher heating value (HHV), bio-methanation achieves an energy efficiency of 94.32%, making it the most efficient of the three pathways. However, when the substantial energy demand associated with hydrogen production is taken into account, the efficiency of bio-methanation decreases to approximately 83.9%. Under this assumption, biogas upgrading, with an efficiency of 87%, becomes the most energy-efficient option among the evaluated pathways. This result highlights the strong influence of hydrogen supply on the overall performance of the bio-methanation route.

It should also be noted that both bio-methanation and biogas upgrading produce a methane-rich gas that can be more readily stored, transported, or injected into the natural gas grid, offering greater flexibility in energy use. In contrast, the CHP system generates a substantial amount of heat, and even in the presence of relatively advanced infrastructure, such as district heating networks, a considerable fraction of this heat may remain underutilized or be lost, particularly during the summer period when heat demand is low(Chen et al., 2020). This characteristic gives both bio-methanation and biogas upgrading a practical advantage over CHP in terms of product versatility and storage potential.

3.2. Environmental Results

The results of the constructed LCA models for the three processes, covering all 16 impact categories included in the EF v3.1 method, are presented in Figure 5. Based on these results, the following discussion highlights the principal findings and their implications:

Figure 5. Comparison of weighted environmental category results across three utilization pathways



Across all utilization pathways, Eutrophication: Freshwater exhibits the highest environmental burden. This outcome is primarily attributable to the large quantities of digestate sludge produced as a by-product of biogas production. Digestate sludge contains high amount of bioavailable nutrients — principally ammonium and phosphate — that are readily mobilized by leaching and surface runoff. During storage or field application, these nutrients can be transported to adjacent freshwater bodies under rainfall or irrigation, resulting in strong eutrophication effects (Martín-Sanz-Garrido et al., 2025; Van Stappen et al., 2016).

The second-largest impact category for all three modelled processes is climate change. Similar to eutrophication, this is largely attributable to the substantial volumes of digestate generated during anaerobic digestion. The digestate contains dissolved methane and biodegradable organic residues, which may be released to the atmosphere during storage, handling, or land application, resulting in high GHG emissions. In addition, when digestate sludge is applied to soil as a biofertilizer, some of its ammonia content is converted to nitrous oxide (N_2O) through nitrification and denitrification. Nitrous oxide is a greenhouse gas with a high global warming potential, thereby further increasing the climate burden (Häfner et al., 2021). Manure used as feedstock for anaerobic digestion also contributes to this category because its partial decomposition during collection, transport, and storage releases methane and other greenhouse gases to the atmosphere.

Unlike the first and second impact categories, which are common to all three pathways, the third-largest category differs between them. For the CHP and upgrading pathways, the third-largest impact category is particulate matter formation. This impact is mainly associated with substantial ammonia emissions from digestate and manure. These emissions contribute to PM2.5 formation in the atmosphere and cause adverse effects on human health (Kral et al., 2020). In contrast, for the bio-methanation pathway, the third-largest impact category is material resources, reflecting the greater demand for materials and components required for the manufacture of the electrolyser and the bioreactor.

Another finding that can be drawn from Figure 5 is that the three processes can also be compared from an environmental perspective. As shown in the Figure 5, the CHP pathway is the most environmentally favourable, producing the lowest impacts across nearly all categories. Results for the biogas-upgrading pathway are only marginally higher than those for CHP. In contrast, bio-methanation consistently exhibits the greatest environmental burden across all categories. The higher environmental burdens of the bio-methanation pathway can be attributed not only to its substantial electricity requirements for water electrolysis but also to the greater material demand for constructing the electrolyzer and reactor compared with the other two processes.

4. Conclusion

This study compared three farm-scale biogas utilization pathways — combined heat and power (CHP), biogas upgrading, and bio-methanation — in terms of both energy efficiency and environmental performance. By combining Aspen Plus process simulation with life cycle assessment using openLCA and the EF v3.1 method, the research provided an integrated basis for evaluating the suitability of these pathways for on-farm application.

The results showed that bio-methanation achieved the highest energy efficiency when hydrogen was evaluated only based on its higher heating value. However, when the actual energy required for hydrogen production was considered, its efficiency decreased significantly, and biogas upgrading became the most energy-efficient pathway. CHP showed slightly lower energy efficiency but remained a technically viable option for decentralized farm-scale systems.

From an environmental perspective, freshwater eutrophication and climate change were identified as the most significant impact categories across all three pathways. These impacts were mainly driven by digestate and manure management, particularly nutrient losses and greenhouse gas emissions during storage and land application. CHP had the lowest environmental burdens overall, while biogas upgrading showed only slightly higher impacts. In contrast, bio-methanation was associated with the highest burdens due to its high electricity demand and greater material requirements.

Acknowledgment

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Appendices

The LCI used for LCA modelling of the three processes is shown here,

Table A1. Inventory Data Used for LCA Of CHP Pathway

		Amount	Unit	Amount per FU
Biogas		29	(m^3/hr)	1
CHP Device		1	item	2.14E-07[1]
Utility (Lubricating Oil)		1.94E-02	kg/hr	6.68E-04
Energy for CHP Operation		1.50	kWh	5.17E-02
Waste (Used Oil)		1.94E-02	kg/hr	6.70E-04
Direct Emission	CO_2	51.65	kg/hr	1.78E+00
	CO	3.20E-02	kg/hr	1.10E-03
	CH_4	1.52E-02	kg/hr	5.23E-04
	N_2O	1.65E-03	kg/hr	5.68E-05
	NO	9.89E-03	kg/hr	3.41E-04

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[1] It is calculated based on a lifetime of 20 years, and 8000 hrs. operation per year.

Table A2. Inventory Data Used for Biogas Upgrading Pathway

	Amount	Unit	Amount per FU
Biogas	29	m^3/hr	1
Charcoal	0.01305	kg/hr	0.00045
Monoethanolamine	0.002279	kg/hr	7.86E-05
Organic chemicals	0.000489	kg/hr	1.69E-05
Light fuel oil	5.17E-05	kg/hr	1.78E-06
Silicon product	6.75E-03	kg/hr	2.33E-04
Sodium chloride	0.001722	kg/hr	5.94E-05
Reactor	1	Item	3.53E-11
Energy	79.1207	MJ	2.7283
Compressed air	2.74E-02	m^3/hr	9.46E-04
Tap water	0.001405	kg/hr	4.84E-05

Table A3. Inventory Data Used for LCA Of Bio-Methanation Pathway

	Amount	Unit	Amount per FU
Biogas	29	m^3/hr	1
Hydrogen	3.78	kg/hr	1.30E-01
Electricity	12.43	kWh	3.45E-02
NaOH	3.29E-02	kg/hr	1.14E-03
NH_3	1.36E-02	kg/hr	4.69E-04
NH_4CL	1.71E-01	kg/hr	5.89E-03
Water, Nutrient	2.16E-01	kg/hr	7.44E-03
Water, NaOH	3.67E-01	kg/hr	1.27E-02

Contradictions Faced by Dairy Farming Families in the Netherlands Viewed from a Long-term Perspective Centred on Energy and Resources

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At the macro level, the Netherlands has become an agricultural giant thanks to its efficient, intensive farming practices. At the micro level, farmers are under pressure to make ever-larger investments and focus heavily on improving operational efficiency. This has led to a series of business decisions, which in turn have significant macro-level effects on nature and energy use. When researching Western industrial agriculture, it is useful to place developments in a long-term perspective, in which available forms of energy, natural resources, technology, ecology and population growth play a crucial role. Sociologists and cultural anthropologists who adopt a long-term approach regard a society's ability to harness and control energy from its environment as the primary function of culture. As the amount of energy used increases, socio-economic structures evolve, and the use of new technologies offers new opportunities when pressure is placed on existing resources.

Since 1950, the number of farms in the Netherlands has decreased by 85%, and a system has emerged that exerts pressure on the various participants. In the dairy farming sector, farming families are facing rising costs and encountering contradictions when it comes to government regulations, bank loans, and a wide range of societal challenges. This paper presents preliminary findings from an ongoing study based on public data, ethnographic research involving 34 in-depth interviews, and participatory observation. The first findings show that energy use in dairy farming has increased over the long term and that dairy farming families are adapting their business practices in response to efficiency requirements and the wider environment. Farmers need the support of society as a whole to develop new farming methods; they cannot do this on their own.

Keywords: Agriculture, Dairy farming, Energy, Long-term perspective, Contradictions. Adaptation, The Netherlands

09

1. Introduction

Over the past 175 years, the Netherlands has experienced a period of constant increases in production and efficiency, first in industry through the use of resources such as coal and oil, and subsequently in agriculture, which can be described as industrial agriculture (Bakker et al., 1992; Pimentel & Pimentel, 2008; Schot et al., 2000). Unlike traditional agriculture, this form of agriculture is capital-intensive, with a heavy reliance on industrial inputs such as fertilisers, fuels and metals (Barlett, 1989 ; Wojtynia et al., 2021).

According to some scientists, the era upon which the Western production system of agriculture and industry is built has reached its peak (Michaux, 2019; Smit, 2018; TNO, 2024; Weis, 2010). This is primarily due to the growing realisation since the beginning of the twenty-first century that the era of cheap and easily extractable fossil fuels, including coal, oil and natural gas, is reaching its limits (IEA, 2025; Heinberg, 2007). Some experts see new technologies as a solution through the more efficient use of waste streams and the use of renewable energy (Ros et al., 2025). Some experts advocate for agriculture involving more manual labour and a significant reduction in industrial inputs (Smit, 2018), or nature-inclusive agriculture where farming and nature are combined (Doorn, 2016).

The choices made by farming families in the Netherlands are closely linked to long-term developments (Barlett, 1989). Around 1950, farming in the Netherlands was still at the level of the local dairy and hand-milking. Subsequently, farmers were drawn into the process of rationalisation within industrial society through the use of artificial fertilisers, pesticides, new improved seeds and new techniques, resulting in higher yields for a growing population, increased earnings for farming families and an export-oriented focus (Bieleman, 2010; Karel, 2010; van der Heide et al., 2011). With this development, which became increasingly energy-intensive, a production system emerged that is driven by a network of financing, support and processing companies (Runhaar et al; Wojtynia et al., 2021).

A heavy reliance on industrial inputs in farm operations makes agriculture vulnerable to fluctuations in energy costs and the availability of, for example, fertiliser. Geopolitical tensions, such as the conflict between Russia and Ukraine or, very recently, around the Strait of Hormuz, are disrupting the flow of oil and fertiliser. Farming families, for example, are finding themselves facing high fuel and fertiliser prices, which, given their already slim margins, creates uncertainty about the future of their businesses. There are also concerns that the disruption to fertiliser supplies will lead to poorer harvests (FAO, 2026; OECD-FAO, 2025). The NRC recently reported that fertiliser traders are just a handful of companies that can easily collaborate and dictate prices; farmers are too numerous, find it difficult to form partnerships and are therefore unable to stand up to these companies in the fertiliser sector (Weeda, 2026).

However, there has also been an increase in pollution from nitrogen compounds, fertilisers and pesticides, and political and societal action to combat this (Jellema et al., 2025). Farming families are now faced with the need to invest in sustainability techniques that are very costly and therefore involve substantial loans. This gives the banking sector a greater role on the farm (van der Meulen et al., 2020). The involvement of the state and commercial companies on the farm has increased due to complex legislation, monitoring techniques and inspectors (van der Velden et al., 2025). For established farmers, there is uncertainty regarding the extent to which they can develop plans for the future (Vermunt et al., 2022).

This research places the developments in Dutch industrial agriculture within a long-term perspective, in which the available forms of energy, technology, ecology (climate, soil characteristics) and population growth play a crucial role. The aim is to provide insight into how structural historical developments influence the daily lives and business operations of farming families, and the contradictions they face.

2. Theoretical background

The research is situated within the long-term theory of cultural anthropologists and sociologists who emphasise that societies change in interaction with their natural environment (Harris, 1979; Nolan & Lenski, 1995; Steward, 1955). The cultural anthropologist Esther Boserup (1965), for example, views transformations as arising from population pressure on available resources, particularly agricultural land. She argues that new techniques are invented as a response to a crisis. As resources become scarcer, this can lead to a more efficient production process or, in the longer term, to a decline in population (Boserup; 1965). Technical innovations make it possible to convert new ecological resources into food, energy and economic activity. The cultural anthropologist Leslie White argues that culture evolves as per capita energy increases, and the sociologists Nolan and Lenski (1995) demonstrate that this is accompanied by changes in social structures and forms of equality and inequality (Nolan & Lenski, 1995; White, 1959).

What these experts emphasise is that technological progress does not necessarily go hand in hand with socio-economic or ecological improvement (Harris, 1977). Thus, the invention of new technologies is a necessity, but this can, for example, lead to greater dependency or inequality in society. For instance, because certain technologies are financially out of reach or too complex to use for some groups. Nolan and Lenski, as well as the cultural anthropologist Marvin Harris, argue that long-term social transformation processes are accompanied by changes in ideological systems, which are partly determined by the availability or scarcity of resources (Lenki, 2003; Harris, 1979). These social processes can be understood at three different levels; see also Figure 1.

- The conditions for existence: this encompasses society's relationship with its natural environment, such as the climate and resources. Population numbers and technology also form part of these conditions, as they represent the means of obtaining food and energy.
- The rules of existence: economic, political and social arrangements that production entails
- The explanations for existence: such as ideology, symbols, art and religion

In this study, these processes are used to analyse developments in Dutch agriculture and the contradictions faced by farming families.

Figure 1. Long-term societal processes. Adapted from Harris (1979), Nolan & Lenski (1995)

3. Research area and empirical method

In addition to a literature review and the consultation of public (quantitative) data on dairy farming in the Netherlands, fieldwork was carried out between April 2025 and February 2026 in the three northern provinces of the Netherlands: Groningen, Friesland and Drenthe (Figure 2). Data was collected through 34 semi-structured in-depth interviews with dairy farming families, The focus on dairy farming is chosen due to the significance and long history of dairy production in the north of the Netherlands, societal pressure and competition on land that dairy farmers currently face.

Within the dataset, there are 24 active dairy farms, six of which are run by farmers who have no successor. Nine farms have since ceased operations (since 2017) and three families took part in the buy-out scheme. The number of organic dairy farmers is representative of the 5% of Dutch organic dairy farmers (2 in each province).

Figure 2. Study area, number of farms and dairy farmers in Groningen, Friesland and Drenthe

The interviews, lasting an average of two hours, were conducted with the farming family, sometimes with an elderly couple and their children, and sometimes with just the farmer and his son(s). Using a timeline, we mapped out why certain choices were made in farm management, and discussed key events and changes. All interviews took place, following an invitation, at the farming families' homes. The conversations were recorded and transcribed by the first author. Finally, participant observation formed part of the fieldwork. The research was conducted in accordance with informed consent procedures and ethical guidelines. No AI tools were used.

The analysis combined a deductive and inductive approach, and included a light quantitative element by counting how often specific themes emerged. On the basis of literature and the theoretical framework used by anthropologists and sociologists who adopt a long-term perspective, ten characteristics of industrial agriculture guided the interviews and the initial coding phase (Barlett, 1989). Three characteristics (7–10) have been added that are applicable to the Dutch situation (Jellema et al., 2025; van der Meulen et al., 2020).

1. The use of complex technology
2. Energy use
3. The influence of the government
4. A tendency towards competition
5. Specialisation and overproduction
6. Interdependence between agricultura units and companies
7. Demographics; decline in family farms
8. Environmental interventions
9. Economic context; role of banks, credit
10. Social pressure

Relevant interview excerpts within these themes were then analysed, with new patterns and sub-themes emerging inductively from the data. Through an iterative coding process in Excel, the themes were refined and further specified step by step.

4.1 Result 1: How a complex socio-economic system has emerged in Dutch dairy farming

4.1.1 The ecological conditions for existence

Historically, 100% of respondents refer to the ecological conditions, such as the low-lying wet meadows, which have shaped agriculture in the Netherlands for centuries. In areas where arable farming was not possible, combined with a temperate climate, cattle can thrive and are able to turn grass into a product (milk). With few external inputs and low energy use, dairy production offered a chance of survival for farming families. One respondent explains this:

> *The problem is that there's a lot of land where there are farmers and where you can only grow grass, right? If you can do arable farming, that's great, but just like back there too, you really can't do arable farming there…So I think that for the balance of the world, a cow is a wonderful thing. Then they go on and on about our sector, but just look at how much our crops consume (46).*

Until the advent of artificial fertiliser, people were constantly searching for ways to fertilise the soil to make it more fertile. From 1913 onwards, artificial fertiliser was produced on a large scale using the Haber-Bosch process. One respondent explains that this enabled people to settle and grow crops in places where it had previously been impossible. The geographical location of the Netherlands meant that, as early as the 16th century, dairy products (including butter and cheese) were being exported from the Netherlands to countries such as England (Slicher van Bath, 1963). Since then, exports have expanded.

4.1.2 The advent of technology and the dawn of an energy-intensive era

In 1950, dairy farming was still at the stage of manual milking. With a growing population and the exodus of labour from agriculture, a significant intensification followed, leading to a shift in the use of direct energy (manual labour, feed and home-grown technology) towards an increase in indirect energy such as concentrated feed from outside the farm, fuels and artificial fertiliser (Table 1). Thanks to Marshall Aid, larger machinery and land consolidation, farmers were able to work more efficiently. In the 1970s, government subsidies, such as the WIR and interest subsidies, and banks encouraged investment in cubicle housing and milking machines. From 1976 onwards, dairies increasingly made the use of a cooling tank compulsory (Lei, 1992). One respondent recalls the 1980s:

It was all about growth, becoming more efficient. Above all, ensuring that more milk went into your tank. Everything became more expensive; those were also the years of inflation. The farm they bought was actually too expensive, but five years later the land price had already doubled. So that was a bit of a relief. The bank then became a bit more relaxed (47).

Table 1. Long-term technological innovations, yields and shifts in energy use in Dutch dairy farming

Year	Land/ farm (ha)	Yield/cow	Cow/ farm (#)	New technological input	Energy use direct/indirect %	Labour (hr/cow/yr)
1860-1900	8	2,300	5	• Introduction of cream separator (Laval centrifuge) • Beginning of dairy cooperatives • Improved butter and cheese production	90/10	
1901-1940	10	3,000	6	• Mechanisation begins (steam/ early engines. • Expansion of dairy cooperatives - (e.g. Friesland Campina origins) • Improved breeding and feeding		
1941-1960	12	3,900	7	• Introduction of tractors • Synthetic fertilisers increase • Post-war intensification • Early milking machines	60/40	350
1961-1965	14	4,120	10	• Wide-scale introduction of milking machines • Artificial insemination		
1966-1970	16	4,350	14	• Higher fertilizer use on grassland • Specialisation in dairy		
1971-1975	20	4,875	20	• Milk cooling tank • From hay to grass-silage • Loose housing system with cubicles	35/65	
1976-1980	22	5,340	36	• Maize feeding • High concentrate feeding		
1981-1985	25	5,700	40	• Cow identification for individual feeding • Wide-scale use USA Holstein-Friesian blood		100-150

Year	Land/ farm (ha)	Yield/cow	Cow/ farm (#)	New technological input	Energy use direct/indirect %	Labour (hr/cow/yr)
1986-1990	29	6,575	42	▪ Embryo transplantation		
1991-1995	31	6,975	51	▪ Environmental protection (e.g. manure injection)	20/80	
1996-2000	35	7,525	55	▪ Introduction milking robot		
2001-2010	42	8,300	70	▪ Rapid spread of milking robots ▪ Introduction of Precision agriculture ▪ GPS and automated feeding systems ▪ Farm management software		60-90
2011-2020	52	9,100	102	▪ Big data and sensor technology (cow monitoring) ▪ Improved genetics and breeding		
2021-2025	58	9,400	110	▪ AI-based herd management ▪ Low-emission housing systems	30/70	35-60

Source: Agrimatie, 2026; Bieleman, 2010; CBS, van Horne & Prins, 2002, p. 9; Shine et al, 2020; de Haan & Feikema, 2001. Years are estimated based on this literature and quantitative data.

4.1.3 The socio-economic organisation surrounding dairy farmers is taking shape

The generation of greater energy and yields (Table 1) went hand in hand with a network of organisations and extension workers supporting the farmers. With the support of European subsidies, agricultural extension played a key role in the modernisation of agriculture. Extension workers visited farmers to draw up investment plans, so that these could be financed through banks. The purchase of machinery made it more attractive to specialise in a single product or crop, which led to further economies of scale. During this period, 10 families sought a new place to live in order to continue growing, partly due to competition for land from other farmers, housing development and industry.

Farmers realised that producing more milk gave them greater financial scope to move forward. 25 families say that you mustn't fall behind in the changing environment, otherwise you couldn't survive. One respondent explains:

> *You just went along with it… the business had to keep going. Otherwise you wouldn't earn anything, you wouldn't have enough cows (48).*

For a long time, Dutch agriculture benefited from cheap family labour and investments by farming families, keeping production costs low and allowing output to grow. But farmers became increasingly dependent on concentrated feed, artificial fertiliser, the banks and the purchase of additional land. High production generated significant export revenue, but also made the sector vulnerable to overproduction. That is why the milk quota was introduced in 1983. In the 1990s, there was a growing realisation that artificial fertilisers, pesticides and manure had harmful effects on the environment and soil fertility (Bieleman, 2010). Respondents talk about the introduction of MINAS, manure accounting and stricter rules for manure storage. Pig manure was transported from the southern Netherlands to the northern provinces and spread across the countryside.

4.2 Result 2 – Contradictions faced by dairy farming families

4.2.1 Dependency – less freedom of choice

The in-depth interviews reveal that, as a result of the development of industrial agriculture, farming families have become more dependent and part of a network of suppliers and buyer companies, and are at the mercy of the power of supermarkets. They are bound by the major role played by the chemical industry in the production of chemical pesticides. Due to the larger population, there is greater pressure on food production; due to the increased risk of crop failure, there is a strong tendency to apply pesticides prematurely. One respondent says on this subject:

> *That's the same as what arable farming does with pesticides and herbicides; it's about 'protecting crops from external influences' so you can ensure food security. But if you let go of everything, you let nature take its course. That's not a bad thing in itself, but then you also have to be able to take and manage the risks. And that means that if you have a shortfall, there's a shortage, and the person with the most money can pay for it and does pay for it, whilst those without money – the poor – have no food (28).*

11 families report that middlemen and consultants visit to sell products and that feed suppliers want to profit from you. 100% of the accounts show that working with complex techniques creates dependencies. Digitalisation, for example, has meant that feed is tailored more specifically to production. One organic farmer notes that feeding livestock is becoming increasingly complicated and entails consultancy costs.

> *We also still have consultancy fees quite often… I think there's one every month for feed. In the past, I used to do the calculations for the cows and so on myself, but nobody does that anymore. They're better at it. It's getting more and more complicated, and I used to have more time for it… And it has to add up, because you have to balance the books at the end of the year (50b).*

19 families prefer a local feed supplier because they can better tailor the feed to the type of cows and grass they have.

> *The big players have 10 varieties to choose from. They make feed rations sound like advanced maths, but it's not at all (34a).*

16 respondents have bought milking robots due to the increasing size of farms and labour being a limiting factor. The robot makes you more flexible and, in theory, a robot can increase milk yield by 10%. But the milking robot consumes more energy per litre of milk, it makes more dependent on feed suppliers because of the pellets that go into the robot to lure the cow. One respondent explains that the robot supplier claims you can graze perfectly well if you have a robot, but grazing becomes more difficult if, for example, you have fragmented land parcels. The milking robot is prone to breakdowns, which is why farmers have maintenance contracts for repairs. A new milking robot costs €140,000 to purchase, but you soon need two as a single robot can handle around 60 dairy cows. In addition, the barn needs to be adapted. When the robot is around 15 years old, its performance declines; the cows also produce less milk, so you have lower output and must make another investment.

It isn't just the farms that grow larger; the businesses surrounding the families also expanded. The banks, the supermarkets, the animal feed suppliers and the government all centralised. One farmer explains that the big supermarkets want to buy from a listed company.

> *The power of those big players... they want to buy centrally. They don't want to buy from the local farmer. You could say, 'Well, we have a shop in (..), we buy from all the farmers around (..), that's where we source the potatoes.But that's...I'll just mention Albert Heijn, which is a listed company, and they say 'we want to do that centralised purchasing'. From a potato trader in Beverwijk or wherever they're based, at a certain price (57).*

Respondents mention that they want to be as independent as possible, but 100% of respondents are dealing with increasing specialisation on their farms; the feed advisor, the accountant, inspectors for the power station, which entails extra costs. The administration for the annual agricultural census ('de gecombineerde opgave') and manure accounting has become complicated. Eight farmers have outsourced their administration. One respondent explains that, despite the agricultural census having become so complex, he continues to complete it himself because he does not want to lose the knowledge about his farm management.

Finally, all respondents indicate that they are dependent on the bank. If, for example, they want to buy land to expand, or make a sustainable investment, the bank asks how much milk you are going to produce. One family says:

> *You've all jumped on that express train together, and you can't just stop it, can you? …but even now, when you go to the bank, no matter what you do, they always ask, 'Is enough milk being supplied? How much milk are you going to supply?' That's the only thing that counts. So if things are still like that, I do understand the bank. They just want to make money. They're part of that system too. They want their money back, they just want good figures; that makes sense. But then I think: 'Is our food still too cheap?' (46).*

4.2.2 Competition for land – no (circular) agriculture

100% of farmers say that there is pressure on agricultural land in the Netherlands. This makes it difficult to practise extensification, circular agriculture or land-based farming. The growing livestock population creates a need for more land to produce roughage, thereby minimising dependence on purchased feed. However, land prices are being driven up by competition for land, both from other farmers and from societal demands relating to industry, nature, the energy transition and housing construction. The result is that financially strong companies are able to buy land.

Respondents indicate that, due to the high cost of land, they cannot afford to reduce the amount of feed/protein they obtain from it. The use of high-yielding grass varieties in intensive livestock farming forces farmers to keep their animals indoors a lot, otherwise they trample the grass and soil it with their manure. Ten respondents warn that sectors are emerging that can earn more money from the expensive land, including lily cultivation or other economic activities as data centres.

4.2.3 Behaviour is dictated – entrepreneurship is restricted

100% of farmers feel that their behaviour is increasingly dictated from above by the government, banks and dairy processors. Families indicate that their views and arguments are not being listened to, but that only the rules apply. 100% of respondents state that entrepreneurship is being stifled and that this hinders development, particularly towards more sustainable practices. One organic farmer mentions that he would like to bottle his milk and sell it directly in supermarkets, but that hygiene regulations prevent this. Farmers with milk taps by the roadside face additional rules and costs, making it less profitable to have a milk tap.

Good farming practices are incentivised through ecosystem services, which allow farmers to achieve bronze, silver and gold levels and thereby receive an additional CAP payment if they carry out certain activities on their farm. Banks offer farmers interest rate discounts for solar panels, but not for new machinery. Due to the phasing out of the derogation (from 250 kg of nitrogen to 170 kg per hectare), farmers now have to dispose of their manure at a cost of 30 euros per cubic metre. This results in disposal costs of thousands of euros per year for some families. At least 10 respondents are now purchasing artificial fertiliser to compensate for the decline in grass yield. Respondents point out that this is not a case of circular agriculture.

100% of farmers cite uncertainty and a lack of clarity about how to proceed with further investment. Farmers cite the emission-free barn floors in which they have invested, but which have now been phased out as a solution for greater sustainability, rendering the investment pointless. PAS applicants, who have undertaken their expansion legally, have been uncertain since 2019 as to whether their permits are still valid. They are not receiving bank financing until there is greater clarity, and these businesses are now at a standstill.

4.2.4 Societal expectations versus reality

One respondent says:

> *In my view, there is a difference between what is socially desirable and what offers the greatest chance of survival. It is not the biggest or the strongest that survive, but those who adapt best. In the days when my parents were farmers, there was a different survival strategy than there is now, so to speak (62).*

100% of respondents speak of the social pressure they experience through the media or from members of the public gesturing in the street. But social pressure also reaches the farmyard via government regulations, the dairy factory and the bank. Five respondents indicate that this is why the next generation is dropping out. Eight families mention the legal cases currently being brought against farming families, for example by the MOB (Mobilisation of the Environment).

But farmers point out that there isn't actually that much demand for organic produce, and only 10% of the white dairy products in the supermarket end up as pasture-fed milk. Two organic farmers say they aren't keen on a surge in organic milk because the milk price would then plummet for them.

100% of respondents mention that global demand for dairy remains. Respondents expect the number of dairy farmers in the Netherlands to decrease, with a few large ones remaining that can produce even more intensively, and that cows will produce even more milk. There will still be room for a few such farms in the Netherlands.

Respondents see solutions in precision technologies, nitrogen crackers and manure digesters. Farmers indicate that this involves high investment costs and some of the techniques can only be made profitable with 200 cows or more. However, they also point out that farms are becoming more capital-intensive and harder to take over. Due to the size of the farm, staff will soon be required. Ten families indicate that they would prefer not to work with external staff. Eight families mention that they cannot make a transition on their own. One respondent says that we are all part of a cycle, and it is not just agriculture that is a cycle.

Table 2. Findings on contradictions faced by farming families (N=34)

Characteristic	On the one hand	On the other hand	Contradictions Farming families
Decline in family farms	• Working to keep the family business going	• Farms becoming larger and more capital-intensive • No longer able to continue farming at the current location • Children no longer wish to take over the farm	• Prefer not to employ staff • Farms that survive will become larger • Disappointment that the family business cannot be continued
Use of complex technology	• Labour is a limiting factor • Need to work quickly and efficiently	• Want to repair machines themselves	• Significant investment • Maintenance contracts • Consultants
Increase in energy use	• Try to produce energy efficiently • Try to keep energy costs low	• Current production requires concentrated feed, fertiliser, fuel	• Purchasing technology to save energy • Higher costs
Specialisation and overproduction	• Producing efficiently and in large quantities	• Risk of overproduction	• Low prices • Queue for organic or sustainable milk supply
Ecological interventions	• Grass varieties for high protein: high yield • Crop protection and disease prevention • Manure removal and use of fertilisers • The cow is a top athlete	• You want to keep your soil healthy • Benefits of circular agriculture • Cows are vulnerable to health problems	• No circular agriculture • High costs

Competition	▪ Land needed to expand farming, reduce manure disposal costs	▪ Land prices are under pressure from other demands such as nature conservation and housing, the energy transition, and data centres	▪ Major investments ▪ Fewer opportunities for expansion or extensification
Dependence on agricultural units	▪ Feed suppliers and advisers are needed to achieve production targets	▪ They want to make money from you ▪ Large farms do not always have sufficient choice, e.g. feed types	▪ Restriction of freedom of choice by large feed- and fertiliser companies ▪ Companies want to make money of you
Government influence	▪ Stricter regulations and production requirements ▪ Complex schemes ▪ Good behaviour is incentivised through CAP subsidies ▪ Licensing takes long	▪ Maintaining international competitiveness ▪ You need CAP subsidies to survive ▪ You need a licence	▪ Restriction of freedom of choice and free enterprise ▪ Views and arguments are not being listened to
Economic context	▪ Making investments in sustainable technology ▪ Moving to more extensive farming by buying land	▪ The bank asks how much milk you are going to produce ▪ The bank sets the interest rate for investments	▪ You have to milk more cows
Social pressure	▪ Demand for local, sustainable, animal-friendly food	▪ Producing cheap food	▪ Fear of lawsuits, MOB ▪ Gap between aspiration and reality

5. Discussion and Conclusion

The ecological conditions – wet grasslands and climate – mean that dairy can be produced in the Netherlands with low energy use. These conditions have intensified over the years. Various sources indicate that the scaling up of agriculture in the Netherlands has placed pressure on resources such as agricultural land and cheap energy (Smit; 2018; Wojtynia et al. 2021). In addition, there are ecological problems caused by manure surpluses and the use of plant protection products (Benton et al., 2021).

The research shows that farmers are now faced with multiple, conflicting expectations. On the one hand, there is social and political pressure to produce more sustainably, whilst on the other hand, economic competition and low consumer prices continue to encourage economies of scale and intensive production. To make ends meet (with school-age children), a farming household must achieve a certain level of cash income.

Some people believe that we can switch to new technologies—such as solar power, wind turbines, anaerobic digestion and nitrogen crackers—and that everything will simply carry on as before. However, experts are increasingly warning that humanity is reaching the limits of its energy use. Natural resources will eventually become scarce or be exhausted, and they advocate a return to smaller-scale operations (Heinberg, 2021; Meadows et al., 1972; Smit, 2018).

The literature and research findings reveal insurmountable obstacles on the path to greater sustainability that are inherent in the system (Runhaar et al., 2020; Vermunt et al., 2022). The research findings indicate that a complex socio-economic structure prevents farmers from, for example, selling their produce locally. This is due to hygiene regulations, additional inspections and the resulting rising costs. Or that regulations compel farmers to dispose of their own animal manure and purchase fertiliser produced from gas in order to maintain the production levels they need to make ends meet.

It does not depend on the individual preferences of farming families, or political will, but is the result of external demands placed on the farmers' business operations. Namely, the demand for efficiency, that is to say, the efficient and economical use of resources, such as energy. And also demands from government bodies that farmers must be able to provide the required data to external authorities. It is also difficult to scale back to a smaller scale because there would then be insufficient income to cover, among other things, interest and repayment costs. This is not a matter of preference, but an external demand of the economy. It is an impersonal demand. The situation in which farmers find themselves is largely determined by external circumstances, the wider economy, the government, and the entire surrounding environment.

Sociological and cultural anthropological literature emphasises that pressure on resources can be expected to lead to the invention of new techniques (Boserup, 1965). According to the discussed theories of cultural anthropologists and sociologists, this can go hand in hand with an increasingly complex socio-economic organisation with greater regulatory pressure (Nolan & Lenski, 1995; Harris; 1979). The rules are monitored, and as a result, farmers increasingly feel that 'good behaviour' is dictated from above, for example through a points-based subsidy system and the withholding of subsidies if they tick the wrong box in the computer system. The families indicate that they see lawsuits being brought against farmers around them and that this creates tension. The negativity in the media, the long working weeks, and the ever-increasing size of the farm are among the reasons why children no longer want to take over the farm. The risk, as highlighted by farmers, is that if farms cease operations, other parties able to purchase the expensive land will continue with industrial practices that require high energy use. Take, for example, data centres or flower cultivation with high resource and water usage.

The literature indicates that social organisation, based on high energy consumption, is vulnerable and that, in the long term, there will not be sufficient energy and economic resources to sustain it. The cultural anthropologist Marvin Harris emphasises the systematic coherence within societies. The loss of the energy base of the current type of society will cause disruption (Harris; 1977, 1979).

Sustainability in agriculture is therefore not merely a technical challenge, but also an ideological and economic issue. If we now have to return to a lower energy level, then the whole of society will change (Harris, 1979). This is also why farmers say they cannot make the transition on their own. Moving away from these constraints requires cooperation and flexibility from the wider network of surrounding organisations and the society. Research currently in preparation will explore this further.

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One Size Fits One - Fostering Community Energy Implementation through Networked Co-creation

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Community energy initiatives (CEIs) throughout Europe struggle with low participation numbers, hindering the attainment of sustainability goals and exacerbating socioeconomic divides promoting a "transition of the elites" (Germes et al., 2021; Radtke & Ohlhorst, 2021). While research attending to factors influencing participation in CEIs has grown in recent years, translating findings into practice remains challenging and does not yet facilitate governance (Geskus et al., 2024). In this project we therefore address two problems:

1. There is a lack of stakeholder engagement due to top-down practices of researchers and policy makers which hinders contextualization and targeted implementation of policies (Radtke, 2025).
2. Network characteristics are neglected in research and governance of community energy (Goedkoop et al., 2022; Nientimp et al., 2024).

Hence, we combine social network analysis and co-creation in a mixed methods project with two active CEIs in the province of Groningen that encompassed four working sessions. We thereby utilize the potential benefits of network methods for intervention design (Goedkoop et al., 2022; Nientimp et al., 2024) and the benefits of citizen engagement for governance outcomes and contextualization (Mihailova et al., 2022; Radtke, 2014). As co-researchers the initiators assessed the socio-economic background of - and the attitudes and topics relevant to - their community in relation to the energy transition. Further, the initiators mapped their community network describing the links between local clubs (e.g. soccer, church, village heritage etc.). The research team complemented such insights with empirical network and survey data from the respective communities. Further, the co-creation process was evaluated by both researchers and initiators applying the protocol of Canberra – a qualitative tool to evaluate and adapt participatory processes (Jones et al., 2009).

The co-creation sessions facilitated mutual learning and knowledge exchange: researchers were able to contextualize the insights and adjust them to the needs of the initiators, while initiators internalized the research findings. Together we developed possible dissemination strategies that aim to spread CEI participation, through network interventions. The project enabled initiators to take ownership of their CEI and actively engage in the governance and research process, leading to strategies that maximally align with the local context. Further, the project was captured in a public protocol and shared through the CEI umbrella organization Groninger Energie Koepel (GrEK). The project aims to inspire anyone involved with CEI governance to take a co-creation approach and concludes that a “One size fits all approach” to policy and governance is counterproductive.

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1. Introduction

Across Europe, CEIs are promoted as bottom-up drivers of the energy transition, yet many struggle with low participation, socioeconomic bias, and perceptions of elitism (Germes et al., 2021; Radtke & Ohlhorst, 2021; Walsh, 2021). These challenges reflect a deeper structural mismatch between national and supranational top-down governance and the inherently bottom-up governance style of CEIs (Fukuyama, 2016; Sovacool & Brisbois, 2019). Modern conceptions of governance emphasize the regulation of social behavior through citizen networks and distributed agency, yet CEI implementation remains shaped by hierarchical, state-centered approaches that constrain local initiatives and limit social acceptance.

In response, participatory and co-creative approaches have gained traction, showing that deeper stakeholder engagement can enhance procedural justice, legitimacy, and trust (Feenstra et al., 2021; Jenkins et al., 2016; Radtke, 2025). However, such engagement is often limited to consultation rather than genuine collaboration, and CEI initiators rarely participate in the design, analysis, or interpretation of research that informs implementation.

At the same time, social structural variables - particularly local community networks - remain underutilized in CEI governance (Goedkoop et al., 2022; Nientimp et al., 2024), despite growing evidence that social relations, network positions, and community structures shape CEI participation and diffusion (Germes et al., 2021; Middlemiss et al., 2024). Neglecting these relational dynamics reinforces one-size-fits-all implementation strategies that fail to account for local norms, infrastructures, and social realities.

We address both gaps by combining co-creation with community-engaged social network analysis (SNA). This networked co-creation approach positions CEI initiators as co-researchers and integrates their contextual knowledge with empirical network and survey data. In doing so, it aligns with modern governance principles while offering a practical method to overcome the limitations of top-down CEI implementation. We apply this approach in four co-creation sessions with two CEIs in the northern Netherlands to collaboratively design targeted, context-sensitive mobilization strategies.

2. Methods

CEI A consisted of 12 members (only one female and one below 60) in a community of 609 households and CEI B of 3 members (all female and all above 70) in a community of 385 households. A community survey (N = 179) captured demographic, socioeconomic, attitudinal, and network data. Initiators mapped their associational networks using a modified NetMap procedure (Schiffer & Hauck, 2010), after which researchers generated and analyzed weighted networks with the igraph package in R (Csárdi & Nepusz, 2006). We integrated:

- insights from nine earlier CEI case studies (Goedkoop et al., 2022; Nientimp et al., forthcoming),
- initiator generated network maps,
- community survey and network data,
- and qualitative evaluations using the Canberra Protocol (Jones et al., 2009).

Qualitative data were analyzed using a hybrid of thematic analysis (Braun & Clarke, 2021) and Temporal Trajectory Analysis (Spencer et al., 2021), enabling us to trace how initiator reflections evolved across sessions.

3. Results

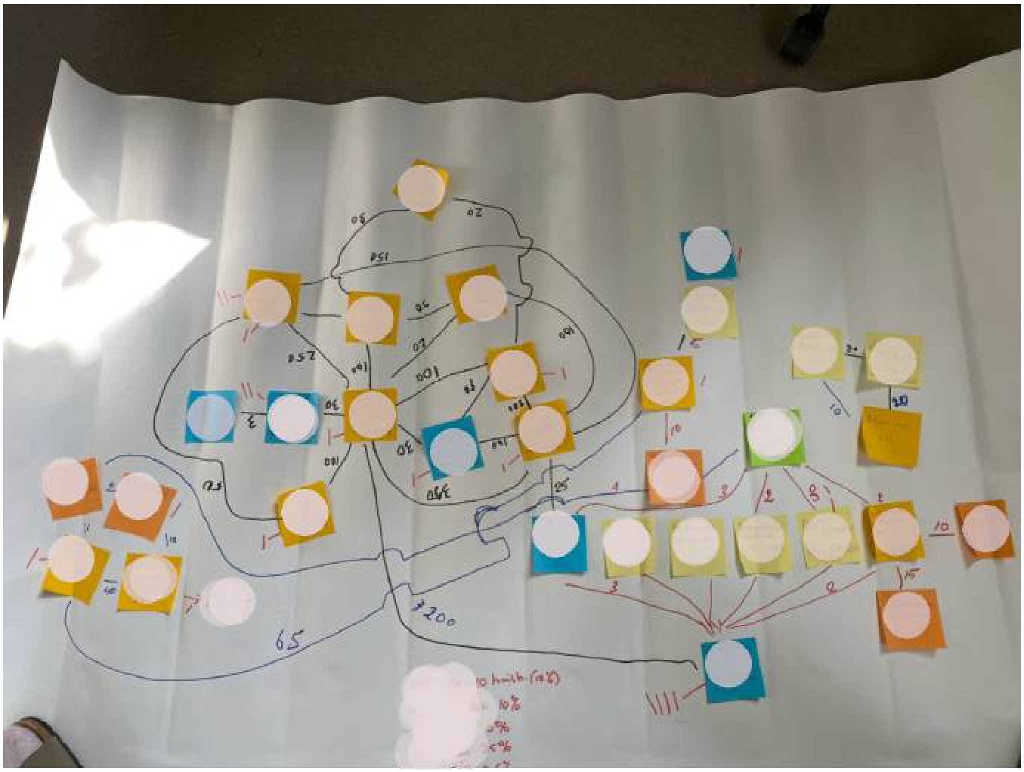
3.1 Session 1: Reality Check and Perspective Taking

Initiators compared their expectations about community attitudes, trust, and motivations with empirical distributions from nine earlier CEI case studies and we looked at open data on housing and sociodemographic variables from their community. This revealed gaps between their own socioeconomic position and that of the broader community, reinforcing concerns about CEIs being perceived as "transitions of the elites" (Radtke & Ohlhorst, 2021). Trust patterns aligned with earlier research: higher trust in local government, lower trust in national government, and strong references to the legacy of the Groninger gas field. The session successfully elicited assumptions and facilitated reflection, which initiators described as "inspirational."

3.2 Session 2: Drawing the Network Together

Initiators collaboratively mapped their associational networks, revealing their perceived network positions. Weighted networks generated in R confirmed some impressions regarding centrality and access but also highlighted blind spots. In both CEIs, initiators underestimated their structural reach: village B showed a clear bridging position, while village A - initially perceived as peripheral - also occupied a central role. The exercise helped initiators see how network structure could inform mobilization.

Figure 1.



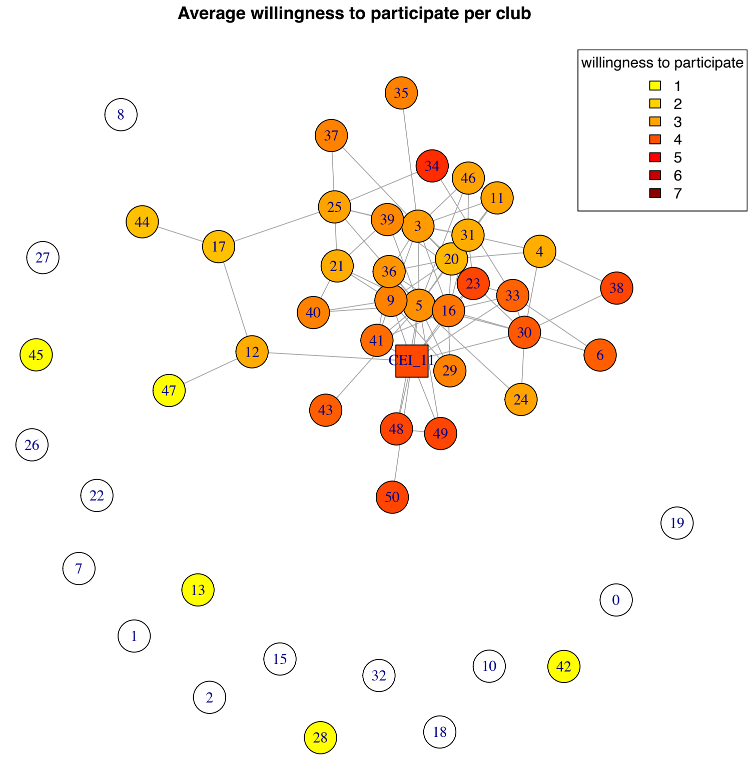
Note: A photo example of the network mapped by the initiators of village B.
The names of the associations are blurred for privacy reasons.

3.3 Session 3: Feedback Loop and Comparative Analysis

Survey results on attitudes, trust, motivations, and reasons for (non) participation were jointly interpreted. Mapping individual characteristics onto the associational network allowed initiators to identify clubs with motivated or vulnerable members that are more easily contactd due to already existing ties to the CEI. Correlations between pro-environmental attitudes and efficacy beliefs helped pinpoint receptive groups.

A key insight emerged when merging initiator-reported and community-reported networks: community members reported many ties that initiators had overlooked. These additional ties increased degree and closeness centrality, revealing greater outreach potential than initiators assumed. The discrepancies underscored the importance of cognitive social structures K(Krackhardt, 1987) and the comparison of initiator perceptions and community perceptions.

Figure 2.



Note: The associational network with individual characteristics drawn from the community sample mapped onto the clubs. The network shows the mapping of the average willingness to participate mapped onto each club.

3.4 Session 4: Designing Implementation Strategies

Initiators and researchers jointly developed mobilization strategies. While targeting central clubs was nothing new to initiators, structural balance theory (Heider, 1958; Koskinen et al., 2023) introduced new opportunities: indirectly connected clubs embedded in incomplete triads are more likely to react or participate in the CEI due to overlapping network contacts – especially if they score high on willingness to participate or pro-environmental attitudes. Initiators discussed how to approach such clubs, including through intermediaries, and how to reach lower-SES groups often underrepresented in CEIs (Radtke & Ohlhorst, 2021).

CEI A defined concrete next steps for engaging the municipality, while CEI B planned internal deliberation. Both CEIs received a comprehensive summary of results and strategies.

4. Discussion

This project demonstrates that co creation can overcome limitations of top down CEI governance by integrating local knowledge with empirical analysis. Alternating between quantitative results and initiator inisghts created a feedback loop that deepened understanding and improved strategy design - echoing earlier findings on participatory governance(Radtke, 2025; Teodoro & Prell, 2023). The approach also fostered trust in a context marked by historical distrust toward governmental institutions due to the Groninger gas field. Providing initiators with agency increased acceptance and internalization of research outcomes, consistent with participatory research literature (Reed et al., 2018; Senabre Hidalgo et al., 2021).

A key contribution lies in revealing discrepancies between initiator perceptions and community reported network structures, in line with work on cognitive social structures (Krackhardt, 1987). Such misperceptions can lead CEIs to underestimate or overestimate their outreach potential, highlighting the need for reflective, data informed and contextualized implementation strategies.

4.1 Limitations and future research

The approach was tested in only two cases, and its effectiveness should be examined in more diverse contexts. Co creation cannot be applied as a one size fits all model and the protocol of this research should be adapted when applied to other cases (Reed et al., 2018). Future work should also explore how to engage policymakers, local officials, CEIs, and community members simultaneously, as political institutions were not directly involved here. Moreover, initiators did not reflect the sociodemographic composition of the northern Netherlands, raising concerns about democratic inclusion and justice (Sauermann et al., 2020). Broader participation is needed to ensure that underrepresented groups are heard and benefit from co creation processes.

4.2 Conclusion

A bottom up energy transition requires meaningful bottom up engagement. Our findings show that co creation and community engaged SNA provide the contextual insights necessary to design situated implementation strategies and overcome the limitations of top down CEI governance. The publicly accessible co-creation protocol - spread via Groningen Energiekoeppel - can inspire CEIs, policymakers, and local governments to better attend to local social structures and support more inclusive, democratic, and effective CEI implementation.

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The Development and Testing of the Quality Framework for Transdisciplinary and Practice-oriented Research

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Carina Wiekens (Entrance)

Transdisciplinary, practice-oriented research requires collaboration across disciplinary and institutional boundaries, involving partners such as local governments, residents and businesses. But how can this collaboration be shaped in a careful and meaningful way? And how can the quality of the research be ensured? In the research program Sprong SURE (Sustainable cities and regions), the Hogeschool Utrecht and Hanze work together to connect social and technological innovation and learn how to work in a more transdisciplinary way. We developed a quality framework to support researchers and practice partners in jointly formulating and answering relevant questions, thereby maintaining the quality of the research.

With a literature review, we assessed five criteria for transdisciplinary and practice-oriented research: Transdisciplinarity, relevance, credibility, legitimacy and effectiveness (Belcher et al., 2016; van Vliet, 2020).

For instance, relevance concerns the extent to which the research addresses societal and scientific needs, and legitimacy refers to the fairness, transparency and ethical accountability of the research process, as well as the inclusion of diverse perspectives and interests. Next, questions were formulated for each of these criteria to help facilitate discussion about the quality of the research. These questions have been prioritized for the various stages of the research process, from exploration to evaluation of the research. This ensures that the most relevant aspects are addressed in each research phase.

The framework was developed and tested iteratively within various settings of the SPRONG SURE program, as well as during kick-off meetings of several research projects within Entrance (Hanze). Based on experience and feedback, the content and format of the framework have been refined. It has now taken the form of a physical card set with a map, making it both visual and interactive to use. In practice, the framework helps to structure conversations and stimulate reflection, revealing blind spots and initiating discussions on goals, collaboration, roles and ethics. The framework can serve as a means to facilitate and monitor learning processes in transdisciplinary research settings. Recently, it has also been used in the evaluation phase of a research project. The newest insights on testing and improving the quality framework will therefore be shared.

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1. Why a quality framework for transdisciplinary, practice-oriented research?

In transdisciplinary, practice-oriented research, collaboration across disciplinary and institutional boundaries is central (Klein et al., 2001; Tappeiner, Tappeiner & Walde, 2007). This involves working together with partners such as local governments, residents, and businesses. But how can this collaboration be shaped in a careful and meaningful way? And how can the quality of the research be ensured? These questions form the basis for the development of a quality framework for practice-oriented and transdisciplinary research. It has been developed to support researchers and their partners in jointly formulating and answering relevant questions, thereby maintaining the quality of the research. The quality framework can be used at different stages of the research: from the research proposal to the initial phase of the research, and from execution to evaluation.

The quality framework is developed in the context of Sprong SURE (Sustainable Cities and Regions): a research program between Hanze University of Applied Sciences (Entrance) and the University of Applied Sciences Utrecht addressing the complex challenges of the energy transition, for instance through the formation of a strong transdisciplinary research group. The aim of this article is to provide insight into the nature of the quality framework, how it is developed, and what the future steps are to further refine and strengthen the framework.

2. What is the quality framework for transdisciplinary, practice-oriented research?

The quality framework serves as a tool to structure dialogue and stimulate critical reflection within research projects, engaging both researchers and external stakeholders (for instance, municipalities, residents and companies). It supports revealing blind spots and initiating discussions on goals, collaboration, roles and ethics. The framework can serve to facilitate and monitor learning processes in transdisciplinary research settings, although, to date, it has primarily been applied within project groups consisting of researchers from different disciplines. The framework takes the form of a physical card set featuring guiding questions, accompanied by a visual map, making it interactive and rendering the process visible.

The current framework is based on a literature review regarding quality assessment of transdisciplinary, practice-oriented research. One article served as the primary foundation for the framework (Belcher, Rasmussen, Kemshaw, & Zornes, 2016), which was subsequently integrated with indicators for practice-oriented research on societal impact developed by Van Vliet et al. (2022) by mapping the 18 criteria for practice-oriented research onto the original framework. Consideration was paid to potential overlap: in some cases, a criterion from Van Vliet et al. (2022) overlapped with one from Belcher et al (2016), while in others, additional indicators were incorporated to address gaps in the original framework. To ensure that transdisciplinarity was explicitly addressed and discussed within project groups, we introduced an additional criterium to the original four principes of Belcher et al (2016): Transdisciplinarity.

Altogether, this resulted in five criteria to assess the quality of transdisciplinary, practice-oriented research: Transdisciplinarity, Relevance, Credibility, Legitimacy and Effectiveness. Below, each criterium is further described and illustrated.

2.1 Transdisciplinarity

The first criterium, transdisciplinarity, concerns exceeding disciplinary and institutional boundaries with active participation of all practice partners in all phases of the research process. It is a term that is defined and described in the literature, emphasizing the broad representation of different parties. For instance, 'Transdisciplinarity is a specific form of interdisciplinarity that, while recognizing the invaluable contribution from different scientific fields, also emphasizes the need for cooperation and communication among the various parts of society with these academic disciplines in order to meet the complex challenges we face today' (Klein et al., 2001, Tappeiner et al., 2007).

In relation to this criterium, questions about the way in which the different parties are represented in the research process will be asked. The different parties refer to the parties from the quadruple helix: research, education, government, businesses and societal organisations, and residents). The questions also refer to the way the goals and the design of the research are established (are they participative and from different perspectives?).

2.2 Relevance

Relevance concerns the extent to which the research addresses societal and scientific needs. It involves the importance, significance, and usefulness of the research problem, objectives, processes, and findings in the problem context (Belcher et al., 2016). Questions that might be asked in relation to this criterium include: Could you tell a bit about the context in which the research is being conducted? What has been the starting point of the research?

2.3 Credibility

Credibility refers to the robustness of the findings and the reliability of the sources of knowledge. This includes clear demonstration of the adequacy of the data and the methods used to generate the data, including a transparent and logically coherent interpretation of the findings (Belcher et al., 2016). Questions relating to this criterium are: What research methods are employed? What tools are being used? How do these contribute to answering the research questions and achieving the objectives? In your opinion, what are limitations or concerns in the research? Is there a justification for these limitations? How are these addressed in the research project?

2.4 Legitimacy

Legitimacy refers to the fairness, transparency and ethical accountability of the research process, as well as the inclusion and consideration of diverse participants, values, interests, and perspectives (Belcher et al., 2016). Questions that can be asked in relation to this criterium include: To what extent has consideration been given to possible biases in the subject and design of the research? Has this been discussed with all parties involved? To what extent does the research comply with ethical standards?

2.5 Effectiveness

Effectiveness refers to generating knowledge and stimulating actions with research, that address the problem and contribute to solutions and innovations (Belcher et al., 2016). This criterion can be met by answering questions such as: In what way does the research contribute to the development and expansion of knowledge, and in what way do the intended target groups and end-users make use of the research? How are the research findings disseminated? To what extent does the research contribute to educational purposes?

3. Development of the quality framework

The framework was developed and tested iteratively across multiple contexts within the SPRONG SURE program, as well as during kick-off meetings of several research projects within Entrance (Hanze). Feedback was systematically collected at different stages of the development of the framework. Based on these experiences and inputs, , both the content and format of the framework were refined. Below, we describe the different steps and lessons learned.

3.1 Rubric and interview guide (November 2023)

The literature review resulted in a comprehensive overview of the different criteria and their components. Next, questions were formulated for each of these criteria to facilitate structured dialogue and discussion about these criteria and ultimately, the quality of the research. An internal pilot was conducted to explore how this approach functioned in practice. It became clear that these topics were not commonly discussed within the research teams, yet participants immediately recognized their relevance and added value. However, the framework proved too extensive to address all components in a single session, and we also noticed the importance of proper introduction of the quality framework, particularly to prevent researchers from feeling evaluated.

Lessons learned:

1. A long list of criteria and questions is not conducive to effective facilitation; a more interactive and accessible format is needed.
2. The purpose of the framework must be clearly communicated: it is not evaluative, but intended to broaden and deepen collective understanding.
3. Creating a safe environment, for instance by emphasizing the aim of the framework, is essential, as participants may become defensive.
4. It is beneficial to prioritize or jointly select topics with participants, or to preselect questions based on the research phase.
5. Mechanisms are needed to track responses over time, including ways to visualize progress and document agreements.

3.2 Prototype card set testing in experimentation area South-East Friesland (March / April 2024)

This was the first external test of the quality framework with a broad group of local stakeholders (municipality and energy cooperative) and researchers from both HU and Hanze. The quality framework was formed as a card set with the definitions of the five criteria and all proposed questions belonging to these criteria. In the area of South-East Friesland, the Hanze was involved in a research project, which now formed the specific context in the discussion. We were able to discuss the topics transdisciplinarity, relevance and effectiveness, that mostly were discussions based on the definition given by the facilitator.

Lesson learned:

1. The card set was way too extensive for practical use within a one-hour session. However, the questions elicited meaningful and productive discussions, marking the emergence of a shared view of the quality framework's potential value, albeit in a revised format.

3.3 Prioritization of questions in the different research stages (October 2024)

To improve usability and relevance of the questions, we decided to prioritize the questions for the various stages of the research process. Four stages were defined: exploration, start, mid-term and the end (evaluation). We then identified the most important questions to ask for each phase of the project, resulting in a separate list of questions for each of the phases mentioned above. This division and the corresponding breakdown of the questions ensured that the most relevant aspects are addressed in each research phase. For example, in the exploration phase, the focus is more on transdisciplinarity and relevance. This phase revolves mainly around the project application, during which the project is still being shaped, and many decisions still need to be made regarding exactly what the project entails and who is involved. In the evaluation phase, the project has been completed, and the results can be compared with the original objectives. That is why, in this phase, the questions addressed are more focused on the effectiveness criterion. Naturally, this division per phase also made it easier to discuss all the questions, simply because there are fewer questions to address at each session.

Lessons learned:

1. Distinguishing between research phases enhances both relevance and efficiency.
2. The framework should remain adaptable, allowing research teams to adjust priorities based on context and needs.

3.4 Testing the quality framework in start phase of different projects (November 2024 – May 2025)

During this period, the framework was repeatedly tested in project kick-off meetings. This way, more researchers became familiar with the quality framework and the way at which one could have conversations and create a shared view as a transdisciplinary research group. At this point, the framework changed from a card set with questions and definitions to 3D cards to be placed on a map to monitor the extent to which the participants themselves feel they are competent and conscious about the aspects.

Figure 1. An example of the use of the quality framework

This should lead to a more interactive conversation about the research from a certain meta-perspective. We also ensured a more long-term perspective, as it is possible to note down made agreements on the map, and the status of the placed cards can form the starting point for a next session (see Figure 1).

Lessons learned:

1. Clear facilitation and framing are essential to prevent perceptions of evaluation and to foster a safe discussion environment.
2. The framework is not intended to produce definitive answers, but to surface differences, ambiguities, and areas requiring further attention.
3. Project leaders play a crucial role in establishing a shared baseline understanding at the start of sessions.
4. Pre-session interviews with participants can enrich discussions and allow certain topics to be addressed more efficiently.
5. Flexibility is key: there is no fixed sequence of questions, and facilitation should adapt to context and needs.
6. Clear role allocation (e.g. facilitator vs. project lead) enhances effectiveness.

3.5 Implementation of the quality framework in research application phase: Checklist (January 2025)

Besides implementing the quality framework in the starting phase of research projects, we also realised that the framework can be a useful tool in the application process. Therefore, we had discussions with organisational units such as HR and business development, who were working on the funnel process for researchers who have new research ideas and are going to draw up a research proposal. We managed to incorporate the list of questions from the start phase of the research in the funnel process, as a recommendation for researchers to think of these questions while developing their research idea.

Lessons learned:

1. Early familiarization with the framework supports more robust project design, even if not all questions can yet be answered.
2. Organizational embedding is crucial for broader implementation.

3.6 Testing the quality framework in evaluation phase of a project (April 2026)

Recently, the quality framework has also been applied in the evaluation phase of a research project. Having learnt from previous experience that it can be useful to conduct short personal interviews before the group framework discussion, we have applied this into the evaluation process as well. As many participants of the meeting as possible were asked a number of questions in advance about the collaboration, roles, expectations, etcetera. They were also asked if there were any specific topics that needed to be discussed together during the group discussion. During the group discussion, a summary was provided of all the responses received, enabling questions from the quality framework to be asked and addressed in a more specific way.

Lessons learned:

1. Preliminary individual interviews are valuable in the evaluation phase, enabling more targeted group discussions.
2. Time can be used more effectively by summarizing non-contentious issues in advance.
3. Additional themes, such as project management and budget performance, can be integrated at this stage, and session outputs may inform final project reporting.

4. Conclusion and discussion

As of now (May 2026), the quality framework consists of the card set and map and is seen as a tool to structure group discussions and stimulate reflection. So far, the quality framework provides a clear overview of the key elements of transdisciplinary practice-oriented research and has been shown to lead to important discussions (between research groups). It helps us as a centre of expertise to start to learn how to work interdisciplinary. The framework is currently applied across multiple stages of research projects. For the two first stages, concrete implementation formats have been established (a checklist for the proposal stage and structured kick-off sessions). For the evaluation stage, initial experience has been gained through one internal evaluation pilot. Working with a prioritized selection of questions has been shown to be both efficient and effective, while still allowing flexibility to address other relevant aspects. That is, this list can still be adapted to the specific research project: irrelevant questions or those that have already been answered can be omitted. We have also found a flexible way of working with the framework, and to adjust the implementation of it to the specific needs from the individual research projects.

In kick-off meetings, a variety of facilitation formats can be employed to discuss the themes of the quality framework. This could, for example, take the form of a group discussion during kick-off meetings (using the card set or not) or a more interactive format in which participants discuss the extent to which they are aware of the themes, based on the questions on the cards. During such a meeting, a visual map (*onderlegger*) is used, onto which the pre-selected cards are placed within four quadrants derived from the Johari window:: Unconsciously incompetent (this point has not yet been considered), consciously incompetent (recognized, but no action has yet been taken), consciously competent (addressed with agreed actions underway), unconsciously competent (effectively embedded without explicit reflection).

Once the framework and the five themes have been introduced, the questions can be discussed in the pre-selected order. The cards can be placed in the correct quadrant based on consensus, whilst encouraging an open discussion and noting down key insights and follow-up actions on the *onderlegger*. At the end of the meeting, points for future consideration, agreements made and follow-up actions are identified. As mentioned earlier, a more 'free-flowing' discussion can also be chosen, in which the questions are addressed one by one without using the worksheet.

Future development of the quality framework will focus on continued refinement and broader testing across research stages, and implementation of the framework with external stakeholders. In parallel, initial steps have been taken to connect the quality framework (and the different research stages) to capacity building and skills development of researchers and research teams. This raises important questions regarding which competencies are required in different stages of transdisciplinary research, and how these can be systematically developed and embedded. Strengthening the integration between quality reflection and skills development may contribute to a more shared and explicit understanding of what it means to be part of and develop a strong transdisciplinary research group.

Through these ongoing efforts, we aim to further develop the quality framework in a participatory manner. The quality framework holds significant potential to foster collective learning processes among researchers and stakeholders, and to support the development of shared practices for conducting high-quality transdisciplinary, practice-oriented research.

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No Energy Transition Without the Right People: Employer Branding for Employee Attraction and Retention

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The shift towards more sustainable energy systems intensifies competition for skilled labour, particularly in the energy sector. In regional contexts where demographic pressures and labour shortages are pronounced, this challenge becomes even more urgent.

This paper examines the role of employer branding (EB) in achieving employer attractiveness from both external and internal perspectives within the energy sector. Drawing on signalling theory, person-organization fit, and stakeholder theory, the study integrates four empirical investigations conducted in the North of the Netherlands, complemented by a cross-country comparison with the North of Germany.

The research uses a mixed-methods approach, including quantitative content analysis of job vacancies, experimental and survey research among job seekers and employees, and analyses of internal communication practices. The findings show that EB is a multidimensional construct encompassing corporate identity, organizational culture, image, reputation, and corporate social responsibility (CSR). From an external perspective, EB shapes employer attractiveness by signalling organizational values and aligning them with job seekers' preferences. Internally, perceived CSR and internal communication, particularly through internal social media, support employee engagement and affective commitment. This, in turn, strengthens employer attractiveness and employee retention.

The findings also show that misalignment between external promises and internal experiences limits organizations' ability to attract and retain talent over time. In the context of the energy transition, this may intensify talent shortages and limit the human capital required to support long-term regional development.

This research contributes to a more integrated understanding of EB as a tool for managing human capital in the energy sector. It shows that EB is not only a recruitment tool but also a strategic, organization-wide process that supports talent attraction, employee retention, and long-term engagement. For organizations operating within regions undergoing energy and societal transitions, the study highlights the importance of aligning external positioning with internal realities to build credible and attractive employer brands. In doing so, EB emerges as a critical mechanism for strengthening regional labour markets and supporting the energy transition.

Keywords: Employer branding, Employer attractiveness, Human capital, Energy transition, Sustainable regions, Corporate social responsibility, Internal communication

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1. Introduction

The global labour market is undergoing significant structural shifts, characterized by demographic changes, evolving workforce expectations, technological advancements, and economic and environmental pressures (World Economic Forum, 2025). Ageing populations in advanced economies are contributing to a shrinking labour force (OECD, 2023), while the energy transition simultaneously reshapes demand for technical, engineering, and project-management skills. The combination is particularly consequential for the energy sector. Achieving the objectives of the European Green Deal and national climate agreements requires a workforce capable of designing, building, and operating renewable energy infrastructure (offshore wind, solar, hydrogen, grid integration) and capable of doing so at a pace that the current labour supply does not support (EURES, 2024; CBS, 2025). Renewables account for nearly 20 percent of national energy consumption in the Netherlands (CBS, 2025), driven by investments in offshore wind, solar, and biomass. However, national labour-market reports identify technical professions, including energy, as among the sectors most exposed to structural shortage (EURES, 2024; CBS, 2024). Consequently, securing and retaining the right talent is essential for achieving the energy transition.

The challenge is bigger still in peripheral regions. The North of the Netherlands, e.g., the three provinces of Groningen, Friesland, and Drenthe, has historically been organized around the Groningen gas field, which for decades shaped the regional economy, infrastructure, and labour market. The decision to phase out gas extraction, combined with major investments in offshore wind, solar, and hydrogen (notably around Eemshaven and Delfzijl), places the region at the centre of the Dutch energy transition (SNN, 2024). At the same time, the region faces demographic pressures: labour-market growth lags national averages, the working-age population skews older, and skilled and highly-educated workers are in short supply (Schramm, 2023; EURES, 2024). This is the paradox the energy sector in the region must navigate: the structural transformation that creates new opportunities is the same transformation that exposes the underlying labour shortage.

Employer branding (EB) offers a promising approach to building employer attractiveness for organizations seeking to attract, engage, and retain talent in increasingly competitive labour markets. Initially defined by Ambler and Barrow (1996, p. 187) as "the package of functional, economic and psychological benefits provided by employment, and identified with the employing company," EB has evolved into a multidimensional construct central to organizational identity and competitiveness in talent markets. Over the past two decades, the literature has moved from a static, one-directional view of EB as recruitment communication aimed at external audiences (Backhaus and Tikoo, 2004) towards a dynamic, multi-directional view in which the employer brand is co-created through both external positioning and the lived experience of current employees (Lievens and Slaughter, 2016; Tumasjan et al., 2020). To establish sustainable employer-employee relationships, corporate social responsibility (CSR) can load an EB strategy (Kolesnicov, 2018) and contribute to the company's internal and external reputation (Vercic and Ćorić, 2018). EB must therefore be internally authentic and externally resonant, with current employees playing a critical role in shaping the employer brand through lived experience and advocacy (Itam et al., 2020).

Despite this conceptual progress, two gaps remain in the EB literature as it applies to the energy sector. First, most empirical work on EB has been conducted in services, hospitality, IT, or retail industries (Punjaisri and Wilson, 2011; Wang and Tsai, 2014; Dabirian et al., 2019), with the energy sector underrepresented despite its structural labour challenges. Second, where EB is studied in energy, it is most often examined through a single lens: either recruitment communication (Beck, 2008) or employee retention. In other words, without integrating organizations' external positioning with employees' internal experiences. In a sector where the employer value proposition is increasingly tied to societal goals, the credibility of an energy company's employer brand depends on whether the sustainability message communicated externally is reflected in internal practices.

This paper addresses these gaps by examining how EB shapes employer attractiveness in the energy sector in the North of the Netherlands, with a cross-country comparison with the North of Germany. Drawing on signalling theory (Spence, 1973; Connelly et al., 2011), person-organization fit (Kristof, 1996), and stakeholder theory (Freeman, 1984), it integrates four empirical investigations into a single analytical frame. Specifically, the paper addresses the following research questions:

1. *How do energy companies use EB in their job vacancies, and how does this differ across national contexts? (external organizational perspective)*
2. *To what extent does EB contribute to employer attractiveness for potential employees in the energy sector, and how do prior preferences moderate this relationship? (job seekers' perspective)*
3. *How is internal social media (ISM) used in energy organizations as part of their internal EB, and how does it relate to employee engagement and employer attractiveness? (internal communication perspective)*
4. *To what extent does perceived CSR relate to employer attractiveness for current employees in the energy sector? (CSR-employee relationship perspective)*

The contribution of the paper is threefold. First, it provides an integrated, multi-method empirical account of EB in the energy sector, combining the external organizational view (vacancy content), the prospective employee view (experiment), the managerial view (interviews), and the current employee view (survey).

Second, it identifies a misalignment between external promises and internal experiences within energy organizations in the North of the Netherlands that creates a structural risk to talent retention and, by extension, to the energy transition itself. Third, it derives practical implications for energy organizations in regions undergoing energy and societal transitions, framing EB not only as a recruitment tactic but as a strategic mechanism for supporting the human capital side of the energy transition.

The remainder of the paper is structured as follows. Section 2 develops the theoretical framework. Section 3 describes the mixed-methods design and the four empirical investigations. Section 4 presents the findings, organized around the external and internal perspectives. Section 5 discusses the conceptual and practical implications, with particular attention to the North of the Netherlands. Section 6 considers limitations and avenues for future research.

2. Theoretical Background

2.1. Employer Branding: External and Internal Perspectives

EB is based on the conviction that the employer organization can be seen as a brand. Employer brands help (potential) employees differentiate an employer from its competitors (Bustamante and Brenninger, 2014). Two interrelated conceptual distinctions structure the literature and inform the design of the present study.

The first distinction is between the *employer brand* and the *EB process*. The employer brand refers to the perceived identity and image of an organization as an employer held by (potential) employees (Backhaus and Tikoo, 2004). The EB process refers to the strategic efforts and communicative activities undertaken by organizations to shape and influence that perception (Ambler and Barrow, 1996). While the employer brand is an emergent outcome of employee interpretations, the EB process is a deliberate, ongoing effort to manage these perceptions. The EB process, in turn, shapes employer attractiveness, defined as the degree to which individuals perceive an organization as a desirable workplace (Berthon et al., 2005). EB is thus a driver; employer attractiveness is the attitudinal outcome.

The second distinction is between the *external* and *internal* views of EB. The external view conceptualizes EB as a one-directional, image-building activity aimed at potential employees, often through recruitment communication (Backhaus and Tikoo, 2004). It focuses on signalling employer value benefits such as career development, compensation, and work-life balance through job advertisements and employer reputation (Collins and Han, 2004; Cable and Turban, 2001). The internal view positions EB as a long-term relationship-management process involving continuous interactions between the organization and its current employees, transmitted through daily organizational practices, culture, and internal communication (Lievens and Slaughter, 2016). In this view, EB does not stop at recruitment but extends to employee experience, engagement, and ultimately retention.

The employer brand is multidimensional. Drawing on Backhaus and Tikoo (2004), Berthon et al. (2005), and subsequent work (Hoppe et al., 2022), it encompasses corporate identity (core values, mission, vision), organizational culture (shared values, behaviour, norms), corporate image and reputation, CSR, and a set of more specific job-related value propositions (development value, social value, application value, economic value, interest value). These dimensions are not equally salient in every context. The cultural context in which a business is embedded influences the norms it adheres to (Hofstede, 2001), and industry context conditions the type of benefits sought (Maxwell and Knox, 2009). EB is therefore contextually embedded and not a one-size-fits-all approach (Vaijayanthi et al., 2011; Landqvist, 2018).

2.2 Three Theoretical Lenses

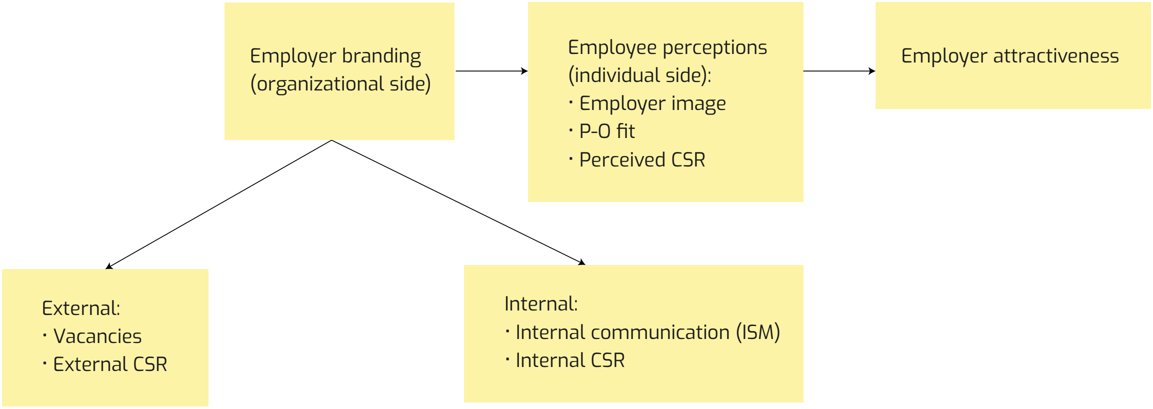
The integrated framework adopted in this paper rests on three theoretical lenses, each addressing a different aspect of the employer branding (EB) process. Together, these perspectives provide a comprehensive understanding of how EB shapes employer attractiveness in the context of the energy sector.

Signalling theory (Spence, 1973; Connelly et al., 2011) explains how organizations communicate unobservable attributes, such as organizational values, working conditions, or social commitments, to (potential) employees who cannot directly verify them. Vacancy texts, EB messages, and CSR communications function as signals through which organizations communicate aspects of their employer value proposition. The credibility of these signals depends on consistency: when externally communicated messages are not reflected in employees' lived experiences, trust and employer attractiveness may weaken over time. In the energy sector, where sustainability increasingly forms part of the employer value proposition, signalling consistency becomes particularly important.

Person-organization (P–O) fit theory (Kristof, 1996; Cable and Judge, 1997) explains how employer attractiveness depends on the perceived compatibility between an individual's values, goals, and norms and those of the organization. P–O fit captures the subjective alignment that emerges when job seekers and employees interpret organizational signals in light of their own preferences and expectations. EB is expected to contribute to employer attractiveness to the extent that it strengthens this perceived fit, which in turn has been associated with both intention to apply and long-term engagement.

Stakeholder theory (Freeman, 1984) frames organizations as accountable to a broader set of stakeholders: employees, customers, communities, regulators, and the public and treats CSR as one expression of this accountability. In the context of the regional energy transition, this perspective is particularly relevant, as energy organizations are accountable not only to internal stakeholders but also to the wider communities in which the transition unfolds. From an external perspective, CSR initiatives can signal ethical and societal values that strengthen employer image among job seekers (Greening and Turban, 2000; Story et al., 2016). Internally, CSR practices as fair labour policies, employee development, and credible environmental commitments may strengthen employees' identification with the organization and reinforce affective commitment (Rupp et al., 2013). In the energy sector, CSR is closely connected to broader sustainability objectives and therefore represents an important element of the employer brand. Figure 1 presents the integrated theoretical perspective adopted in this paper.

Figure 1. Theoretical Perspective



2.3 The Energy Sector as a Distinct EB Context

The energy sector, encompassing fossil, renewable, and grid activities, represents a distinct context for employer branding (EB). Traditionally, energy organizations have emphasized career development, long-term employment opportunities, and the possibility of contributing to large-scale societal challenges (Beck, 2008; Herriot and Pemberton, 1997; Kossivi et al., 2016). However, the ongoing energy transition is reshaping this positioning. Increasingly, work in the energy sector is framed around sustainability, societal purpose, and contribution to long-term environmental goals. At the same time, organizations with more traditional energy activities face the challenge of integrating changing societal expectations into their employer value propositions. Consequently, energy organizations may need to balance established organizational identities with emerging sustainability narratives within a coherent employer brand.

In the North of the Netherlands, the energy sector occupies a particular position within the regional development agenda. The region's Smart Specialisation Strategy (RIS3) identifies the transition from fossil-based to sustainable energy systems as one of its key priorities (SNN, 2024). At the same time, the regional labour market is structurally constrained, with vacancies in technical and energy-related professions exceeding the available labour supply (EURES, 2024). In this context, EB extends beyond a recruitment or marketing activity and becomes increasingly relevant as a strategic mechanism for attracting and retaining the human capital required to support the energy transition.

3. Method

3.1. Mixed-method Design

The empirical strategy adopts a mixed-methods design (Saunders et al., 2019) integrating four investigations conducted between 2021 and 2023 in the North of the Netherlands, complemented by a cross-country comparison with the North of Germany for the vacancy-content study. This design reflects the multidimensional nature EB, which cannot be adequately captured through a single methodological approach. Vacancy content analysis reveals how organizations communicate their employer value proposition externally. Experimental data with potential employees provide insights into how such employer signals are interpreted by target audiences. Manager interviews offer perspectives on how internal EB practices are organized, while employee surveys capture how these practices are experienced and how they relate to employer attractiveness. Together, the combination of methods provides a more comprehensive understanding of EB in the energy sector than any individual approach could achieve. Table 1 summarizes the four sub-studies.

Table 1. Overview of the Four Sub-studies

#	Study	Method	Energy sample	Lens	Key construct(s)
1	Vacancy content analysis	Quantitative content analysis (2-level coding)	52 vacancies (26 NL + 26 DE)	Signalling	External EB content; EB dimensions
2	Experiment with potential employees	2×2 between-subjects experiment	129 final-year students	Signalling × P-O fit	Perceived employer image; P-O fit; employer attractiveness
3a	Manager interviews	Semi-structured interviews; thematic coding	6 energy managers	Stakeholder; internal communication	Strategic useof ISM; integration with internal EB
3b/4	Employee survey	Cross-sectional survey; OLS regression; Sobel	312 energy employees	Stakeholder; signalling consistency	ISM use; perceived CSR; engagement; employer attractiveness

3.2. Study 1: Quantitative Content Analysis

The first study analysed 52 online job vacancies in the energy sector: 26 from the North of the Netherlands and 26 from the North of Germany. The vacancies were collected between 1 September and 15 October 2021 from Indeed.nl, indeed.de, LinkedIn, and selected company websites. Vacancies targeted highly educated graduates and professionals in full-time or part-time early-career positions requiring up to three years of work experience. Systematic randomization was applied to ensure variation within the sample.

Vacancy texts were coded in Atlas.ti by four native-speaking coders, using a four-eye principle and an independent re-coder, resulting in an intercoder reliability of 92 percent. This corresponds to a Cohen's κ above .80, indicating almost perfect agreement (Lombard et al., 2002). The coding scheme was developed through emergent coding (Stemler, 2001) based on an initial set of pilot vacancies and subsequently operationalized at two levels (Table 2). Level 1 captured the presence of EB dimensions, while Level 2 captured specific cues within each dimension. Vacancy-level counts were normalized by the proportion of EB elements per vacancy to control for variation in text length.

Table 2: Coding Scheme

Coding level 1	Descriptors level 2 coding
Identity	Core values, mission, vision, characteristics, history
Corporate Culture	Work environment, team, norms, benefits = material benefits + safety and inclusion
Image/Reputation	Performance/success, reputation (outside in)
USP/uniqueness	Distinctive characteristics, employer value proposition
Training & Development	Training opportunity, professional development
CSR	Ethical, environmental responsibility

3.3. Study 2: Experimental Design with Final-Year Students

The second study used a 2×2 between-subjects experimental design to examine whether EB cues in vacancy texts increase perceived employer attractiveness and whether this effect depends on pre-existing locational preferences. Four versions of the same vacancy were constructed, varying EB cues (present versus absent) and location (Groningen versus Amsterdam). To avoid confounding effects associated with existing organizational reputations, a management trainee vacancy in a virtual organization was developed.

Of the 289 students who initially participated, 129 passed an attention check and were retained for analysis. The sample included students enrolled in technical programmes, including Energy for Society and Renewable Energy, representing a group relevant to energy-sector recruitment.

Employer attractiveness was measured using Highhouse et al. (2003) (Cronbach's α = .86); perceived employer image was measured through a 17-item adaptation of Berthon et al. (2005) (α = .88); and perceived P–O fit was measured using Cable and Edwards (2004) (α = .81). Regression analyses tested direct and moderating effects of pre-existing preferences, while Hayes' (2017) bootstrap procedure tested mediation through perceived employer image and P–O fit.

3.4. Study 3a: Semi-Structured Interviews with Energy Managers

The third sub-study, focusing on internal communication and internal EB, used semi-structured interviews with six HR and communication managers from energy organizations in the North of the Netherlands. Participants held roles such as Head of Communications and Employer Brand Lead. Interviews were conducted between March and May 2023, lasted on average 55-60 minutes, and followed an interview guide covering internal social media (ISM) use, EB practices, and employee engagement. Interviews were transcribed, anonymized, and analyzed thematically using Atlas.ti. The study received ethical approval from the Faculty of Spatial Sciences Research Ethics Committee, University of Groningen (Ref. 2023–15).

3.5. Study 3b/4: Employee Survey

The fourth sub-study used an employee survey distributed through participating organizations in the North of the Netherlands. From a total of 1,260 responses, 938 were retained as valid after exclusions and listwise deletion for CSR-related analyses (74.4 percent valid response rate). For the purposes of the present paper, analyses were restricted to the 312 respondents (33.3 percent) working in the energy sector. The energy sample had an average age of 43.4 years; approximately two-thirds (69 percent) held at least a bachelor's degree, and 17 percent occupied managerial positions.

Employer attractiveness was measured using the 18-item scale developed by Berthon et al. (2005) ($\alpha = .91$). Perceived CSR was measured using the six-item scale developed by Turker (2009), distinguishing between internal and external CSR dimensions ($\alpha = .83$). Employee engagement was operationalized as affective commitment using Meyer's (2014) subscale ($\alpha = .87$), consistent with engagement research emphasizing the emotional and motivational dimensions of the construct (Rich et al., 2010; Bailey et al., 2017). ISM use was operationalized as a composite formative index based on four standardized indicators: frequency of use, purpose of sharing, communication style, and satisfaction with shared information, following Madsen (2017) and van Zoonen et al. (2016).

Control variables included age, gender, tenure, education, and managerial position. Direct and mediated relationships were tested using stepwise OLS regression analyses, while mediation effects through employee engagement were examined using the Sobel test (Sobel, 1982).

4. Results

The findings are organized around the external and internal perspectives of employer branding. Section 4.1 presents the external organizational perspective through the analysis of vacancy content. Section 4.2 presents the perspective of potential employees through the experimental study. Sections 4.3 and 4.4

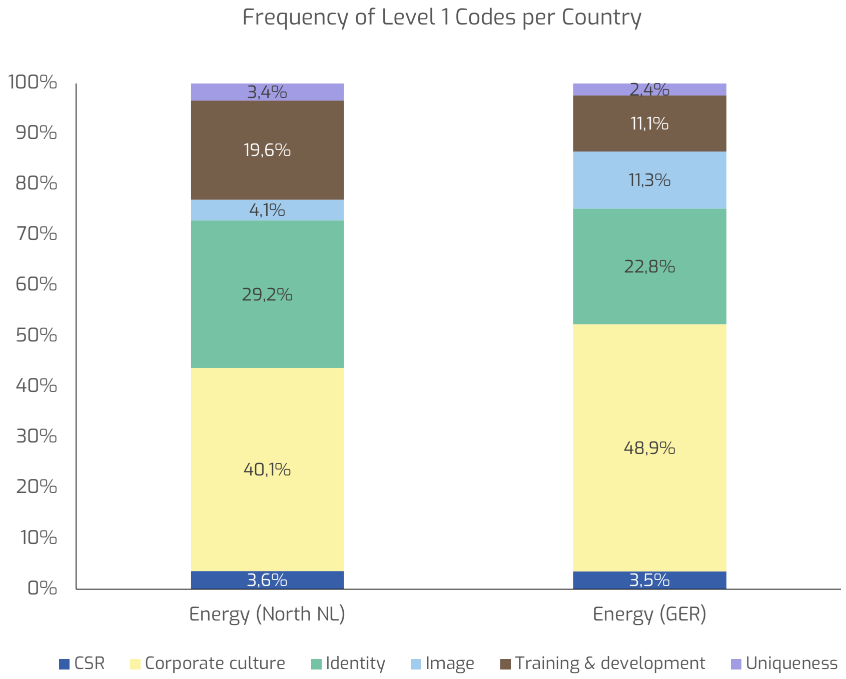
present the internal perspective through manager interviews and employee survey findings related to ISM use and perceived CSR.

4.1. External EB: Vacancy Patterns in the Energy Sector

The analysis of energy vacancies in the North of the Netherlands and the North of Germany reveals that EB is present in all energy vacancies in both countries, although it differs in intensity and emphasis.

In terms of intensity, the average number of EB code occurrences per vacancy is higher in the North of the Netherlands (28 codes per vacancy) than in the North of Germany (19), reflecting both longer Dutch vacancy texts (590 words on average) and more elaborate EB content. This finding suggests that energy organizations in the North of the Netherlands invest substantially in communicating EB attributes through recruitment materials. Figure 2 shows the proportional distribution of EB codes.

Figure 2: EB code Frequencies in Energy Vacancies, North of Netherlands vs North of Germany



Note: Figure 2 presents the "proportional distribution" across dimensions, while 28 vs 19 is the "average code count" per vacancy.

In terms of emphasis, a more nuanced pattern emerges. Dutch energy vacancies place comparatively stronger emphasis on identity and on training and development, whereas German energy vacancies devote a larger share of their EB content to corporate culture and image. Within the corporate culture dimension, Dutch vacancies most frequently highlight benefits and working environment, using descriptors such as "informal", "safe", and "responsible". Within identity, organizations frequently describe organizational characteristics but place comparatively less emphasis on explicit core values and history. In other words, vacancies more often communicate what the organization does than what it stands for.

German energy vacancies, by contrast, more frequently use descriptors directed towards younger talent groups, including everyone is welcome, flexible working time, ambition, innovative company, and modern. This cross-country variation may reflect broader cultural differences in communication styles and employer positioning (Hofstede, 2001).

Environmental responsibility emerged as the least-cited CSR-related sub-code within the energy vacancies. This finding is notable given the central role of sustainability and energy transition objectives within the sector itself. The findings suggest that although energy organizations are actively involved in sustainability transitions, these elements are communicated less explicitly within recruitment messages.

Overall, the external perspective suggests that energy organizations in the North of the Netherlands primarily rely on a more functional or utilitarian framing of employer branding, emphasizing development opportunities, benefits, and work environment characteristics. At the same time, values- and sustainability-oriented elements appear comparatively less visible in recruitment communication.

4.2. External EB: Employee Predisposition and the Effectiveness of EB Cues

The experiment examined whether adding EB cues to a vacancy increased perceived employer attractiveness and whether this effect was moderated by pre-existing preferences. The direct effect of EB cues on employer attractiveness was not statistically significant. However, models including moderating variables indicated that EB cues became more effective when aligned with characteristics already valued by potential employees, particularly those related to location and origin.

Specifically, international students responded more positively to EB cues than Dutch students, irrespective of vacancy location, whereas Dutch students' responses to EB cues varied depending on the location of the vacancy. The combined model including moderators explained 15 percent of the variance in employer attractiveness ($R^2 = .15$), with a positive and statistically significant coefficient for EB ($\beta = .33$, $p < .05$). Significant negative interaction effects were observed for both the Dutch vacancy in Amsterdam with EB (β = –.34, p < .05) and Dutch vacancy in Groningen with EB (β = –.36, p < .05) conditions. The hypothesized mediation through perceived employer image and P–O fit was not supported.

These findings suggest that the effectiveness of EB depends on the alignment between employer signals and pre-existing preferences among potential employees. Rather than functioning as a universally effective recruitment mechanism, EB appears to operate in conjunction with contextual factors that shape individual preferences. For energy organizations in the North of the Netherlands, where attracting and retaining talent remains a challenge, these findings suggest that targeted EB strategies aligned with characteristics valued by specific groups of potential employees may be more effective than generic recruitment messages.

4.3. Internal EB: ISM Use in Energy Organizations

Interviews with the six energy managers reveal that ISM is used in all energy organizations included in the study, although primarily in an ad hoc rather than strategic manner. None of the organizations reported having an explicit policy regarding the integration of ISM within their internal EB activities. Instead, ISM was primarily described as a communication tool used for knowledge sharing, information provision, and social interaction rather than as a mechanism for actively supporting the internal employer brand.

An additional finding concerns differences in ISM accessibility across employee groups. Interview evidence from a large-scale energy producer suggests that employees in operational roles may have less direct access to internal social media than managerial and office-based employees:

> *"What you see is that the people in the factories, there are about 600 of them… the operators and mechanics who actually work in the factories certainly do not use our internal social media on a daily basis and we depend on whether they see the televisions or narrowcasting on the sites…"*

Although this observation is based on qualitative evidence and therefore requires further investigation across a broader set of organizations, it suggests that access to internal communication channels may differ among employee groups within energy organizations.

Survey findings complement these qualitative observations by showing that ISM use is positively associated with both employee engagement and employer attractiveness. ISM use significantly predicts employer attractiveness (β = .37, p < .01). When employee engagement is added to the model, the ISM coefficient decreases (β = .21, p < .01) but remains significant, while employee engagement contributes strongly (β = .56, p < .01), indicating a pattern consistent with partial mediation. The combined model explains 46 percent of the variance in employer attractiveness.

4.4. Internal EB: Perceived CSR and Employer Attractiveness in Energy

The most pronounced finding of the present paper concerns perceived CSR. Within the energy employee sample, perceived CSR is strongly and positively associated with employer attractiveness ($r = .67$, $p < .01$), with the strongest association observed for the internal CSR dimension ($r = .65$, $p < .01$). Employees in the energy sample reported a mean perceived CSR score of 3.95 (SD = .60), an employer attractiveness score of 3.88 (SD = .60), and an employee engagement score of 3.36 (SD = .74). A one-way ANOVA across three of the leading sectors in the North of the Netherlands sectors shows significant differences, $F(2, 914) = 22.99$, $p < .001$ for perceived CSR. Post-hoc Tukey HSD tests reveal that energy employees report significantly higher perceived CSR (M = 3.95, SD = .60) than employees in healthcare (M = 3.72, SD = .64) or IT (M = 3.42, SD = .79). Energy also scores highest on employer attractiveness (M = 3.88, SD = .60) - significantly higher than healthcare (M = 3.64, SD = .56) at $p < .001$. On employee engagement, energy (M = 3.36, SD = .74) is higher than healthcare (M = 3.09, SD = .77) at $p < .001$ and statistically indistinguishable from IT (M = 3.47, SD = .71). Table 3 summarizes these sector-level differences.

Table 3. Sector-level means on main internal-EB variables (employee survey, N = 938)

Variable	Energy (n=312)	Healthcare (n=561)	IT (n=65)	F(2, ~915)	p
Employer attractiveness	3.88 (.60)	3.64 (.56)	3.79 (.60)	17.90	< .001
Perceived CSR	3.95 (.60)	3.72 (.64)	3.42 (.79)	22.99	< .001
Employee engagement	3.36 (.74)	3.09 (.77)	3.47 (.71)	17.01	< .001

Further analysis indicates that employee engagement partially explains this relationship. Perceived CSR remained positively associated with employer attractiveness, while employee engagement contributed strongly to the model, consistent with a pattern of partial mediation. These findings suggest that CSR may contribute not only to perceptions of the organization itself but also to employees' emotional connection with the organization.

Regression analysis confirms that perceived CSR is strongly and positively associated with employer attractiveness ($\beta = .67$, $p < .01$ in the model including controls and perceived CSR only), while employee engagement partially explains this relationship. In the combined model including perceived CSR (external dimension), employee engagement, and control variables, both perceived CSR ($\beta = .39$, $p < .01$) and employee engagement ($\beta = .39$, $p < .01$) remain statistically significant predictors of employer attractiveness, jointly explaining 59 percent of the variance ($R^2 = .59$). The Sobel test further indicates a statistically significant indirect association consistent with partial mediation through employee engagement ($z = 12.62$, $p < .001$). Table 4 summarizes the key regression findings across the four sub-studies.

Table 4. Key Regression Results

Study	Model	DV	Key predictors (β)	R^2
2	Experiment (external)	Employer attractiveness	EB cue: .33; Dutch×Amsterdam×EB: –.34; Dutch×Groningen×EB: –.36*	.15
3b	Survey (internal)	Employer attractiveness	ISM use: .37**	.19
3b	Survey (internal)	Employer attractiveness	ISM use: .21; Employee engagement: .56	.46
4	Survey (internal)	Employer attractiveness	Perceived CSR (overall): .67**	.48
4	Survey (internal)	Employer attractiveness	Perceived CSR (external): .39; Employee engagement: .39	.59

Note. β values are standardized coefficients. All reported coefficients are statistically significant ($p < .05$) and ($p < .01$)** .*

5. Discussion

5.1. An Integrated Picture of EB in the Energy Sector

The four sub-studies, considered together, provide an integrated picture of EB within the energy sector in the North of the Netherlands.

The external perspective indicates that energy organizations invest substantially in communicating EB content but place greater emphasis on functional and utilitarian elements, such as "development opportunities", "benefits", and "working conditions", than on identity- and sustainability-related elements. Notably, environmental responsibility (the EB element most directly connected to the energy transition) was among the least emphasized CSR-related themes in the vacancy material. This suggests that recruitment communication does not yet fully reflect the broader sustainability context in which many energy organizations operate.

The experimental findings indicate that EB cues become more effective when aligned with pre-existing preferences among potential employees. For energy organizations, this suggests that more targeted EB strategies may be more effective than broad and generic recruitment messages. For example, emphasizing sustainability orientation, technical interests, regional embeddedness, or societal purpose.

The internal perspective highlights two related findings. First, ISM was used across all energy organizations but primarily in an ad hoc rather than strategic manner. Qualitative findings further suggest that access to internal communication channels may vary across employee groups. Second, perceived CSR emerged as a strong correlate of employer attractiveness among employees in the energy sector, with employee engagement partially explaining this relationship.

Together, these findings suggest that energy organizations possess a potentially strong EB asset in the broader societal purpose associated with the energy transition. However, this value proposition may not yet be consistently communicated externally or experienced internally across employee groups. The findings therefore point towards a potential misalignment between the substantive characteristics of the employer brand and the way it is communicated and experienced within the labour market.

5.2. Theoretical Contributions

The paper contributes to the EB literature in three ways.

First, by integrating signalling theory, person-organization (P–O) fit theory, and stakeholder theory within an empirical study of the energy sector, the paper demonstrates that these theoretical perspectives are complementary rather than competing. Signalling theory explains how energy organizations communicate employer-related attributes externally. P–O fit theory explains how these signals interact with individual preferences and perceptions. And stakeholder theory explains how CSR and internal communication practices contribute to sustaining longer-term employer-employee relationships. The energy sector provides a particularly relevant context for this integration because sustainability objectives and broader societal responsibilities are closely intertwined with organizational activities.

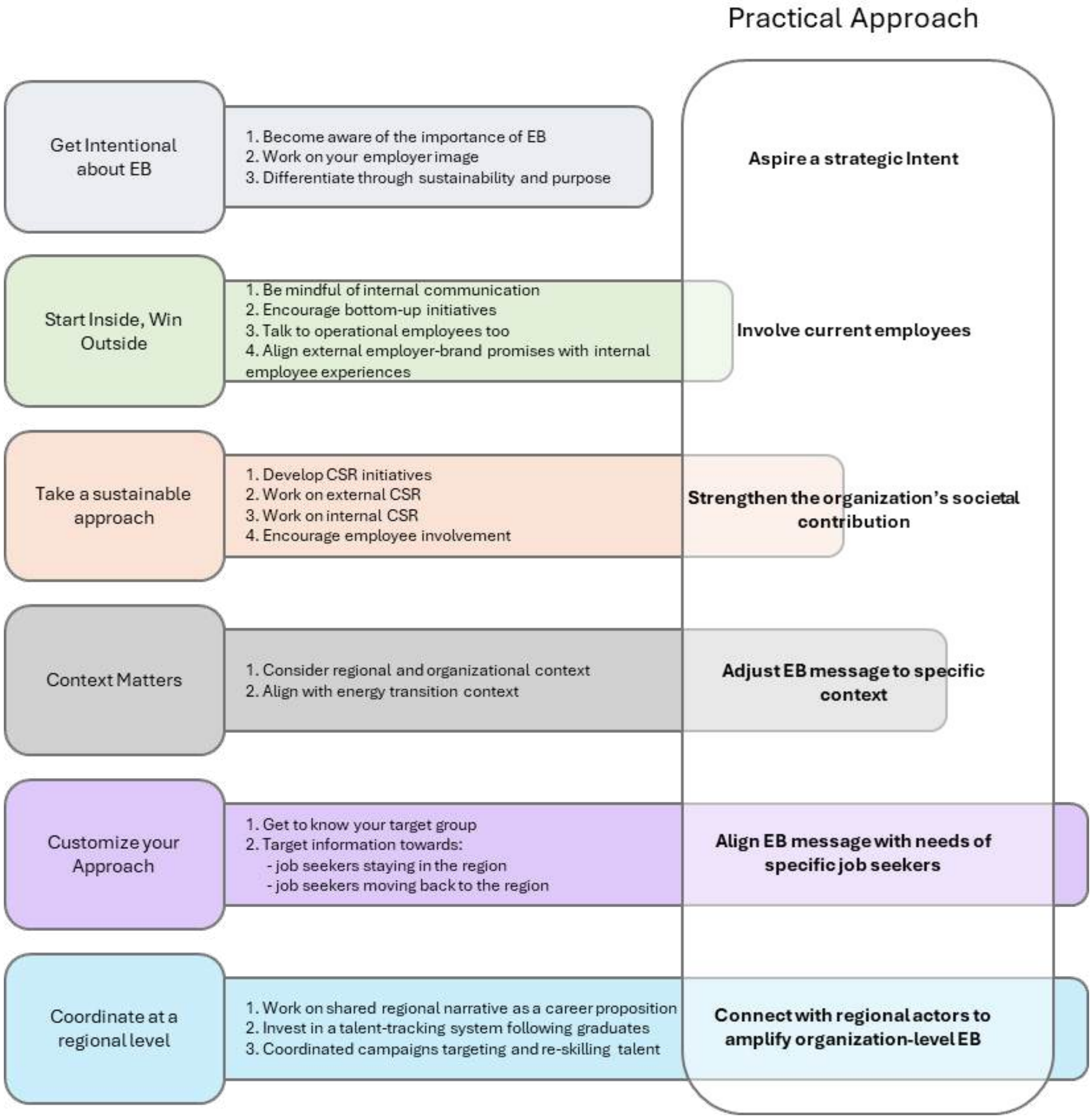
Second, the paper contributes to the literature on internal EB by showing that perceived CSR is strongly associated with employer attractiveness in the energy sector, with employee engagement partially explaining this relationship. This extends earlier work linking CSR with external employer attractiveness (Greening and Turban, 2000; Jones et al., 2016; Lis, 2018) by demonstrating its relevance within the internal organizational context. The findings suggest that employees' perceptions of organizational responsibility may play an important role in shaping employer attractiveness and strengthening longer-term employee relationships.

Third, the paper identifies a potential misalignment between external EB communication and internal EB experiences. Specifically, sustainability-related elements appear relatively less visible in external recruitment communication, while internal communication practices are not consistently embedded within broader EB strategies. This highlights the importance of considering employer branding not only as an external recruitment activity but also as an integrated organizational process that connects external positioning and internal experiences.

5.3. Practical Implications for the North of the Netherlands

The findings of this paper translate into six practical implications for energy organizations and regional stakeholders. Figure 3 presents these implications as an integrated roadmap to strengthen employer attractiveness and support the human capital requirements of the energy transition.

Figure 3. EB Roadmap for Energy Transition in the North of the Netherlands



1. **Get intentional about EB**
   The findings suggest that energy organizations will benefit from developing a more explicit and strategic EB approach. Sustainability-related contributions and organizational values appear relatively less visible in vacancies, despite their relevance within the context of the energy transition. Energy organizations should rewrite their vacancy texts to lead with the values that distinguish the organization.

2. **Start inside, win outside**
   Energy organizations will benefit from strengthening internal communication and actively involving current employees in EB processes. The findings suggest that unequal access to communication channels across employee groups may create inconsistencies in the experience of EB, particularly among operational employees involved in delivering transition objectives. All energy organizations interviewed used ISM, but none had a strategic framework linking ISM to internal EB. A modest set of decisions like which platform for which type of message, who moderates, what content is aligned with the external EB, would convert ISM from an instrumental tool into a strategic asset. Bottom-up employee voice on ISM is a credibility multiplier for the external EB because current employees are the most trusted ambassadors of the organization (Madsen and Johansen, 2019; Itam et al., 2020).

3. **Take a sustainable approach**
   The energy sector's strongest internal EB lever is perceived CSR. Energy organizations should make CSR programmes a priority. Both external (community engagement, local sustainability investments, environmental performance) and internal (employee development, work-life balance, diversity and inclusion, fair labour practices for operational personnel) should be visible and participatory. Active employee involvement in CSR strengthens the programme, surfaces unexpected competencies, and reinforces the link between organizational identity and employee identification that underpins retention (van Tulder and van der Zwart, 2003).

4. **Context matters**
   The effectiveness of EB messages depends on contextual factors according to the findings. Energy organizations will therefore benefit from continuing to anticipate on regional conditions and aligning EB messages with the broader context of the energy transition.

5. **Customize your approach**
   The experimental results indicate that EB is most effective when it reinforces a pre-existing preference. For the North of the Netherlands this means identifying the candidate groups whose predispositions align with the regional energy transition and tailoring EB to them. Three target groups are particularly relevant: 1. students and graduates from the region with a sustainability

or technical orientation; 2. alumni from the region who have moved to the Randstad and may be receptive to a homecoming proposition tied to the transition (Fischer et al., 2021); 3. skilled labour transitioning out of fossil-related activities in the region, for whom internal-mobility EB within and between energy organizations is critical.

6. **Coordinate at the regional level**
   No single energy organization can resolve the regional labour shortage alone. Regional actors like the provinces of Groningen, Friesland and Drenthe, SNN, the University of Groningen, the Hanze University of Applied Sciences and the regional energy cluster can amplify organization-level EB. A shared regional narrative on the energy transition as a career proposition (SNN, 2024) or a talent-tracking system following graduates from vocational, applied-science and university programmes into the regional labour market can be a practical way to do that. Another alternative is coordinated campaigns targeting "homecoming" and re-skilling talent, with organizations collaborating rather than competing for the same narrow pool.

6. Limitations and Future Research

Several limitations should be considered when interpreting the findings of this study.

First, although this paper integrates multiple empirical investigations into a single framework, the studies were originally conducted as part of a broader research programme. For the purposes of the present paper, analyses were restricted to energy-sector findings to ensure conceptual coherence. While this provides a focused understanding of employer branding within the context of the energy transition, future studies may examine whether similar patterns emerge in other sectors experiencing societal and technological transitions.

Second, the experimental study employed a generic management-trainee vacancy rather than an energy-specific vacancy. Although this design reduced potential confounding effects associated with existing employer reputations, it limits direct conclusions regarding recruitment responses within energy-sector contexts. Future research could strengthen external validity by replicating the design with energy-specific vacancies and examining whether different EB signals, such as sustainability-oriented versus more utilitarian messages, influence employer attractiveness differently.

Third, the experimental study relied on a student sample, including students enrolled in technical and energy-related programmes. Although these participants represent a relevant source of future talent, their preferences may differ from those of experienced professionals already active within the labour market. Future studies may therefore investigate whether similar patterns emerge among experienced employees and job seekers in energy-related professions.

Fourth, the survey data used in the present study were cross-sectional, limiting causal interpretation of the relationships examined. Although the theoretical framework suggests that internal communication practices and perceived CSR influence employee engagement and employer attractiveness, reverse causal relationships cannot be ruled out. Longitudinal designs would provide stronger evidence regarding the directionality and development of these relationships over time.

Finally, this study focuses primarily on the North of the Netherlands, with a cross-country comparison limited to the North of Germany in the vacancy analysis. While this regional perspective provides valuable insights into labour-market dynamics within a transition region, the findings may not be fully generalizable to other geographical contexts.

7. Conclusion

The transition towards more sustainable energy systems increasingly depends not only on technological developments but also on the availability of human capital capable of supporting and delivering these transformations. This paper examined the role of EB in achieving employer attractiveness from both external and internal perspectives within the energy sector.

The findings suggest that EB in the energy sector extends beyond a recruitment activity and functions as a broader organizational process connecting external communication, internal experiences, and employee relationships. While energy organizations communicate EB attributes extensively, sustainability-related elements and organizational purpose appear less visible within recruitment communication. At the same time, perceived CSR and internal communication practices emerged as important internal mechanisms associated with employer attractiveness and employee engagement.

Taken together, the findings suggest that energy organizations possess a potentially strong EB asset in the broader societal purpose associated with the energy transition. However, this value proposition is not yet communicated and experienced consistently across external and internal contexts. Aligning external EB promises with internal employee experiences therefore appears critical for strengthening both talent attraction and employee retention. Ultimately, the findings indicate that EB supports not only employer attractiveness but also the broader human-capital requirements needed to support the energy transition in the North of the Netherlands.

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Empowering Maritime Sustainability: Strengthening Internal CSR Engagement at Corvia (Eekels | TBI)

Maria Lazareva (Hanze)

The maritime sector is undergoing a rapid energy transition driven by decarbonisation targets, regulatory pressure, and technological innovation. While sustainability transitions are often approached as technical challenges, the organisational and communicative dimensions of change remain underexplored. This study examines how internal CSR and sustainability communication can strengthen employee engagement, organisational credibility, and internal alignment within a maritime energy-transition context.

The research was conducted at Corvia (Eekels | TBI), a business unit developing hybrid and electric propulsion solutions for the maritime sector. A design research methodology was applied, combining desk research, benchmarking, content analysis, and field research consisting of a survey, semi-structured interview, and focus group. Findings revealed that internal sustainability communication was perceived as fragmented, irregular, and weakly connected to employees' daily work. Key gaps included limited participation opportunities, insufficient evidence-based communication, and weak role-specific translation of sustainability ambitions.

Based on these findings, the study designed and validated an Internal Sustainability Communication System consisting of four interrelated components: a recurring communication cycle, a sustainability KPI dashboard, role-based sustainability content cards, and participatory dialogue formats. Validation with industry peers confirmed the conceptual coherence, contextual relevance, and practical feasibility of the intervention.

The study contributes to the growing intersection between CSR communication and energy transition research by highlighting the importance of internal organisational alignment in sustainability transitions. In practice, it provides a scalable framework for strengthening internal sustainability engagement in technical-industrial organisations.

Keywords: CSR communication, Energy transition, Maritime sustainability, Employee engagement, Internal communication, Sustainability transitions

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1. Introduction

The maritime sector is undergoing a significant sustainability transition driven by increasing regulatory pressure, decarbonisation targets, technological innovation, and shifting societal expectations. Across Europe, the maritime industry faces growing demands to reduce greenhouse gas emissions and contribute to broader climate objectives established through frameworks such as the European Green Deal, FuelEU Maritime, and the International Maritime Organization's decarbonisation agenda. In response, maritime organisations are increasingly investing in hybrid propulsion systems, electrification technologies, and other sustainable innovations aimed at reducing environmental impact.

However, sustainability transitions are not solely technological processes. While much attention is placed on technical innovation and infrastructure development, organisational and human dimensions of sustainability transitions often receive less attention. Successfully implementing sustainability ambitions requires not only new technologies, but also internal alignment, employee engagement, and organisational support. Employees play a critical role in translating sustainability strategies into everyday operational practices, yet sustainability communication within organisations frequently remains fragmented, abstract, or disconnected from daily work routines.

Corporate Social Responsibility (CSR) communication has traditionally focused on external stakeholders, including branding, reporting, and reputation management. However, recent research increasingly highlights the importance of internal CSR communication in strengthening organisational credibility, employee engagement, and participation in sustainability initiatives. Employees are not passive recipients of sustainability strategies; they are active participants whose understanding, trust, and involvement influence how sustainability ambitions are implemented in practice.

This challenge is particularly relevant within technical-industrial organisations operating in the energy transition, where sustainability is often communicated primarily through technical achievements and innovation narratives. Without structured internal communication systems, sustainability ambitions risk remaining strategic concepts rather than becoming embedded in organisational culture and daily practices.

This study examines these challenges through a case study at Corvia (Eekels | TBI), a Dutch maritime technology organisation specialising in hybrid and electric propulsion systems. The research investigates how internal CSR and sustainability communication can support employee engagement and strengthen organisational alignment within the maritime energy transition.

The central research question guiding this study is:

> *How can Corvia develop a structured internal CSR communication approach that strengthens employee engagement and supports its role in the maritime energy transition?*

To answer this question, a design research methodology was applied, combining desk research, benchmarking, content analysis, and qualitative field research. Based on the findings, the study developed and validated an Internal Sustainability Communication System designed to strengthen communication structure, participation, evidence-based sustainability communication, and role-specific relevance.

This paper contributes to the growing intersection between CSR communication and sustainability transition research by emphasising the importance of internal organisational alignment during energy transitions. In addition, the study provides a practical and scalable framework that may also be relevant beyond the maritime sector, particularly for technical-industrial organisations navigating sustainability transformations.

2. Theoretical Background

Corporate Social Responsibility (CSR) has evolved from a primarily philanthropic concept into a broader strategic approach through which organisations address their environmental, social, and economic impacts. Within contemporary sustainability discourse, CSR increasingly functions as a mechanism for aligning organisational operations with societal expectations and long-term sustainability objectives. In sectors undergoing rapid transformation, such as maritime transport and energy systems, CSR is closely connected to organisational legitimacy, stakeholder trust, and the ability to maintain a social license to operate.

Traditionally, CSR communication has focused strongly on external stakeholders through sustainability reporting, branding, and reputation management. However, scholars increasingly emphasise that internal CSR communication is equally important for successful sustainability implementation. Employees are central actors in organisational sustainability transitions because they translate strategic ambitions into operational practices and everyday decision-making. As a result, sustainability communication should not only inform employees, but also support understanding, participation, and organisational alignment.

Internal communication literature highlights that employees are more likely to engage with sustainability initiatives when communication is perceived as clear, credible, relevant, and participatory. Communication that remains abstract or disconnected from employees' daily responsibilities can reduce engagement and create scepticism toward organisational sustainability ambitions. In contrast, transparent and dialogue-oriented communication can strengthen employee trust, ownership, and identification with sustainability goals.

Participation is particularly important within sustainability transitions, which often require behavioural adaptation, organisational learning, and cross-functional collaboration. Research on participatory communication argues that employees should not be treated as passive recipients of sustainability messaging, but as active contributors whose perspectives and experiences shape organisational change processes. Dialogue and co-creation therefore become important mechanisms for strengthening internal engagement and reducing resistance to change.

Another important concept within sustainability transitions is organisational credibility. Sustainability communication that relies heavily on ambition and symbolic narratives without measurable evidence can contribute to perceptions of "greenwashing," where sustainability claims are viewed as disconnected from actual organisational practices. Evidence-based communication, transparency, and visible progress indicators are therefore essential for maintaining employee trust and reinforcing the legitimacy of sustainability strategies.

Within energy-transition contexts, these communication challenges become increasingly complex. Technical-industrial organisations often prioritise technological innovation while underestimating the organisational and cultural changes required to support transition processes. Existing research suggests that sustainability transitions require systems-based approaches in which technological, organisational, and communicative dimensions are integrated rather than treated separately.

This study builds upon these perspectives by examining how internal CSR communication can support sustainability transitions within a maritime technology organisation. Specifically, it explores how structured communication systems can strengthen employee engagement, organisational credibility, and internal alignment in the context of the maritime energy transition.

3. Methodology

This study applied a design research methodology aimed at both analysing an organisational problem and developing a practical intervention. Design research is particularly suitable for practice-oriented organisational studies because it combines theoretical analysis with the creation of actionable solutions.

In this research, the approach was used to investigate how internal CSR communication could be strengthened within Corvia in the context of the maritime energy transition.

The study was conducted as a single-case study within Corvia (Eekels | TBI), a business unit operating in the maritime technology sector. A mixed qualitative approach was adopted, combining desk research, benchmarking, and field research to obtain both organisational and employee-level insights.

The desk research phase consisted of two components. First, a qualitative content analysis was conducted on existing internal sustainability and communication materials, including internal newsletters, intranet content, and communication outputs related to sustainability and innovation. Second, a benchmarking analysis examined sustainability communication practices within comparable technical-industrial organisations, including ABB, Danfoss, DNV, and Croonwolter & Dros. The benchmarking phase focused on communication transparency, employee engagement mechanisms, and evidence-based sustainability communication.

Field research was conducted within the Corvia business unit and included an exploratory survey, one semi-structured interview, and a focus group involving employees from technical, project management, and commercial roles. These methods were selected to capture both individual experiences and collective perspectives regarding sustainability communication, employee participation, and organisational alignment.

The collected data were analysed through reflexive thematic analysis using a hybrid coding approach. Deductive coding was informed by theoretical concepts derived from CSR communication, stakeholder theory, participatory communication, and social license to operate literature. Inductive coding allowed additional themes and patterns to emerge from the empirical data.

Findings from the different research phases were triangulated to identify recurring communication challenges and to translate these insights into design requirements for the intervention. Based on this process, an Internal Sustainability Communication System was developed and subsequently validated through prototype-based feedback sessions with industry peers from the maritime and shipbuilding sector.

The research focused specifically on the internal organisational dimension of sustainability transitions rather than on technical system performance or external marketing communication. Ethical considerations included informed consent, voluntary participation, anonymity of respondents, and secure handling of collected data.

4. Findings

The findings reveal that Corvia's sustainability communication was characterised by strong sustainability ambition but limited internal structure and employee integration. Across the content analysis, benchmarking, survey, interview, and focus group phases, four recurring communication gaps emerged consistently.

4.1. Lack of Communication Structure

The first major finding concerned the absence of a structured and predictable internal sustainability communication process. Sustainability communication within Corvia was experienced as fragmented, irregular, and primarily dependent on isolated updates or informal exchanges rather than embedded organisational routines.

Employees indicated that sustainability-related communication appeared sporadically and lacked continuity, making it difficult to maintain engagement or develop a clear understanding of ongoing sustainability developments. Sustainability communication was therefore perceived more as a collection of disconnected messages than as a coherent organisational process.

Benchmarking findings demonstrated that comparable organisations with stronger sustainability positioning applied recurring communication cycles and structured internal engagement practices, contributing to higher visibility and consistency of sustainability initiatives.

4.2. Credibility and Evidence Gap

The second finding concerned organisational credibility and the limited use of evidence-based sustainability communication. Although employees generally supported Corvia's sustainability ambitions and recognised the company's contribution to maritime decarbonisation, many participants expressed a desire for more concrete, measurable, and transparent sustainability information.

Sustainability communication was perceived as highly ambition-driven, while measurable evidence and operational sustainability indicators remained largely absent from internal communication practices. Employees specifically requested clearer insights into environmental impact, project outcomes, and sustainability performance indicators linked to Corvia's technologies and operations.

This finding aligns with existing CSR communication literature emphasising that credibility depends not only on strategic ambition but also on transparent and evidence-based communication practices.

4.3. Limited Participation and Employee Voice

The third finding revealed limited opportunities for employee participation and dialogue regarding sustainability-related topics. Employees reported that sustainability communication was predominantly top-down, with few formal mechanisms allowing employees to contribute ideas, ask questions, or participate in shaping sustainability initiatives.

While employees demonstrated strong interest in sustainability and the energy transition, participation opportunities were not structurally embedded within organisational communication processes. As a result, sustainability was often experienced as management-driven rather than collectively shaped.

Focus group discussions highlighted that employees valued opportunities for dialogue and preferred communication approaches that encouraged interaction, collaboration, and shared interpretation of sustainability developments.

4.4. Weak Role-Specific Relevance

The fourth finding concerned the limited translation of sustainability ambitions into role-specific meaning. Employees frequently struggled to connect broad sustainability goals and transition narratives to their own daily work practices and responsibilities.

Although employees recognised Corvia's role in the maritime energy transition, many participants indicated uncertainty regarding how their individual contributions supported broader sustainability objectives. Sustainability therefore remained conceptually distant from operational routines.

This gap was particularly visible among technical and operational employees, who expressed a need for communication formats that translated sustainability ambitions into concrete examples, role-specific relevance, and practical implications for everyday work.

4.5. Integrated Interpretation of Findings

Importantly, the findings do not suggest employee resistance toward sustainability or the energy transition. On the contrary, employees generally expressed strong support for sustainability ambitions and demonstrated motivation to contribute to organisational transition goals.

The central issue identified by this research was therefore not a lack of employee willingness, but rather the absence of a structured communication system capable of supporting sustainability engagement in practice.

Taken together, the findings indicate that Corvia's challenge is systemic rather than informational. Increasing the volume of sustainability communication alone would not resolve the identified issues. Instead, the organisation requires a structured internal communication approach that integrates credibility, participation, continuity, and role-specific relevance into everyday organisational processes.

5. Designed Intervention

Based on the findings, this study developed an Internal Sustainability Communication System for Corvia. Rather than functioning as a single communication tool or isolated campaign, the intervention was designed as a coherent organisational communication system aimed at embedding sustainability into everyday organisational processes and employee experiences.

The intervention was developed through a design research approach in which empirical findings were translated into practical design requirements. The resulting system addresses the four core communication gaps identified in the research: lack of communication structure, limited credibility, insufficient participation, and weak role-specific relevance.

The Internal Sustainability Communication System consists of four interrelated components.

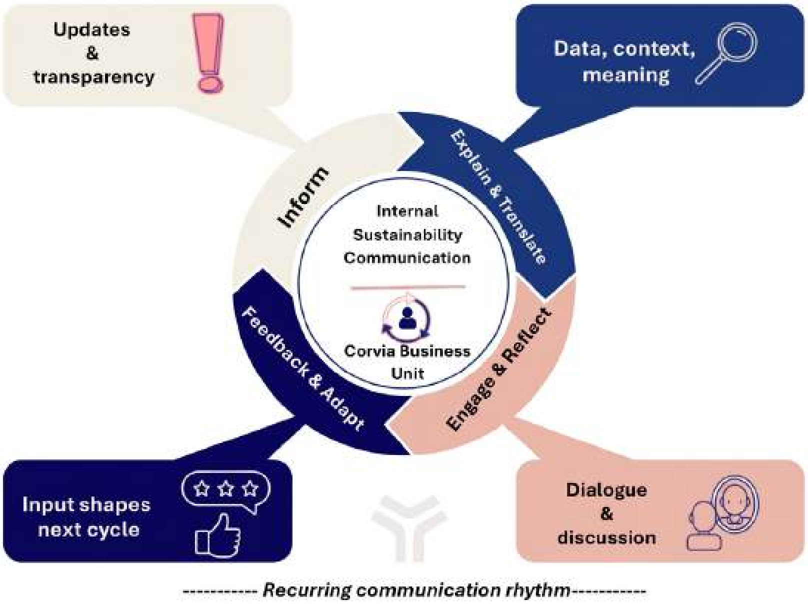
5.1. Recurring Internal Sustainability Communication Cycle

The first component introduces a recurring internal sustainability communication cycle designed to create continuity and predictability within sustainability communication practices.

Instead of relying on isolated updates or ad hoc messaging, the communication cycle establishes a structured rhythm for sharing sustainability developments, project updates, organisational progress, and employee-focused sustainability information. The cycle supports regular communication moments linked to ongoing organisational activities and sustainability objectives.

This component addresses the identified structure gap by transforming sustainability communication from occasional messaging into an ongoing organisational process embedded within existing routines. The figure below visualises how sustainability communication at Corvia is organised as a recurring, participatory process rather than ad-hoc messaging.

Figure 1. Recurring communication rhythm.



5.2. Sustainability KPI Dashboard

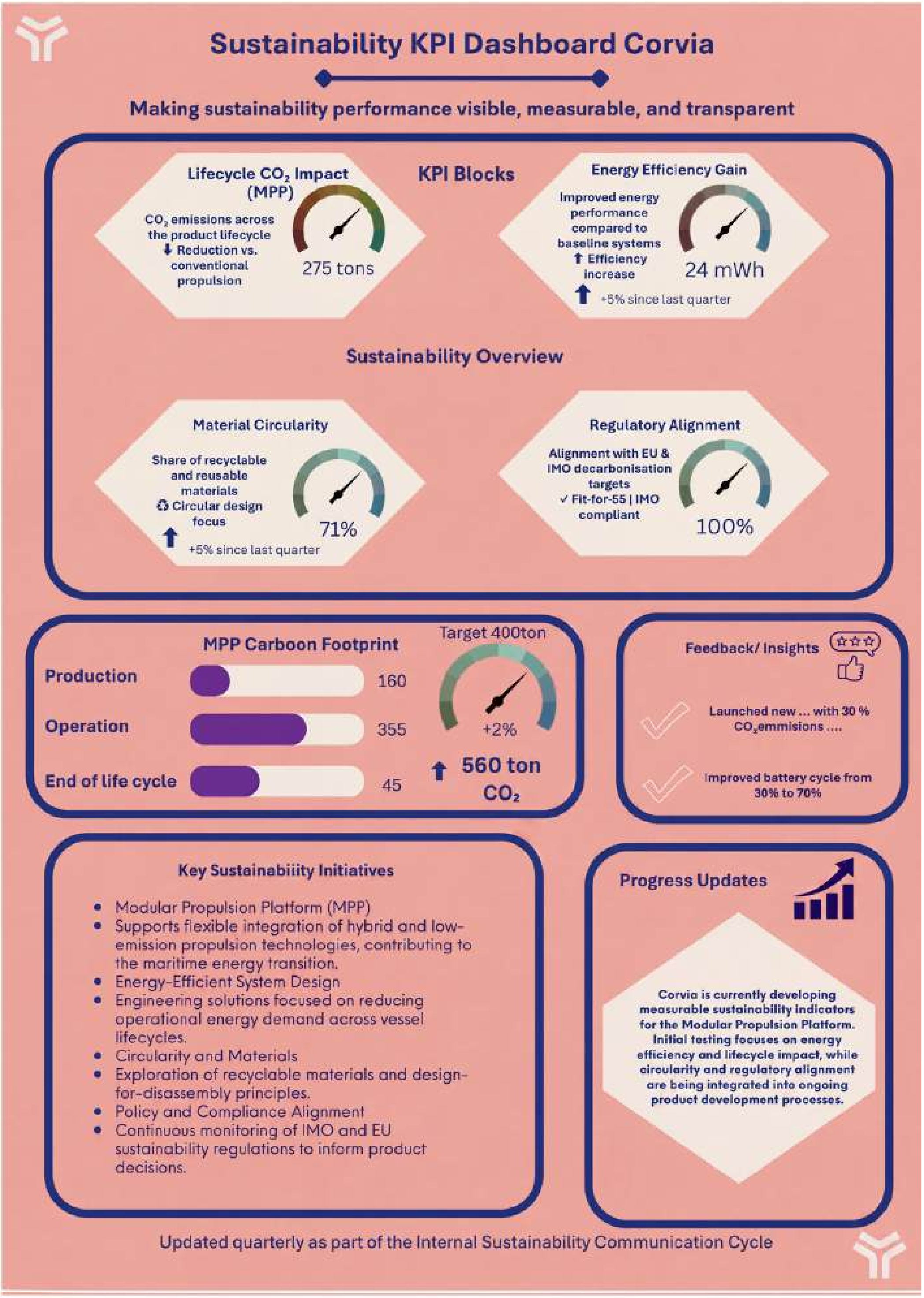
The second component is a Sustainability KPI Dashboard that translates sustainability performance and transition-related information into accessible internal communication formats.

Employees indicated a strong need for more measurable, transparent, and evidence-based sustainability communication. In response, the dashboard was designed to visualise sustainability indicators, environmental impacts, and progress related to Corvia's technologies and operations.

The dashboard aims to strengthen organisational credibility by making sustainability performance more tangible and understandable for employees across departments. Rather than relying solely on strategic ambition or symbolic sustainability narratives, this component introduces visible evidence into internal communication practices.

This dashboard provides a clear overview of Corvia's sustainability performance.
It translates technical and environmental data into accessible indicators that support internal understanding, credibility, and dialogue.

Figure 2. Dashboard



Sustainability KPI Dashboard Corvia

Making sustainability performance visible, measurable, and transparent

KPI Blocks

Lifecycle CO_2 Impact (MPP)

CO_2 emissions across the product lifecycle
⬇ Reduction vs. conventional propulsion
275 tons

Energy Efficiency Gain

Improved energy performance compared to baseline systems
⬆ Efficiency increase
24 mWh
⬆ +5% since last quarter

Sustainability Overview

Material Circularity

Share of recyclable and reusable materials
♻ Circular design focus
71%
⬆ +5% since last quarter

Regulatory Alignment

Alignment with EU & IMO decarbonisation targets
✓ Fit-for-55 | IMO compliant
100%

MPP Carboon Footprint

Production	160
Operation	355
End of life cycle	45

Target 400ton
+2%
⬆ 560 ton CO_2

Feedback/ Insights

✓ Launched new … with 30 % CO_2emmisions ….

✓ Improved battery cycle from 30% to 70%

Key Sustainabiiity Initiatives

- Modular Propulsion Platform (MPP)
- Supports flexible integration of hybrid and low-emission propulsion technologies, contributing to the maritime energy transition.
- Energy-Efficient System Design
- Engineering solutions focused on reducing operational energy demand across vessel lifecycles.
- Circularity and Materials
- Exploration of recyclable materials and design-for-disassembly principles.
- Policy and Compliance Alignment
- Continuous monitoring of IMO and EU sustainability regulations to inform product decisions.

Progress Updates

Corvia is currently developing measurable sustainability indicators for the Modular Propulsion Platform. Initial testing focuses on energy efficiency and lifecycle impact, while circularity and regulatory alignment are being integrated into ongoing product development processes.

Updated quarterly as part of the Internal Sustainability Communication Cycle

Lifecycle CO_2 Impact

Measures emissions from production, operation, and end-of-life of the Modular Propulsion Platform.

Energy Efficiency Gain

Shows how Corvia solutions reduce energy consumption during operation.

Material Circularity

Indicates how design choices support reuse, recycling, and reduced waste.

Regulatory Alignment

Tracks progress against external sustainability requirements affecting maritime systems.

5.3. Role-Based Sustainability Content Cards

The third component consists of role-based sustainability content cards designed to connect sustainability ambitions to employees' daily work practices.

The findings revealed that employees often struggled to understand how sustainability related to their specific roles and responsibilities. The content cards therefore provide role-specific examples, operational relevance, and practical sustainability implications tailored to different functions, including engineering, project management, commercial, and operational roles.

By translating abstract sustainability ambitions into concrete role-level meaning, this component strengthens relevance, ownership, and employee understanding of organisational sustainability objectives.

Figure 3. Role cards

Role & Sustainability at Corvia

Engineer

Name...

Your role in Corvia's sustainability story

As an Engineer at Corvia, you are directly involved in designing, developing, and implementing technologies that enable the maritime energy transition. Your technical decisions shape the actual environmental performance behind Corvia's sustainability ambitions.

How you contribute to the energy transition?

You contribute by translating sustainability goals into concrete engineering solutions. Choices related to system efficiency, material use, integration, and performance directly influence emissions reduction and lifecycle impact. Through your work on the Modular Propulsion Platform, sustainability becomes operational reality rather than aspiration.

What sustainability looks like in your daily work?

- Designing and optimising systems for energy efficiency and reduced emissions
- Making technical trade-offs that balance performance, reliability, and sustainability
- Providing input for lifecycle data, performance indicators, and sustainability metrics
- Collaborating with other functions to ensure technical feasibility of sustainability claims

Why your role matters?

The credibility of Corvia's sustainability communication depends on real technical performance. Your work ensures that sustainability claims are accurate, defensible, and grounded in engineering reality, strengthening trust internally and externally.

See Sustainability KPI Dashboard for current progress

Marketing Specialist

Name...

Your role in Corvia's sustainability story

As a Marketing Specialist, you translate Corvia's sustainability performance into clear, credible, and engaging stories for internal and external audiences. Your work shapes how sustainability is understood, trusted, and valued by employees, clients, and partners.

How you contribute to the energy transition?

You play a key role in connecting technical sustainability achievements to meaningful narratives. By aligning marketing messages with real product data and regulatory context, you help prevent greenwashing and strengthen Corvia's credibility in the maritime energy transition.

What sustainability looks like in your daily work?

- Translating sustainability KPIs (e.g. CO_2 reduction, lifecycle impact, efficiency gains) into accessible messaging
- Ensuring consistency between internal communication and external branding
- Supporting campaigns, product launches, and employer branding with evidence-based sustainability claims
- Collaborating with engineers and product teams to accurately represent technical innovations

Why your role matters?

Clear and honest sustainability communication builds trust. By grounding stories in data and real outcomes, you help Corvia maintain its social licence to operate and position itself as a credible player in the maritime energy transition.

See Sustainability KPI Dashboard for current progress

Manager Sales

Name...

Your role in Corvia's sustainability story

As a Sales Manager, you connect Corvia's sustainability performance with customer needs and decision-making. You translate technical and regulatory sustainability aspects into customer value, trust, and long-term partnerships.

How you contribute to the energy transition?

You support the energy transition by enabling customer adoption of sustainable maritime solutions. By explaining how Corvia's technologies respond to regulatory pressure, emissions targets, and operational efficiency demands, you help move sustainability from intention to market uptake.

What sustainability looks like in your daily work?

- Communicating sustainability benefits in customer conversations and proposals
- Explaining regulatory relevance (e.g. IMO targets, EU decarbonisation policies)
- Aligning product sustainability performance with customer business cases
- Ensuring consistency between sales messaging and verified sustainability data

Why your role matters?

Customer trust is critical for the energy transition. By using credible, evidence-based sustainability communication, you reduce uncertainty, avoid overpromising, and strengthen Corvia's position as a reliable partner in sustainable maritime innovation.

See Sustainability KPI Dashboard for current progress

BU Director

Name...

Your role in Corvia's sustainability story

As Business Unit Director, you are responsible for embedding sustainability into strategic decision-making, operational priorities, and leadership communication. Your actions determine how seriously sustainability is taken across the unit.

How you contribute to the energy transition?

You shape how sustainability is embedded in strategy, investments, and organisational culture. By aligning Corvia's operational goals with Eskela and TBI sustainability frameworks, you enable the organisation to contribute meaningfully to the maritime energy transition.

What sustainability looks like in your daily work?

- Translating group-level sustainability ambitions into unit-level priorities
- Supporting evidence-based decision-making using sustainability KPIs
- Creating space for internal dialogue, learning, and employee involvement
- Ensuring consistency between strategy, communication, and operational practice

Why your role matters?

Sustainability requires leadership commitment and structural support. By providing clarity, consistency, and legitimacy, you enable employees to engage meaningfully with sustainability and align their work with Corvia's long-term transition goals.

See Sustainability KPI Dashboard for current progress

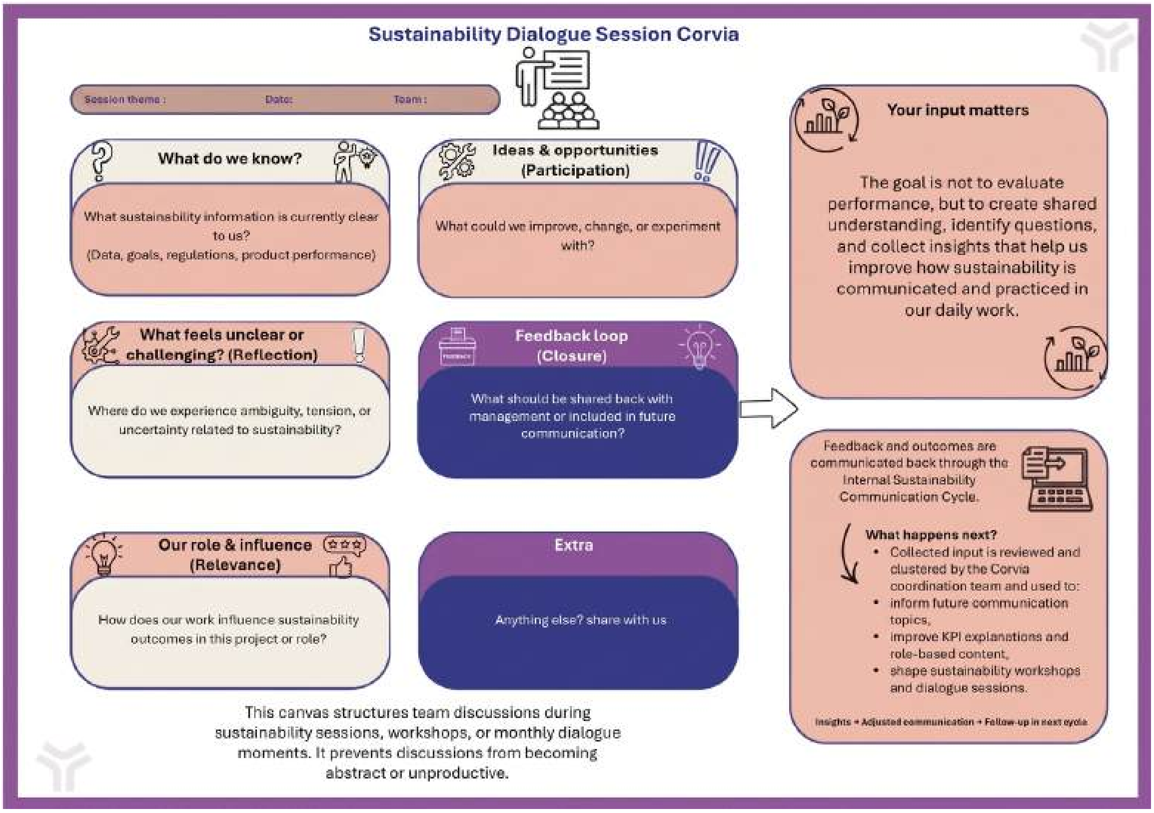
5.4. Participatory Dialogue and Co-creation Formats

The fourth component introduces participatory dialogue and co-creation formats aimed at institutionalising employee voice within sustainability communication processes.

These formats include sustainability dialogue sessions, workshops, feedback mechanisms, and co-creation activities that allow employees to actively discuss, interpret, and contribute to sustainability initiatives.

This component addresses the participation gap identified throughout the research by shifting communication away from predominantly top-down information transfer toward more interactive and dialogue-oriented engagement processes.

Figure 4. Dialogue example



Sustainability Dialogue Session Corvia

Session theme :
Date:
Team :

What do we know?

What sustainability information is currently clear to us?
(Data, goals, regulations, product performance)

Ideas & opportunities (Participation)

What could we improve, change, or experiment with?

What feels unclear or challenging? (Reflection)

Where do we experience ambiguity, tension, or uncertainty related to sustainability?

Feedback loop (Closure)

What should be shared back with management or included in future communication?

Our role & influence (Relevance)

How does our work influence sustainability outcomes in this project or role?

Extra

Anything else? share with us

This canvas structures team discussions during sustainability sessions, workshops, or monthly dialogue moments. It prevents discussions from becoming abstract or unproductive.

Your input matters

The goal is not to evaluate performance, but to create shared understanding, identify questions, and collect insights that help us improve how sustainability is communicated and practiced in our daily work.

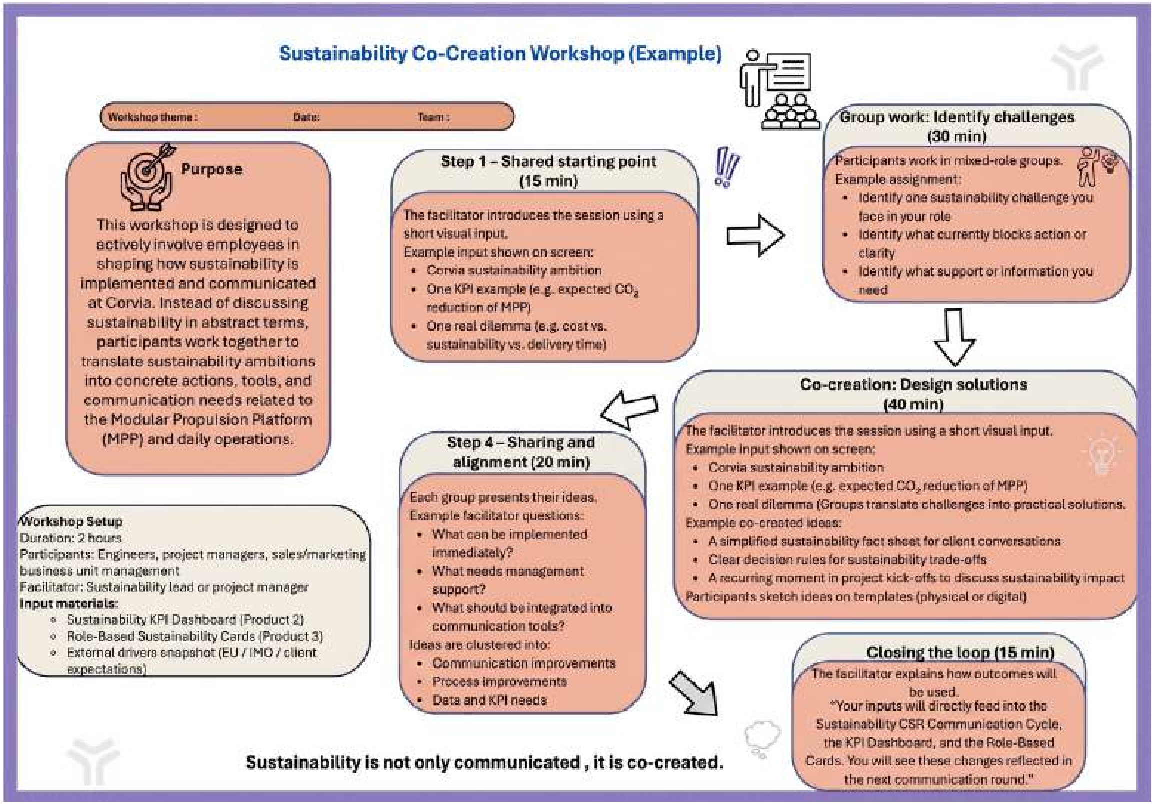
Feedback and outcomes are communicated back through the Internal Sustainability Communication Cycle.

What happens next?

- Collected input is reviewed and clustered by the Corvia coordination team and used to:
- inform future communication topics,
- improve KPI explanations and role-based content,
- shape sustainability workshops and dialogue sessions.

Insights → Adjusted communication → Follow-up in next cycle

Figure 5. Workshop



Sustainability Co-Creation Workshop (Example)

Workshop theme : Date: Team :

Purpose

This workshop is designed to actively involve employees in shaping how sustainability is implemented and communicated at Corvia. Instead of discussing sustainability in abstract terms, participants work together to translate sustainability ambitions into concrete actions, tools, and communication needs related to the Modular Propulsion Platform (MPP) and daily operations.

Step 1 – Shared starting point (15 min)

The facilitator introduces the session using a short visual input.
Example input shown on screen:
- Corvia sustainability ambition
- One KPI example (e.g. expected CO_2 reduction of MPP)
- One real dilemma (e.g. cost vs. sustainability vs. delivery time)

Group work: Identify challenges (30 min)

Participants work in mixed-role groups.
Example assignment:
- Identify one sustainability challenge you face in your role
- Identify what currently blocks action or clarity
- Identify what support or information you need

Co-creation: Design solutions (40 min)

The facilitator introduces the session using a short visual input.
Example input shown on screen:
- Corvia sustainability ambition
- One KPI example (e.g. expected CO_2 reduction of MPP)
- One real dilemma (Groups translate challenges into practical solutions.

Example co-created ideas:
- A simplified sustainability fact sheet for client conversations
- Clear decision rules for sustainability trade-offs
- A recurring moment in project kick-offs to discuss sustainability impact

Participants sketch ideas on templates (physical or digital)

Step 4 – Sharing and alignment (20 min)

Each group presents their ideas.
Example facilitator questions:
- What can be implemented immediately?
- What needs management support?
- What should be integrated into communication tools?

Ideas are clustered into:
- Communication improvements
- Process improvements
- Data and KPI needs

Workshop Setup
Duration: 2 hours
Participants: Engineers, project managers, sales/marketing business unit management
Facilitator: Sustainability lead or project manager
Input materials:
- Sustainability KPI Dashboard (Product 2)
- Role-Based Sustainability Cards (Product 3)
- External drivers snapshot (EU / IMO / client expectations)

Closing the loop (15 min)

The facilitator explains how outcomes will be used.
"Your inputs will directly feed into the Sustainability CSR Communication Cycle, the KPI Dashboard, and the Role-Based Cards. You will see these changes reflected in the next communication round."

Sustainability is not only communicated , it is co-created.

5.5. Integrated System Logic

Although each component addresses a specific communication challenge, the intervention was intentionally designed as an integrated system rather than a collection of separate tools.

The communication cycle creates continuity, the KPI dashboard strengthens credibility, the role-based content cards improve relevance, and the participatory formats support dialogue and engagement. Together, these components reinforce one another and create a more coherent internal sustainability communication infrastructure.

Importantly, the intervention was designed to align with Corvia's existing organisational context, technical structure, and sustainability ambitions. The system was therefore developed not as a generic CSR communication model, but as a context-specific organisational intervention capable of supporting sustainability alignment within the maritime energy transition.

6. Validation of the Intervention

The proposed intervention was validated through prototype-based feedback sessions with professionals from the maritime and shipbuilding sector. Participants evaluated the conceptual coherence, contextual relevance, and practical feasibility of the intervention.

Validation results indicated that the system was perceived as realistic, practically applicable, and well aligned with the communication challenges faced by technical-industrial organisations undergoing sustainability transitions. Feedback mainly focused on improving clarity, accessibility, and implementation sequencing rather than altering the underlying system logic.

The validation phase therefore confirmed the feasibility of the intervention while further strengthening its practical relevance and organisational applicability.

7. Discussion and conclusion

This study examined how internal CSR and sustainability communication can support employee engagement and organisational alignment within the context of the maritime energy transition. While sustainability transitions are frequently approached through technological and regulatory perspectives, the findings of this research demonstrate the importance of internal organisational processes in supporting transition implementation.

The results indicate that Corvia's sustainability ambitions were not undermined by employee resistance, but rather by the absence of a structured communication system capable of translating sustainability goals into meaningful organisational practice. Employees generally demonstrated strong support for sustainability and recognised Corvia's contribution to the maritime energy transition. However, fragmented communication structures, limited participation opportunities, insufficient evidence-based communication, and weak role-specific translation reduced the organisation's ability to embed sustainability internally.

These findings contribute to existing CSR communication literature by reinforcing the importance of internal stakeholder engagement in maintaining organisational credibility and legitimacy. While previous CSR research has often focused on external branding, reputation, and stakeholder management, this study highlights the strategic role of internal communication systems during sustainability transitions. In particular, the research supports growing arguments that sustainability communication should move beyond informational approaches toward more participatory and dialogue-oriented organisational practices.

The study also contributes to energy transition research by addressing the relatively underexplored organisational dimension of sustainability transitions. Existing transition literature frequently prioritises technological innovation and policy frameworks, while paying less attention to how sustainability ambitions are operationalised within organisations. This research demonstrates that successful sustainability transitions require not only technological innovation, but also organisational alignment, employee engagement, and internal legitimacy.

The designed Internal Sustainability Communication System represents a practical contribution to addressing these challenges. By integrating communication continuity, evidence-based sustainability information, role-specific relevance, and employee participation into one coherent system, the intervention provides a scalable framework for strengthening sustainability engagement within technical-industrial organisations.

Although the study was conducted within a single maritime technology organisation, the findings may also hold relevance for other sectors undergoing sustainability transitions. Many technical-industrial organisations face similar challenges related to organisational alignment, employee engagement, and sustainability credibility. The communication principles identified in this research may therefore be transferable beyond the maritime sector.

Several limitations should nevertheless be acknowledged. The research focused on a single-case organisational context and applied primarily qualitative methods within a relatively limited timeframe. In addition, the intervention was validated conceptually rather than fully implemented longitudinally within the organisation. Future research could therefore explore long-term implementation effects, comparative sector analysis, and the relationship between internal sustainability communication and measurable organisational outcomes.

In conclusion, this study demonstrates that sustainability transitions require more than technological innovation alone. Organisations must also develop internal structures capable of supporting employee understanding, participation, and alignment with sustainability ambitions. By addressing the organisational and communicative dimensions of transition processes, this research contributes both academically and practically to the broader challenge of implementing sustainability transitions within industry.

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Limitation of Power-to-Methanol: Identifying the Barriers of Bridging Energy and Bio-Carbon to Produce Decentralized Renewable Methanol via Integrated Economic and Environmental Evaluation

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Power-to-X technologies play a crucial role in accelerating the energy and material transition. A key opportunity lies in integrating these systems with existing bio-based infrastructures such as anaerobic digesters, providing a reliable source of biogenic carbon. Developing effective Power-to-Methanol (PtM) pathways requires a comprehensive understanding of process behavior through detailed simulation, including technical performance, economic feasibility, and environmental consequences. Despite growing interest, substantial variation remains in published levelized methanol costs, and many assessments insufficiently account for the full environmental footprint of production routes. This study evaluates the potential of PtM deployment in the Netherlands by comparing two pathways that utilize biogenic carbon sources: (i) hydrogenation of captured CO_2 using green hydrogen and (ii) dry methane reforming (DMR) of biogas, followed by catalytic syngas conversion to methanol. Results indicate that operational expenses—mainly driven by renewable electricity consumption—far outweigh capital investment. Both routes yield an LCoMeOH of approximately €2630 per tonne, about five times the cost of fossil-based methanol. Life cycle analysis shows that DMR performs more favorably overall, although elevated freshwater ecotoxicity and eutrophication result from digestate application as fertilizer. Continued improvements in renewable energy integration and nutrient recovery technologies are essential for enhancing future economic and environmental performance.

Keywords: Power-to-methanol, Hydrogen, Sustainable methanol, Techno-economic analysis, Life cycle analysis

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1. Introduction

The energy and raw-material transition has become a central research focus, driven by the need to achieve net-zero emissions by 2050 in line with the Paris Agreement (1,2). Key strategies include renewable energy deployment, electrification, and carbon capture, utilization, and storage (CCUS), which is highlighted in the European Green Deal as essential for meeting climate targets (3). CO_2 valorization has gained interest due to its potential integration into the chemical industry, creating new opportunities for carbon recycling and decentralized production (4). Within this context, sustainable methanol (MeOH) has emerged as a versatile platform chemical.

Methanol plays a key role in chemical and pharmaceutical industries and in synthetic fuel production (5). Global production reached approximately 90 Mt in 2021, largely based on fossil feedstocks such as natural gas and coal (6). Conventional production relies on synthesis gas derived from fossil resources through reforming or gasification (7). However, increasing decarbonization efforts have stimulated interest in renewable pathways, particularly those based on green hydrogen and biogenic carbon sources (8).

Sustainable methanol can be produced via different routes, including direct CO_2 hydrogenation and dry methane reforming (DMR) of biogas followed by syngas conversion (9). These pathways fall under the broader Power-to-Methanol (PtM) and Power-to-X (PtX) concepts, which convert renewable electricity into chemical energy carriers (10–13). Evaluating these systems requires techno-economic analysis (TEA) and life cycle analysis (LCA), which assess performance, cost, and environmental impacts. Reliable analyses depend on detailed process mod-elling, accurate cost estimation, and full cradle-to-gate system boundaries (14,15).

Although TEA and LCA studies exist, many focus on large-scale centralized plants and show large variability. Studies by Perez-Fortes et al. (2016) identified hydrogen cost as a major bottleneck, with CAPEX and OPEX varying widely (16,17), while Nizami et al. (2022) reported methanol costs of 1040–1670 $/t (18). More recent work indicates that decentralized production remains economically uncompetitive due to high electricity and hydrogen costs (19). Even large-scale systems show production costs above market prices, despite high efficiencies and low emissions (20–22).

Other studies often rely on optimistic assumptions. For instance, Douglas et al. (2026) reported relatively low methanol costs based on low electricity prices (23), while Tariq et al. (2025) assumed high operating hours and low hydrogen costs (24). From an environmental perspective, renewable methanol pathways generally reduce greenhouse gas emissions, particularly when powered by low-carbon electricity (25). However, environmental performance varies by pathway and electricity source, with CO_2 hydrogenation only beneficial under low-carbon electricity conditions (26).

Small-scale integrated systems show improved environmental performance compared to fossil routes but may increase impacts such as eutrophication (27). Comparative assessments confirm lower overall impacts for CCU-based methanol, although trade-offs remain in other impact categories (28). Overall, methanol production costs vary widely (530–2706 €/t) and remain significantly higher than fossil-based methanol (~530 €/t), mainly due to electricity and hydrogen costs (7,21,29). Despite climate benefits, biomass-based pathways may increase eu-trophication and ecotoxicity, and methodological inconsistencies hinder direct comparison across studies. Differences in system boundaries, assumptions, and geographic conditions limit comparability. Therefore, a site-specific, integrated TEA–LCA approach is needed.

This study addresses these gaps by comparing two decentralized methanol production pathways in Twente (NL): (i) CO_2 hydrogenation using green hydrogen, and (ii) DMR of biogas followed by methanol synthesis. The work provides a combined economic and environmental assessment of small-scale, renewable methanol production applicable to decentralized energy systems.

2. Process Description

The case study considers a large-scale (bio)digestion plant in the eastern part of the Netherlands (30). Organic waste and manure from households and farms are converted into biogas and subsequently into biomethane for injection into the national gas grid. Biomethane upgrading is carried out using a three-stage membrane separation process, which generates a CO_2-rich waste stream. Producing sustainable MeOH to valorize this CO_2 by-product represents a promising alternative. The required green H_2 is produced on-site using a 20 MW electrolyser system powered by a nearby solar-PV field. CO_2 from the biogas-upgrading process is available on-site and directly supplied to the methanol synthesis and purification units (30).

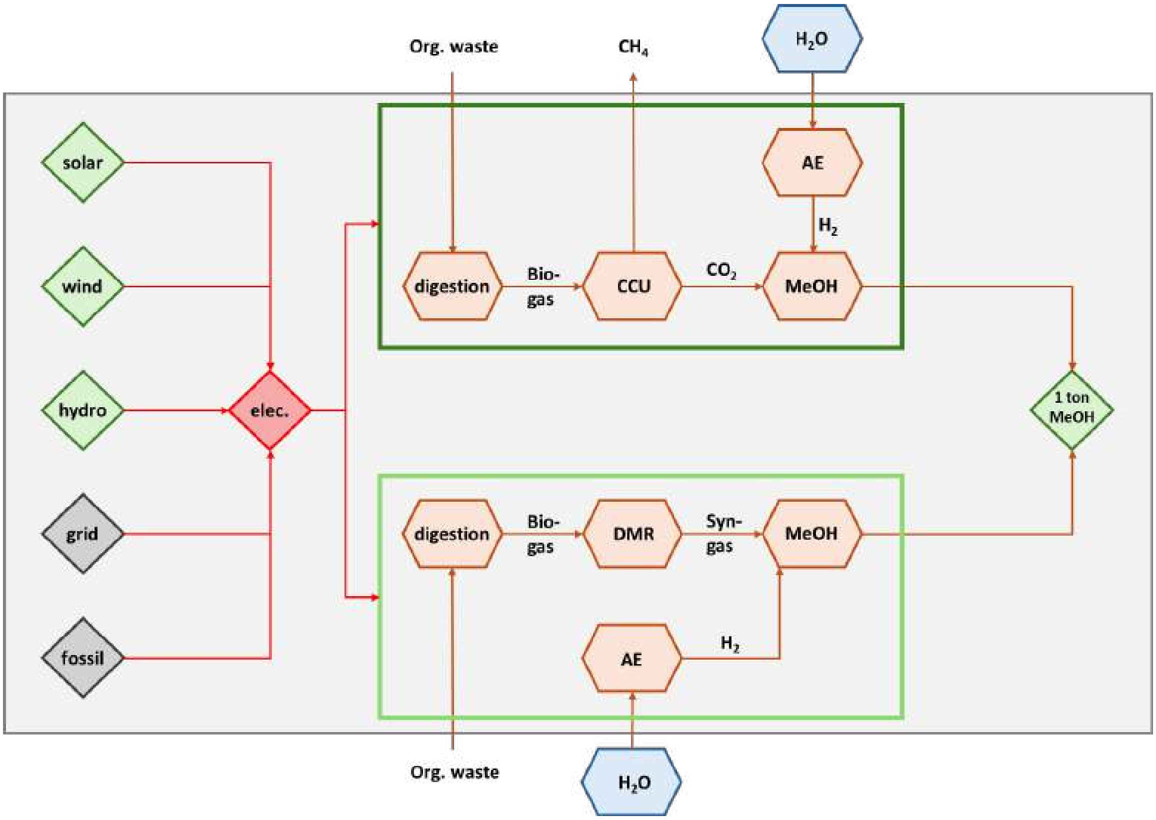
During periods when biogas upgrading is less attractive, this route is compared with direct DMR, which produces syngas that is subsequently converted to MeOH. In this pathway, most hydrogen is generated via DMR; however, a 5 MW electrolyser system remains necessary to supply additional H_2 to achieve the correct stoichiometry.

Based on these scenarios, a combined techno-economic analysis (TEA) and life cycle analysis (LCA) is performed to evaluate two production routes and assess their implications for the ongoing energy and materials transition.

2.1. Boundaries

The TEA and LCA evaluate two routes for producing sustainable methanol using renewable energy and a biogenic carbon source. The system boundaries for both routes are shown in Figure 1. Water purification for the alkaline electrolyser (AE) is excluded from both TEA and LCA analyses.

Figure 1. Boundaries of the Power-to-Methanol processes evaluated with TEA and LCA. Two scenarios: MeOH from CCU (dark green box) and MeOH from DMR (light green box).



Within Figure 1, two pathways for producing sustainable MeOH are illustrated:

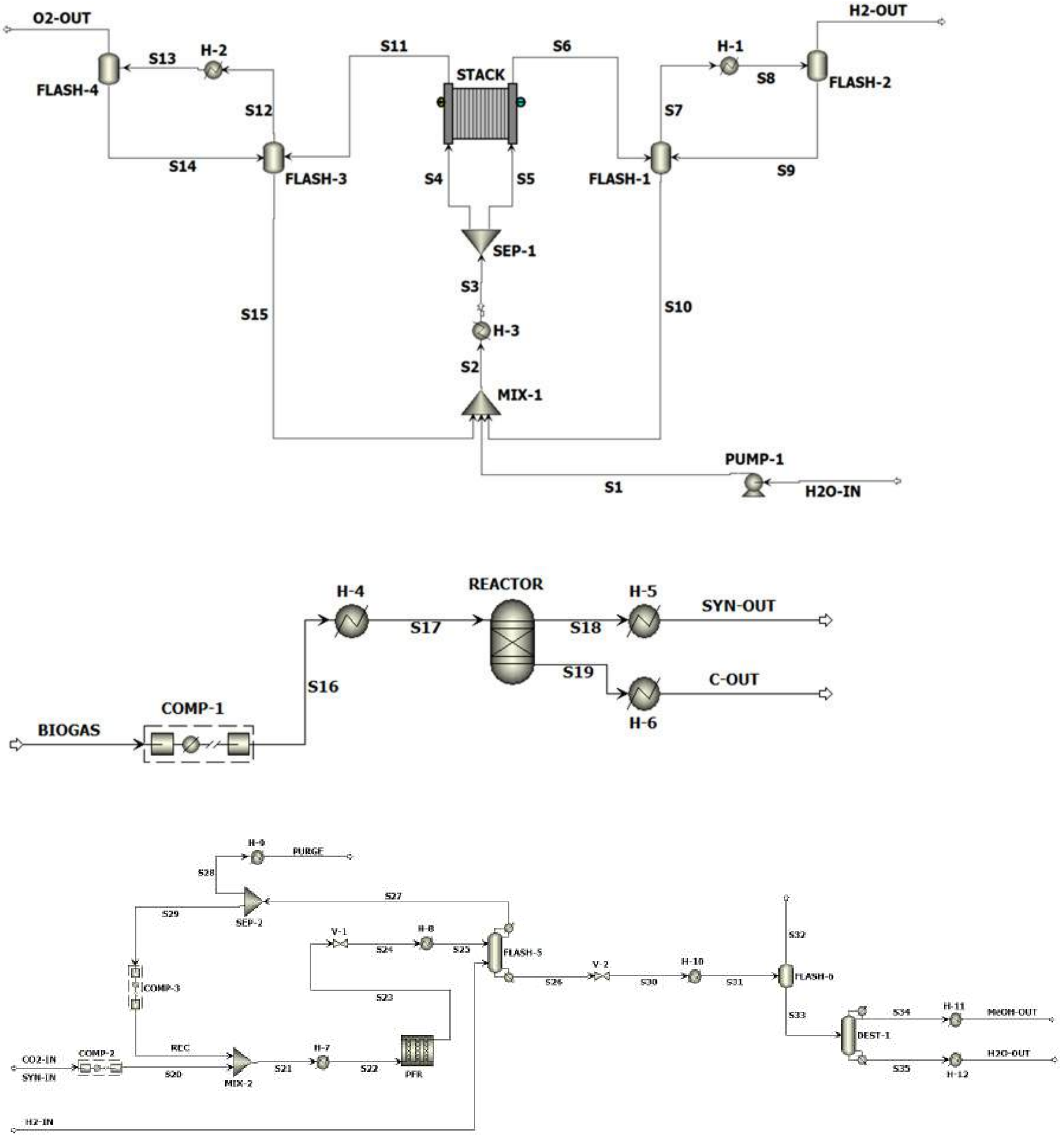
i. Renewable energy sources (wind, solar, hydro, nuclear) power an alkaline electrolyser (AE) that produces green H_2. This hydrogen is combined with CO_2 from the CCU unit to synthesize sustainable MeOH. The CCU unit is included in the analysis, and scenarios using grey electricity sources (grid or fossil-based) are evaluated for comparison. The functional unit is 1 tonne of MeOH.

ii. Renewable energy sources (wind, solar, hydro, nuclear) are used to drive the DMR process of biogas, producing a syngas mixture. Syngas is then combined with additional H_2 from the AE unit to achieve the required stoichiometry for MeOH synthesis. Grey electricity scenarios are again assessed for comparison, and the functional unit is 1 tonne of MeOH.

2.2. Process Flow Diagrams

Aspen Plus® V14.0 is used to simulate both production routes. The corresponding process flow diagrams (PFDs) are presented in Figure 2.

Figure 2. Process flow diagram of electrolysis (**2A**), dry methane reforming (**2B**) and methanol synthesis (**2C**).



For both production routes, the electrolysis section (top of the PFD) is identical. In the DMR process flow diagram (middle), biogas is first brought to reaction conditions of 909 °C and 16 bar (COMP-1 and HE-4) before entering the reactor. The reactor is modelled as a Gibbs reactor, where reaction equilibrium is determined by minimization of the Gibbs free energy. The following gas-phase reaction converts CH_4 and CO_2 into a syngas mixture:

$$CO_2 + CH_4 \leftrightarrows 2\ CO + 2\ H_2 \qquad (1)$$

The products are subsequently cooled in H-5 and H-6, yielding a syngas stream and solid carbon. The syngas proceeds to the MeOH synthesis section, while the solid carbon is considered a valuable co-product for other applications.

The bottom process (MeOH synthesis) is described in detail by Gelten et al. (2026), where either syngas from the DMR process or residual CO_2 from the CCU unit is used as the feedstock [19].

3. Process Modelling

3.1. Model Assumptions

To obtain mass and energy balances, both processes are simulated in Aspen Plus® V14.0 following the PFDs in Figure 2. The assumptions are adapted from previous work [19] and extended with the following:

- Owing to the high reaction rates, the catalytic DMR process is represented by a thermodynamically controlled Gibbs reactor.
- The process purge stream is collected and treated for further purification before atmospheric release.
- The digestion process and biogas-upgrading steps are not modelled explicitly; cost estimates for these components are taken from the literature.

3.2. Kinetic Model

The kinetic model for methanol synthesis employs a Langmuir–Hinshelwood–Hougen–Watson (LHHW) mechanism over a $Cu/ZnO/Al_2O_3$ catalyst. The full kinetic description is provided in Gelten et al. (2026) [19].

3.3. Techno-Economic Analysis

The TEA follows the methodology described by Turton (2018), which is well established in both the literature and previous work [15,19,31]. Table 1 lists the key parameters used for the technical and economic evaluation.

The levelized cost of methanol (LCoMeOH) is calculated as the amortized CAPEX plus annual OPEX, divided by the annual MeOH output (Equation (2)). Results are compared with the current grey methanol market price reported by Methanex, which is 530 €/t as of September 2025 [21]:

$$\mathrm{LCoMeOH} = \frac{\mathrm{CAPEX}_{\mathrm{am.,total}} + \mathrm{OPEX}_{\mathrm{total}}}{\mathrm{MeOH}_{\mathrm{mass\ output}}} \qquad (2)$$

Table 1. Economic parameters for techno-economical evaluation of the processes.

Parameter	Value	Ref
Biogas cost (from the digestion process)	140 €/t	[32]
Carbon dioxide cost (from the biogas upgrading)	72 €/t[1]	[33]
Catalyst for MeOH synthesis	128.80 €/kg	[34]
Lifetime of the catalyst	3 y	[16]
Cooling water	0.025 €/t	[35]
LcoE	75 €/MWh[2]	[17]
Energy efficiency of H_2 production	65 kWh/kg	[36]
Annual operating labor cost	€40,000	[35]
Plant capacity factor	4975 h/y	[17]

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[1] Levelized cost of CO_2 is based on economic numbers and calculations of the CCU unit of the considered use-case.

[2] Fluctuations in the LCoE are not taken into account.

3.4. Life Cycle Analysis

The life cycle assessment (LCA) follows the ISO 14040:2006 framework, including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [37]. The analysis is conducted using OpenLCA 2.4.0 with the EcoInvent 3.11 database, although newer versions (e.g., 3.12) are recommended for improved regional accuracy.

The LCA aims to quantify environmental impacts of methanol production via two process routes under different electricity scenarios. A cradle-to-gate system boundary is applied, excluding use and end-of-life phases. The func-tional unit is 1 tonne of methanol. Electricity inputs include solar, wind, hydro, nuclear, and fossil-based sources.

All process steps are incorporated into the LCI based on mass and energy balances. Standard processes such as electricity production are sourced from EcoInvent, while other components rely on literature and engineering assumptions. Electricity consumption is assumed from a low-voltage grid, with pricing based on ENTSO-E data [38]. On request, detailed inventories can be provided in supplementary material. Some information on LCA simulation of the different processes is given below:

i. Alkaline electrolysis is not included in EcoInvent and is therefore modelled using data from Wei et al. (2024), scaled to an electrolyser capacity of 9298 kW per functional unit [39].
ii. Methanol synthesis is modelled using a plug-flow reactor consisting of approximately 4000 tubes, with $Cu/ZnO/Al_2O_3$ catalyst replaced every three years [20]. The dry methane reforming (DMR) reactor is scaled based on inlet mass flows due to limited design data. Catalyst use in DMR (Ni-based) contributes negligibly (<0.1%) to total emissions [40,41].
iii. The CCU process relies on membrane-based biogas upgrading [42,43]. Due to limited LCA data, membrane characteristics are estimated using manufacturer data [44], assuming typical module size, configuration (18 modules), stainless-steel housing, 10-year lifetime, and 0.2 kW/m^3 energy consumption.
iv. The compression system includes multi-stage compressors with intercooling, modelled using literature data [45].
v. Gas–liquid separators are based on scaled stainless-steel tank data [46], with corrosion-resistant materials assumed to have negligible environmental differences [47].
vi. Methanol purification is achieved via tray-based distillation, consistent with TEA modelling assumptions [48].
vii. Pumps are adapted from EcoInvent datasets and scaled to match system requirements, with electricity demand linked to respective energy scenarios.
viii. Minor components such as piping, valves, and mixers are excluded due to limited data availability. Packaging materials are also omitted to focus on major contributors to environmental impact.

4. Results and Discussion

4.1. Model Validation

The process modelling framework is developed to simulate two production routes: (i) the MeOH-from-CCU process, and (ii) the MeOH-from-DMR process. The mass and energy balances for the MeOH-from-CCU pathway, shown in Figure 2a,c, are described extensively in previous work [19]. The mass and energy balances for the MeOH-from-DMR pathway, illustrated in Figure 2b,c, are provided in Table 2. Both processes are simulated to produce approximately 2127 kg/h of methanol, corresponding to roughly 10.6 tonnes per year.

Table 2. MeOH from DMR process: mass and energy balance.

Stream Name	BIO-GAS	S17	SYN-OUT	C-OUT	S22	S23	REC	H_2-IN	S26	S33	H_2O-OUT	MeOH
Pressure (bar)	1	16	16	1	110	110	110	30	30	1	1	1
Temperature (°C)	25	909	110	20	150	267	65	50	60	20	20	20
Mass flow (kg h^{-1})	3440	3440	2974	466	42,061	42,061	39,086	94.7	2674	2564	414	2150
Phase	vapor	vapor	vapor	solid	vapor	vapor	vapor	vapor	liquid	liquid	liquid	liquid
Mass flow rate (kg h^{-1})												
H_2	0	0	212	0	2347	2065	2135	94	3	0	0	0
CO	0	0	1817	0	5417	3644	3600	0	7	0	0	0
CH_4	1208	1208	214	0	19,265	19,265	19,051	0	22	1	0	1
CO_2	2223	2223	389	0	11,427	11,232	11,038	0	83	21	0	21
H_2O	0	0	335	0	571	571	156	0.7	413	413	412	1
MeOH	0	0	0	0	2514	4684	2514	0	2145	2129	2	2127
C	0	0	0	466	0	0	0	0	0	0	0	0
N_2	7	7	7	0	600	600	593	0	1	0	0	0
O_2	2	2	0	0	0	0	0	0	0	0	0	0

The DMR section, in which biogas is converted to syngas, is simulated at a temperature of approximately 900 °C and an elevated pressure of 16 bar to ensure high and selective conversion of methane toward hydrogen. The resulting methane conversion of 83% and hydrogen selectivity of ~70% align well with other reported simulation and ex-perimental findings in the literature [49,50].

The produced hydrogen stream (H_2-IN) amounts to 94 kg/h and contains 99.3% H_2 (the remainder being H_2O), which is consistent with values reported in previous studies [6,22,51]. This hydrogen is required to achieve the correct stoichiometric ratio of reactants in the gas stream entering the PFR reactor (stream S22), expressed as the modulus (M), which must fall between 2.0 and 2.3 [52]. The modulus is defined in Equation (3):

$$M = \frac{[H_2] - [CO_2]}{[CO] + [CO_2]} \tag{3}$$

Using this hydrogen input, a corresponding biogas flow of 3440 kg/h is processed, resulting in the production of 2127 kg/h of methanol at 99.0 wt% purity (with the remainder consisting of traces of CO_2).

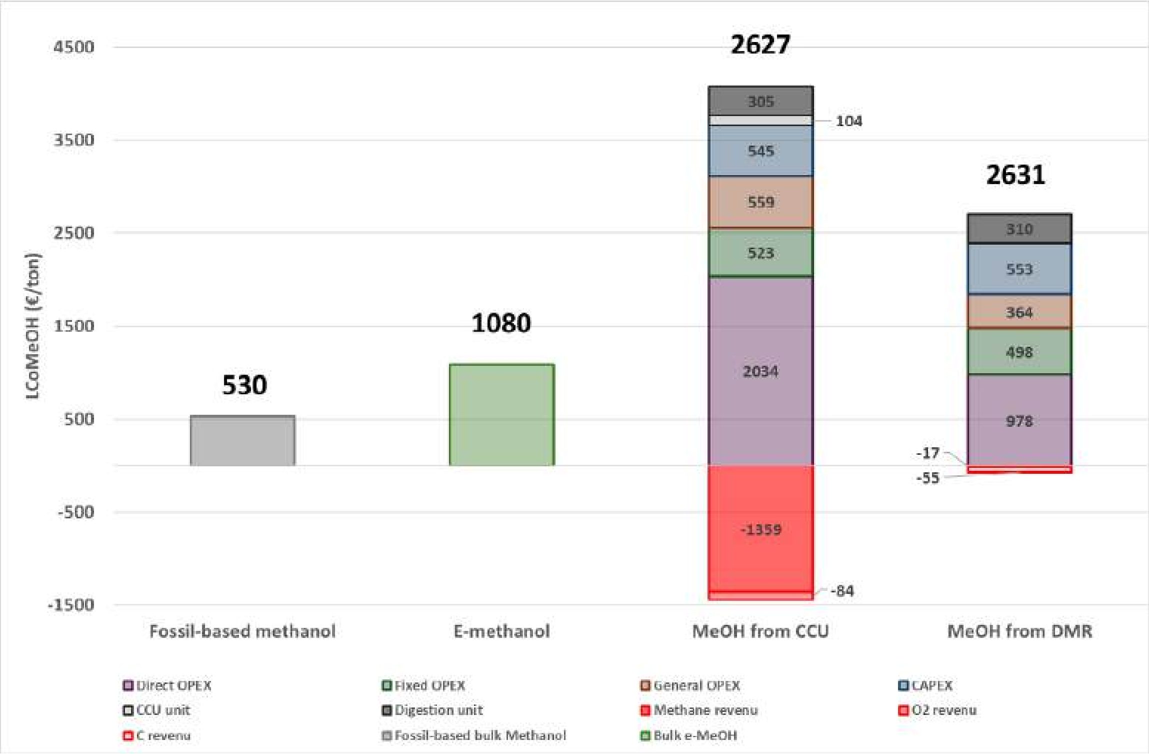
Following gas–liquid separation (FLASH-5 and FLASH-6), the crude methanol enters a single-stage distillation column. The column has 10 stages, with the feed introduced at stage 6 and an operating pressure of 1.1 bar [18]. This single-column configuration yields fuel-grade methanol, consistent with the findings of Dieterich et al. (2020) [53].

4.2. Levelised Cost of MeOH

Using the modelling framework described above, the levelized cost of methanol (LCoMeOH) is calculated for both the MeOH-from-CCU and MeOH-from-DMR pathways and compared to fossil-based methanol prices [21] and e-methanol estimates reported by IRENA (2021) [6] (Figure 3).

Fossil-based methanol is benchmarked using Methanex contract prices, with a European price of approximately 530 €/t in September 2025, although regional variations range from 380 €/t in China to 800 €/t in the United States [21]. Literature reports similar global ranges of 275–700 €/t [53]. **E-methanol**, produced from captured CO2 and renewable hydrogen, has significantly higher production costs. IRENA estimates costs between 800–1600 $/t for BECCS-derived CO2 and 1200–2400 $/t for DAC-derived CO2, depending largely on electricity and hydrogen costs [5,54].

Figure 3. Cost breakdown of the Levelized Cost of MeOH



For the **MeOH-from-CCU** pathway, the amortized CAPEX is 823 €/t (≈19% of LCoMeOH), dominated by installation costs. OPEX is primarily driven by direct costs, particularly electricity (˜34%, 1425 €/t) and raw materials (˜13%, 541 €/t). Additional contributions include digestion and CCU costs (˜10%) [32,33]. Revenues from biomethane and oxygen partially offset costs [55,56]. The resulting LCoMeOH is approximately 2627 €/t.

For the **MeOH-from-DMR** pathway, CAPEX is slightly higher (849 €/t) and contributes a larger share (˜27%). OPEX is again dominated by electricity (˜20%, 632 €/t), while raw-material costs remain limited (˜6%, 181 €/t). Digestion costs contribute ˜13% [32], and solid carbon is assumed to generate minor revenue (90–270 €/t). The resulting LCoMeOH is approximately 2631 €/t, similar to the CCU route.

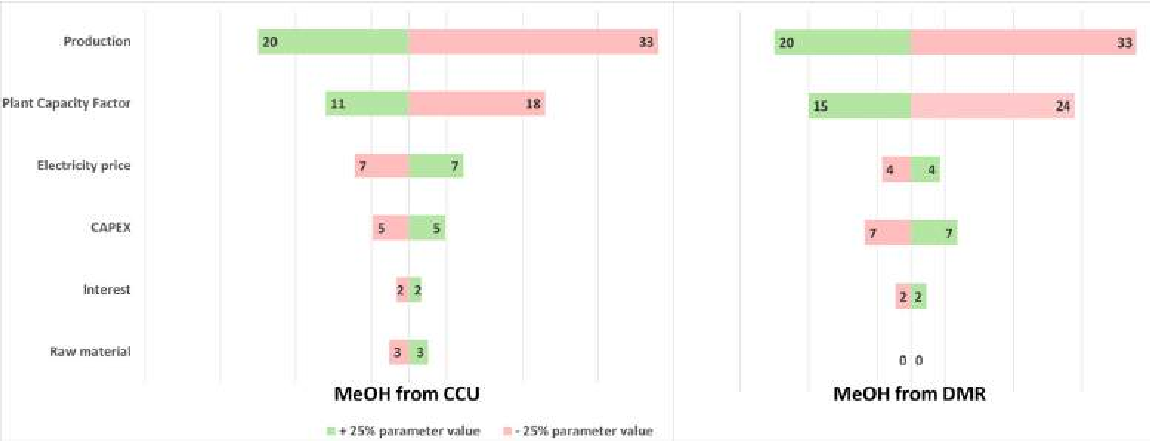
CAPEX estimates align with literature values [2,54]. For the electrolyser, a cost of 270 €/kW is assumed, corre-sponding to ˜€4.86 million for a 20 MW system [57,58]. With a typical lifetime of 60,000 hours [57], one stack replacement is required over a 15-year plant lifetime.

Both pathways exhibit similar cost distributions, with OPEX dominating over CAPEX. The CCU route shows a breakdown of 67% direct, 15% fixed, and 18% general costs, while the DMR route shows 55%, 26%, and 20%, respectively, consistent with literature findings [5,18,59]. Overall, high electricity prices and hydrogen costs remain the primary drivers of LCoMeOH. Improvements in electrolyser efficiency, electricity pricing, and system integration are therefore essential to enhance the economic competitiveness of sustainable methanol production.

4.3. Sensitivity Analysis of the Levelized Cost of MeOH

The sensitivity analysis evaluates the influence of several key parameters — production capacity, plant capacity factor, electricity price, interest rate, total CAPEX, and raw-material costs — on the LCoMeOH (Figure 4). Varying each parameter by ±25% illustrates its relative impact on the resulting LCoMeOH.

Figure 4. Results of sensitivity analysis in terms of percentual change of the levelized cost of MeOH, considering the MeOH from CCU pro-cess (**left**) and the MeOH from DMR process (**right**).



For both processes, the methanol (MeOH) production capacity and the plant capacity factor exert the strongest influence on the LCoMeOH. Both parameters show an inverse relationship with the LCoMeOH: increasing either parameter by 25% reduces the LCoMeOH, while a 25% decrease results in higher costs. The magnitude and direction of these effects are consistent with trends reported in earlier studies [16,60]. Sensitivity analysis indicates that the MeOH-from-DMR route is less sensitive to electricity prices—due to its lower reliance on green hydrogen—but more sensitive to CAPEX, reflecting the higher investment required for additional process equipment.

These findings underscore the importance of process flexibility, dynamic operation, and integration with energy-storage solutions such as batteries to improve full-load operating hours and increase production rates. Optimizing and integrating wind, solar, or grid electricity with storage systems is essential to enhancing the competi-tiveness of PtM processes.

For the MeOH-from-CCU route, electricity price sensitivity is higher due to the significantly larger electricity demand of the alkaline electrolyser compared with the DMR route (28 vs. 12 MWh). However, CAPEX sensitivity is lower for the CCU route, as the DMR pathway requires higher capital expenditure for the reforming reactor and associated equipment (807 vs. 849 €/t).

The influence of raw-material inputs for MeOH-from-CCU (water and CO_2) is relatively small, accounting for roughly 3% of the LCoMeOH, whereas raw-material costs are virtually negligible for MeOH-from-DMR (only water). The levelized cost of CO_2 (LCoC), derived from the CCU-unit cost in the case study, aligns with conclusions from the TNO final report [33].

4.4. Life Cycle Analysis impacts

The LCA is conducted using electricity source as a key variable, including renewable (wind, solar, hydro, nuclear) and fossil-based/grid electricity scenarios. Results are normalized and expressed in person years (PYs), enabling comparison across impact assessment methods (IAMs), as shown in Table 3(a, b).

Table 3. (a) Normalized environmental impact (in PY) for the MeOH from CCU process using different energy sources. (b) Normalized environmental impact (in PY) for the MeOH from DMR process using different energy sources.

Environmental Impact	MeOH from CCU Source of Electricity					
	Fossil	Grid	Solar	Wind	Nuclear	Hydro
(a)						
Ecotoxicity: freshwater	54.45	67.29	45.63	41.40	42.98	40.76
Eutrophication: freshwater	40.38	51.67	34.65	33.20	33.08	32.96
Energy resources: non-renewable	31.84	23.86	6.05	2.89	42.56	2.44
Material resources	10.06	17.21	25.43	11.12	8.64	7.91
Climate change	49.19	36.09	10.75	5.62	5.10	4.91
Acidification	2.51	0.78	0.02	−1.03	−1.16	−1.25

Environmental Impact	MeOH from CCU Source of Electricity					
	Fossil	Grid	Solar	Wind	Nuclear	Hydro
Human toxicity: carcinogenic	1.17	1.61	1.25	1.12	1.09	1.08
Human toxicity: non-carcinogenic	4.72	4.96	3.28	2.56	2.48	2.40
Ionizing radiation	0.38	1.18	0.52	0.37	20.66	0.36
Land use	−1.09	−1.47	2.13	−1.20	−1.20	−1.22
Ozone depletion	0.06	0.05	0.04	0.01	0.01	0.01
Particulate matter formation	7.53	7.98	8.13	6.17	6.93	5.87
Photochemical oxidant formation	6.84	6.49	3.82	2.86	2.82	2.74
Water use	3.04	3.93	4.41	2.17	4.34	2.05
(b)						
Ecotoxicity: freshwater	34.51	39.17	29.48	27.27	28.10	26.94
Eutrophication: freshwater	25.91	30.21	22.77	21.93	21.87	21.81
Energy resources: non-renewable	17.88	13.33	3.51	1.87	22.59	1.63
Material resources	6.55	9.40	12.95	7.05	5.75	5.37
Climate change	27.97	20.67	6.55	3.86	3.59	3.49
Acidification	1.25	0.38	−0.06	−0.71	−0.78	−0.82
Human toxicity: carcinogenic	0.77	0.94	0.80	0.73	0.72	0.72
Human toxicity: non-carcinogenic	3.04	3.04	2.16	1.84	1.76	1.76
Ionizing radiation	0.25	0.58	0.34	0.24	10.85	0.24
Land use	−0.73	−0.90	0.95	−0.79	−0.80	−0.81
Ozone depletion	0.03	0.03	0.02	0.01	0.01	0.01
Particulate matter formation	4.82	4.97	5.12	4.07	4.37	3.92
Photochemical oxidant formation	4.08	3.76	2.39	1.88	1.86	1.82
Water use	1.90	2.23	2.63	1.42	2.55	1.36

The Environmental Footprint v3.0 (EF v3.0) methodology is applied, using normalization factors from the literature [61]. Additional classification results are provided in the Supplementary Material.

Across all scenarios, freshwater ecotoxicity and eutrophication dominate environmental impacts for both methanol production routes. These impacts are primarily driven by nutrient emissions and heat, which stimulate biological activity in aquatic systems and lead to ecosystem stress and biodiversity shifts [62].

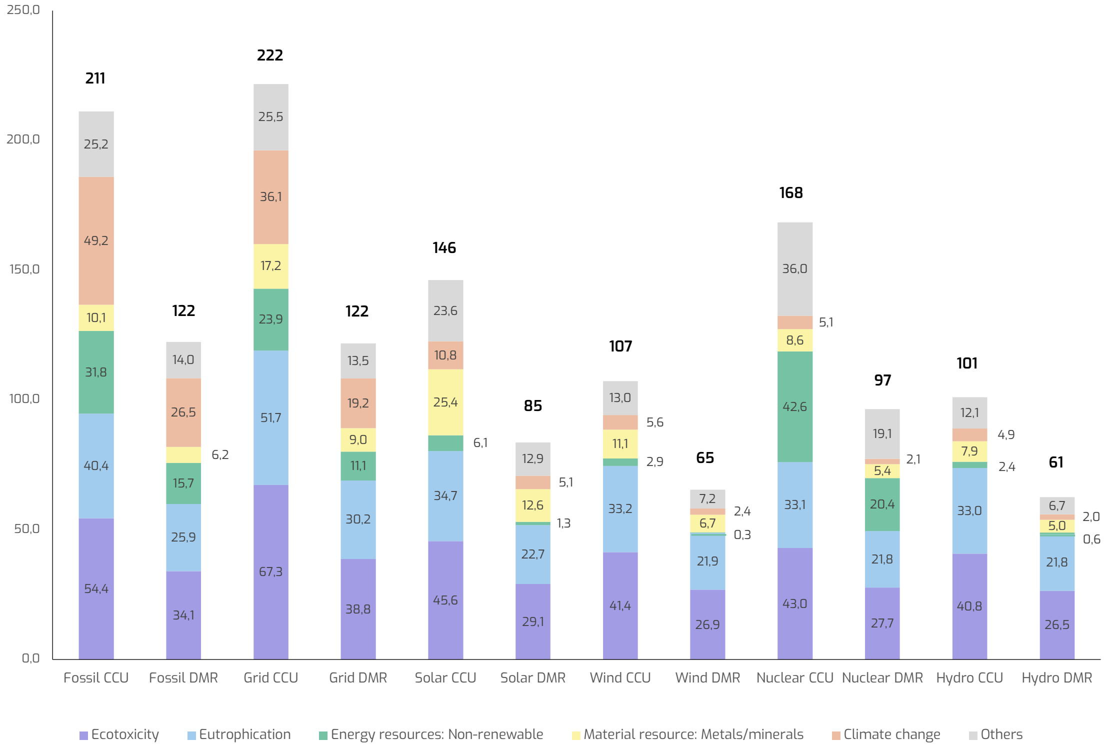
In general, renewable electricity reduces environmental impacts substantially, with reductions often exceeding 50% in categories such as climate change, acidification, non-renewable energy use, ozone depletion, and photochemical oxidant formation. However, solar-based systems show higher impacts in material resource use and land use due to the material intensity of photovoltaic installations [63]. Nuclear energy leads to elevated contributions to non-renewable energy use and significantly higher ionizing radiation impacts.

To compare both pathways, normalized results are weighted using European Commission factors [64], resulting in aggregated scores (Figure 5). Freshwater ecotoxicity and eutrophication remain the dominant contributors, accounting for up to 73% of total impact for the CCU route and up to 79% for the DMR route. This dominance is amplified by the relatively low contribution of other impact categories.

When comparing both pathways under identical electricity inputs, the DMR route shows a reduction of approximately 34–42% in freshwater ecotoxicity and eutrophication compared with the CCU route. This difference is likely related to lower heating and cooling demands (−4.7 MW for DMR vs. −7.4 MW for CCU at ~10 kt/y production).

Overall, DMR combined with renewable electricity — particularly wind — shows the lowest environmental impact within the Dutch context, where hydropower availability is limited.

Figure 5. Comparison of the MeOH from CCU process and the MeOH from DMR process with different energy sources (only top five of environmental impacts and total score is given).



4.5. Sensitivity Analysis of the LCA

For the LCA sensitivity analysis, only the MeOH-from-DMR with wind-energy scenario is evaluated, as it exhibits one of the lowest environmental impacts and aligns with Europe's strong potential for renewable-energy expansion through onshore and offshore wind farms [62]. Moreover, this route also yields significantly lower LCoMeOH values, as shown in Figure 3.

The sensitivity analysis is structured in three layers, each reflecting deeper variation in specific parameters. Sensitivity outcomes are expressed as the percentage change in total environmental score (Points):

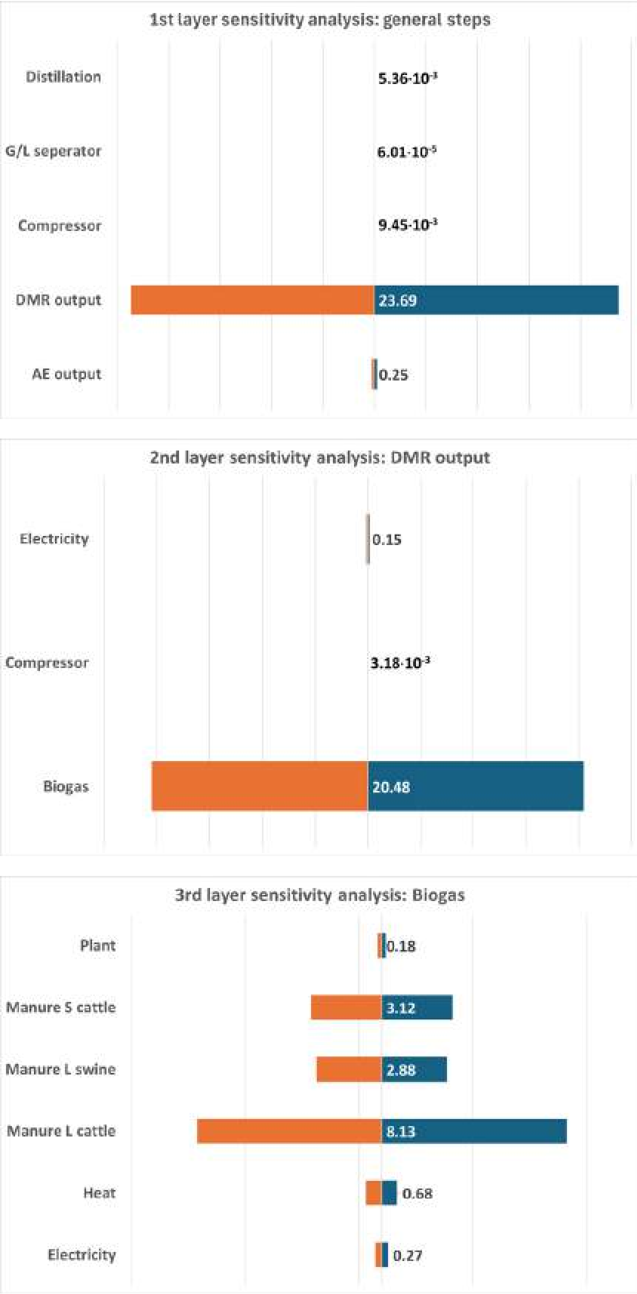
i. First-layer sensitivity: Major process steps — AE output, DMR output, compression, flash separation, and distillation — are each varied by ±25% sequentially.

ii. Second-layer sensitivity: Based on first-layer results, key internal DMR-process parameters — biogas flow, compression load, and electricity use — are varied by ±25%.

iii. Third-layer sensitivity: Based on second-layer outcomes, upstream biogas-system parameters — electricity demand, heat demand, liquid manure (cattle), liquid manure (swine), solid manure (cattle), and plant operation — are each varied by ±25%.

The results of all three layers are presented in Figure 6:

Figure 6. Multi-layer sensitivity analysis on MeOH from DMR with wind energy



Results from the first and second layers of the sensitivity analysis clearly show that the dominant contribution to freshwater ecotoxicity and eutrophication originates from the anaerobic digestion of organic waste into biogas. The third-layer analysis further reveals that manure is the primary source of these environmental burdens. This aligns with findings from the literature, where ammonia emissions during the land application of digestate were shown to increase eutrophication impacts by approximately 715% compared with fossil-based reference systems [63,65].

4.6. MeOH from DMR Using Wind Energy vs. Conventional Fossil-Based MeOH Production

The MeOH-from-DMR pathway powered by wind energy is compared with three conventional fossil-based methanol production routes: biomass gasification, coal gasification, and natural-gas reforming [66–70]. These conventional processes, obtained from the EcoInvent database, are normalized to the functional unit of 1 tonne of methanol. Results are presented in Figure 7, including both total environmental impacts and values excluding freshwater ecotoxicity and eutrophication.

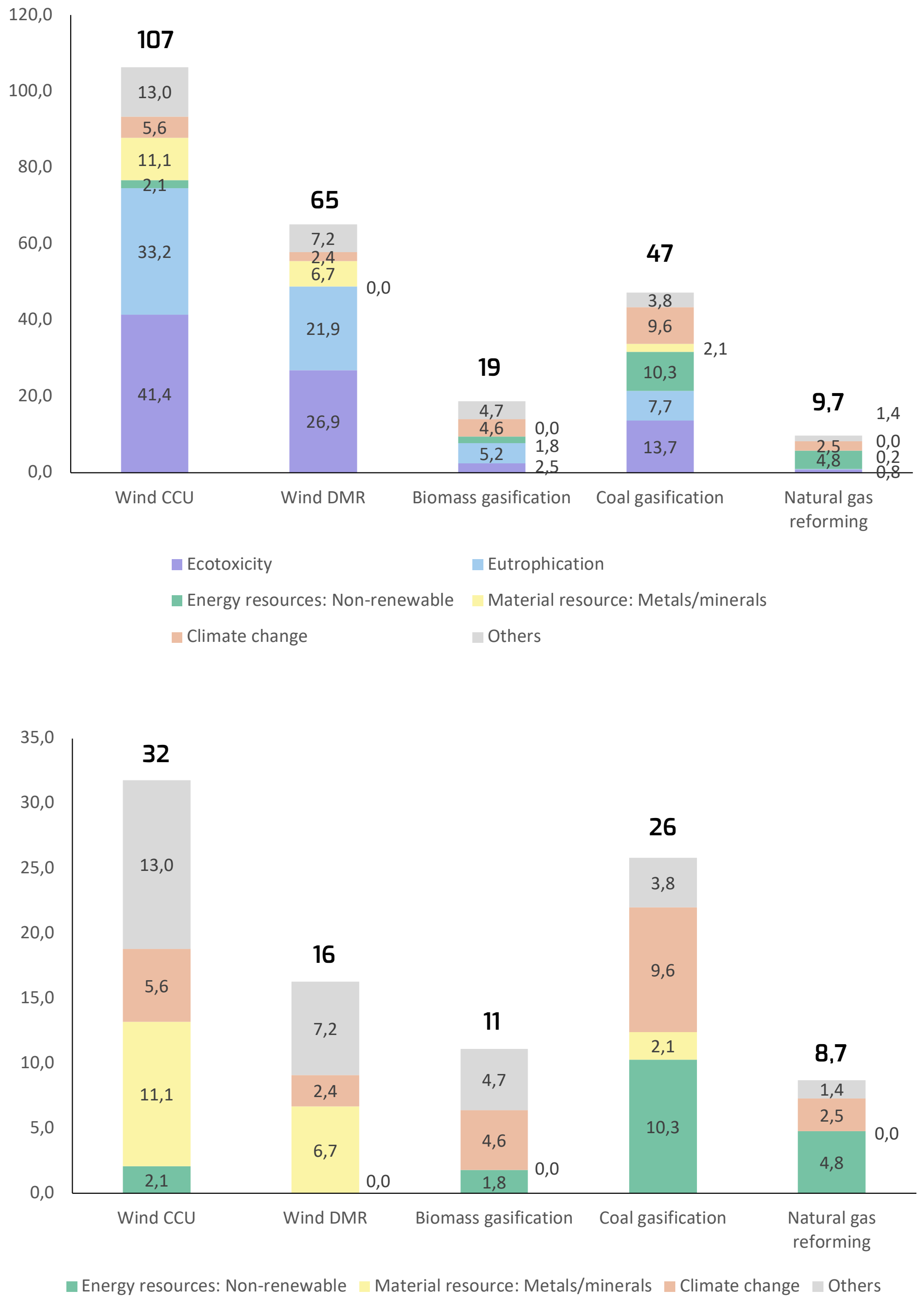
The comparison reveals that the biogenic route exhibits the highest total environmental impact across all categories, despite showing favorable results for specific indicators. For climate change, renewable methanol pathways per-form well, with impacts comparable to or lower than biomass and coal gasification (2.4–5.6 Points versus 4.6–9.6 Points). Natural gas reforming shows relatively low climate impact (2.5 Points), mainly due to reduced upstream processing requirements.

In terms of non-renewable energy use, the renewable routes show clear advantages (0–2.9 Points versus 1.8–10.3 Points), reflecting their reliance on renewable electricity. However, impacts on material resources are significantly higher (6.7–11.1 Points versus 0–2.1 Points), driven by the material intensity of wind turbines, electrolyser systems, and associated infrastructure.

The dominant contributors to total environmental impact are freshwater ecotoxicity and eutrophication (48.8–74.6 Points versus 1.0–21.4 Points for fossil routes). These impacts are linked to the application of untreated digestate from anaerobic digestion, which releases nutrients that drive ecological degradation. While digestate use supports soil fertility and agricultural productivity, it also introduces significant environmental burdens.

Literature shows that digestate post-treatment can mitigate these impacts. For example, resource depletion can be reduced significantly, although trade-offs may occur in eutrophication and acidification under certain conditions [71]. Advanced treatment options, such as separation, membrane filtration, and nutrient recovery, can reduce eu-trophication impacts by approximately 30–60% [73,74]. More advanced solutions, such as vermifiltration, can reduce total environmental impacts by up to 80–90% [75].

Figure 7. MeOH from CCU or DMR powered by wind compared to conventional processes (**top**: all environmental impacts included, **bottom**: freshwater ecotoxicity and eutrophication excluded)



These findings indicate that untreated digestate is the primary driver of environmental impact in the baseline scenario. Although detailed modelling of post-treatment is beyond the scope of this study, incorporating mitigation measures could significantly reduce environmental burdens. Under such conditions, MeOH-from-DMR powered by wind energy could achieve environmental performance comparable to conventional fossil-based methanol production routes.

5. Conclusions

This study evaluates the techno-economic and environmental performance of two decentralized pathways for sustainable methanol production from biogenic carbon in the eastern Netherlands: CO_2 hydrogenation and syngas production via dry methane reforming (DMR) of biogas. By integrating process modelling, techno-economic analysis, and cradle-to-gate life cycle assessment, the study provides a comprehensive evaluation of feasibility within a regional context.

Economically, methanol production is strongly influenced by electricity demand and capital investment, reflecting the energy-intensive nature of hydrogen production and reforming. Operational factors — especially production rate and plant capacity factor — are critical for reducing costs. Improving process integration and operational stability is therefore essential.

From an environmental perspective, upstream biomass processing and digestate management dominate impacts. Freshwater ecotoxicity and eutrophication emerge as key hotspots, mainly due to nutrient emissions from digestate application. These findings highlight the importance of nutrient recovery and effective digestate treatment. Environmental performance is also highly sensitive to the electricity mix, emphasizing the role of low-carbon sources such as wind power.

Overall, decentralized methanol production remains economically and environmentally challenging compared to fossil-based routes. However, improved renewable integration, process optimization, and resource management could significantly enhance performance. These systems have potential to contribute to circular carbon use and renewable fuel production, supporting future decentralized energy systems.

6. Future Research

Future research should assess the policy compatibility and large-scale deployment potential of sustainable methanol pathways under varying regulatory frameworks. Policy instruments such as carbon pricing, renewable-energy subsidies, and certification mechanisms strongly influence economic and environmental performance. Carbon pricing can improve competitiveness by internalizing fossil-fuel externalities, while incentives such as feed-in tariffs and biomethane support schemes enhance economic feasibility (76).

Integration with broader decarbonization strategies requires alignment with renewable-energy and circular-bioeconomy policies. In Europe, biomethane expansion is prioritized to improve energy security and reduce fossil dependence (77).

Future work should combine TEA, LCA, and policy modelling to assess regulatory impacts and guide sustainable deployment strategies (78).

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A Feasibility Study into the Expansion of the Hydrogen Storage at Entrance

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With more emerging technologies for hydrogen storage, it has become more important than ever to properly evaluate different options to ensure technical feasibility and legal compliance. In this study the technical aspects and legal requirements of two main storage technologies: underground gas cylinders and metal hydride have been researched for installation at the Energy Transition Centre in Groningen. The technical strengths, weaknesses and suitability of the technologies are explored and quantified using engineering calculations, then verified by experts at Entrance. Both technologies operate based on different principles, both offering improvements in safety but each focusing on various other characteristics of hydrogen storage as their main selling point. In terms of legal compliance, the current legal framework for hydrogen storage under the Environment and Planning Act (2024) is insufficient. This is especially the case for people who initiate hydrogen projects and local authorities who need to assess and decide whether the required Environmental and Planning permits can be granted in accordance with the current legal framework. It is however uncertain how the legal framework for hydrogen storage needs to be applied and which interests should be considered in in the decision-making process based on the new criterion: balanced allocation of functions to locations (ETFAL) and the instruction rules concerning safety from the national government. It was found that underground gas cylinders offer a more standard and practical approach at the cost of a more labour- intensive instalment period due to the need for ground excavation, whereas the metal hydride approach is more complex and less efficient, favouring volumetric energy density over gravimetric energy density. However, the less standard technology provides more areas for study at Entrance compared to underground cylinders. The expected results on the legal front reveal that in most cases a Planning permit is required for deviating from the Environmental plan from the local authority. This is the case since not many Environmental plans provide an assessment framework for hydrogen storage. An Environmental permit is only needed when a large amount of hydrogen is stored. Whether these permits will be granted depends on the specific facts and circumstances of the initiative, if there remains a balanced allocation of functions to locations (ETFAL) and whether the initiative is in line with the instruction rules concerning safety from the national government.

1. Introduction

With more technologies emerging in the field for hydrogen storage, it has become more important than ever to properly evaluate different these new options to ensure legal compliance and technical feasibility. In this case study both the legal and technical aspects of two new storage technologies are considered: they have been researched as add-on to Athe existing hydrogen research facilities at the Entrance – Centre of Expertise Energy at Hanze in Groningen. The two technologies considered are underground gas cylinders and metal hydrides.

2. Legal feasibility

The societal objectives of the Environment and Planning Act (EPA) (IPLO, 2024) focuses, on the one hand, on maintaining a safe and healthy physical living environment and good environmental quality – partly due tot the intrinsic value of nature – and, on the other hand, on the efficient management, use and development of the physical living environment to meet societal needs. These objectives reflect the tension within environmental law: 'Maximum protection leads to unfulfilled societal wishes. Maximum development leads to an unlivable environment.' Governmental bodies always need to strive to find a balance between these societal objectives in their decision-making process. With the EPA the legislator wants to regulate as many activities in the physical environment by means of general rules. These are rules are applicable to everyone. These rules can be found in the EPA and the accompanying Decrees. These rules can also be found in local legislation of a municipality. A permit is the exception to the rules.

2.1 Environmental permit

Whether a environmental permit is required for hydrogen storage depends primarily on the quantity of hydrogen that is stored. The Decree on Activities in the Living Environment uses ceratin threshhold numbers to decide whether a permit is required. When these numbers are exceeded a environmental permit will be needed before storing hydrogen is allowed.

The Decree has two legal frameworks for the storing dangerous substances (Programmabureau, 2026). Hydrogen storage qualifies as a dangerous substance due to the possible safety risks for the nearby environment.

The storage in gas cylinders focusses on relative small quantities of hydrogen (< 150 litres). If hydrogen is stored in a tank with a volume that exceeds 150 litres an environmental permit will be required to comply with the EPA.

- Storing hydrogen in *underground cylinders* falls under the legal framework for storage tanks. Therefore a environmental permit will be required. This permit will only be granted if the Best Available Techniques (BAT) are applied.
- Storing hydrogen in a *metal hydride* does not fall under any framework. However it does not mean that it is not regulated. It is regulated via the duty of care in the EPA, but it is more difficult to implement this technique.

2.2. Planning permit

If the local rules of the Municipality don't mention the possibility for hydrogen storage a planning permit to deviate from the local rules will be needed. This planning permit will only be granted on the basis of balanced allocation of functions to locations (IPLO, 2024). The Municipality achieves this balance by establishing rules regarding different activities at locations and weighing them against each other.

3. Technical feasibility

All the quantifiable information below has been derived from data sheets and contact from industry leaders. eBoth technologies have an inherently safe design, reducing safety zoning by over 50% compared to the traditional hydrogen gas storage technology, the underground gas cylinders achieve this by storing the high-pressure gas (up to 500 bar) in an inert well underground, with the possibility of digging to depths of 100 meters and offering a surface footprint of 1-2 square meters used for ventilation (Vallourec, 2026).

Metal hydrides achieve superior safety standards by dealing with lower pressure hydrogen (less than 35 bar) and chemically bonding the hydrogen atoms in a lattice, while taking up more surface area than the underground gas cylinders as they are usually stored in 10-20 ft ISO shipping containers (GRZ, 2026).

A PESTEL analysis revealed metal hydrides to be the more appropriately sized option (1-675 kg of hydrogen) compared to underground cylinders. Even with a lower technological readiness level (TRL) and more variables to control, these all align more with Entrance' sub-industrial scale requirements and allow for greater research opportunities because this is quite a different technology with really different characteristics when compared with the existing storage. At the same time it is also at a higher capital expenditure (CAPEX) of roughly 3-5 times the price per kg of hydrogen stored. Underground storage is also cheaper because its TRL is already 7-8, compared to about 5-6 for metal hydrides.

Thermodynamic calculations revealed the energy used to compress hydrogen in the underground gas cylinders was about half that of the thermal energy needed to drive the metal hydride reaction (both backwards and forwards), it was however noted that the CAPEX and maintenance costs for hydrogen compression and purification was omitted and that metal hydrides can benefit from thermal recycling.

Using the above input, a Kesselring matrix was created using requirements from Entrance and the best-to-worst method (BWM) for multi-criteria decision-making (MCDM). This shows metal hydrides as the best of the two options, providing a safe, pilot scale system with many research opportunities but at a higher investment cost. However due to the ability to more easily downscale the system this effect can be minimized when compared to the underground gas cylinders which require a higher minimum cost due to the need for civil works while creating the storage well.

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Method to assess technical feasibility of regional renewable hydrogen distribution network designs using simulations

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Renewable ('green') hydrogen can be a suitable substitute for natural gas in the transition to a low-carbon industrial sector. Autonomous regional hydrogen distribution networks can act as a catalyst for industry to switch to cleaner molecules. Renewable hydrogen is typically produced through electrolysis of water, which is not necessarily continuous due to its dependence on variable renewable electricity sources. Therefore, distribution infrastructure designs should account for the supply-demand matching, network resilience, transportation capacity and flexibility requirements needed to accommodate renewable hydrogen. This research proposes a method to assess the technical feasibility of different hydrogen network designs, using a simulation-based approach. First, electrolyser production profiles are developed which operate within the EU regulatory framework for renewable hydrogen production. Second, a hydrogen network simulation tool is developed based on pandapipes and with added functionality to improve model accuracy and increase simulation automation. Using this tool, network design analysis is performed considering variations in operating pressure and effective pipe capacity. For this analysis, a full year is simulated considering hydrogen demand and supply profiles at 15-minute intervals. Network designs are evaluated in terms of adequate mass flows, the degree of network pressure fluctuations, and flexibility requirements. To illustrate the proposed method, a case study in the combined industrial parks of Eemshaven and Delfzijl in the Netherlands was analysed. The results show that the geographic locations of the major suppliers, consumers and storage facilities define the technical feasibility and constraints of a given network design. Additionally, network constraints are shown to be resolved by increasing effective pipe capacity and/or operating pressure. Finally, it was shown that flexibility is crucial for maintaining mass balance and pressure levels within the network. However, while a large amount of flexibility is not required often (13.5% of the time in the case study), its magnitude can be significant (up to 41% of system capacity throughput in the case study). How this flexibility is achieved is a matter for future research (e.g., implementing demand-side flexibility or onsite buffers). These results illustrate how the proposed simulation-based approach provides valuable insights into design considerations of autonomous distribution networks with dynamic participants such as renewable hydrogen producers.

Keywords: Renewable hydrogen, Green hydrogen, Distribution system, Hydrogen storage, Flexibility

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1. Introduction

To mitigate climate change and increase energy sovereignty, the European Union (EU) is pursuing an energy transition from fossil fuels to renewable energy sources (Directorate-General for Energy, n.d.). For many industries, this entails replacing natural gas as a process input (Gas Quality Harmonization Working Group, 2026). Hydrogen is often seen as a suitable alternative to natural gas and can be produced renewably through electrolysis (Directorate-General for Energy, n.d.).

Within the EU, for hydrogen to be considered renewable (i.e., 'green'), it must be produced through electrolysis using electricity sources which meet one of the following criteria, according to the EU regulatory framework for renewable fuels of non-biological origin (RFNBO) (Regulation (EU) 2023/1184) (The European Commission, 2023):

a. **A direct connection to a renewable power source** (e.g. wind and/or solar parks), which came into operation no earlier than 36 months before the electrolyser.
b. **The electricity grid, within a bidding zone consisting of at least 90% renewable electricity on average yearly**, with the number of hydrogen production hours being proportional to the share of renewable electricity.
c. **The electricity grid, using a power purchasing agreement** for renewable sourcing of electricity with a bidding zone emission intensity below 18gCO_2eq/MJ averaged over a year.
d. **The electricity grid, using a power purchasing agreement** for renewable sourcing of electricity, with a clearing price of electricity on the day-ahead market within a one-hour period lower or equal to €20/MWh, or lower than 0.36 times the price of an allowance to emit 1 tonne of CO_2 equivalent on the European Trading System (ETS).
e. **The electricity grid, for redispatch support**, with the electricity being consumed during an imbalance settlement period in which renewable power-generating installations are redispatched downwards or the consumption of electricity reduces the need for redispatching.
f. **Battery storage**, containing stored electricity from one of the above-mentioned sources.

These criteria will not always be satisfied, meaning that renewable hydrogen production will likely be non-continuous. This differs from traditional fossil-based hydrogen production through steam-methane reforming (SMR). As a result, a distribution system for renewable hydrogen will have different design requirements than a traditional gas distribution system (H_2opper consortium, 2026).

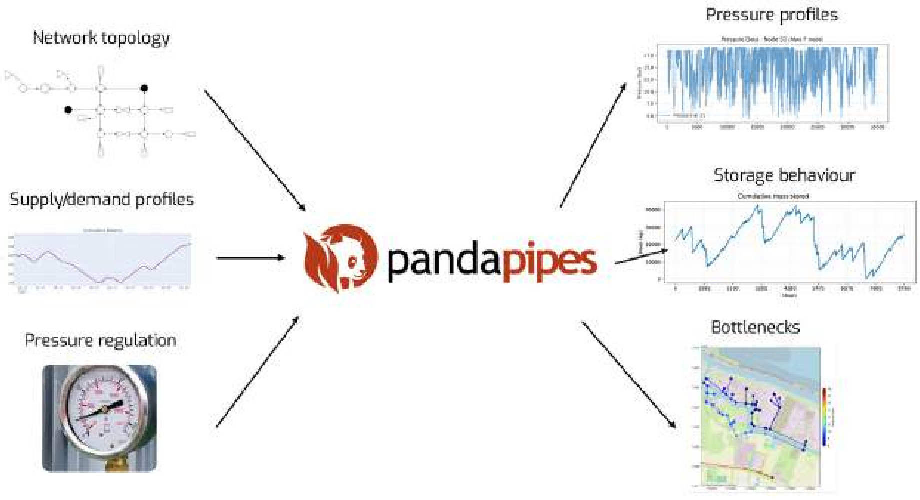
Further, as with historical energy infrastructure developments (Hughes, 1987), it is expected that hydrogen production, distribution and consumption will begin on a regional level before national supporting infrastructure is developed. Therefore, regional hydrogen distribution infrastructure must be run autonomously (at least initially), further adding to the system design requirements.

This paper proposes a method to assess the technical feasibility of different (autonomous) hydrogen distribution network designs using a simulation-based approach. The method is applied to a case study in the Eemshaven-Chemie Park Delfzijl industrial cluster in the north of the Netherlands to illustrate how this works in practice. The results from this case study analysis are indicative of the implications of renewable hydrogen production on distribution infrastructure design requirements.

2. Method

The method proposed in this paper assesses the technical feasibility of different hydrogen distribution system designs. This is achieved by evaluating the mass flows and pressure profiles resulting from given supply and demand profiles within a given network topology and pressure regime using the pandapipes simulation software, as illustrated below. The degree to which the desired mass flows are achieved, and to which the network operates within the desired pressure range, are indicative of the design's technical feasibility. Storage behaviour is also assessed to quantify the flexibility required to operate a renewable hydrogen distribution network.

Figure 1. Hydrogen network simulator



2.1 Hydrogen network simulator

In this paper, simulations are used to assess the performance of a given network design under given operating conditions. The proposed hydrogen network simulator is built around the pandapipes simulation tool (described below) with added functionality, including:

- The ability to read in a standardised network design file to automatically setup the simulated network.
- The ability to read in a standardised set of consumer/producer profiles to simulate over a longer period.
- Automated calculations of loss coefficients resulting from bends in pipes (i.e., z-factors). Specifically, at each pipe junction, the bend angle was calculated based on the pipe vectors. Then, the following equation was used to approximate the z-factor based on the bend angle (in degrees) (Mott, 2023):

  If bendAngle > 45°:

  $$z = 0.000014 \times bendAngle^2 - 0.001244 \times bendAngle + 0.154667$$

  Else:

  $$z = 0.000007 \times bendAngle^2 - 0.000041 \times bendAngle + 0.116197$$

- A customised storage controller, which prioritises flexibility sources based on a given merit order and imposes given constraints.

The hydrogen network simulator uses pandapipes (v. 0.13.0) to model pressure regimes and mass flows within defined network topologies. Pandapipes is an open-source, fully validated, Python-based network calculation program which is aimed at static (i.e., steady-state) analysis of balanced fluid systems (Lohmeier et al., 2020).

Pandapipes is developed on the foundation of pandapower, a similar tool for electricity grid simulation. It uses HyFlow, a power transport formulation implementation for power, gas and/or heat networks (Böckl et al., 2019). These formulations are coupled in a matrix and then solved using a Newton-Raphson approach, which uses iterative root-finding algorithms to approximate the roots of the coupled functions. Pandapipes provides static or quasi-static solutions of predefined discrete instances (i.e., it is a steady state model). For the application in a hydrogen distribution network, pandapipes computes the hydrogen mass-flow, velocities and pressures at each node in the network at each time step. Since it provides steady state solutions, pandapipes is not suitable for gaining insights into transients or short-term dynamics (e.g., sub-minute scale).

2.2 Model inputs

The following inputs must be defined to run the hydrogen network simulations.

2.2.1 Network topology

Networks in pandapipes are represented as nodal networks. As such, it is necessary to define every pipe junction, bend and consumer/producer/storage point-of-connection within the network as a node. Each node requires a unique ID and name, nominal operating temperature and pressure, and optionally a longitude and latitude. In this paper, consumer/producer/storage nodes are referred to as active nodes, and the remainder as passive nodes. Between nodes, the properties of the interconnecting pipes must be defined. Each pipe is defined by their unique ID and name, type (which includes nominal width, inner and outer diameters, standard dimension ratio and material type, which translates to pipe roughness), start and end nodes, and length.

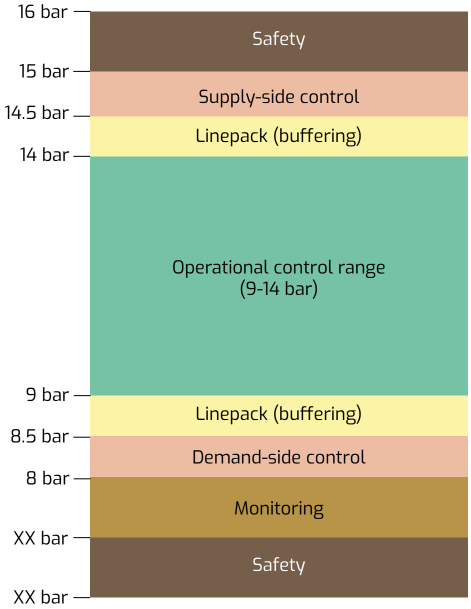
2.2.2 Supply and demand profiles

At each consumer/producer node in the defined network topology, a hydrogen supply and/or demand profile must defined for each timestep within the simulation period. Storage and flexibility injection and take-off rates can be determined dynamically (within given constraints) based on the system-wide mismatch between supply and demand, following a given merit order.

2.2.3 Pressure regulation

In the hydrogen network simulator, one or more pressure regulators must be defined. Pressure regulators can be an external (high-pressure) network, a storage system or another source of flexibility. Pressure regulators must maintain mass balance within the local network for each timestep (by injecting/taking-off hydrogen as needed) and work towards maintaining nominal pressure at pre-defined reference nodes within the network. It is important to select the proper location and value for the reference nodes such that system pressure remains within the allowable operating range. E.g., in the Netherlands, distribution system operators may only operate networks between 8-14.9 bar, as illustrated in Figure 2.

Figure 2. Nominal operating pressure range (green) and maximum operating pressure range (light and medium brown) for distribution system operators in the Netherlands (HyDelta: WP4a – Innovations for Hydrogen Grid Balancing).



2.3 Model outputs and analysis

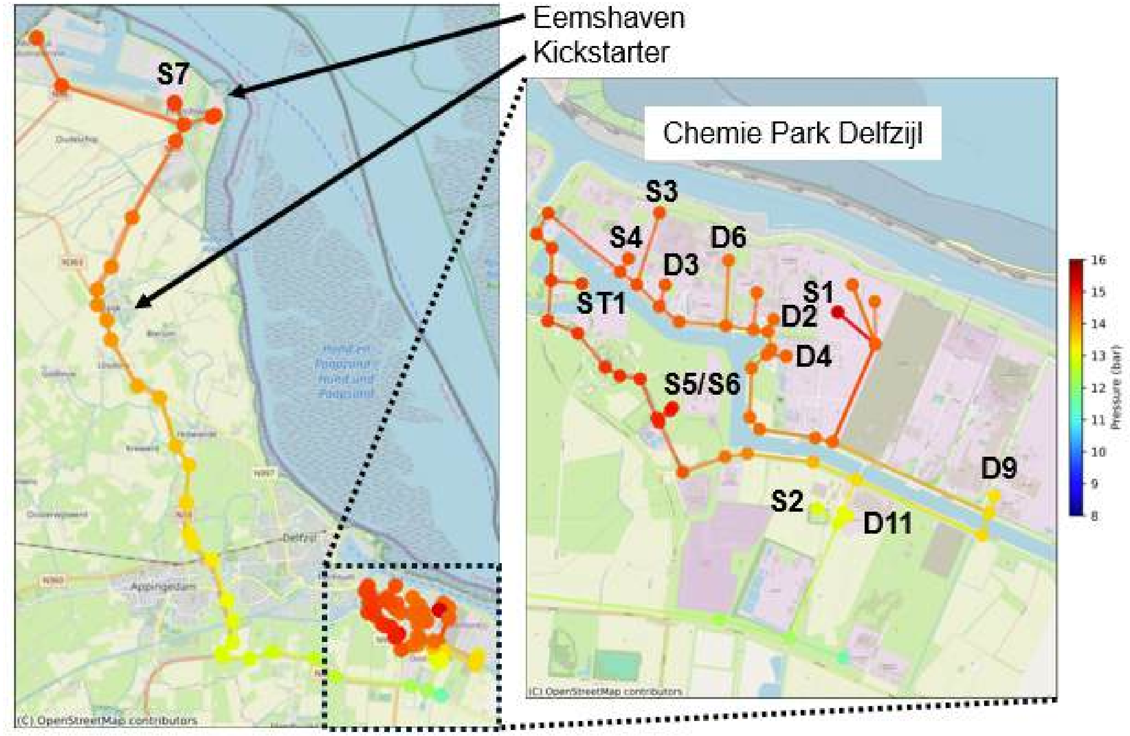
In the hydrogen network simulator, mass flows and pressures at each node are calculated for each timestep. Using the results, it is possible to evaluate whether or not the given network configuration remains within the desired pressure range and whether or not sufficient hydrogen can be supplied to the consumers (i.e., the system is technically feasible). Further, bottlenecks can be identified by locating the nodes which consistently experience higher or lower pressures (relative to the network's nominal operating pressure). Finally, storage and flexibility requirements can be quantified by analysing the degree and duration of supply-demand mismatch over the analysis period.

3. Case study – H_2opper project

To illustrate how the proposed method can be used in practice, a case study based on the H_2opper project (H_2opper consortium, 2026) was analysed. H_2opper considers a local hydrogen network in the north of the Netherlands which interconnects two industrial areas: Eemshaven and Chemie Park Delfzijl, as illustrated in Figure 3.

Within each industrial park, companies have the potential to consume, produce or store hydrogen. Appendix 1 lists the relevant companies along with their expected annual hydrogen consumption/production. The case study considers a ring network for the industry at Chemie Park Delfzijl. It is interconnected with Eemshaven via a piping infrastructure denoted as the 'Kickstarter'. The piping follows road right-of-ways and existing piping infrastructure. Note that the labelled nodes are active network participants. Unlabelled nodes are passive nodes for bends, junctures or placeholder nodes for potential future participants.

Figure 3. Case study project area including Eemshaven and Chemie Park Delfzijl industrial parks, Kickstarter interconnection, hydrogen consumers (DX), producers (SX) and storage (STX) locations, and a pressure map of the system during a period with low hydrogen production (see section 4.1 for details). Note that unlabelled points-of-connection were not considered in this case study.



The network is an autonomous system, meaning that it has no interaction with other networks and that hydrogen import to or export from other networks is not possible, at least initially. Therefore, hydrogen supply and demand need to be matched within the network. The hydrogen pipe type is pre-selected and concerns a SoluForce PVC pipe designed for hydrogen transport. The pipe has a 15.2 cm outer diameter and a 12.2 cm inner diameter. The case study aims to investigate the effect of varying pipe capacity and network operating pressure.

3.1 Network Participants

Three distinct company types participate in the network. First is the industry that require hydrogen for their processes, the consumers in the network. Second are the producers, consisting of the electrolysers that produce hydrogen from renewable electricity and ammonia crackers which chemically obtain molecular hydrogen by cracking ammonia in a continuous process. Finally, hydrogen storage facilities can charge from or discharge into the network when demand and supply do not match.

3.2 Hydrogen supply and demand profiles

The hydrogen consumers in the network are assumed to have a constant baseload demand. This means that consumers are assumed to have no flexibility to adapt to the network imbalance in this case study.

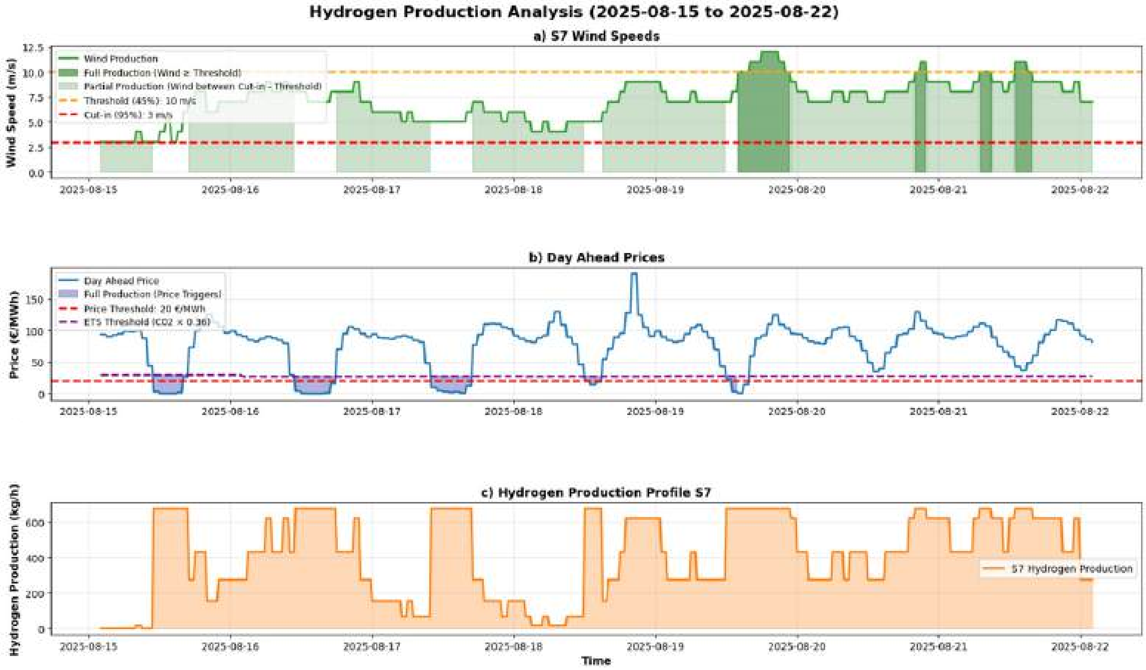
The hydrogen producers are separated into two types: electrolysers and an ammonia cracker. The electrolysers produce hydrogen from (renewable) electricity by electrolysis. For the hydrogen to be considered renewable it must be produced according to the RFNBO regulations (Regulation (EU) 2023/1184) as described in the introduction. The main technical requirements are applied to the electrolysers in the model as follows:

1. First, the electrolyser will produce hydrogen at full capacity when sufficient electricity is delivered directly from a renewable power source (e.g. wind or solar park).
2. If insufficient electricity is available to run at full capacity, the electricity prices are considered. If the day-ahead prices are below 20€/MWh or below 36% of the EU ETS prices (described below), the electrolyser will produce at full capacity.
3. Finally, if both conditions are not met, the electrolyser will produce at a fraction of its capacity, proportional to the available electricity. Below a certain cut-off fraction, production is stopped.

The electrolyser will produce at the highest rate possible under the above conditions, regardless of the network mass balance. Further, it is assumed that electrolysers can freely ramp production up and down without consequence and that production efficiency is constant. The directly delivered renewable energy considered under requirement 1) was assumed to originate from offshore wind parks. This was assumed due to the geographic location of the project area, which is on the North Sea coast near existing wind parks. Wind data from unique North Sea weather stations from December 1st 2024 to December 1st 2025 (KNMI, 2026) were used to develop unique production profiles for each electrolyser. Wind generation was assumed to be linearly proportional to windspeed, with a production cut-off when the wind speeds are in the lowest 5% of the wind speed duration curve. The wind speed duration curves are provided in Appendix 2. Wind park capacity factors were assumed to be 45% (Taminiau & van der Zwaan, 2022), although it was assumed that wind parks would be dimensioned such that the electrolyser would achieve a capacity factor of 70% from this source, on average.

The EPEX (day-ahead) SPOT prices of the bidding zone of the Netherlands were used for the electricity price requirements (ENTSO-E, 2026), together with the ETS CO_2 allowance rates (Energy Instrat, 2026) from December 1st 2024 to December 1st 2025. An illustration of an arbitrary week of hydrogen production for an electrolyser is given in Figure 4. Utilising SPOT market electricity enabled the electrolysers to increase their capacity factors by a further 5%, to 75% on average.

Figure 4. Illustration of (a) offshore wind, (b) EPEX SPOT price with price (red line) and ETS (purple line) thresholds, and (c) the resulting hydrogen production profiles of a single electrolyser (S7) for an arbitrary week. Note that in Figure 4(a) the dark shaded regions indicate being the driver for production at full capacity, where the lightly shaded regions drive production proportional to available wind power.



The ammonia cracker can produce hydrogen continuously without additional requirements. In this case study, it was assumed that 80% of its capacity provides a constant baseload production regardless of network mass balance. The remaining 20% of its capacity is reserved to provide flexible production for periods when the electrolysers are unable to produce sufficient hydrogen to maintain network mass balance. More on the flexible component of this plant is described below.

3.3 Flexible actors

In the proposed method, consumer and producer profiles are pre-determined and do not respond to network imbalance. Flexible actors are participants tasked with restoring the network mass balance and maintaining network pressures at nominal operating levels. Two flexible actors are defined in this case study: a storage facility and the flexible capacity of the ammonia cracker described above. The latter will act first to mitigate hydrogen deficits (i.e., it has a higher merit order), but it is limited to resolving production deficits (i.e., the ammonia cracker can increase production by up to 20%, but it cannot reduce production below the baseload of 80%).

If a deficit (or surplus) remains, the storage facility will discharge (or charge) hydrogen as required to maintain mass balance within the network. It is assumed that the hydrogen storage facility has sufficient storage capacity and a sufficient rate of (dis)charge to meet the network's requirements. This assumption is crucial for creating solvable simulations and for quantifying the network's flexibility requirements. Further, the hydrogen storage will only store sufficient surplus hydrogen to maintain the same state of charge at the start and end of the simulation period (i.e., there are no year-on-year changes in stored hydrogen volumes); Additional hydrogen surpluses are assumed to be exported outside the system at an extraction point.

3.4 Topology/pressure regime designs

The network design variables were limited to number of pipes and nominal operating pressure in the proposed hydrogen distribution network. Configuration 1 considers a low-pressure system (11.5 bar nominal operating pressure) with small effective pipe capacity (single pipe system). Configuration 2 considers a high-pressure system (24 bar nominal operating pressure) with a small effective pipe capacity. Configuration 3 considers a low-pressure system with a large effective pipe capacity (each pipe in the system is given a duplicate, parallel pipe to effectively double the available pipe capacity[1]). Otherwise, each configuration is identical and follows the layout shown in Figure 3. The design configurations are summarised in Table 1.

3.5 Time resolution

The network will be simulated for a full year to gain insights into daily, weekly, monthly and seasonal variations in the network. These timescales are relevant due to the characteristics of the production

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[1] Alternatively, it is possible to increase pipe diameter to increase pipe capacity by defining a new standard pipe type. But for ease of implementation, it was chosen to double the number of pipes in this example.

Table 1. Case study design configurations

Configuration no.	No. of parallel pipes	Nominal operating pressure
1	1	11.5 bar
2	1	24.0 bar
3	2	11.5 bar

profiles, which are dependent on variable weather data and electricity market price data. The simulation is solved for time steps of 15 minutes. This is a typical timescale used in network analysis and provides adequate insight into the aforementioned timescales.

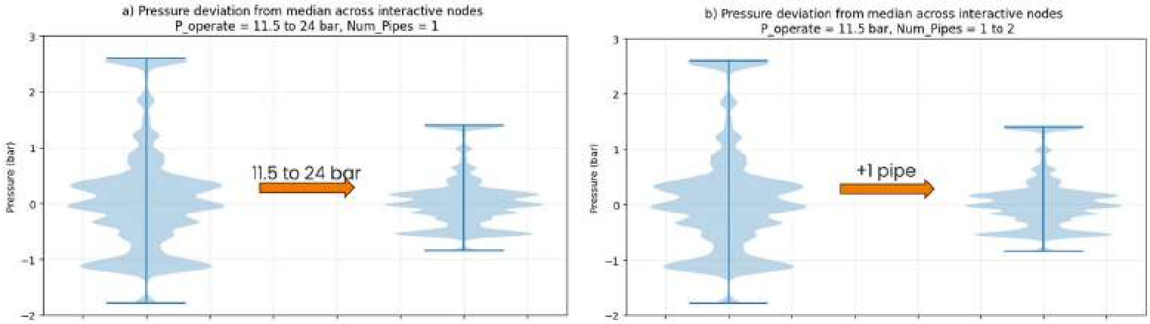
4. Results

4.1 Operational feasibility

All network configurations were found to be operationally feasible (i.e., they could deliver the required mass flows within the desired pressure range), but network behaviours varied between configurations. Specifically, Figure 5 shows the relative occurrence of different pressure deviations from the median (i.e., the nominal pressure) within the network for the three different network configurations during the simulation period. The results from configuration 1 are shown on the left side of Figures 5(a) and 5(b). In this configuration, the nominal pressure was set at 11.5 bar. Therefore, configuration 1 can operate within the desired pressure range (i.e., between 8.0 and 14.9 bar), though it does experience large fluctuations in pressure (which cause additional stress on network components) and approaches the safe operational limits of a low-pressure gas distribution network, as shown in Figure 2.

In contrast, increasing the network's nominal operating pressure to 24 bar (configuration 2) reduces the pressure fluctuations within the system, as shown in the Figure 5(a). Similarly, in Figure 5(b) the effects of doubling pipe volume (by adding an additional parallel distribution pipeline – configuration 3) are shown to reduce both the pressure fluctuations within the system as well as the minimum and maximum pressure within the system. Notably, the effect of increasing pipe capacity correlates quadratically with a decrease in pressure fluctuations within the system.

Figure 5. Effects on system pressure fluctuations when (a) increasing nominal pressure to 24 bar and (b) doubling pipe volume



Further, the network bottlenecks can be identified by analysing the pressure map shown in Figures 3 and 6. In Figure 3 it can be observed that pressures reach their highest levels when the electrolysers are not producing, due to the fact that the hydrogen supply is now fully dependent on the storage and the baseload supply from the ammonia cracker. This results in a high concentration of mass flow and a pressure drop from these facilities towards the consumers. In particular, note the pressure drop towards D9, the largest consumer.

Figure 6 shows a pressure map of Chemie Park Delfzijl for configuration 1. It shows the influence of the geographic position of the participants on the pressure distribution at a time during which all the electrolysers produce at full capacity, causing a hydrogen surplus. The bulk of the surplus is taken off by the storage facility to restore mass balance. This causes a significant pressure drop throughout the system, particularly from the biggest suppliers towards the (charging) storage facility, to accommodate the high mass flow.

4.2 Flexibility requirements

The Figure 7 illustrates the annual flexibility requirements from the ammonia cracker's production flexibility and the hydrogen storage in the form of a load duration curve. As shown, the ammonia cracker's flexibility will be used more often when there is a production deficit due to its higher merit order. However, the hard limit of 20% additional production capacity is also visible as the ammonia cracker reaches its maximum capacity. When this occurs, the hydrogen storage takes over by discharging hydrogen

Figure 6. Pressure map of the Chemie Park Delfzijl at a time where electrolyser production is maximal and thus the mass flow towards the storage peaks

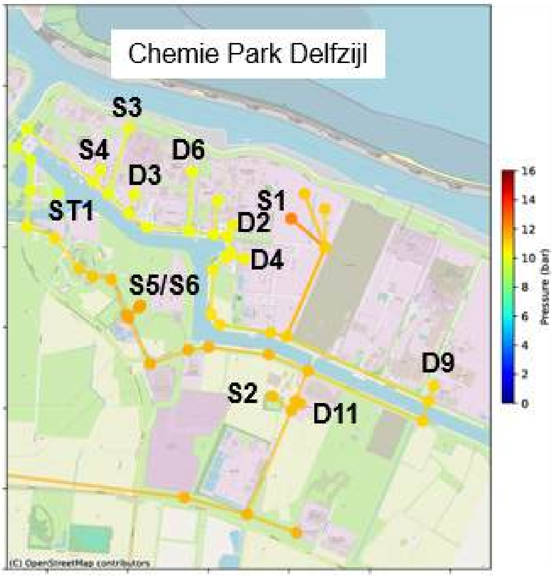
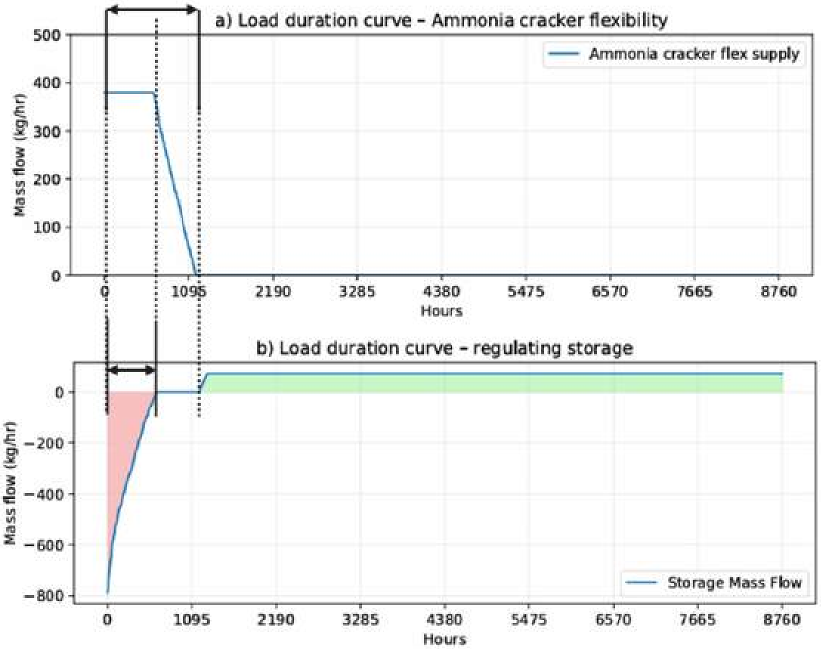


Figure 7. Flexibility requirement load duration curve for (a) ammonia cracker and (b) hydrogen storage to maintain system mass balance.

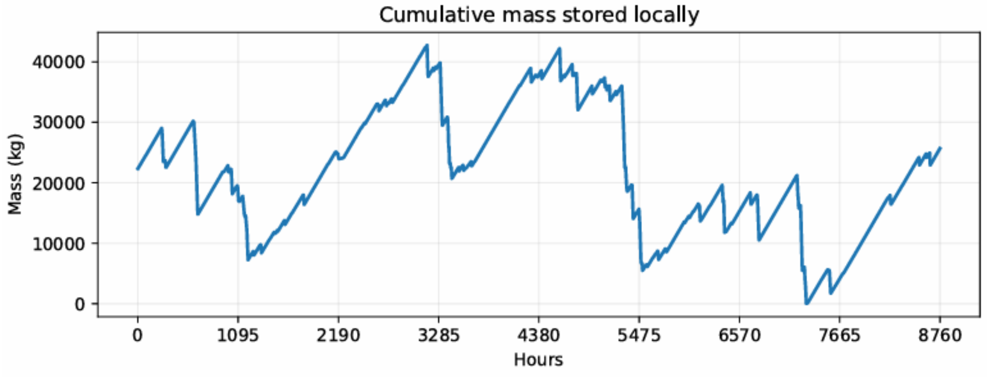


as needed to maintain system balance (red area). During periods with surplus production, the storage charges at the rate needed to maintain mass balance annually (green area). The area and magnitude of the ammonia cracker flexibility and storage discharge are indicative of the flexibility required to maintain a renewable hydrogen distribution network.

An analysis of this figure indicates that the combined flexibility must be able to support supply deficits for 1186 hours per year, or 13.5% of the time. Further, the combined flexibility must be able to reach a magnitude of up to 1100 kg/hr, or 41% of system throughput. Supply surpluses are less of a concern, since any hydrogen that cannot be stored is assumed to be exported.

Also of interest is the time-of-use of storage, which is illustrated in Figure 8. This figure shows that storage is not only used during periods of extreme surplus or deficit, but is continuously charging and discharging to offset minor differences between supply and demand. Thus, storage plays a crucial balancing role in an autonomous distribution system, such as the one proposed in this case study.

Figure 8. Hydrogen storage throughput - Increasing values indicate storage charging and decreasing values indicate storage discharging. Note that the storage ends the year at a slightly higher level than it began at – this is the result of a rounding error in the simulation.

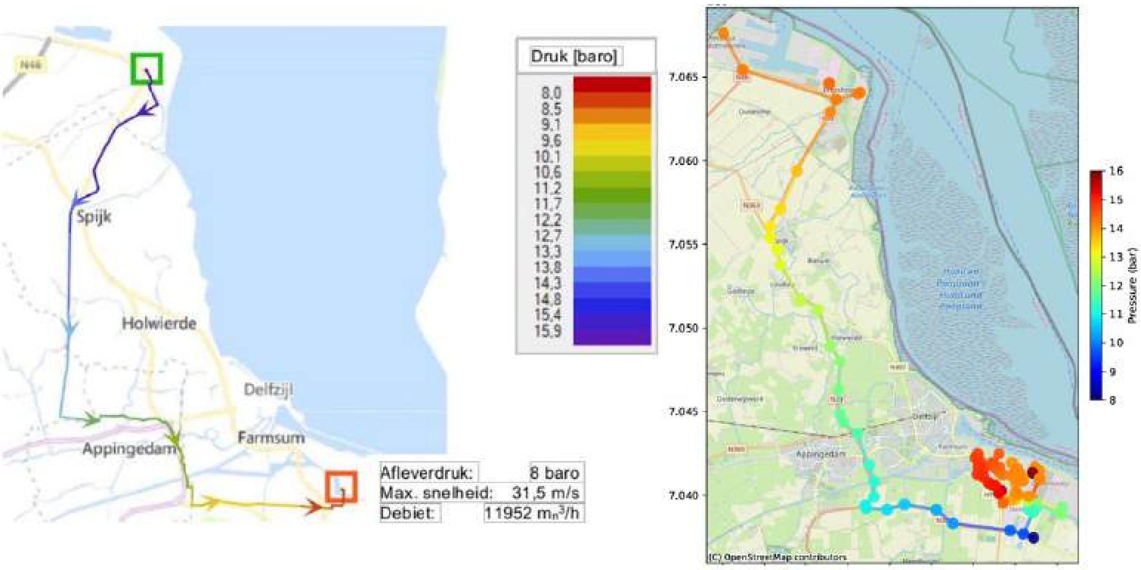


5. Discussion

5.1 Hydrogen network simulation methodology evaluation

The results of the case study show how the proposed methodology can be used in a practical analysis. The simulation results behave according to established theory (e.g., doubling pipe volume reducing pressure fluctuations quadratically) and the simulated pressures were within the expected ranges. For example, Figure 9 shows the expected pressure drop over the Kickstarter interconnection comparing the method proposed in this study with a previously published result (Baardink & Hartholt, 2023). Although the routes of the interconnection are not identical, the total pipe length and total pressure drop across the interconnection are comparable. This comparison indicates that the loss coefficients described in section 2.1 are having a realistic impact on the simulation results.

Figure 9. Comparison of the pressure drop over the Kickstarter interconnection between (a) Antea study (Baardink & Hartholt, 2023) and (b) this paper. Note that the colour map between the two images is inverted and that the interconnection route differs slightly, but that the total pressure drop is comparable in both cases



5.2 Renewable hydrogen network design requirements

This proposed method provides insight into the design requirements of a renewable hydrogen distribution network. Specifically, the results of this paper indicate that for the proposed implementation, a single-pipe, low-pressure network design (configuration no. 1) would be able to operate within allowable pressure ranges while maintaining sufficient mass flows at all active nodes. However, future system expansion and transient effects may push this design outside of its operational limits, in which case a larger pipe capacity or a higher operating pressure should be considered.

5.3 Flexibility requirements

As shown in the results, the non-continuous nature of renewable hydrogen production adds additional requirements for a hydrogen distribution network design. Specifically, a renewable hydrogen network must be able to provide dynamic flexibility to keep the network in operation. This flexibility can take many forms, such as local storage, on-site buffers, high-pressure network support or greater production and consumption flexibility. Regardless, sufficient flexibility is crucial to maintaining system mass balance for the hours of the year when production is insufficient.

Interestingly, in the case study, the magnitude of the flexibility required to support supply deficits is relatively large (reaching 41% of system throughput), but its occurrence is relatively infrequent (occurring 13.5% of the time). The estimated system flexibility requirements exceed the capacities of the proposed local storage. Therefore, flexibility must be distributed among several sources in the network (e.g., demand-side flexibility and/or onsite buffers).

5.4 Follow-up research

To follow-up on this research, the behaviour of the electrolysers themselves could be further constrained to reflect realistic operating conditions, such as restricting ramp rates. Further, additional sources of flexibility could be modelled to better distribute flexibility and reduce pressure variations and extremes within the network. To simulate this, flexibility sources must be realistically sized and given the proper merit order to achieve a functional renewable hydrogen distribution network.

6. Conclusion

This paper describes a hydrogen network simulation tool which was used to analyse and evaluate the design requirements of a proposed regional, autonomous renewable hydrogen network. The proposed method produced expected results which were in line with earlier results. Further, the proposed method considers the implications of non-continuous renewable hydrogen production. This impacts the design requirements of the network, which must allow for higher hydrogen flows during periods with high production, and provide sufficient flexibility/storage to support demand during periods with low production, all while maintaining system pressures within allowable ranges. Additionally, it was shown that the relative locations of producers and consumers influence pressure distributions throughout a network.

The value of the proposed method was illustrated by applying it to a case study. This case study was based on a constant hydrogen demand, production from electrolysis powered by offshore wind generation together with an ammonia cracker (with 20% output flexibility), and a hydrogen storage system. In this case, it was found that supply flexibility was required for 13.5% of the time and that peak supply flexibility was equal to 41% of system throughput. These results indicate that achieving a renewable hydrogen distribution network (based on a variable renewable electricity source) requires a relatively large amount of in-built flexibility, though for only relatively short periods of time.

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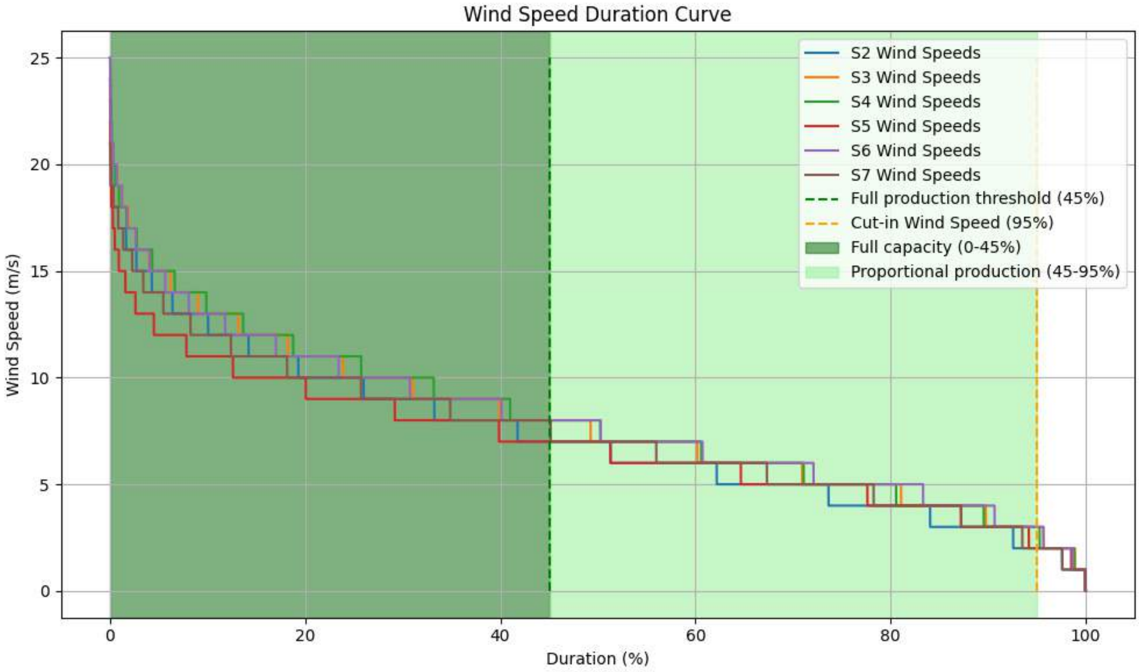
Appendices

Appendix 1: Annual hydrogen production and consumption of network participants

ID	kt/y	S/D/ST
D11	4,5	Demand
D2	1	Demand
D3	0,25	Demand
D4	2,8	Demand
D6	4	Demand
D9	11	Demand
S1	14,8	Supply (ammonia cracker)
S2	1,3	Supply (electrolyser)
S3	1,5	Supply (electrolyser)
S4	0,5	Supply (electrolyser)
S5	4	Supply (electrolyser)
S6	10	Supply (electrolyser)
S7	3,25	Supply (electrolyser)
ST1	0,25	Storage (throughput)

Appendix 2 – Wind speed duration curves

Figure 10. Graph showing the wind speed duration curves of the unique wind profiles for each electrolyser (S2 through S7). The shaded areas indicate whether the electrolyser is able to produce at full capacity (dark green), or proportional to the wind speed (light green).



Energy Transition and Middle Powers: Turkey’s Regional Role

Yavuz Tuyloglu (University of Groningen)

The global energy transition is not being shaped only by great powers and international institutions. As IEA Executive Director Fatih Birol has noted, “our energy and climate future increasingly hinges on the decisions” made by emerging and developing economies. Among these are middle powers such as Turkey, Brazil, and Indonesia: states that do not match the global reach of the United States or China, but still combine significant regional influence, strategic autonomy, and growing energy demand. Their importance is becoming more visible under conditions of multipolarity, as a less hierarchically ordered international environment creates more space for regionally influential states to pursue strategic opportunities in energy policy. Their choices help shape regional decarbonisation pathways, cross-border energy relations, and the wider political economy of transition. Yet they remain underexplored as a category in energy transition research.

This paper uses Turkey to show why middle powers matter. Turkey is a particularly revealing case because it combines high import dependence with ambitious renewable-energy expansion, investment in nuclear power, and an active role in the regional politics of gas, electricity, and energy connectivity. Positioned between the Eastern Mediterranean, the Black Sea, the South Caucasus, and European markets, Turkey illustrates how middle powers experience energy transition not only as a domestic policy challenge, but also as a regional strategic one.

The paper argues that middle powers face a distinctive transition dilemma because they occupy an intermediate position in the international system: their energy choices shape regional dynamics, yet they remain constrained by external markets, technologies, and geopolitical pressures. They must therefore pursue decarbonisation, energy security, and domestic economic development while seeking to turn regional influence into strategic leverage. To analyse this, the paper brings together three dimensions that are often studied separately: energy security, geopolitics, and industrial strategy. It examines Turkish policies on gas diversification, renewable energy expansion, and nuclear power development in order to show how these dimensions interact in practice.

Methodologically, the paper is based on qualitative policy analysis and process tracing. It draws on policy documents, legislation, regulatory decisions, and official statements to reconstruct key choices in Turkish energy policy. The paper shows that, for middle powers, energy transition is not simply a matter of technological change or emissions reduction. It is also a matter of balancing vulnerability and ambition, managing old and new dependencies, and turning regional position into strategic advantage. In this sense, the Turkish case offers broader insight into how middle powers shape, and are shaped by, the regional politics of energy transition.

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1. Introduction

The global energy transition is often narrated as a drama staged in Beijing, Brussels, and Washington, DC. But the transition is not being made in these capitals alone. A set of emerging middle powers, states with significant but not system-defining capabilities that exercise outsized influence in specific regions and policy domains, are shaping the pace, geography, and outcomes of the global energy transition in ways that existing research has been slow to recognize. Among emerging middle powers, three stand out as particularly consequential: Turkey, Brazil, and Indonesia. Each recorded power generation growth of five to six percent in 2024, well above the world average of around four percent (Enerdata, 2025). The International Energy Agency has been unambiguous about what this means: "our energy and climate future increasingly hinges on the decisions made in emerging market and developing economies" (IEA, 2021, p. 13). What makes emerging middle powers analytically interesting is not simply that they occupy a middle rank. It is that they act from a structurally ambivalent position: consequential enough for their energy choices to matter beyond their borders, yet constrained enough to confront the transition on terms they did not set. This paper examines how that position shapes the role of emerging middle powers in the global energy transition: the pressures they face, the choices they make, and the forms of leverage they can exercise in an increasingly multipolar world.

To do so, it develops a framework for middle-power energy policy that treats energy security, geopolitics, and industrial strategy as connected parts of the same problem. It illustrates the value of this framework through an early-stage empirical engagement with Turkey. Turkey serves as the revelatory case through which the framework is developed and initially tested: a site where the theoretical problem is especially clear, and where ongoing empirical research will refine and test the framework's indicators and propositions. The goal is not to present completed findings, but to propose a structured analytical approach that can be applied to other middle powers and, if needed, revised.

The rest of the paper is organized in two steps. Section 2 develops the middle-power concept and introduces the transition trilemma as the paper's central analytical framework. Section 3 applies the framework to Turkey. It first establishes Turkey's regional energy significance, then examines how the three dimensions of the trilemma appear in Turkish energy policy, before outlining the theoretical contribution and comparative agenda that follow from the case.

2. Middle Powers and the Energy Transition

2.1 What Is a Middle Power?

The first step is to define the paper's central concept. Middle powers are neither great powers nor small states. They possess sizeable military and economic capabilities, but not enough to organize the international system around their preferences. They often exercise considerable influence in a specific policy domain, as Norway has done in diplomatic mediation; have strategic significance in a key industry, as the Netherlands does through ASML in semiconductor supply chains; and/or enjoy geostrategic leverage, as Turkey does between the Black Sea, the Eastern Mediterranean, the South Caucasus, and European energy markets. The concept, however, does not sit comfortably in a single definition. There is no agreed list of indicators that fixes middle-power status once and for all, and some contend that the category remains historically and analytically unstable (Robertson & Carr, 2023). Yet, as Shin et al. (2026) argue, this conceptual fluidity is not simply a weakness. It points to a central feature of middle-power agency: the ability to adapt to structural change and seek advantage in moments when norms, institutions, and governance frameworks are being remade. In their formulation, middle powers are best understood not by fixing their definition but by tracking how they respond to a changing world order and attempt to seize a "first-mover advantage in shaping emerging norms, institutions and governance frameworks" (Shin et al., 2026, p. S7).

Scholars have long sought to complement material definitions with accounts of what middle powers actually do. Jordaan (2003) identified multilateralism, coalition-building, and compromise-seeking as characteristic behaviors, captured in the influential notion of "good international citizenship." But critics (Shin et al., 2026) contend that this behavioral model was rooted in a specific Cold War context, namely the affluent Western liberal democracies whose security and prosperity were intimately tied to US hegemony, and its analytical utility for understanding emerging middle powers in the current era is limited. The emerging middle powers that are most consequential for the energy transition, Brazil, Indonesia, and Turkey among them, operate according to a more pragmatic and instrumentalist logic, one oriented less around normative commitments to multilateralism and more around the strategic exploitation of their intermediate position, increasingly expressed as the pursuit of strategic autonomy (Aydın-Düzgit et al., 2026).

This flexibility should not be mistaken for incoherence. It reflects the political position of middle powers: influential enough to shape regional outcomes, but too constrained to dictate the terms of systemic change. As Jordaan notes (2003, p. 172), emerging middle powers tend to be powerful, or even dominant, within their region and are keen participants and often initiators of regional integration and cooperation. It is through their regional role in shaping the energy choices, infrastructure decisions, and decarbonization pathways of their neighbors that middle powers make their most consequential contribution to the global energy transition. Regional influence reflects the capacity to shape outcomes beyond a state's borders through a combination of geographic position, economic weight, control of infrastructure, and diplomatic leverage. This regional role is precisely what makes the energy transition so strategically complex for middle powers, and it is what the transition trilemma, introduced in the next section, is designed to capture.

2.2 Middle Powers' "Transition Trilemma"

The global energy transition confronts middle powers with three simultaneous imperatives that do not sit easily together. The first is decarbonization: reducing greenhouse gas emissions in line with international climate commitments and responding to the growing pressure from trading partners, investors, and multilateral institutions to demonstrate credible transition pathways. The second is energy security: ensuring reliable, affordable access to the energy supplies that underpin economic activity and social stability, in contexts where import dependence, supply disruption, and price volatility remain live political risks. The third is domestic economic development: the attempt to turn the transition from an externally imposed adjustment into an opportunity for industrial upgrading, employment creation, and technological autonomy. Each of these imperatives has its own logic, its own constituencies, and its own timeline. The difficulty is that they frequently pull in different directions.

Surely, this three-way tension is not unique to middle powers. All states navigating the transition face some version of it. What is distinctive about middle powers is the structural position from which they face it. On one side, their energy choices carry consequences that extend beyond their own borders: the pipelines they build, the grids they connect, the technologies they adopt, and the partnerships they enter all shape the energy landscape of their region. On the other side, they remain significantly constrained. Capital, technology, and standards arrive through channels that are never politically neutral, and key technologies, from advanced solar manufacturing to battery storage and nuclear reactors, remain concentrated among a small number of powerful suppliers, with China's position increasingly prominent among them (Sim & Griffiths, 2024). Geopolitical pressures also bear down on middle powers because they lack the leverage to resist or reshape them unilaterally. Turkey illustrates this structural position with unusual clarity: a state whose combination of import dependence, transit leverage, and renewable industrial ambition makes the transition trilemma visible across all three dimensions (Tüyloğlu, 2025).

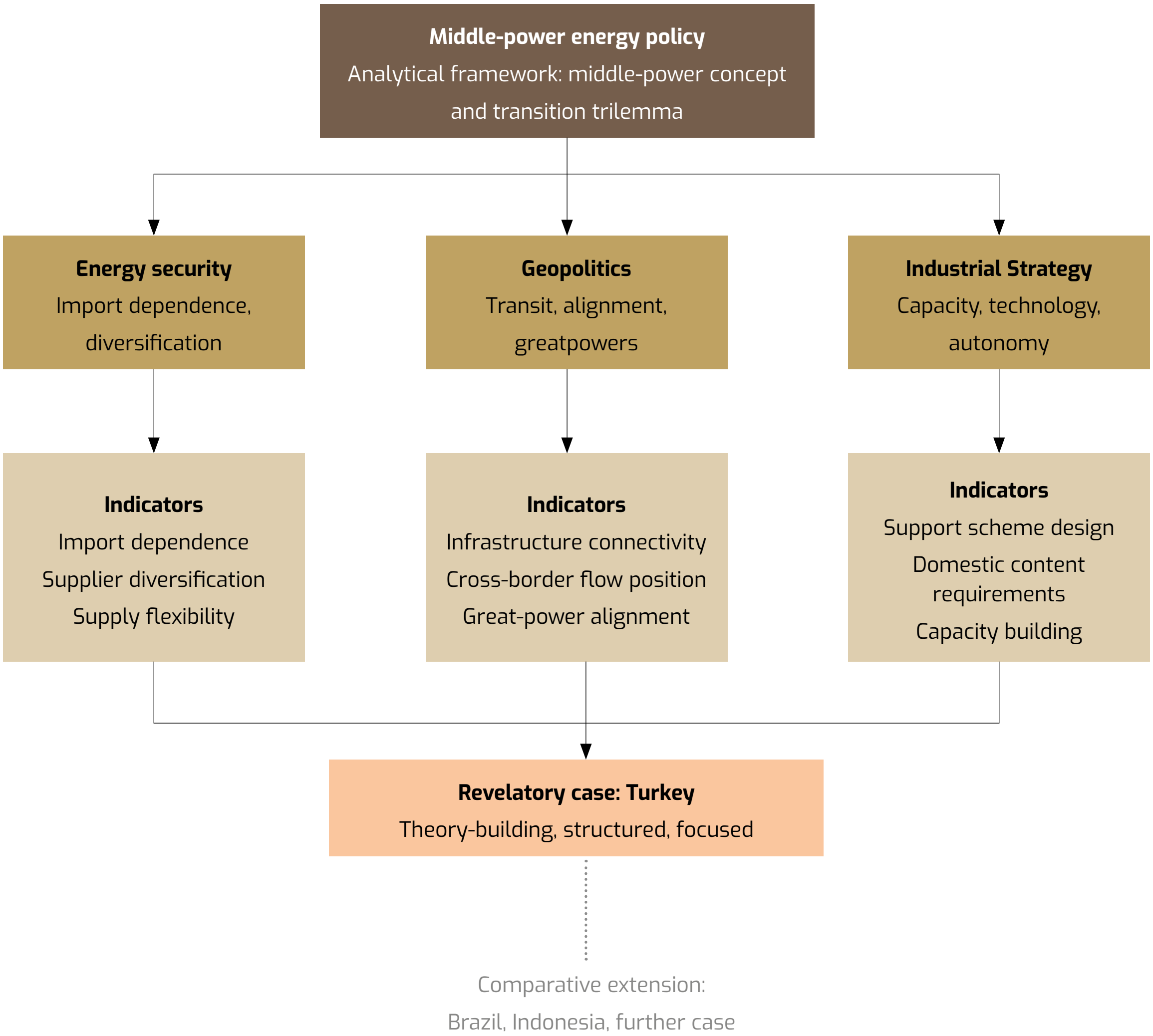
This is what I call the transition trilemma. The term is adapted from the energy policy literature's concept of the energy trilemma (World Energy Council, 2020), but is modified here for the study of middle powers: it names the simultaneous pursuit of decarbonization, energy security, and domestic economic development under conditions of regional consequence and structural constraint. Middle powers operate within dependencies, whether on particular gas suppliers, foreign clean technology manufacturers, or Western capital markets, that cannot be unwound overnight. At the same time, their regional position offers potential leverage: geographic location, transit infrastructure, market size, and diplomatic relationships can all be converted into strategic assets if managed effectively. The transition trilemma, then, is not simply a problem of resource scarcity or technological lag. It is a political and strategic problem of navigating between structural vulnerability and potential ambition. Managing that balance, rather than resolving it, is the defining challenge of middle-power energy policy.

This paper analyzes the transition trilemma through three dimensions that interact in ways that single-dimensional accounts cannot capture (Figure 1). The first is energy security, understood here not merely as reliable supply but as the management of import dependence, the diversification of supply relationships, and the use of energy infrastructure as a source of strategic leverage. The second is geopolitics, encompassing the role of energy in shaping a state's regional relationships, its positioning between rival great powers, and its capacity to act as a transit state, mediator, or connectivity hub. The third is industrial strategy, meaning the use of energy transition policy as an instrument of domestic economic development: building manufacturing capacity, promoting technology transfer, and reducing dependence on foreign suppliers of both fossil fuels and clean energy technologies. In practice, decisions in one dimension regularly constrain or enable choices in the others. A gas transit agreement shapes geopolitical alignment; a domestic content requirement in renewable energy procurement affects access to technology; a nuclear partnership creates new dependencies while resolving old ones. Analyzing these dimensions in isolation would miss precisely the interactions that define middle-power energy politics.

To make the framework usable, each dimension needs to be measured through concrete, observable indicators. For energy security, the indicators are import dependence and diversification, and investments in supply flexibility. For geopolitics, they are infrastructure connectivity and cross-border flow positions. For industrial strategy, they are the design of support schemes and capability-building in renewables. These indicators are not imposed on the case from the outside; they are built up through the analysis, following the logic of theory-building case study research (Eisenhardt, 2002) and the measurement validity standards set out by Adcock and Collier (2001). Together they produce what George and Bennett (2005) call a structured, focused comparison: a consistent set of questions applied across cases without flattening their differences. The framework follows a logic that Katzenstein (1985, p. 21) identifies for structurally defined categories of states: selecting a group "large enough to allow some plausible inferences about the effects of structural constraints and opportunities, yet not so large as to defy intellectual mastery."

The research design treats Turkey as a "revelatory case" (Yin, 2003, p. 42), meaning a site where the transition trilemma is unusually visible and where the theoretical problem can be examined in enough depth to produce a reusable analytical framework. The framework that emerges, including its dimensions, indicators, and the relationships among them, is designed to be applied to other middle powers in subsequent comparative work and refined or challenged as it travels (Eisenhardt, 2002; George & Bennett, 2005). Brazil and Indonesia are identified as theoretically informative candidates for that next step. Whether the indicators need to be adapted, the dimensions redrawn, or the propositions revised in light of those cases remains an open question. The aim is not a fixed comparative design but a structured starting point: a transparent, evidence-based framework that other researchers or I can build on.

Figure 1. A framework for middle-power energy transition research



3. Turkey: Middle Power Energy Transition in Practice

3.1 Turkey's Regional Energy Significance

Turkey's importance for the global energy transition cannot be understood from its domestic energy profile alone. It is a function of where Turkey sits. Positioned at the junction of the Eastern Mediterranean, the Black Sea, the South Caucasus, and European energy markets, Turkey occupies one of the most strategically consequential geographic locations in the Eurasian energy system. This position is not incidental to Turkish energy strategy; it is constitutive of it. The decisions Turkey makes about pipelines, grid connections, gas contracts, and energy partnerships ripple outward into the energy systems of its neighbors and into European supply security. It is this combination of geographic centrality and regional consequence that makes Turkey a particularly revealing case for the study of middle-power energy transition.

Turkey's starting point is one of significant structural vulnerability. In 2022, the country imported 100 percent of the natural gas it consumed, 91 percent of its oil products, and 77 percent of its coal, making it one of the most energy-import-dependent large economies in the world (Siccardi, 2024, p. 4). This dependence is not simply a policy problem to be managed; it is the structural condition that shapes the entire logic of Turkish energy strategy. High import dependence means high exposure to price volatility, supply disruption, and the geopolitical leverage of supplier states. It also generates a persistent current account deficit driven in large part by the energy import bill, which constrains the government's macroeconomic room for maneuver. In 2022 alone, Turkey's energy trade deficit reached a record $81.1 billion, driven by the spike in energy prices following Russia's invasion of Ukraine (Siccardi, 2024, p. 13). For Ankara, energy policy is inseparable from economic security: the drive to diversify supply sources, develop domestic renewables, and reduce gas consumption is as much a macroeconomic imperative as a climate one.

Yet Turkey's structural position is not defined solely by vulnerability. It is equally defined by the leverage that geography confers. Turkey is not merely a consumer of energy flows; it is a router of them. The Trans-Anatolian Pipeline (TANAP) and the Trans-Adriatic Pipeline (TAP), which together form the Southern Gas Corridor, carry Azerbaijani gas across Turkish territory to European markets, currently delivering over 16 billion cubic meters annually (Shaffer, 2024, p. 16). Turkey's state energy company Botaş holds a 30 percent share in TANAP, while Turkish upstream company Turkish Petroleum Corporation (TPAO) holds equity stakes in Azerbaijani gas fields and export infrastructure, giving Ankara both commercial and strategic interests in the corridor's continued operation (Shaffer, 2024, p. 31). These relationships give Turkey structural leverage over the energy security of its neighbors and of Europe more broadly: a domestic regulatory decision, a bilateral pricing dispute, or a geopolitical realignment in Ankara has immediate consequences for gas flows from the Caspian to the Balkans.

Turkey's regional energy significance extends beyond gas transit. The country is connected to the European electricity grid via interconnectors with Bulgaria and Greece and maintains electricity trade relationships with Georgia, Azerbaijan, and Iran to the east (Sakal, 2021; Shaffer, 2024). These links make Turkey a participant in Balkan and Caucasian electricity markets, while its integration with ENTSO-E has facilitated electricity trade with EU neighbors and created a channel for renewable electricity to enter wider regional markets. As Turkey's installed renewable capacity has grown substantially, placing it among the top fifteen countries globally, the question of how that capacity integrates with regional electricity markets has become increasingly consequential.

Taken together, Turkey's import dependence, transit role, and grid connections give its energy choices inherently regional effects. When Turkey negotiates a gas transit agreement, signs a pipeline protocol, or expands its electricity interconnection capacity, the consequences extend well beyond its own borders. A decision to route more Azerbaijani gas through Turkish territory affects the supply options available to Balkan states. Turkey does not have the global reach of a great power, but its position across the Southern Gas Corridor, TurkStream, TANAP, and regional electricity links gives it a form of structural influence within its region (Shaffer, 2024; Shokri, 2026). This is precisely what the transition trilemma looks like in a specific geographic context. Turkey must pursue decarbonization under conditions of extreme import dependence; it must manage energy security while its transit infrastructure makes it simultaneously a resource for neighbors and a target of great-power competition; and it must develop domestic industrial capacity in new energy technologies while remaining dependent on foreign capital, technology, and fuel. The next subsection examines how these three dimensions have played out in Turkish energy policy in practice.

3.2 Turkish Energy Policies Across Three Dimensions

At first glance, Turkey's energy policy appears to be a catalog of contradictions. The same government that has committed to ambitious renewable energy targets continues to expand gas import infrastructure. The same state that positions itself as a bridge between Russia and Europe hosts a Russian-financed nuclear power plant while deepening trade and investment ties with Western partners. The same industrial policy that promotes domestic solar manufacturing still operates within an energy system dependent on foreign fuel suppliers. These contradictions look less like policy incoherence when viewed through the lens of the transition trilemma. What appears incoherent from the outside reflects a strategic logic: using available levers to manage the three imperatives, even when this entails accepting new dependencies. This subsection examines how that logic plays out across the three dimensions of energy security, industrial strategy, and geopolitics.

3.2.1 Energy Security: Gas Diversification and the Hub Ambition

Turkey's approach to energy security is built on the logic of multi-vector sourcing. Rather than consolidating supply relationships with a single partner, Ankara has deliberately cultivated a diversified portfolio of gas suppliers and import routes. Russia remains the largest single source, delivering gas through both the Blue Stream pipeline and TurkStream. TurkStream came into operation in 2020 and has a total annual capacity of 31.5 bcm, divided between two lines of 15.75 bcm each: one supplying Turkey and the other carrying gas onward to South and Southeast Europe (Novikau & Muhasilović, 2023). Azerbaijan supplies gas through the Trans-Anatolian Natural Gas Pipeline (TANAP), with volumes contracted to rise as the second phase of the Southern Gas Corridor expansion proceeds. Iran provides a third pipeline route through the Tabriz-Ankara pipeline, commissioned in 2001, though volumes have been irregular due to technical disruptions, weather-related interruptions, and political tensions (Gümrükçü, 2026). Alongside these pipeline sources, Turkey has invested heavily in liquefied natural gas import capacity, operating multiple floating storage and regasification units that allow it to access spot LNG markets and reduce its exposure to any single pipeline supplier. Since 2022, the United States has emerged as Turkey's leading LNG supplier, and the expansion of American LNG purchases has materially strengthened Ankara's bargaining position in contract negotiations with its pipeline suppliers (Yılmaz, 2023, pp. 718–719).

The most structurally significant development in Turkey's energy security posture, however, is the discovery and development of domestic natural gas reserves in the Black Sea. The Sakarya field, discovered in August 2020, entered production in September 2023 and yielded 2.26 bcm in its first full year of operation. Production has since accelerated: Phase 1 was completed in April 2025 at a nameplate capacity of 9.5 million cubic meters per day, and Phase 3 is projected to raise output to 14.6 bcm annually by 2028, at which point domestic production could supply approximately 25 percent of Turkey's total gas consumption (Sharples & Bowden, 2025, p. 8). While diversification mitigates vulnerability by distributing it across multiple external suppliers, domestic production offers the prospect of reducing it at the source, which is a qualitatively different form of energy security. The combination has already altered the structural terms of Turkey's gas import relationships: as major pipeline contracts with Gazprom and the National Iranian Gas Company approach expiry, Ankara negotiates from a considerably stronger position than at any previous point in its recent energy history (Sharples & Bowden, 2025, p. 16).

The tension embedded in this strategy, however, runs counter to decarbonization. Maintaining and expanding gas import infrastructure (e.g., storage facilities, regasification terminals, pipeline capacity) locks in assets that will need to be decommissioned or repurposed as the energy transition proceeds, creating stranded asset risk and institutional path dependence. This tension is taken up in the geopolitics section below, where the hub ambition and its strategic logic are examined alongside the Akkuyu nuclear commitment as expressions of Turkey's broader pattern of managing one form of dependence by accepting another.

3.2.2 Industrial Strategy: Renewable Expansion with Domestic Content

Turkey's renewable energy policy tells a different story about middle-power agency, one oriented not around transit leverage but around industrial ambition. The policy architecture has evolved significantly over the past decade. Under the earlier Renewable Energy Sources Support Mechanism (YEKDEM), Turkey relied on feed-in tariffs, later combined with bonuses for domestically produced components. The later Renewable Energy Resource Areas (YEKA) model introduced competitive auctions for large-scale renewable projects and made domestic manufacturing, technology transfer, and local-content requirements more central to project design. Under YEKA, developers bidding for large-scale solar and wind contracts have been required to meet specified domestic-content conditions, creating protected demand for a domestic clean-energy supply chain (Özcan, 2021).

The results have been mixed but significant. In solar, the YEKA model supported domestic panel manufacturing alongside large-scale generation. The first YEKA solar tender included factory and R&D center obligations and a 70 percent minimum local-content requirement, while YEKA-1 Wind included the same obligations and a 65 percent minimum local-content requirement (Özcan, 2021). The first solar tender, held in 2017 for the Karapınar site, led to the establishment of a panel factory that began operations in 2020 and to a solar plant that was completed by the end of 2023 (Gümüş, 2025). Yet the model has also faced limits: less than a quarter of tendered wind and solar capacity is currently operational, and the first YEKA wind project was canceled in May 2024 (Gümüş, 2025). These outcomes show both sides of Turkey's industrial strategy: the effort to use renewable deployment to build domestic manufacturing capacity, and the continuing dependence on foreign capital, technology, and consortium partners in a market shaped by EU-China competition (Ergenç et al., 2023).

The logic driving this expansion is not purely about decarbonization. Ankara has used renewable energy policy as a vehicle for broader industrial goals: reducing foreign-currency outflows on clean-energy equipment, generating employment in high-value manufacturing, and building competitive positions in sectors that will remain strategically important for decades. Renewables, on this reading, are an instrument of industrial development and technological sovereignty as much as a response to climate pressure (Tüyloğlu, 2025). This industrial logic, however, sits uneasily with Turkey's broader decarbonization trajectory: Turkey ratified the Paris Agreement only in 2021 and plans to increase greenhouse gas emissions until 2038, despite its net-zero target of 2053 (Siccardi, 2024). The renewable expansion is real; the emissions trajectory it implies remains considerably less certain.

3.2.3 Geopolitics: Nuclear Power and Managed Dependency

Turkey's geopolitical energy strategy operates on two distinct yet related tracks: the exploitation of transit leverage via gas infrastructure and the management of strategic dependencies through selective alignment with rival great powers. Both tracks reflect the same underlying logic, namely the conversion of Turkey's intermediate position into usable leverage, and both generate the same characteristic tension between short-term strategic gain and long-term structural constraint.

The first track is the hub ambition. By positioning itself as the point where multiple gas streams from different origins converge, Turkey has sought to become not merely a transit state but also a pricing node and distribution center for gas reaching European markets. The ambition is to replicate, in a gas context, something of the role that trading hubs like the Dutch TTF play in European gas markets: a location where supply from multiple sources meets demand from multiple buyers, generating pricing power and market influence for the state that hosts the infrastructure. President Erdoğan articulated this ambition at the opening of the expanded Silivri gas storage facility in December 2022: "Our goal is to transform our country into a global hub where natural gas reference prices are set as soon as possible" (AK Parti, 2022). Major infrastructure investment decisions, including the development of storage capacity at Tuz Gölü and the expansion of Botaş's trading operations, have followed from this strategic vision (Novikau & Muhasilović, 2023). Whether the ambition is fully achievable under current geopolitical conditions remains contested, not least because neither the TANAP nor the TurkStream agreements included re-export rights, which a functioning hub requires (İpek, 2026, p. 259).

Russia's invasion of Ukraine in February 2022 subjected this strategy to a severe stress test. European states moved rapidly to reduce their dependence on Russian gas, with European LNG imports rising by more than 60 percent in 2022 as Russian pipeline flows fell sharply (IEA, 2023, p. 8). This created both risks and opportunities for Turkey. The risk was the potential disruption of TurkStream flows and the broader destabilization of the supply relationships on which the hub ambition depended. The opportunity lay in Turkey's positioning as one of the few states maintaining working relationships with both Russia and Western energy markets. Ankara secured deferred payment terms for part of its Russian gas imports following the 2022 price spike, while maintaining its energy cooperation with Moscow (Devranoglu & Coskun, 2023). Turkey's refusal to join Western sanctions on Russia allowed it to maintain TurkStream flows throughout the conflict and to advance the idea of a Turkish gas hub, although the proposal remained politically controversial in Europe because it risked keeping Russian gas connected to European markets through a third country.

The second track is nuclear energy. The Akkuyu plant under construction on Turkey's Mediterranean coast is being developed under a build–own–operate model fixed in the 2010 intergovernmental agreement between Turkey and Russia. Under that agreement, the project company owns the plant and the electricity it generates, Russian authorized organizations must retain at least 51 percent ownership, Turkey guarantees electricity purchases for fifteen years, and nuclear fuel is to be supplied through long-term agreements, with spent Russian-origin fuel potentially reprocessed in Russia (The Republic of Turkey & The Russian Federation, 2010, p. Arts. 5, 6, 10, 12). This makes Akkuyu a long-term dependency relationship as well as an energy-security project: Turkey gains baseload generation and nuclear capacity, but through a model that concentrates ownership, revenue guarantees, fuel supply, and lifecycle management in a Russian state enterprise (Duru, 2025). The strategic rationale is straightforward: Turkey has no domestic uranium resources, a rapidly growing electricity demand, and an acute need for reliable baseload generation that intermittent renewables cannot yet supply at scale. Akkuyu addresses these concerns while positioning Turkey as the first nuclear-power producer in its immediate region.

The paradox is unmistakable: Akkuyu resolves one form of external dependence by creating another. As Tüyloğlu (forthcoming) shows through process tracing of the 2008–2010 decision sequence, the BOO model was assembled through specific mechanisms, including Rosatom's ownership and operational control, purchase guarantees underwriting Rosatom's revenue stream, and a reactor-specific fuel cycle that makes supplier substitution prohibitively costly, that together codified a durable structural asymmetry in a treaty-level commitment substantially harder to exit than any gas contract. That Turkey continued Akkuyu's construction throughout the Ukraine war, despite the diplomatic and reputational costs of deepening financial ties with Rosatom under Western sanctions pressure, illustrates what this paper calls geopolitical compartmentalization: the capacity of middle powers to separate specific strategic relationships from broader geopolitical alignments, accepting the costs of inconsistency in order to preserve the benefits of flexibility.

What connects the hub ambition and the Akkuyu commitment is the same underlying strategic logic: both involve accepting or deepening a specific dependency to extract a strategic benefit otherwise unavailable. Both choices are geopolitical in the precise sense, not primarily about energy economics but about converting energy infrastructure into positional advantage in a competitive regional order.

3.2.4 Synthesis

Taken together, these three policy domains show that Turkey's energy policy is not simply confused or contradictory. It is an uncomfortable middle-power response to the transition trilemma. Turkey is using several levers at once: transit infrastructure to turn geography into bargaining leverage; domestic content rules to turn renewable deployment into industrial capacity; and nuclear power to meet baseload needs through a long-term supply relationship that reduces, even as it restructures, energy import dependence. Each choice accepts a new constraint to manage an existing one. None resolves the trilemma; each manages one dimension while creating tensions in the others. The sharpest tension runs between energy security and geopolitics on one side and decarbonization on the other. The hub ambition requires Turkey to maintain and expand gas infrastructure, just as the energy transition calls for reducing gas dependence. New transit capacity creates stranded asset risk and institutional path dependence. Akkuyu compounds this dynamic: a sixty-year nuclear commitment financed and controlled by a foreign state enterprise is not easily unwound. Turkey's energy security strategy, in other words, complicates its decarbonization commitments. If pursued on their current terms, the hub ambition and Akkuyu commitment would deepen this unresolved tension. Rather than showing a simple failure of strategy, this points to the defining condition of middle-power energy politics.

Turkey is not a unique case. It is a clear instance of a structural condition that other emerging middle powers face in their own regional contexts. Brazil combines an extraordinary renewable energy endowment with continued offshore oil expansion and an industrial strategy focused on green hydrogen and critical minerals exports. Indonesia sits atop major critical mineral reserves while managing a coal-dependent electricity system, high financing costs for renewables, and an industrial strategy aimed at turning mineral wealth into domestic battery manufacturing. The policy choices and regional geographies differ, but the underlying structure is the same: regional consequences combined with structural constraints, producing pressure across all three dimensions of the trilemma.

The framework developed here is designed to make that structure visible and comparable. By specifying three dimensions with concrete indicators, it produces a profile of middle-power energy policy that can be applied across cases. The goal is not to show that all middle powers are the same, but to identify where they converge, where they diverge, and what accounts for the variation. That comparative agenda is what this paper proposes.

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Mapping Regional Green Hydrogen Market Systems: Evidence from the Green Hydra Project

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Green hydrogen is increasingly positioned as an important element of Europe's energy transition, particularly for decarbonising sectors that are difficult to electrify directly and for integrating growing shares of renewable electricity. Yet regional hydrogen ecosystems often remain fragmented and immature. This paper uses evidence from Green Hydra regional market system mapping exercises to analyse green hydrogen market development across partner regions, with particular attention to recurring barriers, enabling conditions, and patterns of market-system fragmentation. Based on stakeholder input generated through the Green Hydra market system mapping exercise and subsequent comparative analysis, the paper distinguishes barriers in the hydrogen value chain, the enabling business environment, and supporting services. The findings show that renewable potential and early pilot activity are widespread, but integrated value chains, demand formation, infrastructure, regulatory clarity, and supporting services remain underdeveloped. The paper argues that regional green hydrogen development should be understood as a market-system formation challenge, in which technology, infrastructure, demand, regulation, finance, and supporting services must develop together.

Keywords: Green hydrogen, Market system mapping, Regional innovation ecosystems, Energy transition, Hydrogen barriers, Participatory methods

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1. Introduction

Green hydrogen is increasingly framed as part of the European transition to climate neutrality. It can support decarbonization in sectors that are difficult to electrify directly and may provide flexibility in energy systems with growing shares of variable renewable electricity (European Commission, 2020; International Energy Agency (IEA), 2024). However, translating this strategic promise into functioning regional markets is not a straightforward matter of technology adoption. Green hydrogen deployment requires coordinated development across renewable electricity generation, electrolysis, storage, transport, industrial demand, regulation, finance, skills, safety standards, and supporting services (IEA, 2024; Van de Graaf et al., 2020). In this sense, green hydrogen is not only an energy carrier but also an emerging market system whose components must develop together.

This systemic character is particularly visible at regional level. Some regions possess strong renewable resources but lack hydrogen infrastructure or stable offtake. Others have industrial capabilities, research organisations, or pilot projects but do not yet have clear regulatory pathways, market information, finance mechanisms, or coordinated value chains. As a result, green hydrogen development often remains at an early stage, characterised by isolated initiatives rather than mature market structures. Recent hydrogen-market assessments similarly show that low-emissions hydrogen deployment remains constrained by uncertain demand, high costs, regulatory uncertainty, limited infrastructure, and insufficient investment certainty (IEA, 2024). The central challenge is therefore not only whether hydrogen can be produced, but whether regional market systems are sufficiently enabling for production, distribution, storage, and use to scale beyond demonstration projects. This also positions Green Hydra within debates on hydrogen futures, contrasting supply-led visions of large-scale production and transport with regionally embedded market formation, demand development, and system integration (Dignum, 2013; Baarslag et al., 2026).

This paper addresses that challenge through market system mapping within the Green Hydra project[1]. The project examines green hydrogen ecosystems across several European regions and uses participatory methods to identify barriers and opportunities for market development in several regions across Europe (Interreg Europe, n.d.). Green Hydra provides a particularly relevant empirical setting because it is concerned not only with hydrogen production, but also with the regional ecosystem conditions that enable green hydrogen markets to develop. The project focuses on improving policies for engaging small and medium-sized enterprises in local, regional, and national green hydrogen ecosystems, thereby drawing

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[1] Green Hydra – Improving policies for engaging SMEs in the green hydrogen ecosystem is a project co-funded by the European Commission under the programme Interreg Europe: https://www.interregeurope.eu/green-hydra

attention to the wider set of actors, services, infrastructures, and policy conditions required for market formation. In this paper, the regional mapping exercises are therefore interpreted not simply as workshop outputs, but as structured evidence on the maturity, fragmentation, and enabling conditions of regional hydrogen market systems. Market system mapping is particularly suitable for this purpose because it does not treat barriers as isolated technical obstacles. Instead, it distinguishes between the core value chain, the enabling business environment, and supporting services (Albu & Griffith, 2005, 2006; United Nations Development Programme [UNDP], 2010). This allows stakeholders and policymakers to analyse how the system is functioning, where links are missing, and which enabling conditions are needed to accelerate deployment.

The paper asks: How can evidence from Green Hydra mapping exercises be used to analyse regional green hydrogen market development, and what shared barriers and opportunities does this reveal for policy and investment action? The contribution is twofold. Empirically, the paper synthesises evidence from Green Hydra regional mapping exercises to identify recurring structural barriers and enabling conditions in regional hydrogen market-system development. Methodologically, it shows how market system mapping can convert dispersed stakeholder knowledge into a structured diagnosis of market formation by connecting value-chain actors, policy and regulatory conditions, and supporting services in one analytical framework (Albu & Griffith, 2005, 2006; UNDP, 2010). The paper therefore uses the Green Hydra evidence base to demonstrate how regional hydrogen ecosystems can be analysed as developing market systems rather than as isolated collections of projects, technologies, or policy ambitions.

The remainder of the paper is structured as follows. Section 2 introduces the conceptual background, focusing on green hydrogen as a socio-technical and market-system challenge and on the role of participatory market system mapping. Section 3 presents the Green Hydra market system mapping approach and explains how the regional mapping evidence was interpreted. Section 4 reports the cross-regional results, organized around shared barriers and shared opportunities. Section 5 discusses the implications of the findings, with particular attention to curtailment, system integration, and the conditions under which hydrogen can function as a flexibility solution. Section 6 concludes.

2. Conceptual Background

Green hydrogen development for the energy transition can be understood as part of a wider socio-technical transition rather than as the diffusion of a single technology. Socio-technical transition theory emphasises that major system changes involve the co-evolution of technologies, infrastructures, institutions, markets, user practices, and policy frameworks (Geels, 2002; Markard et al., 2012). This perspective is useful for green hydrogen because deployment requires more than electrolysers and renewable electricity. It also depends on demand formation, transport and storage infrastructure, certification systems, safety regulation, financing mechanisms, skills, public acceptance, and coordination between different levels of governance. Hydrogen ecosystems are therefore still being assembled, and their barriers are distributed across technological, institutional, economic, and social domains.

The transition perspective also highlights the importance of enabling environments. Early-stage sustainability technologies often depend on experimentation, policy support, and the gradual formation of markets and user practices. In many regions, green hydrogen is at such an early stage: pilot projects, regional strategies, and industrial use cases exist, but they often lack the coordinated market conditions required for scale-up. Policy ambition alone is insufficient when permitting procedures remain unclear, infrastructure investment is uncertain, demand is not yet anchored, and specialized supporting services are weak.

This makes regional green hydrogen development a market-formation problem as much as a technological one. The central issue is not only whether hydrogen can be produced, but whether the surrounding ecosystem enables production, distribution, storage, financing, regulation, and use to develop together. This requires an analytical perspective that can capture the interaction between actors, institutions, infrastructure, and services rather than treating barriers as isolated technical constraints.

A participatory research design is particularly relevant in this context. Regional hydrogen ecosystems involve public authorities, firms, infrastructure operators, financiers, research institutions, technology providers, and potential users. No single actor has complete visibility over the whole system. Participatory approaches are therefore useful because they bring together distributed knowledge about assets, missing links, bottlenecks, and opportunities, a point also emphasised in wider literature on stakeholder participation, participatory systems mapping, and energy-system planning (Reed, 2008; Lang et al., 2012; Barbrook-Johnson & Penn, 2021; McGookin et al., 2021). They also support shared learning among stakeholders, which is important in emerging markets where roles, expectations, and investment pathways are still being formed.

The conceptual background of this paper therefore combines two ideas. First, green hydrogen deployment should be understood as part of a broader socio-technical transition in which technology, infrastructure, regulation, markets, and user practices co-evolve. Second, because these elements are distributed across multiple actors and governance levels, participatory system-oriented analysis is needed to diagnose where regional ecosystems are functioning and where they remain incomplete. Market system mapping is used in this paper to operationalise this perspective by translating stakeholder knowledge about regional hydrogen ecosystems into evidence on value-chain development, enabling conditions, supporting services, and system-level gaps.

3. Green Hydra Market System Mapping Approach

The study uses a qualitative, comparative, and participatory research design. The empirical material consists of regional market system mappings developed within the Green Hydra project and analysed as evidence of regional green hydrogen market-system development. During the project workshop at Donegal (Ireland, July 2025), project partners and regional stakeholders developed and discussed regional market system maps that provided the basis for identifying barriers and enabling conditions across the hydrogen value chain, the policy and business environment, and supporting services. The purpose of the analysis is therefore to develop market literacy on green hydrogen markets in different European regions and identify ways to improve market systems for scaled up adoption of green hydrogen use. The mapping evidence can subsequently be used as a structured basis for cross-regional comparison.

The Donegal workshop formed part of a broader Green Hydra policy-learning sequence aimed at moving from regional baseline assessment toward policy implementation measures. Prior project activities had already established an initial overview of regional hydrogen conditions, including policy settings, business environments, hydrogen-related assets, and early barriers and opportunities. The market system mapping exercise built on this baseline by examining how these elements relate to one another within regional hydrogen market systems. In this sense, the mapping exercise did not start from a blank slate but translated earlier project knowledge into a more structured analysis of market-chain development, enabling conditions, supporting services, and system-level gaps.

Subsequent Green Hydra activities are intended to move from diagnosis of barriers toward prioritisation, policy learning, and the development of implementation-oriented actions to clear barriers. These later stages fall outside the empirical scope of this paper. The present analysis focuses on the market mapping stage because it provides the diagnostic foundation on which later prioritisation and policy design can build.

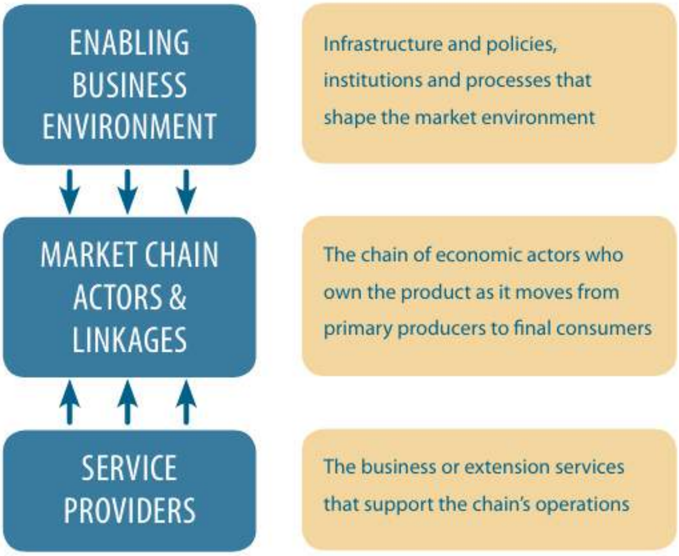
In this sense, the Donegal workshop functioned as a bridge between the initial State-of-Play assessment and subsequent work on targeted actions to overcome barriers in regional green hydrogen ecosystems.

3.1. Market System Mapping Framework

Market system mapping was selected because it provides a structured way to analyse how emerging markets function in practice. The approach was developed by Albu and Griffith (2005, 2006) to examine why promising innovations do not always scale and was based on the observation that their deployment and diffusion is often impeded by surrounding market systems not being sufficiently enabling. Rather than focusing only on producers and consumers, the method examines the wider system of actors, institutions, rules, services, and relationships that shape whether an innovation can move from pilot activity to broader deployment.

The original market system mapping logic distinguishes between three interrelated parts of a market system: the market chain, the enabling environment, and supporting services. Figure 1 illustrates this general market system mapping framework, adapted from UNDP (2010) after Albu and Griffith (2005). In the Green Hydra project, this framework was translated into a green hydrogen context, as shown in Figure 2. The workshop templates used to structure stakeholder input around these three components are provided in Appendix A.

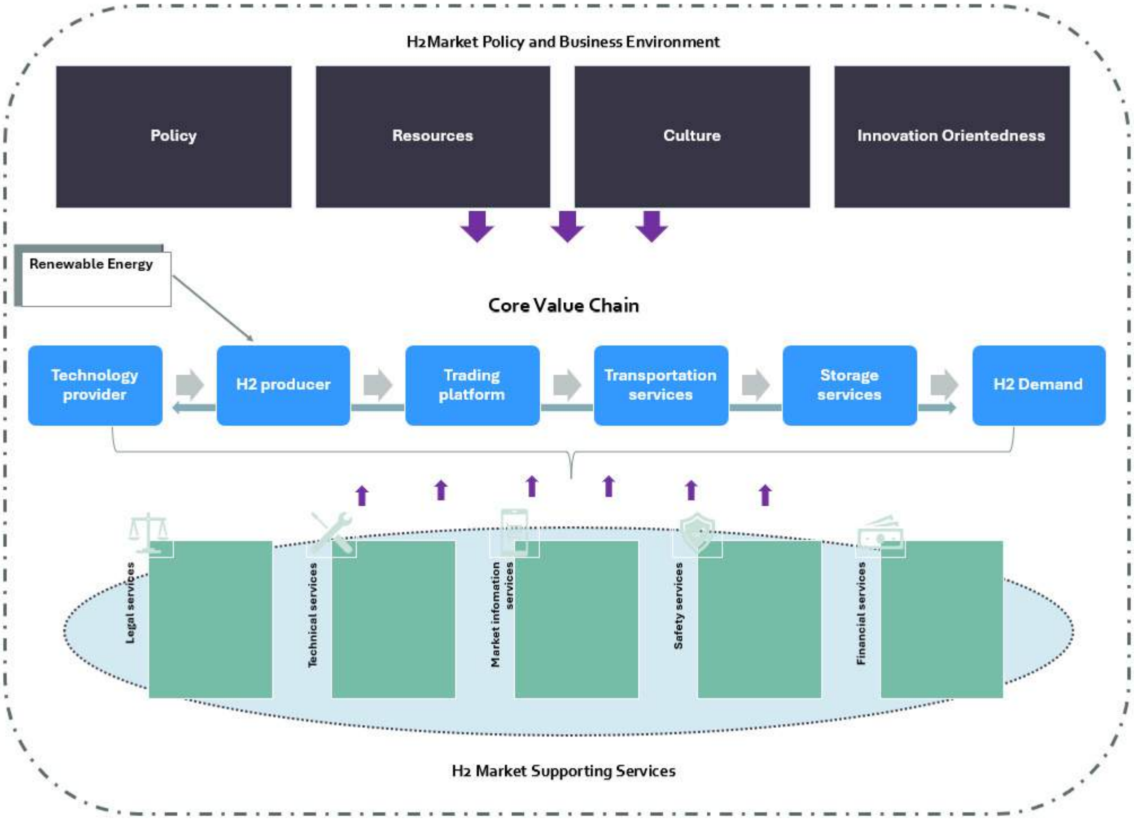
Figure 1. Market System Mapping (UNDP, 2010, after Albu & Griffith, 2005)



In the context of this paper, these three components are used not only to structure the workshop discussion, but also to interpret the degree to which regional hydrogen ecosystems show signs of market-system development. Each component therefore functions as an analytical lens: the value chain indicates the presence and connectivity of core market actors; the enabling environment indicates the institutional and infrastructural conditions for market formation; and supporting services indicate whether practical capacities exist to move from strategic ambition to project implementation.

The first component is the hydrogen market value chain. This represents the core chain of actors involved in producing, distributing, storing, and using green hydrogen. In the workshop, stakeholders were asked to identify actual or potential actors involved in renewable electricity supply, electrolysis,

Figure 2. Market system mapping in Green H_2 context (source: Hanze/Entrance)



hydrogen production, transport, storage, distribution, infrastructure development, finance, and end use. Depending on the region, this could include renewable electricity producers, electrolyser operators, project developers, infrastructure providers, storage and transport operators, utilities, industrial users, mobility users, technology providers, and financiers. Mapping these actors helped clarify which parts of the value chain were already present and which remained missing or weakly connected.

The second component is the policy and business environment. This captures the wider regulatory, institutional, infrastructural, and cultural conditions that shape hydrogen market development. In the Green Hydra workshop at Donegal, this included policy frameworks, permitting procedures, renewable energy resources, grid and transport infrastructure, public support mechanisms, sustainability values, innovation orientation, and broader business conditions. This part of the mapping was important because several barriers to hydrogen development do not occur inside the value chain itself, but in the surrounding environment that determines whether projects can be approved, financed, connected, and scaled.

The third component is the system of supporting services. These are the services that enable the hydrogen market chain to function effectively. In the Donegal workshop, supporting services were grouped into legal services, technical services, safety services, finance, and market information services. This category included, for example, advisory services, technical expertise, safety guidance, certification, standards, skills development, legal support, financial mechanisms, and market intelligence. Mapping supporting services helped identify whether regions had the practical capacities needed to move from general hydrogen ambition to project development and implementation. Together, these three components provided a common analytical structure for comparing regional hydrogen ecosystems. They were used both to guide stakeholder input during the workshop and to organise the subsequent cross-regional analysis.

3.2. Analytical Approach and Interpretation Method

As a participatory method, market system mapping reflects the knowledge, perspectives, and priorities of the stakeholders involved. The maps should therefore be understood as structured, context-specific representations of regional hydrogen ecosystems rather than as complete inventories of all relevant actors, institutions, and services.

The workshop applied a stakeholder-based mapping procedure. In general, market system mapping can be applied in several ways: researchers may first construct an initial map and ask stakeholders to validate or amend it; a core stakeholder group may build a preliminary map for later validation by a wider group; or stakeholders may construct the map from the beginning during a facilitated workshop. In the Donegal workshop, the third approach was used. Stakeholders worked from a template developed by Hanze/Entrance and collectively identified relevant elements of the hydrogen value chain, policy and business environment, and supporting services. This approach was appropriate because the workshop included a sufficiently diverse group of regional stakeholders to support meaningful data collection while remaining small enough for focused discussion. Cross-regional interaction also supported reflexive comparison between ecosystems, although facilitation was needed because solutions from one region are not automatically transferable to another.

Given the varying levels of detail and completeness across regions, the analysis adopts a qualitative and interpretive approach. Rather than relying on exhaustive measurement or statistical comparison, the assessment focuses on patterns of presence, absence, and connectivity within each mapped system as indicators of regional hydrogen market-system development. Elements that are clearly identified in the mapping, such as renewable resources, specific actors, infrastructure assets, or supporting services, are interpreted as indicators of existing capabilities or enabling conditions. Conversely, elements that are missing, unclear, or marked as unknown are interpreted as potential gaps, barriers, or areas requiring further development.

The interpretation also considers the degree of integration across the hydrogen ecosystem. Particular attention is paid to linkages between renewable electricity supply, hydrogen production, storage, transport, demand, regulation, finance, and supporting services. Systems in which several components are present but weakly connected are interpreted as fragmented. Systems in which actors, infrastructure, services, and enabling conditions appear more clearly connected are interpreted as showing a higher degree of market-system maturity. This does not imply a precise maturity score, but provides a comparative way to distinguish between emerging, fragmented, and more consolidating regional hydrogen ecosystems.

The maturity characterisation is therefore used as a comparative interpretation rather than as a formal scoring exercise. It allows the paper to identify where regions share similar barriers despite different resource bases, and where region-specific opportunities or constraints require more tailored policy and investment responses.

The cross-regional analysis proceeded in three steps. First, the regional market system mappings were reviewed to identify barriers and opportunities within each of the three system components: the hydrogen value chain, the policy and business environment, and supporting services. Second, recurring barriers and opportunities were grouped into shared categories across regions. Third, these categories were interpreted in relation to the overall functioning of the regional hydrogen market system, with attention to missing actors, weak institutional conditions, underdeveloped services, and insufficient connectivity between system components.

It should be noted that the absence of certain elements in the mappings does not necessarily imply their non-existence. An element may be missing because it was not visible to workshop participants, because the relevant market function is still emerging, or because the workshop discussion did not capture it in detail. For this reason, the findings should be interpreted as indicative rather than definitive. The value of the method lies in providing a structured diagnostic basis for identifying where further investigation, stakeholder engagement, and policy action may be needed.

4. Results: Evidence from Regional Hydrogen Market Mapping

The results are presented not as a catalogue of workshop outputs, but as evidence of how regional hydrogen market systems are developing across the Green Hydra regions. Based on the regional market system mappings, the emphasis is on recurring patterns of market-system fragmentation, missing enabling conditions, and emerging opportunities for coordinated intervention. Each regional mapping was analysed individually using the same three-part structure: the hydrogen value chain, the policy and business environment, and supporting services. The detailed summaries of the individual regional mappings are provided in Appendix B. The results below therefore focus on shared patterns across the regional cases rather than presenting each region separately.

The nine regional cases differ in renewable-resource profiles, hydrogen-market maturity, policy context, infrastructure development, and availability of supporting services. Some regions are primarily resource-driven, with strong renewable energy potential but limited hydrogen-specific infrastructure or demand. Others show early pilot activity, research capacity, industrial capabilities, or potential mobility and maritime applications, but still lack coordinated value chains, clear regulatory pathways, or mature supporting services. This variation makes the cases useful for comparative analysis: although the regions differ in their starting conditions, several recurring barriers and opportunities emerge across the market mappings.

Across the regional mappings, green hydrogen ecosystems are generally early-stage or emerging. Hydrogen activity is often characterised by isolated projects, resource potential, or strategic interest rather than by mature and coordinated market structures. The following subsections therefore synthesize the shared barriers and opportunities that emerge from the cross-regional market system mapping analysis.

4.1 Shared Barriers to Regional Hydrogen Market-System Development

4.1.1. Fragmented and incomplete value chains

A central barrier across most regions is the absence of a fully developed and integrated hydrogen value chain. Some regions show early production activities, pilot projects, renewable resources, or potential demand, but critical components such as transport infrastructure, storage systems, trading mechanisms, and stable offtake arrangements are often missing. This fragmentation limits the ability to scale hydrogen from isolated pilots to coordinated market structures. The problem is not simply that individual components are absent, but that existing components are often weakly connected. Without clearer links between producers, infrastructure providers, users, financiers, and public authorities, project development remains uncertain and region-wide deployment is difficult.

4.1.2. Limited regulatory clarity and policy implementation

A second shared barrier is the gap between hydrogen strategies and operational policy frameworks. Several regions have national or regional ambitions related to hydrogen, but these are often not yet supported by clear rules for production, transport, storage, safety, certification, and permitting. This creates uncertainty for project developers and investors. In emerging markets, regulatory clarity is not only a compliance issue; it is also a market-formation condition. When the rules for infrastructure development, safety approval, certification, and public support are unclear, actors may delay investment even when technical potential exists.

4.1.3. Underdeveloped supporting services

The mappings also show that supporting services remain underdeveloped. Finance mechanisms, technical advisory services, safety expertise, legal guidance, certification support, skills development, and market information systems are often weak, fragmented, or not visible. These services are essential for turning renewable-resource potential into investable projects. Even where individual research institutions or technical actors are present, they are not always embedded in a coordinated support ecosystem. This reduces the capacity of regions to develop bankable hydrogen projects, navigate regulatory processes, and build confidence among investors and users.

4.1.4. Infrastructure and system integration constraints

Many regions face infrastructure limitations, including insufficient storage capacity, weak transport and distribution networks, grid constraints, and limited integration between renewable electricity generation and potential hydrogen production. These constraints are especially important because green hydrogen depends on the availability of renewable electricity and on the ability to use that electricity productively. Where grid congestion or curtailment occurs, hydrogen may appear to be a promising flexibility solution. Yet the mappings show that hydrogen can only play that role if electrolysers, storage, transport infrastructure, and demand are also coordinated. Without these elements, curtailment remains a symptom of wider system-integration failures rather than an opportunity automatically converted into hydrogen production.

4.1.5. Uncertain demand and early-stage market formation

A further shared barrier is the absence of clearly defined and stable demand. In many regions, demand is limited to pilot applications or potential future use cases in industry, mobility, maritime transport, or energy storage. This weak demand makes it difficult to establish viable business cases for production and infrastructure. The result is a chicken-and-egg problem: producers hesitate without credible offtake, while users hesitate without reliable supply and infrastructure. Market formation therefore requires more than technology demonstration. It requires demand anchors, long-term offtake arrangements, public procurement, or other mechanisms that reduce uncertainty for both producers and users.

4.2 Shared Opportunities for Regional Hydrogen Market-System Development

4.2.1. Strong renewable energy potential

Across the participating regions, renewable energy resources such as wind, solar, and hydropower provide an important foundation for green hydrogen production. However, the role of renewable electricity differs by region. In some cases, such as regions with strong wind resources, hydrogen may provide a way to valorise surplus electricity and reduce curtailment. In other cases, such as regions with dispatchable hydropower, hydrogen may be less important as a grid-balancing option but still relevant for industrial, maritime, or mobility applications. Renewable-resource potential is therefore a shared opportunity, but its strategic meaning depends on the regional energy system.

4.2.2. Emerging pilot projects and early implementation activities

Several regions demonstrate early-stage hydrogen production initiatives, pilot projects, testing activities, or planned investments. These initiatives are important because they create learning opportunities, build technical knowledge, and reduce perceived risks. Pilot projects do not yet constitute mature markets, but they can help establish credibility and reveal practical barriers that are not visible in strategic plans. They also provide starting points around which wider ecosystems can form.

4.2.3. Research and innovation actors

Universities, research institutions, technology providers, and innovation organisations are present across multiple regions. These actors can support technical development, skills formation, testing, and knowledge transfer. In early-stage hydrogen ecosystems, research and innovation actors may function as catalysts by connecting firms, public authorities, and potential users. Their role is particularly important where commercial hydrogen actors are not yet fully established.

4.2.4. Public funding and policy support

EU funding mechanisms, national schemes, and regional support instruments provide important resources for hydrogen development. Even where policy frameworks remain incomplete, the availability of public funding can support pilot projects, infrastructure planning, and innovation activities. However, funding is most effective when combined with regulatory clarity and market coordination. Isolated subsidies are unlikely to create mature hydrogen markets unless they are connected to demand formation, infrastructure planning, and supporting services.

4.2.5. Potential for system integration and energy transition

Hydrogen offers a strategic opportunity to support system integration and decarbonization. It can connect renewable electricity generation with industry, transport, storage, and energy security objectives. The market mappings show that stakeholders increasingly recognize hydrogen not only as a clean fuel but also as a possible system-level solution. However, this opportunity is conditional. Hydrogen contributes to system integration only when renewable supply, grid capacity, electrolysis, storage, transport, and demand are coordinated. The opportunity is therefore real, but it depends on the development of an enabling market system.

5. Discussion

The regional mapping evidence shows that the main challenge for green hydrogen development is not simply a lack of interest, resource potential, or strategic ambition. Across the Green Hydra regions, renewable resources, early pilot activity, research capacity, and policy interest are present, but these elements are not yet sufficiently integrated into functioning regional hydrogen market systems. The central challenge is market-system formation: the alignment of actors, infrastructure, demand, regulation, finance, skills, and supporting services into coherent regional hydrogen ecosystems. Market system mapping is therefore useful because it reveals how barriers are distributed across the market chain, enabling environment, and supporting services. It also shows that weaknesses in one part of the system reinforce weaknesses elsewhere. For example, uncertain demand reduces project bankability; weak finance and advisory services make it harder to develop projects; regulatory uncertainty delays infrastructure; and infrastructure gaps reduce the credibility of future demand.

The issue of renewable electricity curtailment and system integration is especially important. In the Donegal case, curtailment and grid limitations are not merely technical constraints. They reveal a deeper misalignment between renewable energy potential and the enabling infrastructure required to use that potential. Grid limitations and insufficient long-duration storage reduce the ability to fully utilise renewable generation, thereby limiting the immediate scalability of hydrogen production. Consequently, in regions such as Donegal, offshore wind potential has not yet translated into a fully developed basis for green hydrogen production. The enabling infrastructure and system coordination required for hydrogen to become a solution are still incomplete.

This point has broader significance for how hydrogen is discussed in energy-transition policy. Hydrogen is often presented as a flexibility solution that can absorb surplus renewable electricity and reduce curtailment. The market-mapping results suggest that this claim should be treated as conditional rather than automatic. Hydrogen can help address curtailment only if several conditions are met: sufficient renewable electricity must be available; electrolysers must be located and operated in ways that match system needs; storage and transport infrastructure must be developed; and there must be credible demand for the hydrogen produced. Without these conditions, hydrogen remains a potential solution rather than an operational flexibility mechanism.

These findings have practical implications for regional policy. First, hydrogen strategies should be linked explicitly to renewable-energy and grid-development plans. Regions with strong offshore wind potential, for example, need coordinated planning for grid reinforcement, electrolysis capacity, storage, ports, pipelines, and industrial offtake. Second, policy should not focus only on production subsidies. Supporting services, permitting guidance, safety frameworks, certification, finance instruments, and market information might be equally if not more important for market formation. Third, demand creation should be treated as a central part of hydrogen policy. Without anchor users, offtake agreements, or public procurement, production projects face substantial investment risk.

The findings also suggest that different regions require different hydrogen pathways as their green hydrogen use cases differ. In wind-rich regions with curtailment, hydrogen may be most valuable as a storage and flexibility option. In hydropower-based regions, where electricity is more dispatchable, hydrogen may be more relevant for maritime transport, industrial uses, or export rather than grid balancing. In industrial regions, existing infrastructure and demand may provide stronger starting points, while in early-stage regions, policy development and supporting services may need to come first. A one-size-fits-all hydrogen policy is therefore unlikely to be effective. Market system mapping helps identify which pathway is most plausible in each regional context.

The study has limitations. The market mappings are based on stakeholder input from a workshop setting and should be interpreted as indicative rather than exhaustive. Some missing elements may reflect limited stakeholder knowledge or visibility rather than actual absence. The analysis focuses on the market-mapping stage of the Green Hydra process and therefore does not claim to provide a final prioritisation of barriers or a completed set of policy measures. Future work could structure such cross-regional learning more explicitly. It should be complemented by subsequent Green Hydra steps: root cause analysis, barrier prioritisation, action development, and policy-instrument design. These exercises are beyond the scope of this paper, although the diagnostic insights generated here are intended to inform such subsequent steps. Nevertheless, this scope is appropriate for the purpose of the paper: to show how market system mapping can provide a structured diagnostic basis for analysing regional green hydrogen market development and informing subsequent policy development.

6. Conclusion

This paper examined how evidence from Green Hydra regional mapping exercises can be used to analyse green hydrogen market-system development. Rather than treating the mapping process as a methodological exercise in itself, the paper used it as a diagnostic framework for identifying how regional hydrogen ecosystems are forming, where they remain fragmented, and which enabling conditions are needed for further development. The findings show that participating regions generally possess important enabling conditions, including renewable energy resources, early pilot initiatives, research and innovation actors, and access to public funding. However, they also face recurring structural barriers: fragmented value chains, limited regulatory clarity, underdeveloped supporting services, infrastructure and system-integration constraints, and uncertain demand.

The main contribution of the paper is to show that these barriers are best understood as interconnected market-system problems rather than isolated technical or financial obstacles. Green hydrogen development depends not only on the availability of renewable electricity or electrolysis technology, but also on the alignment of actors, infrastructure, regulation, finance, knowledge services, and demand. Market system mapping provides a practical framework for making these interdependencies visible and for identifying where targeted interventions may be needed.

The paper also highlights a key implication for regional hydrogen policy: hydrogen should be treated as a conditional flexibility solution rather than an automatic response to renewable electricity curtailment. It can support storage and system integration only when the wider market system is sufficiently developed, including renewable supply, grid capacity, long-duration storage, electrolysis, transport infrastructure, and credible demand. Advancing green hydrogen therefore requires coordinated policy and investment action across all dimensions of the market system. For regional policymakers, the priority is not only to support hydrogen production, but to strengthen the market-system conditions that allow production, distribution, storage, demand, finance, regulation, and supporting services to develop together.

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Featured Abstracts

V2G-Quests:
Towards an Equitable Mobility Transition

Gijs van Stekelenburg (HAN University of Applied Sciences)

As battery electric vehicles (BEV's) gain more popularity and cities increasingly face net congestion challenges, Vehicle-to-Grid (V2G) technology is becoming recognized as a high-potential tool for managing net congestion, supporting the EV-transition and supporting the development of Positive Energy Districts (PEDs). However, the large-scale adoption of such innovations depends not only on early adopters or the “happy few”, but rather on full-scale community engagement and social acceptance. This paper examines the socio-technical conditions for V2G adoption through a case study of Kanaleneiland: a densely populated, multicultural neighbourhood in Utrecht, the Netherlands.

The research utilized a mixed-methods approach to capture citizen perspectives. Data collection involved a questionnaire survey, two targeted focus group sessions, and street interviews all conducted in Kanaleneiland. This methodology was specifically designed to be inclusive, reaching residents who might not typically participate in formal research settings.

The findings reveal a complex landscape of perceptions. While residents show moderate familiarity with electric vehicles (EVs), knowledge of V2G remains critically low: approximately 67% of survey respondents had never heard of the technology prior to the study. Despite this initial lack of awareness, the conceptual appeal of V2G as an energy buffer for grid stability is high once the technology is explained. However, significant structural barriers persist. The high purchase cost of EVs remains the most prominent obstacle, followed by “range anxiety” and the perceived scarcity of local, accessible charging infrastructure. Furthermore, the neighbourhood's physical layout, dominated by multi-story “portiekflats” without private parking, creates scepticism regarding the equitable distribution of V2G benefits. Residents expressed valid concerns that V2G could result in social inequalities unless business models ensure that financial rewards reach those in social housing as well.

The paper concludes that for V2G to be successful in diverse urban contexts, an integrated socio-technical approach is essential. Key recommendations include leveraging shared mobility to bypass high ownership costs and investing in local ambassadors to build EV and V2G acquaintance and trust within the community. These insights offer a roadmap for policymakers to ensure the energy transition is both technologically robust and socially legitimate.

Faster, Fairer, Cleaner: Overcoming Myths That Hold Back Renewable Energy

Tania Ouariachi (Hanze)

The success of the energy transition will depend not only on the rapid deployment of zeroemission technologies, but also on the expansion of renewable energy sources such as wind, solar, and hydrogen. Equally important is meaningful engagement with the communities affected by this transition. Despite these requirements, debates around renewable energy are increasingly shaped by misinformation and coordinated disinformation campaigns, especially on social media, where renewable energy is often framed negatively.

Solar energy is among the most frequently targeted technologies by misleading narratives, particularly those related to environmental and health risks. Examples circulating online include claims that solar panels 'breed mosquitoes that spread dengue fever', 'produce waste 300 times more toxic than nuclear waste', or 'contaminate nearby soil and water bodies with harmful chemicals'. Wind energy projects are similarly affected by misinformation, with claims such as 'wind turbines cause cancer or serious health issues', 'turbines kill massive numbers of birds and destroy ecosystems', or 'wind power is unreliable and causes blackouts'.

Many projects face local resistance and 'delayism' due to limited public knowledge, low trust in developers, and perceptions of unfair decision-making. Mis- and disinformation are among the most influential factors, heavily amplified by social media ecosystems and emotional narratives. Within this polarized and complex information environment, effectively addressing mis- and disinformation is an urgent step towards achieving a faster, fairer, and cleaner energy transition.

Communication plays a pivotal role. Strategies generally fall into two broad categories: those that promote accurate information and those that expose false or misleading claims. These approaches can be implemented either proactively, through prebunking, or reactively, through debunking. Beyond debunking and prebunking interventions, existing literature emphasises the importance of strengthening open dialogue, active collaboration, as well as media literacy to increase resilience to mis- and disinformation, particularly in digital contexts. Programmes designed to enhance critical thinking, source evaluation, and fact- checking skills can improve individuals' ability to navigate complex information environments.

This presentation follows two objectives: to share prevailing trends in disinformation narratives related to the energy transition, and to propose a communication toolbox to support transition developers. For this purpose, a preliminary social media analysis using Meltwater and a literature review of recent publications are employed as methodology. In practice, guidance for policymakers, communicators, and energy stakeholders will be offered in this domain.

Assessing Techno-economics of Solar Power Systems and Energy Storage Deployment in West Africa

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West Africa stands at a critical juncture in its energy transition, facing persistent electricity access deficits alongside rapid population growth. Despite ambitious targets, large-scale solar photovoltaic (PV) deployment remains constrained by infrastructure deficits and limited transparency regarding economic performance. This study addresses this gap through a bottom-up high-granular techno-economic assessment of utility-scale PV across 184 districts in the West African Power Pool under 13 climate scenarios, and a multi-objective optimization of off-grid hybrid energy systems integrating batteries and hydrogen technologies. Our results reveal pronounced spatial heterogeneity in grid-connected PV costs, with the levelized cost of electricity ranging from $0.087/kWh to $0.319/kWh. This heterogeneity is driven by a distinct urban-rural divide, where remote inland regions face prohibitive transmission penalties, while dense urban centers are constrained by elevated land rental costs. Coastal tropical countries such as Sierra Leone and Liberia exhibit heightened vulnerability to future climate uncertainty, whereas nations like Senegal and The Gambia demonstrate consistent investment resilience. Electricity tariff subsidies and risk-inflated financing costs, remain the dominant barriers to solar PV implementation. Furthermore, the optimization of hybrid energy systems highlights a critical geographical divergence in storage technology. Regions with stable solar resources (e.g. Nigeria) favor battery storage for short-term variability, while tropical regions with prolonged rainy seasons (e.g. Liberia) require hydrogen-based systems for seasonal balancing. The storage-driven cost structures fundamentally reshapes regional competitiveness, enhancing the viability of countries such as Niger and Guinea-Bissau. By capturing these spatial, climatic, and technological tradeoffs, this study establishes a quantitative framework for policymakers to design targeted zonal electrification strategies and for investors to optimize investment allocation.

Keywords:
Solar PV; West Africa; Techno-economic assessment; Levelized cost of electricity; Hybrid energy systems

PreMadona: Governing Digital Innovation of Urban Renovation

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The Netherlands is undergoing a massive (re)construction challenge. In addition to building new housing, a substantial part of the existing building stock of housing corporations is undergoing renovation. This renovation challenge has varying interactions with the energy transition, testified by the Dutch government's ambitious target of connecting 200,000 buildings to fossil-free energy infrastructure (Rijksoverheid 2019). Improving the building quality, including the energy efficiency, of buildings, might reduce the overall energy consumption of households. Yet, a closer look at the interactions between renovation and energy are more instructive, as renovation is coupled with decisions regarding the energy-use and specifically heat-use of buildings. Renovation processes are a natural moment to take decisions regarding low-carbon heating: will houses and other buildings be renovated with an eye to district heating, or to supply their energy needs through electricity alone (or another solution altogether)?

Such strategic decisions require coordination between decision-making processes at the level of building owners (such as households or housing corporations), municipalities, as well as energy infrastructure operators (such as heat companies or grid operators), all of which operate at different time scales.

The importance of coordination becomes all the more salient given ambitious targets around renovation and energy transition set by the Government's climate accords. In fact, according to the construction industry, such ambitions can only be reached through the implementation of new strategies for clustering and coordinating projects. A failure to coordinate might lead to failed business cases for district heating if renovation plans are more aligned with all-electric options, unnecessary costs for electricity grid reinforcement (if DH-connection would have reduced electricity consumption peaks) or grid congestion issues (if grid operators are unable to timely make the necessary investments in grid reinforcement), and incapacitate housing corporations from timely making the right decisions. A failure to coordinate renovation and energy transition successfully, in other words, will lead to an inefficient allocation of limited (human) resources, delays, and a potential cascade of other negative socio-economic and political consequences considering the salience of housing and energy costs as pivotal issues in the Dutch political landscape.

The NWO-KIC funded PreMadona project aims to develop and interrogate a new digital ecosystem to enable renovation flow and clustering approaches proposed by the construction sector. These digital innovations are envisaged to help undertake this urban renovation and infrastructural challenge more efficiently, speedily, and intelligently, and are promoted by the building industry (Rovers and Tigchelaar 2024). PreMadona seeks to develop the required digital innovation, including by tackling sociotechnical challenges of data, trade-offs between context-awareness and collective optimisation, operational coordination, and the misalignment of technology and practice. Rather than developing technology alone, PreMadona simultaneously co-develops the digital innovation as well as the governance frameworks required for its proper implementation, in order to engender a properly embedded sociotechnical innovation.

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Understanding Farmers' Perceptions of Alternative Fuel Vehicles (AFVs) for Sustainable Development in Africa

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The transport sector is a major contributor to global greenhouse gas (GHG) emissions while also serving as a key driver of economic development. The transportation of farm produce, which is an important activity on the value chain of farmers, contributes significantly to rural development and at the same time contributes to the overall transportsectors' GHG emissions (United Nations, 2023). As developing countries are increasingly exploring low carbon transport systems as affordable and environmentally friendly options, it is important to understand the perceptions of stakeholders involved in agricultural logistics. In particular, stakeholders responsible for transporting farm produce are central to the adoption of low carbon transport vehicles. This research aims to examine stakeholders' perceptions of using alternative fuel vehicles (AFVs) for transporting farm produce in developing countries. The study is underpinned by the diffusion of innovation (DOI) theory, that examines user perceptions based on five key elements: relative advantage, complexity, compatibility, observability, and trialability (Rogers, 2003). A survey will be conducted to collect data from stakeholders who engage in transporting farm produce within rural communities in Nigeria. The collected data will be analysed using the DOI framework to assess farmers' perceptions of alternative fuel vehicles (AFVs) and key factors that determine their choice of transport mode. The findings from this study are expected to provide policy direction for the transport sector in developing countries. The study will also contribute to literature that promotes sustainable transport solutions while fostering the integration of social inclusiveness and economic development.

Keywords: Alternative fuel vehicles; diffusion of innovation; sustainable transportation; developing countries; agricultural sector.

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Integrating Electric Two-Wheelers into Mini-Grids: Insights from Kakuma Refugee Camp, Kenya

Phillip Peters (Hanze)

The electrification of two-wheeler transport represents a key opportunity to decarbonise mobility in Sub-Saharan Africa while reducing dependence on volatile fossil fuel supply chains. In off-grid regions, mini-grids, which distribute electricity locally using solar PV generation and battery storage, offer a potential backbone for this transition. Battery swapping, where depleted batteries are exchanged within minutes for fully charged ones at dedicated swapping stations, is an emerging service model that enables e-mobility business models across Sub-Saharan Africa. This study investigates the system-integration potential of battery-swapping services for electric two-wheelers (E2Ws) within mini-grids, using data from an E2W pilot integration in the Kakuma refugee camp mini-grid in Kenya as a case study.

Based on the Kenyan regulatory and operational context, a techno-economic bottom-up model was developed to simulate how a battery-swapping hub can be integrated into the existing mini-grid infrastructure. The model combines hourly load modelling, fleet sizing, and battery charging demand of E2Ws with generation and storage dynamics, capturing the interaction between battery-swapping services and mini-grid operations. The analysis evaluates the impact of different fleet sizing scenarios of an E2W battery-swapping hub on mini-grid system utilisation, storage requirements, and resulting E2W load profiles.

Results show that battery-swapping services can significantly increase electricity demand and reduce curtailed electricity generation under different E2W utilisation scenarios. The system sizing analysis reveals that the integration of E2Ws can reduce curtailed electricity by up to 4%, while maintaining system stability without requiring additional mini-grid infrastructure investments in solar PV or battery storage capacity, and without compromising electricity supply to existing residential and commercial end-users. The flexible charging characteristics of battery swapping enable demand-side management strategies, including load shifting to periods of high solar PV generation, thereby improving mini-grid system efficiency. However, system performance remains sensitive to E2W utilisation levels and fleet sizing, highlighting the need for a coordinated design of the mini-grid and battery-swapping infrastructure.

The findings demonstrate that integrating e-mobility services based on battery swapping into mini-grids can enable transport electrification and enhance mini-grid system performance. By increasing income-generating electricity demand and improving asset utilisation, battery-swapping service models represent a technically viable and scalable pathway for sustainable mobility in underserved regions. The study contributes a transferable modelling framework for assessing the integration and optimal sizing of E2W battery-swapping hubs in solar PV-battery based off-grid mini-grids.

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The energy transition is reshaping the way we live, work, and power our future. In *Breaking Barriers: Accelerating Transitions*, researchers, innovators, and practitioners share fresh insights into the challenges and opportunities driving this transformation. Drawing on contributions presented at the New Energy Forum 2026, this volume explores topics ranging from hydrogen and renewable energy to sustainable mobility, workforce development, community engagement, and international cooperation. Together, these chapters demonstrate how interdisciplinary collaboration can turn ambitious goals into practical solutions. As the first volume of the New Energy Forum Conference Proceedings, this book captures the ideas, knowledge, and partnerships needed to accelerate the transition toward a more resilient and sustainable future.

> "If we want to change the world… and we do because we are running out of time… we have to work together. In this publication more than twenty researchers and professionals transformed their research into scientific articles. For us to use in everything we do. Changing together is fun! And we are good at it. So let's do it. And please step up.
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