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ORIGINAL ARTICLE

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Stakeholder engagement in hubs for circularity in Europe

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Abstract. This research highlights the critical role of stakeholder engagement in the successful implementation of industrial symbiosis (IS) in the circular economy (CE). Although stakeholder engagement is recognised as a key driver in advancing circular economy models, research in this area is limited. In this paper, we examine four industrial hubs within the context of the IS2H4C project. These hubs are referred to as Hubs for Circularity (H4C) and are located in Spain, the Netherlands, Germany and Turkey. Qualitative interviews with key stakeholders from industry, policy, academia and society were used as the research method. The results show that a stakeholder analysis alone is insufficient for H4Cs. This research proved that active and continuous engagement is necessary, with a regional and local approach. Governance structures at these levels are key to long-term engagement. The results suggest that regulatory frameworks, such as the ReFuelEU Aviation Regulation in the German hub, are the main drivers of stakeholder participation, as well as infrastructure delays. Industrial clusters and companies also play an active role in promoting social acceptance, as do trade unions. However, in order to create a sustainable and inclusive environment involving all categories of stakeholders, including society, academia, industry and politics, it is essential to coordinate local and regional authorities, including universities and research institutes. Key barriers include the high cost of investment and uncertainty surrounding long-term financing, both of which can hinder the scalability of hydrogen technologies and sustainable aviation fuel. All hubs face challenges relating to the complexity and instability of regulations. This undermines stakeholder trust, particularly among investors and private companies. Finally, a shortage of skilled labour and limited public acceptance, particularly with regard to safety and environmental concerns, pose ongoing social and implementation challenges.

Keywords: circular economy / stakeholder engagement / hubs for circularity / industrial symbiosis / hydrogen

1 Introduction

Industrial Symbiosis (IS) is a systems-based approach that fosters collaboration between stakeholders from industry, policy, research, and civil society. It is also an approach to create a "more sustainable and integrated industrial system" [1], which helps to identify better ways to use materials, resources, capacities, skills, among others. Industrial symbiosis main objectives are improvements to operational processes, networks, and materials. One of the key aspects of this approach is the integration of circular economy principles into IS processes [2].

The principles of the circular economy include, for example, the circularity of materials and the transition from consumers to users, with the aim of increasing circularity and reducing resource use. These principles are particularly relevant in Europe when it comes to creating renewable energy solutions and improving competitiveness [3]. More specifically, the circular economy (CE) seeks to maximise the lifespan of resources through reuse, repair, refurbishment and recycling [4]. Industrial symbiosis is often considered to be the practical implementation of CE at an industrial level, by facilitating the reuse of waste and by-products across different industries. The IS conserves resources and fosters innovation and collaboration between industries. However, its implementation faces challenges, for example, complex governance [4], policy gaps in appropriate legislation, high infrastructure and logistics complexity due to physical proximity [5], but also lack of trust [6,7]. These can be summarised as "economic, technical, regulatory/legal, organisational, social and cultural" barriers [6].

Modern approaches to the circular economy, suggest CE as a transformative approach that concerns not only industrial and technological sustainable systems, but also societal actors in circular processes [8]. Although this has not yet been analysed much, recent debates on industrial symbiosis increasingly recognise the relevance of its social dimension [6,7,9]. The social dimension of IS includes the complexity of collaboration processes between various

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stakeholders and integrating technological and social innovation [10]. For example, according to Spekkink [9], this dimension refers to 'institutional capacity of actors to coordinate their actions and interactions towards industrial symbiosis'. In the past, these actions were usually analysed in terms of the exchange of waste, by-products, and water use between industrial stakeholders. However, our research broadens the scope of these actions and relationships by adopting a sociological perspective and including stakeholders from politics, society, and academia, rather than focusing solely on economic actors.

Previous research on stakeholder participation in circular economy processes has primarily focused on industrial stakeholders and their relationships at the company level e.g. within circular business models [11], or on specific aspects of participation, such as management's influence on the adoption of circular economy practices [12]. However, little research has adopted a holistic approach to stakeholder participation [11,13], or considered urban areas and their local stakeholders as opportunities for societal participation due to local proximity [5]. Further research is needed to improve our understanding of stakeholder engagement in CE and on circular practices [12,14]. Therefore, our research recognises these gaps and focuses on stakeholder participation in local and regional context.

Stakeholder participation plays a fundamental role in the development of industrial symbiosis and, more generally, circular economy systems [15]. Stakeholder engagement in energy transitions often encounters substantial societal challenges, typically associated with resistance to change [16]. Societal resistance can therefore arise from fears of pollution, doubts about corporate intentions or broader environmental concerns [17]. At the community level, this resistance is often expressed as 'NIMBY' (not in my backyard) [18], and can be related to legitimate concerns rather than just self-interest [18, 19]. Therefore, the active participation of relevant stakeholders requires new forms and structures of continuous participation, such as dialogue, collaboration, mutual commitment, and trust building. Some authors even acknowledge the influence of stakeholders on system change. In other words, stakeholder participation and relationship management can facilitate sustainable transitions [20, 21]. For such participation to be effective, it is necessary to consider the drivers and barriers faced by stakeholders and to create ongoing ways to address these issues.

The factors that drive or hinder stakeholder participation are referred to here as 'drivers' and 'barriers', respectively. These factors can be economic, technical, regulatory/legal, organisational, social or cultural [6] as mentioned before. Some of these barriers are material and some are non-material. For example, social, cultural, and legal barriers are non-material and relate to power, access to resources or skills, to governance structures, and to legal structures. Some researchers recognise the dimension of power as a relevant factor in facilitating or hindering participation, stating that "power of actors in a network depends on the dependence of other actors on the resources they control" [22]. Others suggest that governance structures facilitate communication, cooperation, and trust [23]. Governance is defined here "as an ensemble of programmatic and decision-making activities guiding organisations towards desired aims and objectives." [4, p.1.] By 'governance structures' we mean: the use of one's own assets, public services and waste management companies to support the circular economy; the implementation of economic standards and/or regulations; and the facilitation, coordination, collaboration and promotion of circular economy practices [24].

With stakeholder engagement, we adopt the perspective of Kujala and colleagues [25], who define it as "Stakeholder engagement refers to the quality of the relationships that businesses have with stakeholders, allowing them to build a common understanding of a focal issue, such as joint value creation, or to promote joint interest and collaboration" p. 20. This perspective recognises not only the company value but the creation of a joint value in CE, which can be economic, social or environmental. It also refers to the participation of heterogeneous stakeholders organised in networks [14], as well as to the understanding of the objectives, activities, and impact of stakeholder relationships in a 'moral, strategic, and pragmatic' way [26]. These values relate to the good intentions of stakeholders and voluntary relationships, as well as to the environmental and social responsibilities of companies and the good intentions of stakeholders (moral). They also refer to reciprocal economic advantages (strategic) and to practical solutions and joint value (pragmatic).

While stakeholder engagement is increasingly recognised as crucial for the transitioning to a circular economy, its practical implementation, particularly within regional and cross-sectoral contexts like Hubs for Circularity (H4C), remains under-researched [13]. This article thus contributes to the literature on CE and IS by presenting empirical research that sheds light on stakeholder engagement in CE, particularly in the context of regional and local agreements such as H4Cs in Europe.

We refer to regional platforms designed to drive the transition to a circular economy by encouraging collaboration and innovation as H4Cs. Originally launched under the SPIRE (Sustainable Process Industry through Resource and Energy Efficiency) initiative, it later evolved into the Process4Planet partnership [27]. H4Cs aim to act as centres for innovation and collaboration. They bring together a diverse range of local and regional stakeholders from urban and rural areas to identify synergies [28]. H4Cs offer a flexible and inclusive framework for scaling up circular practices at a regional level while aligning with broader policy and sustainability goals. They blend top-down strategic direction with bottom-up stakeholder engagement.

This article analyses the drivers and barriers to the development and implementation of H4C from the perspective of the relevant stakeholders involved. Focusing on four H4Cs in the Basque Country, Germany, the Netherlands and Turkey. The analysis of these drivers and barriers is based on qualitative interviews. The primary research questions investigated in this paper are:

- From a stakeholder perspective, what are the main drivers and barriers to the development and implementation of H4C?
- Who are the key stakeholders of the four H4Cs investigated here, and how well are they represented?

– Which intangible resources are provided or lacking (e.g. trust, approvals, acceptance, and skills)?

In the next section, we introduce the European context and, more specifically, the four regional settings in countries in which the H4C takes place.

1.1 The European context of this research

This article focuses on stakeholder engagement in the context of the “From Industrial Symbiosis to Hubs for Circularity” project IS2H4C [29]. The project aims to transform existing industrial parks, networks and clusters into H4Cs. While industrial symbiosis is a well-established concept, having been in existence since the Kalundborg example in Denmark was published [30], H4C is a more recent approach introduced by the public-private partnership Processes4Planet.

In the IS2H4C project [29], we define H4C as: “H4C provide spaces where diverse actors, such as businesses, governments, researchers, and civil society, collaborate to accelerate the Circular Economy (CE) transition.” This definition prioritises the collaboration of these four stakeholder groups in H4C solutions, which highlights the significant role of stakeholder engagement in the IS2H4C project. In addition to this, the exchange of resources between partners in industrial symbiosis is a central feature of IS and H4C. While this exchange usually refers to physical resources (e.g. by-products, waste, water and energy), the IS2H4C project also focuses on non-physical resources (e.g. approvals, acceptance, and skills), which stakeholders must contribute to enable the successful implementation and scaling up of H4C solutions. Non-technical aspects also play an important role in the project to ensure these resources are sufficiently considered (e.g. economic viability, regulatory uncertainties, societal relations, regional development, and environmental aspects).

In the context of the IS2H4C project, we propose an innovative action plan to develop solutions for H4C in various industrial sectors in rural and/or urban areas in the Netherlands, Germany, Spain, and Turkey [31]. The work plan involves the development and deployment of innovative sustainable technologies and the integration of infrastructure in four demo hubs, and is supported by research into societal, governmental and business innovations for H4C. The four H4Cs have incorporated the demonstrated synergies and technologies used in the project’s design. The analysis presented in this research is based on these synergies and technologies. The authors of this paper had no influence on the selection of the H4Cs.

The IS2H4C project scales up industrial areas for H4C by implementing systemic change and integrating surrounding ecosystems with industrial areas. IS2H4C will pave the way for the development of H4C in line with the circularity and resilience requirements of existing and future industrial zones and their surrounding ecosystems. This will be achieved by prioritising resource efficiency, maximising the use of renewable energy, preventing waste and promoting industrial, urban and rural symbiosis through reuse, recycling of unavoidable solid, liquid and gaseous waste streams. Ultimately, IS2H4C’s ambition is to promote H4C as a sustainable model for regional development in Europe. As part of this holistic approach, IS2H4C ensures societal and governmental engagement to H4C via securing acceptance and trust among citizens based on clear communication, transparency, and inclusion, by proposing sustainable business and financial models, as well as respecting the planetary health boundaries.

2 Methods

For this research, we focused on qualitative methods to identify the key stakeholders and their interdependencies in the four hubs (Netherlands, Germany, Spain, and Turkey), as well as the drivers and barriers to developing H4C. To capture stakeholders’ perspectives across the hubs, we conducted semi-structured interviews with experts. By ’experts’, we mean representatives of stakeholder organisations that are key to the respective H4Cs, such as individuals who influence decision-making processes or have access to critical resources for the development and implementation of industrial symbiosis (referred to here as ’key stakeholders’).

The *semi-structured expert interviews* were conducted with representatives of stakeholder organisations from the relevant IS hubs in all four hubs of the IS2H4C project. In line with the research questions addressed here, the interviews aimed to identify key stakeholders and examine their interdependencies. They also explored the perception of drivers and barriers affecting the development and implementation of H4Cs, providing an in-depth stakeholder perspective. The interviews were distributed exclusively to official representatives of institutions involved in the EU-funded IS2H4C project, and English was used as the language of communication. Therefore, language was not considered a barrier to survey response.

The interviewers followed a standardised interview guide that covered topics such as organisational characteristics, the role of information systems within the organisation, the interests and needs of stakeholders, non-technological challenges and issues, relationships with other stakeholders, and the connections between information systems and roles within the organisation. Responses were summarised using a pre-structured analysis template, and analysed through content analysis to ensure comparability across hubs. Interview partners were selected based on their relevance and influence within each hub, as well as their relevance to the focus of IS, using the snowball technique. By snowball sampling technique, we mean that initial interviewees provided referrals to additional relevant stakeholders for subsequent interviews. We used these referrals to expand our participant pool and reach further subjects who might otherwise have been difficult to identify.

A total of *26 interviews* were conducted with stakeholders from all four categories: industry, policy, civil society and academia. All interviews were anonymised, meaning that the results presented cannot be linked to specific individuals or organisations. Table 1, presented below, provides an overview of all the stakeholder entities referenced in this study. Some of these entities were only contacted for reference purposes or to provide information

Table 1. Overview of anonymised stakeholder entities referenced in this study.

Stakeholder code	Type of stakeholder	Hub	Interviewed stakeholders
B-I1	Industry – Specific Industry	Basque hub	(Interviewed on 13th November 2024)
B-A1	Academia – Technology centre	Basque hub	(Interviewed on 13th November 2024)
B-P1	Policy – Public Agency (Policy Body)	Basque hub	(Interviewed on 15th November 2024)
B-P2	Policy – Public Agency (Policy Body)	Basque hub	(Interviewed on 26th November 2024)
B-P3	Policy – Regional Government (Policy Body)	Basque hub	
B-I2	Industry – Association of Steelworks (Services and management stakeholder)	Basque hub	(Interviewed on 15th November 2024)
B-I3	Industry – Association of specific industries, services and development stakeholders	Basque hub	(Interviewed on 19th November 2024)
B-I4	Industry – Association of specific industries, services and development stakeholders	Basque hub	(Interviewed on 21st November 2024)
B-I5	Industry – Association of specific industries, services and development stakeholders	Basque hub	(Interviewed on 26th November 2024)
B-I6	Energy Company (Oil & Refining Sector)	Basque hub	
B-I7	Energy Company (Electricity & Renewables Sector)	Basque hub	
NL-S1	Society – Community, local energy cooperation, non-profit	Dutch hub	(Interviewed on 6th November 2024)
NL-I1	Industry – Services	Dutch hub	(Interviewed on 13th November 2024)
NL-A1	Academia – Technology and Innovation	Dutch hub	(Interviewed on 21st November 2024)
NL-I2	Industry – Specific industry (group of companies)	Dutch hub	(Interviewed on 26th November 2024)
NL-I3	Industry – Specific industry	Dutch hub	(Interviewed on 4th December 2024)
NL-I4	Industry – Specific industry	Dutch hub	(Interviewed on 12th December 2024)
NL-I5	Industry – Industrial association / cluster organisation	Dutch hub	
NL-I6	Industry – Energy infrastructure and distribution stakeholder	Dutch hub	
NL-I7	Industry – Specific industry	Dutch hub	
NL-I8	Industry – Local business / real estate stakeholder	Dutch hub	
NL-P1	Policy – Local public authority	Dutch hub	
NL-P3	Policy – National public programme	Dutch hub	
NL-P4	Policy – National regulatory authority	Dutch hub	
NL-P5	Policy – Regional public authority	Dutch hub	
NL-A2	Academia – University / higher education institution	Dutch hub	
NL-A3	Academia – Applied research organisation	Dutch hub	
NL-S1	Civil Society – Local cooperative energy initiative	Dutch hub	
NL-S2	Civil Society – Local community cooperative	Dutch hub	
DE-I1	Industry – Services and management & specific industry	German hub	(Interviewed on 7th November 2024)
DE-P1	Policy – state-owned competence centre	German hub	(Interviewed on 8th November 2024)
DE-A1	Academia – Research and Education (Technology and Innovation)	German hub	(Interviewed on 19th November 2024)
DE-C1	Civil Society – NGO & Advocacy	German hub	(Interviewed on 14th November 2024)
DE-I2	Industry – Specific industry	German hub	(Interviewed on 15th November 2024)
DE-A2	Academia – Research and Education (Technology and Innovation)	German hub	(Interviewed on 18th November 2024)
DE-C2	Civil Society – NGO & Advocacy	German hub	(Interviewed on 19th December 2024)
DE-I3	Industry – Labour related stakeholder	German hub	(Interviewed on 31st January 2025)
DE-I4	Industry – Industrial services and site management stakeholder	German hub	
TU-I1	Industry – Specific Industry	Turkish hub	(Interviewed on 15th November 2024)
TU-P1	Policy – Economic development Agency	Turkish hub	(Interviewed on 15th November 2024)
TU-I2	Industry – Specific Industry	Turkish hub	(Interviewed on 22nd November 2024)
TU-I3	Industry – Specific Industry	Turkish hub	(Interviewed on 29th November 2024)

about other key stakeholders. Those that were interviewed using a semi-structured approach are marked in the right-hand column of the table.

3 Results

The results are presented in this section three. First, we present the results of the Dutch hub (Sect. 3.1), the German hub (Sect. 3.2), the Basque Country hub (Sect. 3.3) and finally, the Turkish hub (Sect. 3.4). In each section, we present the key stakeholders and summarise the main drivers and barriers found in each hub. The results are presented and discussed in the context of the literature in Section 4.

3.1 Dutch hub

The Dutch hub is located in Twente and the Almelo Energy District, is a fully operational Living Lab within the IS2H4C project. Living Labs involve stakeholder roundtables and various participatory methods to ensure engagement and enhance social acceptance. Situated in the Twente region in the eastern Netherlands, the hub serves as a real-world testing and co-creation environment for hydrogen-based and circular economy innovations. This hub brings together entrepreneurs, researchers, local government, distribution system operators, water boards, citizens, and knowledge institutes to pilot integrated solutions in energy generation, storage, high-temperature industrial use, mobility, and the built environment (residential houses and SME buildings).

This hub is anchored by NL-I5, NL-S1, and NL-I4 and supported by key players, such as NL-P1, NL-I3, and NL-P2. The hub integrates renewable energy (solar and wind), green hydrogen production and local distribution, and the reuse of treated wastewater for circular water systems. It also facilitates urban-industrial symbioses, for example, between wastewater systems and local businesses.

3.1.1 Key stakeholders

The stakeholders of the Dutch hub are divided into the following categories: society, academia, industry, and public authorities.

a) Society

Local community and citizen organisations are important figures in community engagement and societal adoption. Stakeholders include three building owners, the cooperation of the village (cf. NL-S2 (T2), NL-S1 (T1)), and other citizen engagement initiatives in Aadorp (T2), each supporting public awareness and adoption of hydrogen technologies in residential and community applications.

b) Academia

Academic institutions, such as the NL-A2 and organisations like NL-P3 - NL-A1 and NL-A3, contribute to researching and testing innovative solutions. These stakeholders provide technical expertise, conduct pilot studies, and research new hydrogen technologies, contributing to the scientific foundation of the hub's projects.

c) Industry

Industrial stakeholders are pivotal in deploying, maintaining, and expanding hydrogen applications. Key players include NL-I6, NL-I3, NL-I7, as well as local business in Twente (e.g. NL-I8 and NL-I4). These companies contribute to various projects, such as the use of hydrogen in energy distribution, and the creation of district energy solutions, all of which aim to replace traditional natural gas usage.

d) Policy/Public Authorities

Local and regional authorities, such as the municipality (cf. NL-S1, NL-P4, NL-I1), and the province of Overijssel, provide regulatory oversight, policy direction, and safety measures to ensure the sustainable and safe implementation of hydrogen technology. Emergency services and the NL-P5 also play a vital role in maintaining safety standards for new hydrogen systems.

3.1.2 Drivers and barriers

Stakeholders in this hub are primarily interested in advancing hydrogen technology as a means of achieving sustainable energy solutions and a circular economy. By using green hydrogen for energy storage, industrial processes and community heating, they aim to reduce their dependence on natural gas and fossil fuels. Specific interests include developing high-temperature hydrogen combustion for industrial use and using improvements in electrolysis technology to make hydrogen production more efficient. Specifically, the H4C in Twente, named H2hub Twente aims to increase the scale of hydrogen infrastructure and reduce production costs in order to make green hydrogen competitive. To achieve this, it is collaborating with other stakeholders [32].

Despite the promising advancements, there are several risks that impede the implementation of hydrogen. One such risk is the high initial costs and the uncertainty surrounding the securing of continuous funding for large-scale adoption. Other risks stem from technical challenges, such as the degradation of electrolysis systems under fluctuating loads, and the shortage of skilled workers needed to operate and maintain these technologies. Furthermore, public acceptance and regulatory ambiguities pose risks to the expansion of hydrogen initiatives, particularly when transitioning from natural gas-dependent systems. To address these challenges, the hub is engaging with local communities through awareness campaigns and collaborating with policymakers to streamline regulatory processes.

The Dutch hub's goals are enabled by several factors, such as existing hydrogen-friendly infrastructure and a supportive network of research institutions and private companies. Other supporting factors include substantial European Union funding for green hydrogen R&D and a strategic location that facilitates hydrogen transport and storage [33].

There are still significant barriers, especially around regulations that have not fully adapted to the requirements of hydrogen energy. Market and distribution challenges are also substantial, given that hydrogen supply chains are still underdeveloped and competition with established energy sources remains intense. Technical issues, such as energy losses during storage and conversion processes, limit the cost-effectiveness and operational reliability of hydrogen. Lastly, local community concerns about the safety and environmental impact of hydrogen infrastructure present social barriers that require comprehensive citizen engagement strategies.

Apart from the mentioned drivers and barriers, job creation and skills development also play a decisive role in the Dutch hub. In this regard, network operators are the most relevant stakeholders in the Dutch hub in terms of future changes. Installation and maintenance skills for hydrogen infrastructure are particularly important for the synergies to be demonstrated in the Dutch hub. Other stakeholders in the Dutch hub are anticipating changes in terms of personal skills, for example in the form of new combinations of electrical engineering, process/installation engineering, and approval/safety knowledge. Proactive 'learning communities' have already been developed in the Dutch hub to analyse the changes in skills, ensuring that qualified workforce is available when needed, in order to drive a successful IS implementation in the hub.

3.2 German hub

Industriepark Höchst has a long tradition as one of the Europe's largest and most well-established sites for the chemical and pharmaceutical industry. The further development of the Industriepark towards a H4C focuses on Carbon Capture and Utilization (CCU) and production of e-fuels (e-methanol, or synthesis gas as intermediary product). Founded in 1863, it aims to become CO_2-neutral by 2050. The industrial park is home to 90 companies from the pharmaceutical, chemical, biotechnology and services sectors, occupying 4.6 square kilometers of space close to the airport and the city of Frankfurt. It includes 120 production plants and 980 buildings and employs 22,000 people. It consumes 2,000 gigawatt hours of electricity and 3,500 gigawatt hours of heat [34].

3.2.1 Key stakeholders

This section presents the categories of stakeholders that either facilitate or hinder the scaling up of carbon capture and utilisation (CCU) and sustainable aviation fuel (SAF) as a final product made from CO_2.

a) Industry

Companies in Industriepark Höchst, including well-established businesses and innovative start-ups, are spearheading technological advancements and pilot projects. With their long tradition of resource utilisation and circular economy, not to mention the provision of essential infrastructure, they are enabling the scaling up of sustainable solutions. This stakeholder group is crucial to combining economic feasibility and technological innovation in order to achieve the hub's sustainability goals. The relevant companies for CCU and SAF production are the operator of the incineration plant, which captures CO_2 and provides CO_2 networks and hydrogen, and two SMEs producing intermediary products for SAF. In addition to these manufacturers, important stakeholders identified include airlines (as consumers of SAF), mineral oil companies (which produce SAF as an end product) and a trade union.

b) Policy

Political actors and regulatory authorities, such as the European Commission, the federal, federal state ministries, and regional authorities are key drivers of sustainable innovation in areas such as sustainable aviation fuel (SAF), carbon capture and utilisation (CCU) and industrial symbiosis (IS). They establish the legal and economic framework conditions, such as the ReFuelEU Aviation regulation, and set clear objectives, such as achieving climate neutrality, which are crucial to enabling companies to invest in and successfully implement forward-looking technologies (cf. DE-I2).

c) Academia

Research and education play a supporting but indispensable role in the development and scaling of technologies such as SAF, CCU; and IS. Stakeholders such as universities, educational institutions and research institutes provide the necessary technical expertise, promote innovation and train qualified specialists who are needed to implement these technologies.

d) Society

Society, represented by environmental organisations, NGOs and local communities, plays a key role in the implementation of SAF, CCU and IS projects in Industriepark Höchst. Its influence ranges from promoting public acceptance to actively shaping it through campaigns and dialogue formats. Non-governmental organisations (NGOs), most of which in this context are environmental organisations (such as DE-C1) actively promote sustainability in aviation and act as an important voice in public and political debate (cf. DE-P1, DE-A2). Citizens and local communities can influence the implementation of projects through their acceptance or resistance. Their approval is particularly crucial for large-scale infrastructure projects (cf. DE-I2).

3.2.2 Drivers and barriers

According to the interviews, political and regulatory stakeholders have a significant impact on framework conditions and the speed of implementation. Regulations such as the ReFuelEU Aviation set binding quotas and standards that aim to create clear market incentives. According to this, EU jet fuel suppliers must deliver 2% SAF blend already in 2025 increasing up to 6% in 2030 and 70% in 2050 (cf. DE-A2, DE-I3). This regulation puts pressure not only on the mineral oil industry, but also on airlines and oblige them to consume SAF. However, according to the experts interviewed, the airlines highlight the effect of SAF (regulation) on their competitiveness as they have to pay higher costs for SAF compared to conventional kerosene. This situation limits their willingness to engage in SAF (cf. DE-C1). In this context, the interviewees state that uncertainties, such as the planned review of these SAF quotas in 2027, are further aggravating a reluctance to buy or even invest – especially for the main target groups, airlines and mineral oil companies, among which there is concern that potential both, the current regulation of aviation fuels as well as its future volatility, for example regarding blending rates, SAF definitions or penalties, could impact the profitability of future SAF refiners (cf. DE-I1, DE-I2, DE-I3, DE-I4). Thereby, a dilemma of responsibility can be stated: while the airlines (as SAF consumers) wait for further development of aviation fuel regulations, oil companies refuse to invest in scaling SAF and wait for the Technology Readiness Level (TRL) to rise (together with increasing regulatory certainty and profitability), while investors, such as banks and venture capital firms are hesitant because of high investment volumes, low demand for SAF, high complexity of SAF production, regulatory uncertainty, technological risks and first mover disadvantage.

Stakeholders in society, such as NGOs, influence the public and political debate. Organisations like DE-C1 promote ambitious environmental standards addressing companies and regulators (cf. DE-A2, DE-P1). The resulting EU-regulation to acknowledge only biogenic sources of CO_2 as sustainable (from 2038) leads to concern of the industry to calculate pay-off periods reliably.

At the same time, local communities are crucial for the acceptance of infrastructure projects such as SAF production plants and related infrastructure. Resistance from the population could delay projects, which is why transparent dialogue formats are necessary – and already in place, at least for discussing noise emissions from aviation (cf. DE-I2, DE-P1).

For the upscaling of SAF production at the German hub, including its intermediary products, the provision of infrastructure by the state and energy suppliers is of great importance. Although renewable energy generation has increased sharply in recent years, mainly due to offshore wind farms in northern Germany, the transport of renewable energy has been slow. This is because the necessary power lines are not widely available. This is due to political decisions made by the German government, a lack of social acceptance and bureaucratic hurdles. The last German government postponed the construction of a hydrogen infrastructure from 2028 to 2035 (cf. DE-I1). This makes the German energy infrastructure a significant barrier to the energy transition. These barriers show that there is currently no business case for producing and using SAF and its intermediary products. Consequently, industry stakeholders argue that the state must provide risk protection, necessary infrastructure, start-up financing and reliable planning.

Decisive potential drivers or barriers also lie in the areas of job creation and skills development. The Höchst Industrial Park is home to companies of various sizes, ranging from 2 to 7,000 employees, with a total employment of 20,000. However, the number of employees is expected to decline overall in the coming years, partly due to rising energy prices, which pose major challenges for the hub's chemical companies in particular. However, the demand for personnel is rising among SAF producers. It is expected that digital skills and engineering skills, as well as high demands on lifelong learning among employees, will become increasingly important in the coming years.

3.3 Basque hub

The Basque Country is one of the largest industrial concentrations in Europe, with a significant presence of energy-intensive and emission-intensive sectors. In the framework of innovative regional strategies and cooperation, last year, a group of Basque companies decided to explore specific cross-sectoral synergies and joined the European project IS2H4C. The H4C in this region and so-called Basque Industrial hub for Circularity (BIH4C) involved in this project is comprised of ten companies from the oil refining, steel, paper, and lime sectors. Within the Basque hub, three primary industrial synergies are being explored in real environment: Firstly, trials will be conducted using oxy-combustion and hydrogen burners for ladle preheating a steel plant located in the Basque country. Secondly, the development of a carbon capture solution is pioneered, specifically tailored to the needs of the lime industry. This initiative seeks to integrate advanced CO_2 capture technology into the facilities, enabling the efficient reduction of carbon emissions in the production of lime. The captured CO_2 will subsequently be utilised in an innovative process of steel slag carbonation. Thirdly, in addition to its application in steel slag carbonation, the captured CO_2 demonstrates significant potential in the production of synthetic fuels through methanation. This process converts carbon dioxide into methane by combining it with hydrogen derived from renewable sources. The resulting synthetic fuels can serve as a sustainable energy carrier, reducing reliance on fossil fuels. The versatility of this technology highlights its applicability across a wide range of industries, fostering innovation, and promoting a greener energy transition. Another key objective of the Basque hub is the continuous exploration of new synergies through the incorporation of additional stakeholders, thereby demonstrating the potential for cross-sector innovation to drive sustainability across various industries.

3.3.1 Key stakeholders

The stakeholders listed below are driving a transformative shift that is establishing the Basque region as a leader in IS. Through collaboratyeyees, technological advancement, and the alignment of economic and regulatory interests, they are paving the way for a sustainable, resource-efficient industrial future.

a) Industry

Industrial stakeholders are at the forefront of integrating innovative processes such as waste valorisation, electrolysis, CO_2 capture, and hydrogen-based heating. These technologies not only reduce operational costs but also generate valuable by-products, enhancing economic and environmental outcomes. A good example is the Net-Zero Basque Industrial SuperCluster (NZBISC), led by the Basque Government–SPRI in collaboration with B-I7 and B-I6, which accelerates industrial decarbonisation while fostering new business opportunities for technology and service providers (cf. B-I4). The strong focus on waste repurposing reflects a commitment to lowering dependency on primary materials and addressing local environmental concerns. By aligning practices with evolving regulatory frameworks, industries ensure long-term environmental stewardship and resource efficiency. Clusters act as facilitators of cross-sector innovation, leveraging their influence to promote decarbonisation and the adoption of secondary raw materials. Through the dissemination of information on funding mechanisms and the organization of collaborative R&D programs, clusters enhance regional competitiveness and economic resilience. Their role is critical in stabilizing supply chains, reducing material imports, and unlocking significant cost savings, particularly for high-impact sectors like steelmaking, automotive, and aerospace.

b) Policy

Public authorities play a pivotal role in enabling a green transition in the Basque country. Their support for R&D funding and decarbonization incentives drives systemic change, aligning public policies with industrial needs. This proactive approach facilitates the emergence of competitive value chains, integrating circular economy principles and reducing emissions across sectors. In particular, the Basque Government and its business development agency (SPRI) lead strategic initiatives such as the Net-Zero Basque Industrial SuperCluster, and public agencies promote industrial symbiosis through funding programmes, sector studies, and strategic guidance for collaboration between industries (cf. B-I3, B-I4).

c) Academia

Research centres complement this ecosystem by advancing low-TRL technologies into practical industrial solutions. Their strategic focus on technological development, economic feasibility, social acceptance, and regulatory readiness ensures that innovations are not only market-ready but also widely adopted. This alignment between research and industry strengthens the technological foundation necessary for IS, bridging the gap between scientific discovery and real-world application.

d) Society

Society plays a decisive role in the successful implementation of industrial symbiosis in the Basque hub. Public acceptance is often a prerequisite for the introduction of new technologies, yet social resistance has repeatedly delayed or prevented projects. For example, the expansion of renewable energy plants, the establishment of CO_2 storage facilities or the construction of waste recycling plants (cf. B-I1). A striking example is the resistance to the planned paper waste plant in Bergara, despite several paper companies wanting to jointly promote a circular economy project (cf. B-A1). Transparent communication, sustainable operating methods and tangible reductions in environmental impact are necessary to meet the growing environmental demands of local communities (cf. B-I1). At the same time, the availability of skilled workers is crucial for operating and maintaining new technologies (cf. B-I2, B-A1). Targeted involvement, educational opportunities and participatory planning processes can strengthen the necessary social trust and thus ensure the long-term resilience of the region.

3.3.2 Drivers and barriers

A key driver of industrial symbiosis in the Basque hub is the close public-private partnership based on long-standing cooperation between public authorities and private companies. This combines the complementary strengths of both sides – from the technical and financial capabilities of industry to the creation of favourable market conditions by government actors (cf. B-I3, B-I2, SPRI). Strategic alliances such as the *Net-Zero Basque Industrial Super-Cluster* and the *DCARTECH Alliance* promote cross-sector exchange and the development of new decarbonisation technologies (cf. Basque Energy Cluster, SPRI). Research institutions such as TECNALIA also contribute significantly to the implementation of innovative IS concepts through technology-oriented projects and the further development of low-TRL solutions (cf. B-A1).

Another success factor is the hub's strong technological focus. Innovation-driven clusters such as the Basque Energy Cluster are committed to developing new processes, for example for resource efficiency, waste recycling and the use of by-products (cf. B-I4, B-I1). The strategic geographical location, integration into international initiatives such as the Ebro Hydrogen Corridor, and extensive training measures in the field of hydrogen also strengthen competitiveness and international networking (cf. B-I5). Initiatives to promote renewable energies, efficient use of energy and resources, and platforms for knowledge transfer and trust-based cooperation complete the foundation for a resilient, innovative and sustainable industrial system (cf. B-P1, B-I2, B-I1).

Despite the strong commitment to sustainability and collaboration across industries and the supporting work of clusters, public authorities, and research centres, the path towards a fully integrated model of IS is not without challenges. While there is a shared vision of innovation and resource efficiency, stakeholders have identified several risks and barriers that could hinder the successful implementation of these initiatives. The economic barrier of high capital and operational costs expenditures (CAPEX and OPEX) remains a significant concern, particularly in relation to emerging technologies such as hydrogen production and CO_2 capture. The need for substantial infrastructure investments, including upgrades to electrical grids and the development of hydrogen pipelines, adds to these financial pressures. Without clear business models that demonstrate both economic and strategic benefits, companies may be reluctant to adopt circularity schemes.

Technological readiness also poses a challenge, as many of the solutions required for IS are still in their developmental stages. Ensuring a continuous integration into existing processes requires further technological maturation and careful risk assessments to avoid operational disruptions. The absence of robust hydrogen distribution networks and CO_2 storage facilities further complicates logistical planning, particularly in regions where production and consumption sites are geographically separated.

Moreover, regulatory and bureaucratic inefficiencies exacerbate these challenges, with slow permitting processes and unclear legal frameworks leading to significant project delays. In the hydrogen sector, this has been particularly evident, as regulatory uncertainty and rising financing costs have slowed development, despite the growing portfolio of decarbonisation projects.

As already mentioned above, social resistance is another recurring barrier in this hub, with opposition to new renewable energy installations, waste management facilities, and CO_2 storage sites reflecting broader public concerns. Potential strategies for overcoming this resistance include public consultations, educational campaigns, and partnerships with community organisations to foster dialogue, build trust, and address these concerns proactively. To overcome these barriers, strong public-private collaboration will be essential. Coordinated efforts between governmental institutions and private entities are needed to develop supportive regulatory frameworks, streamline permitting processes, and create incentives that facilitate IS. Addressing these risks and barriers will be crucial for transforming the Basque region into a leader in sustainable industrial ecosystems, paving the way for a resilient and resource-efficient future.

For the development of the Basque hub, it is also important to successfully manage upcoming changes in terms of employment and skill requirements, in order to avoid potential bottlenecks in this regard. The analysis shows that, as the main aim of the synergies in the Basque hub is to demonstrate the use of hydrogen and oxygen, the domain of significant employment changes will take place in these areas. By 2027, new skill requirements are expected to focus primarily on handling new equipment, while new tasks are also expected to arise in the production process and in equipment maintenance. New skills in the field of safety are also important in the Basque hub.

3.4 Turkish hub

The Turkish hub is located in the Izmir-Manisa region, an industrialised port area on the Aegean coast. The region is heavily characterised by oil refineries and the production of household appliances. This context provides ideal conditions for the use of waste and by-products as resources. The Turkish hub focuses on several key areas that drive innovation and sustainability in industrial processes. One major focus is CCU, where adsorption technologies are employed to capture CO_2 emissions from oil refineries. This captured CO_2 is then repurposed to produce e-methanol, a sustainable alternative to conventional fuels and chemical feedstocks. Another central theme is the production of green hydrogen, generated through electrolysis powered by renewable energy sources. Green hydrogen serves as a critical raw material for various industrial applications and plays a significant role in decarbonisation efforts. By combining these innovations, the hub facilitates the production of e-methanol, which integrates captured CO_2 and green hydrogen to create a versatile and eco-friendly product that supports a circular economy.

3.4.1 Key stakeholders

a) Industry

Industry stakeholders are contributing significantly to the success of the Turkish hub and comprise different sub-stakeholder groups. Industrial companies in the Turkish hub provide the technological, material and organisational basis for IS projects, which includes the provision of hydrogen and CO_2 capture processes for the production of polymers and e-methanol, or the development of innovative chemical products (cf. TU-P1). Technology providers support these efforts by supplying specialised technologies and solutions for waste recycling, resource efficiency and sustainable production (cf. TU-I3). Industry associations play a key role by networking companies and promoting the exchange of knowledge and technologies (cf. TU-I2, TU-I3). Suppliers in the Turkish hub are crucial for providing the raw materials, technologies and services required to implement sustainable processes, while customers in the Turkish hub drive companies' innovation and production strategies through their specific requirements (cf. TU-I1, TU-I2, TU-P1). Electricity suppliers are also crucial to the operation of the Turkish hub, as electricity is the most important raw material for the production of industrial gases such as hydrogen and has a significant impact on the efficiency and sustainability of industrial processes (cf. TU-I2).

b) Policy

Key policy actors in the Turkish hub include local and national authorities, which contribute to the implementation of projects through regulatory measures, infrastructure investments and strategic support. National ministries develop the legal framework necessary for IS and the circular economy and also promote projects through political support and governance mechanisms that enable sustainable development. Local authorities, on the other hand, play an important role in providing local infrastructure, supporting approval procedures and cooperating with companies and organisations. Regional economic development agencies are also of central importance, particularly in the areas of financing and infrastructure provision, as well as for the coordination of IS projects (cf. TU-I3, TU-I2, TU-P1).

c) Academia

The group of Academia comprises universities, research institutions and external experts who make a significant contribution to the implementation of projects in the Turkish hub through their scientific expertise and technological innovations. This interest group is crucial for the development and implementation of new technologies for waste recycling and for increasing resource efficiency. Universities and academic institutions in the region, for example, provide research capacities and work closely with companies in the Turkish hub. These partnerships promote the development of new technologies and strengthen innovation in the circular economy (cf. TU-I1, TU-I3, TU-P1).

d) Society

Stakeholders from society play a decisive role in ensuring social acceptance and support for the Turkish hub's projects, promoting dialogue between industry and society, address concerns and raise awareness of the benefits of IS and the circular economy. Non-governmental organisations (NGOs), for example, play an important role in fostering cooperation between different stakeholders and further developing sustainable practices. The public and local communities are also important stakeholders in the Turkish hub, as their acceptance and support are crucial to the success of IS projects (cf. TU-I2, TU-I3).

3.4.2 Drivers and barriers

Stakeholders in the Turkish hub operate in a complex network of interdependencies and synergies that form the basis for the success of IS and circular economy projects. The regulatory environment thereby has a significant influence on the activities and decisions of stakeholders in the Turkish hub. National entities enforce laws and regulations designed to promote IS and sustainable practices. At the same time, regulatory uncertainties, such as changing regulations or unclear legal requirements, can slow down projects and complicate investments. These challenges particularly affect industrial companies that have to bear high costs for adapting to new standards, as well as suppliers that have to provide technological solutions to meet legal requirements (cf. TU-I3, TU-P1, TU-I1, TU-I2). Regional economic development agencies have a balancing effect in this regard by developing funding programmes and providing financial resources to facilitate compliance with regulatory requirements. Such support measures help companies to meet legal requirements while maintaining their economic competitiveness. Despite these efforts, regulation remains a double-edged sword. On the one hand, it drives sustainable innovation. On the other hand, it can create bureaucratic and financial barriers. (cf. TU-I3, TU-P1, TU-I1, TU-I2).

Customer demands significantly influence the strategic decisions of companies in the hub, while suppliers also play a central role by providing raw materials, technologies and services for sustainable production processes. Companies thereby work closely with suppliers to integrate innovative materials and technologies (cf. TU-I3, TU-I1).

The Material Marketplace Turkey (TMM) online platform connects companies and promotes the exchange and reuse of waste materials and resources. Although the platform itself is not a stakeholder group, it is a tool worth mentioning, which enables companies in the Turkish hub to achieve their recycling targets while increasing resource efficiency. The Material Marketplace Turkey serves as an example for platforms that create synergies between different actors, including companies, NGOs and academic institutions, and help to reduce costs and promote the circular economy. It facilitates the identification and implementation of industrial synergies, which is particularly beneficial for new companies in the hub (cf. TU-P1, TU-I3).

Universities and research institutions contribute to the optimisation of processes through research and development. These partnerships drive the introduction of new technologies and strengthen the innovation capacity of the hub. Academic institutions also provide technical knowledge and scientific support for the development of sustainable solutions (cf. TU-P1, TU-I1).

Despite the strong synergies in the Turkish hub, challenges remain. A recurring problem is the lack of trust and a partly insufficient and ineffective communication between stakeholders, especially when using waste materials, which negatively affects the smooth implementation of projects and leads to resistance for new initiatives (cf. TU-I3, TU-P1, TU-I1). One of the interviewees explains in more detail how the use of recycled materials can lead to trust issues among customers: There are concerns about the quality of recycled materials and doubts that they can match the original raw materials in terms of durability, reliability and performance (cf. TU-I3). Furthermore, regulatory hurdles and diverging interests between actors (in that the long-term goals of stakeholders often are not aligned) often cause delays in projects. Additionally, a lack of societal awareness and resistance from local communities can complicate the feasibility of IS projects (cf. TU-I3).

Regarding changes in the area of job creation, it is essential for the Turkish hub to coordinate industry needs with universities and other continuing education providers to prevent skill gaps from arising and to successfully match supply and demand. At the same time, the analysis shows that blue-collar jobs in Turkish industry will increasingly be automated. This shows a visible trend in the whole Turkish economy which is also relevant in the hub, bringing both challenges in terms of workforce transition and opportunities for creating higher-skilled positions.

4 Discussion

The analysis of stakeholders in the four hubs show that societal actors are a crucial aspect of circular processes [8]. In the context of this research, we observed that analysing multiple stakeholders is relevant, of course [6,7,9], but this is not enough. It is also necessary to actively engage stakeholders with social concerns, which are usually related to safety and environmental impacts. Such concerns also impact the acceptance or rejection of new technologies or energy production methods. As we saw in the literature, the NIMBY phenomenon impacts consumer acceptance. For example, passengers show limited trust to airlines to handle the additional charges they pay for sustainable aviation fuel SAF and carbon offsetting responsibly. Instead, other potential stakeholders who enjoy greater trust among passengers should also be included.

At the same time, a holistic approach, as suggested by previous research [11,13], indicates that stakeholder engagement in this study was carried out at a regional level within the analysed hubs. This involved municipal stakeholders and local citizens, thereby contributing to urban–rural relations. A good example is the Dutch hub, where local community organisations and citizens were engaged, as well as local universities and municipal stakeholders, including local and regional ones. In other hubs, engagement formats were also used to address concrete barriers: in the Basque hub, public–private collaboration and dialogue-oriented approaches were applied to respond to social resistance and regulatory complexity. In the German hub, established transparent dialogue formats and demands for state-backed risk protection aimed to reduce investment uncertainty; while in the Turkish hub, regional development agencies supported compliance through targeted funding schemes and coordination with universities helped to address emerging skill gaps.

Across all hubs, similar structural role patterns can be observed, with industry acting as a central implementing actor, often dependent on regulatory stability and economic incentives, academia contributing technological expertise, public authorities shaping the regulatory and planning framework, and societal actors influencing acceptance and legitimacy. However, the way these roles interact and gain relevance differs substantially across regional contexts.

This research thereby highlights clear differences in the focus and organisation of the hubs. The Dutch hub prioritises early involvement of local communities and municipalities and relies on living-lab formats to test technologies in real-world settings and build acceptance. In contrast, the German hub is primarily driven by industrial implementation, with regulatory requirements and market demand acting as key drivers of stakeholder engagement. The Basque hub is characterised by a highly coordinated, strategy-led collaboration among energy-intensive industries, supported by established cluster structures and public policy. The Turkish hub focuses mainly on industrial development and economic competitiveness, with particular emphasis on establishing stable organisational, financial and regulatory conditions for industrial symbiosis.

Our research also shows that governance structures are relevant for managing diversity among stakeholders [24], as well as diversity among companies and regulations. In this research, therefore, H4Cs play a key role in centralising this function within H4C management, for example, we analysed current governance structures in hubs (such as multi-stakeholder approaches like competence centers, and stakeholder platforms? clusters across different hubs), grouped them together, and used them to address identified stakeholder issues. Although the importance of stakeholder engagement in the transition to a circular economy is widely recognised, its practical implementation, particularly in regional and cross-sectoral contexts, has been under-researched [13]. This research, therefore, conducted within the context of the IS2H4C project, explicitly addresses the practical implementation of this transition. This includes conducting an initial stakeholder analysis, identifying current governance structures, and bundling them into a concrete space for the co-creation of solutions and identifying potential new local-regional partnerships.

4.1 Outlook

This study lays the groundwork for understanding the non-technological factors that influence circularity hubs, and contributes to answering the general question of how stakeholder participation can support and accelerate the development of these hubs. As mentioned in the introduction of this research, stakeholder participation plays a key role in the development of industrial symbiosis [15], and through this research we observed that the active participation of relevant stakeholders requires new forms and structures for continuous participation.

Therefore, future lines of research show the need to use participatory research methods in circular economy processes. For example, we will conduct more research on Living Labs, where participatory research is documented in real time through workshops and experimental spaces where different stakeholders are invited to discuss. These are often moderated in a semi-structured manner to identify perceptions of barriers and drivers, a process that facilitates even more tangible discovery and enables the co-creation of solutions. Barriers often arise from the different positions of various stakeholder groups, which need to be managed in the context of living labs.

Our research not only contributes to analyse who the key actors are, but also what their main concerns are, a process that facilitates industrial symbiosis with circular processes. This research also contributes to a better understanding of the extent to which social aspects of circular processes can drive or even hinder policy implementation, and how important such stakeholder engagement is.

4.2 Summary of results

The results show that the main drivers of stakeholder engagement can be regulatory frameworks, such as the ReFuelEU Aviation regulation in the German hub, and infrastructure delays. Industrial clusters (e.g. the Basque hub) and companies (e.g. the Turkish hub, German hub) also play an active role, as do trade unions (e.g. the German hub) through advocacy for societal acceptance. But also, coordination between local and regional authorities, including universities and research institutes, is crucial in creating a sustainable and inclusive environment that engages all stakeholder categories, including society, academia, industry and policy (e.g. the Dutch hub)

The main barriers are varied. High investment costs and uncertainty surrounding long-term financing hinder the scalability of hydrogen technologies and sustainable aviation fuel. All hubs face challenges relating to the complexity and instability of regulations, particularly the Turkish hub. This undermines stakeholder trust, especially among investors and private companies. Technical limitations, such as system degradation in electrolysis (Dutch hub) and a lack of renewable energy transport infrastructure (German hub), further restrict implementation. Additionally, the shortage of skilled labour and limited public acceptance particularly regarding safety and environmental concerns, pose ongoing social and implementation obstacles.

The key stakeholders in all hubs demonstrate a strong industrial presence. In the case of the Dutch hub, civil society is strongly represented by citizen cooperatives and local communities that support the adoption of hydrogen systems. By contrast, the Basque hub leans towards industrial clusters and public policy alignment, whereas the Turkish centre is characterised by a more diverse supply chain and more active company stakeholders The German hub is characterized by a broader landscape of industrial stakeholder, policy makers and public authorities, research institutions and civil society.

We observe interdependencies between stakeholders that can be translated into barriers. For example, industry requires policy stability and societal approval, while policymakers rely on its innovation capacity. Academia bridges technological gaps, and societal actors influence implementation through acceptance (e.g. all hubs).

The successful deployment of H4C therefore depends on these groups acting in coordination, underpinned by trust, inclusive governance, and shared risk. In this context, a relevant form of governance we observed, and is currently under research, is the form of living labs, which are regional exchange and working formats with key stakeholders from all categories (industry, policy, academia, civil society). They will be set up in all four H4Cs of the IS2H4C project.

A deep understanding of intangible resources involved in circular solutions are essential for the success of H4C. At the Dutch hub, local trust, community involvement and academic expertise have been key enablers. However, similar to the Basque and Turkish hubs, shortcomings remain in terms of public trust, regulatory transparency and the availability of technical expertise. In the German hub, there is strong technical expertise and active public debate, but confidence in long-term regulatory stability and investment security is limited. Unreliable planning, coupled with public concerns about large-scale infrastructure projects, is an obstacle to progress.

Overall, most hubs stakeholders emphasised the need for a long-term commitment, transparent governance and the development of skilled human capital to ensure the successful implementation of H4C.

The final point regarding job creation and skills development is crucial for achieving a long-term, resilient transformation. As we saw in the different hubs, learning communities are already active (e.g. the Dutch hub), analysing changes in current and future skill requirements for this transformation. This aspect is important not only for long-term planning, but also for addressing societal and worker concerns about job losses or changes in job skills (e.g. the German hub), and for developing the necessary skills, which have high standards in terms of security and environmental issues, as well as handling new equipment (e.g. the Basque hub). Finally, this also demands new partnerships between companies, universities and educational institutions to create a balance between the demand for and supply of such new skills (e.g. Turkish hub).

These findings suggest that that successfully implementing H4C depends on incorporating industrial symbiosis principles and circular economy strategies into governance structures that facilitate inclusive, trust-based collaboration between industry, policymakers, academia, and civil society. By addressing underlying social barriers through regulatory stability, economic viability, infrastructure investment, human capital development, and job creation, this study makes a valuable contribution to the existing literature on industrial symbiosis and the circular economy. It emphasises the importance of region-specific, multi-stakeholder coordination in the context of H4C, taking into account regional and local factors. To achieve joint value creation, as seen in the literature [14], there must be societal awareness of the economic, environmental and social value created through different circular technologies and circular practices. This will also help to improve understanding of the complexity of such processes, which involve appropriate regulation and expensive infrastructure, but which can contribute significantly to sustainable transitions in European countries. In our research, the dimension of power, as described by [22], was not analysed in depth. However, this dimension needs to be studied further in order to change power structures and facilitate transitions.

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Conflicts of interest

The authors have nothing to disclose.

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The data associated with this article cannot be disclosed for legal and ethical reasons. Therefore, the results from the interviews were anonymised.

Author contribution statement

Conceptualization, M.K, A.G, and K.M.; Methodology, M.K, A.G, and K.M.; Investigation, M.K, A.G, and K.M.; Writing – Original Draft Preparation, M.K, A.G, and K.M.; Writing – Review & Editing, M.K, A.G, and K.M.; Funding Acquisition, M.K.

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