From Atoms to Allies:
A network analysis of how collaboration shapes circular innovation

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1. Background

- Industrial Symbiosis (IS) promotes circular resource exchange between industries.
- Its success depends on trust, communication, and knowledge sharing.
- H4C extend this idea into **regional H4C**, uniting *industry, policy, research, and communities* to advance carbon-neutral transitions.

2. Research gap

- Studies focus on material flows, but communication and knowledge sharing remain underexplored.

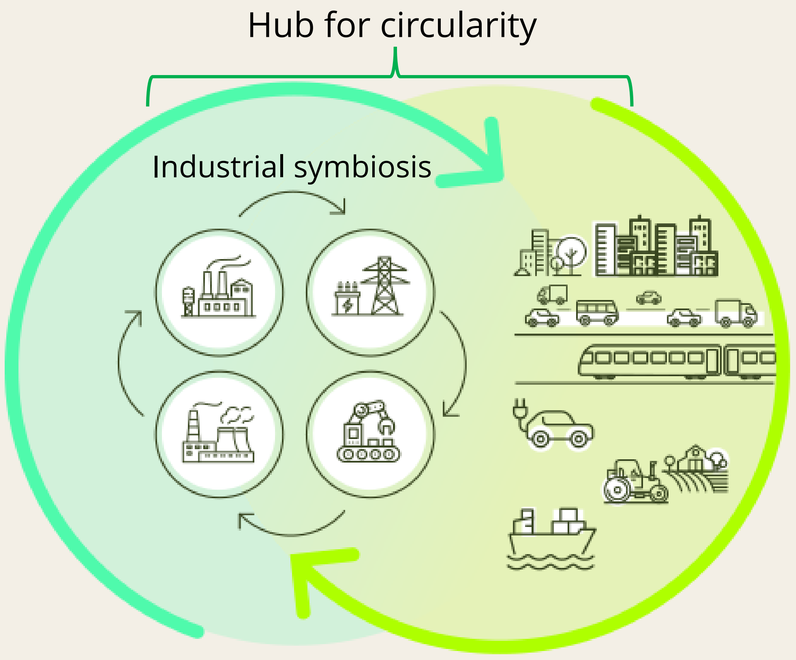

Fig 1. IS (industrial stakeholders) → H4C (various stakeholders)

3. Research aim

- We map how stakeholders connect and exchange knowledge in four H4C using Social Network Analysis to reveal structure and roles.

4. Methods

Two networks analysed across four H4Cs – **resource flows** and **communication** links.

Social Network Analysis (NetworkX, Python):

→ Centrality (influence)

→ Structural holes (bridges)

→ Core–periphery (hierarchy)

5. Results

- Resource production is **locally implemented**, yet relies on **international knowledge inputs** from research actors.
- Communication is **cross-hub and research-driven**, linking dispersed stakeholders.
- Highly central nodes include **research institutions** and **industrial partners**, bridging between diverse stakeholders.
- Networks show a **core–periphery pattern**, with limited peripheral collaboration.

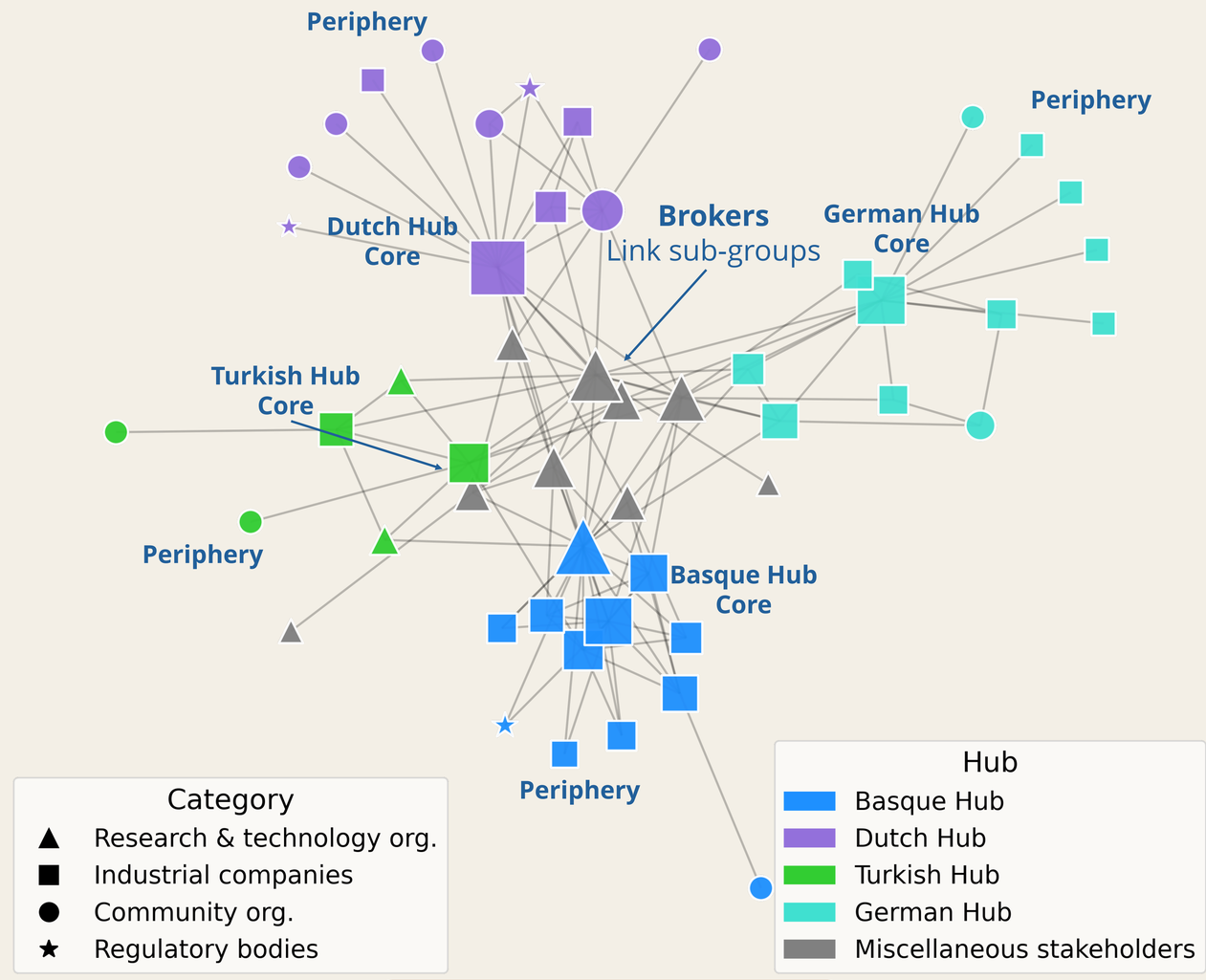

Fig 2. Communication network of H4C

6. Discussion

Difference between H4C & IS networks

Characteristics	H4C networks	Traditional IS networks
Network structure & communication	Dual-layered: dense within hubs, sparse between; links often via research actors.	Dense inter-firm exchanges within industrial clusters.
Resource flows & geography	Resources local; knowledge and communication global.	Resources local and confined to industrial zones.
Stakeholder & knowledge roles	Mix of industry, research, community, and regulators.	Industry-led; others marginal or absent.
Governance	Multi-core, shared across stakeholder types.	Centralized around dominant firms or sectors.
Innovation & strategic focus	Systemic, cross-sectoral, sustainability-oriented innovation.	Firm-led eco-efficiency and cost reduction.

What are the roles of stakeholders in H4C?

Actors	Characteristics
Industrial entities	Structurally central; act as anchor nodes.
Research & technology	Bridge actors enabling knowledge transfer.
Community actors	Central or peripheral depending on governance and engagement.
Regulatory bodies	Peripheral; influence through policy and funding.

H4Cs transform industrial symbiosis into collaborative ecosystems where *knowledge flows*, not just materials.

7. Call to action

Circularity is not only about technologies, it's about **how people**, organisations, and ideas **connect**.

→ How can we collaborate more effectively across sectors?

→ What helps trust and knowledge grow among different stakeholders?

→ How can innovation and inclusion go hand in hand in circular regions?

Tleuken, A., Rogetzer, P., Fraccascia, L., & Yazan, D. M. (2025). *From Atoms to Allies: A Social Network Analysis of Information and Knowledge Exchange in Hubs for Circularity.* Submitted to the *Journal of Industrial Ecology*, Wiley.

Acknowledgments
This project has received funding from the European Union's HORIZON Research and Innovation Actions programme under grant agreement number 101138473.